STRUCTURAL ANALYSIS OF COMPLEX AERIAL PHOTOGRAPHS

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A new system for the structural analysis of complex aerial photographs is presented. This system has the ability of focussing its attention of the analysis on the limited local areas where objects are highly supposed to exist. Several kinds of strong and typical features ire extracted, and these primary features of objects are combined to extract rough areas of the oblects. This focussing mechanism saves the total processing time and facilitates the detailed analysis. The recognition process of the system is Implemented according to the 'production system'. The knowledge sources in this system are object-detection subsystems which analyse their individually focussed local areas and recognize specific objects respectively. All the results of the analysis are written in the common blackboard, and the system finds out conflicts and recovers errors by backtracking to feature extractions and low level processings. This architecture enables us to organize smoothly the diverse knowledge required to describe the complex structure on the ground surface.

1. INTRODUCTION

Recently several systems for the analysis of aerial photographs have been developed to locate objects on the ground surface[1],[2],[3]. When we are going to get a description of the structure on the ground surface by analysing an aerial photograph, we find several difficulties which are not encountered in other image analysis areas:

(1) The size of a picture is very large.
(2) As It is impossible to control photographing conditions, the quality of a picture is apt to change.
(3) The sizes and the textural properties of objects vary quite widely.
(4) Variation of objects in a scene entails calculation of many different features and the diverse knowledge of the world.
(5) There are too many situations on the ground surface to build a general model which can represent all possible spatial arrangements of objects.

In order to overcome these difficulties and to realize an efficient and reliable analysis, we have developed a new system based on the ' production system[1][A], The system consists of a group of object-detect Ion subsystems which individually search for specific objects by communicating with each other via a common 'blackboard[1] [5],[6],

The analysis process of this system is divided into the following steps.

(1) Segmentation: After noise removal, an aerial photograph is segmented into elementary regions according to the multispectral property.
(2) Global survey of the whole scene: Regions with characteristic properties are extracted These are used to confine the spatial domains of objects where object-detection subsystems work.
(3) Detailed analysis of focussed local areas: Each object-detection subsystem focuses its attention on a specific local area and checks the existence of a specific object.
(4) Communication among object-detection subsystems: All the information about the properties of regions and recognized objects is stored in the blackboard. Object-detection subsystems interface with it In a uniform way. The system controls the overall flow of the analysis by managing the information in the blackboard. It solves conflict among object-detection subsystems, and corrects errors by backtracking.

This paper mainly describes the control structure of the system, and demonstrates its performance with experimental results. The detailed algorithms of picture processing routines are described in [7].

2. FOCUS OF ATTENTION IN THE ANALYSIS OF AERIAL PHOTOGRAPHS

Aerial photographs we want to analyse are A band multispectral images of complex suburban areas taken from the low altitude(Fig. 1).

As the size of a picture is very large, the analysis should be done as efficiently as possible. If each object-detection subsystem, which is very sophisticated and time-consuming, were applied to the whole picture area, it would take a prohibitive time to complete the analysis. In order to solve this problem, we adopted the focussing mechanism which human being seems to use when he interprets a complex scene. When he sees a scene, at first he globally surveys it to find the characteristic areas which attract his interest. Then, he goes into the detailed examination of some local area to find out objects using his knowledge of the world. The more intensively he focuses, the more specialized knowledge he comes to use.

In our system, several kinds of regions with prominent features(characteristic regions) are extracted by simple picture processing programs. Then, object-detection subsystems apply sophisticated programs only in the local areas where specific objects are supposed to exist. As the time-consuming processings are applied only in small local areas, the total processing time can be reduced very much. Fig.2 shows the schematic drawing of this focussing process.

Tn order to specify the spatial domains of objects as correctly as possible, we utilize such features as size, shape, brightness, multispectral properties, texture and spatial relations among regions. We extract seven types of characteristic regions, i.e. large homogeneous regions, elongated regions, shadow regions, shadow-making regions, vegetation regions, water regions and high contrast texture regions.

Fig.1 A picture of a complex suburban area

All the features used here are stable against the change of photographing conditions, and all parameters are automatically and adaptively determined from the picture data under analysis. Therefore extracted characteristic regions can be the reliable basis for the subsequent detailed analysis.

Fig.3 shows the characteristic regions extracted from the picture of Fig.l.

3. OBJECT-DETECTION SUBSYSTEM

An aerial photograph contains a variety of objects such as crop fields, forest areas, grass lands, roads, rivers, houses and so on. The diverse knowledge should be incorporated to describe the structure on the ground surface. In addition, these objects,especially in a small country as Japan, are intricately arranged without definite spatial relationships.

Taking these conditions Into account, it seems to be natural to divide the system into a group *of* object-detection subsystems. Each of them is designed to find out specific objects using the knowledge of their intrinsic properties and the environments in which they are embedded. The diverse knowledge of the world is distributed in object-detection subsystems. This facilitates the implementation of the system.

The type of object-detection subsystems can be classified into two categories according to the information they use in selecting the candidate regions of objects.

(1) Picture data-driven subsystem

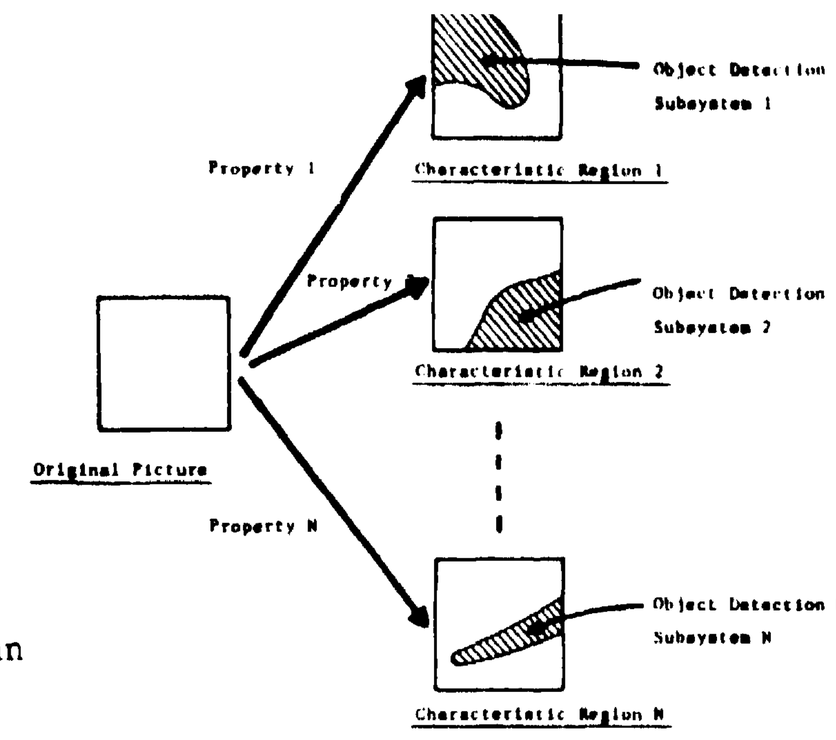


Fig.2 Focussing mechanism of the system

The subsystems of this type check the existence of the local areas with specified properties by combining characteristic regions. If there are such local areas, they examine them in detail by activating special purpose feature extraction programs.

(2) Model-driven subsystem
The subsystems of this type pick up the candidate regions by using the spectral and spatial relationships with already recognized objects. For example, it is very difficult to detect cars by a simple knowledge that they are rectangular unless we impose the condition that they are on the roads or the parking lots. Therefore the subsystem for the detection of cars entails the recognition of roads or parking lots.

The present system has thirteen object-detection subsystems for eight kinds of objects: crop field , bare soil(crop field without plantation), forest, grass land, road, river, car and house. Fig.4 shows intermediate results of detection of these objects.

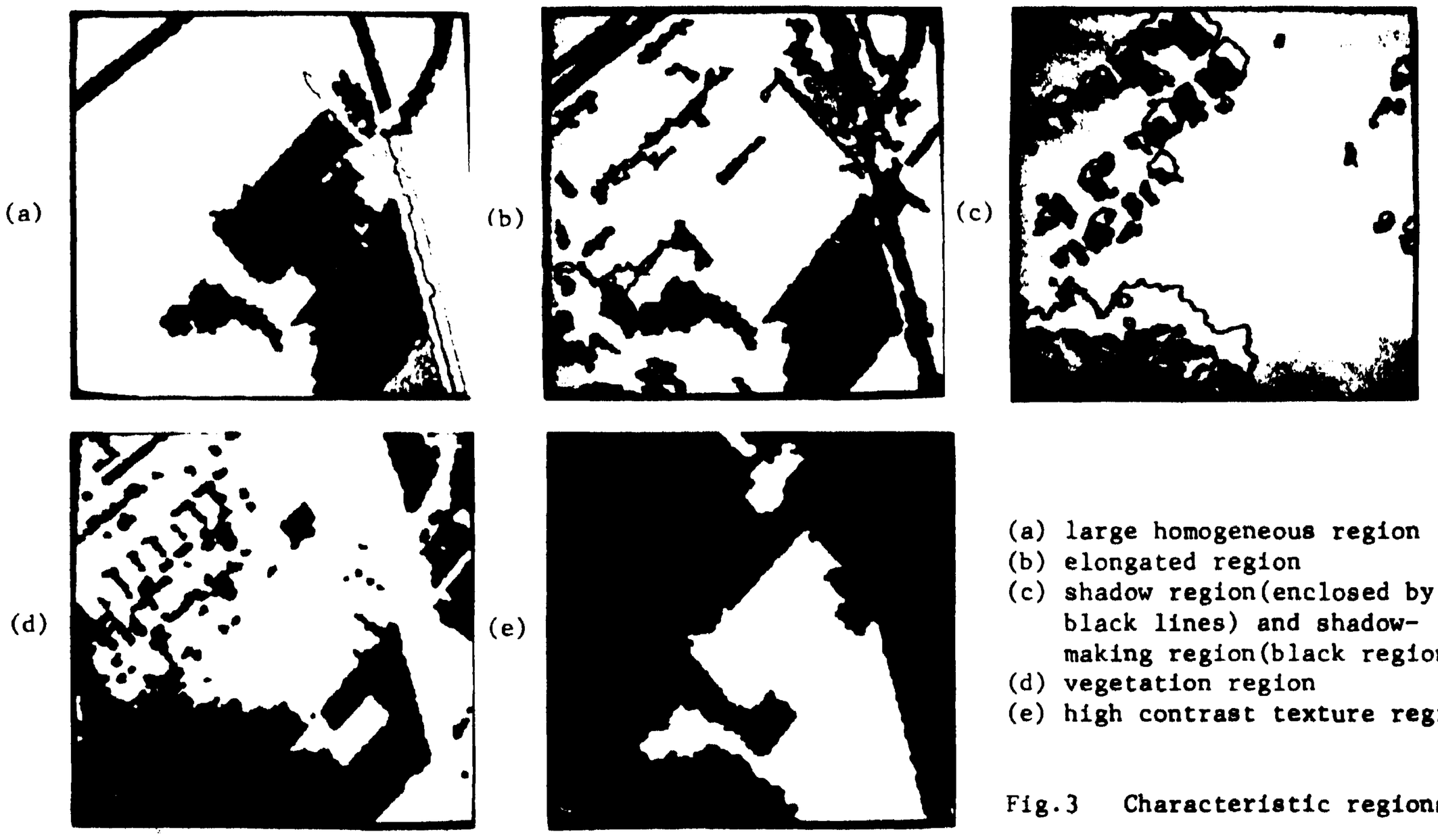
4. THE STRUCTURE OF THE BLACKBOARD

Each object-detection subsystem interfaces with the common data base, the blackboard, in order to test conditions for activation and to write in the result of the analysis. All the communications among object-detection subsystems are made via this blackboard. Fig.5 shows the schematic drawing of the structure of the blackboard

The blackboard contains global parameters as well as the properties of regions and objects. They denote the global properties of the picture data, that is, photographing conditions of an aerial photograph such as the direction of the sun, threshold values for checking the similarity of multispectral propreties and so on. From these global parameters, each object-detection subsystem gets the information of the quality of the picture data under analysis. Therefore, it can successfully find out objects in spite of unstable photographing conditions of aerial photographs.

In this system, elementary regions, which are segmented according to the multispectral property in segmentation, are considered as the basic units for all higher level processings. Their fundamental properties(the average gray level in each spectral band, size, location and some basic shape features) are stored in the property table in the blackboard(Fig.5).

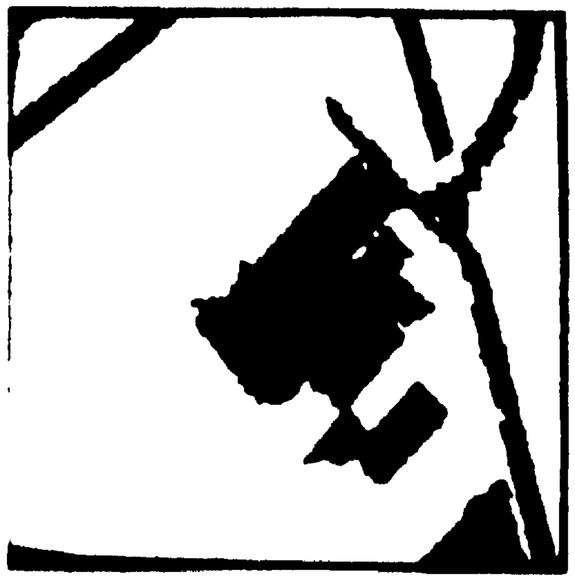
We store LABEL PICTURE in the blackboard in order to denote the spatial relationships among elementary regions. It is the symbolic



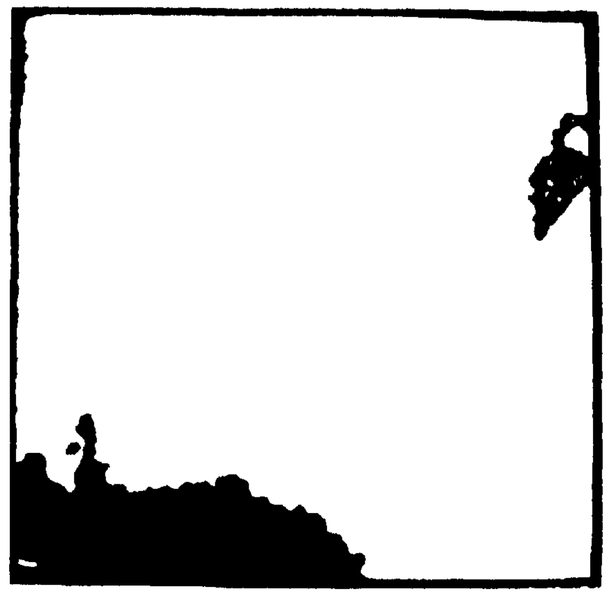
(a) large homogeneous region
(b) elongated region
(c) shadow region(enclosed by black lines) and shadow-making region(black regions)
(d) vegetation region
(e) high contrast texture region

Fig.3 Characteristic regions

(a) crop field



(b) bare soil



(c) forest

(d) grass land

(e) house

(f) road and car
(denoted by "C")

Fig.4 Intermediate results of object detection:
Several regions are recognized as different objects.
These conflicts are solved by the system(see Sec.5).

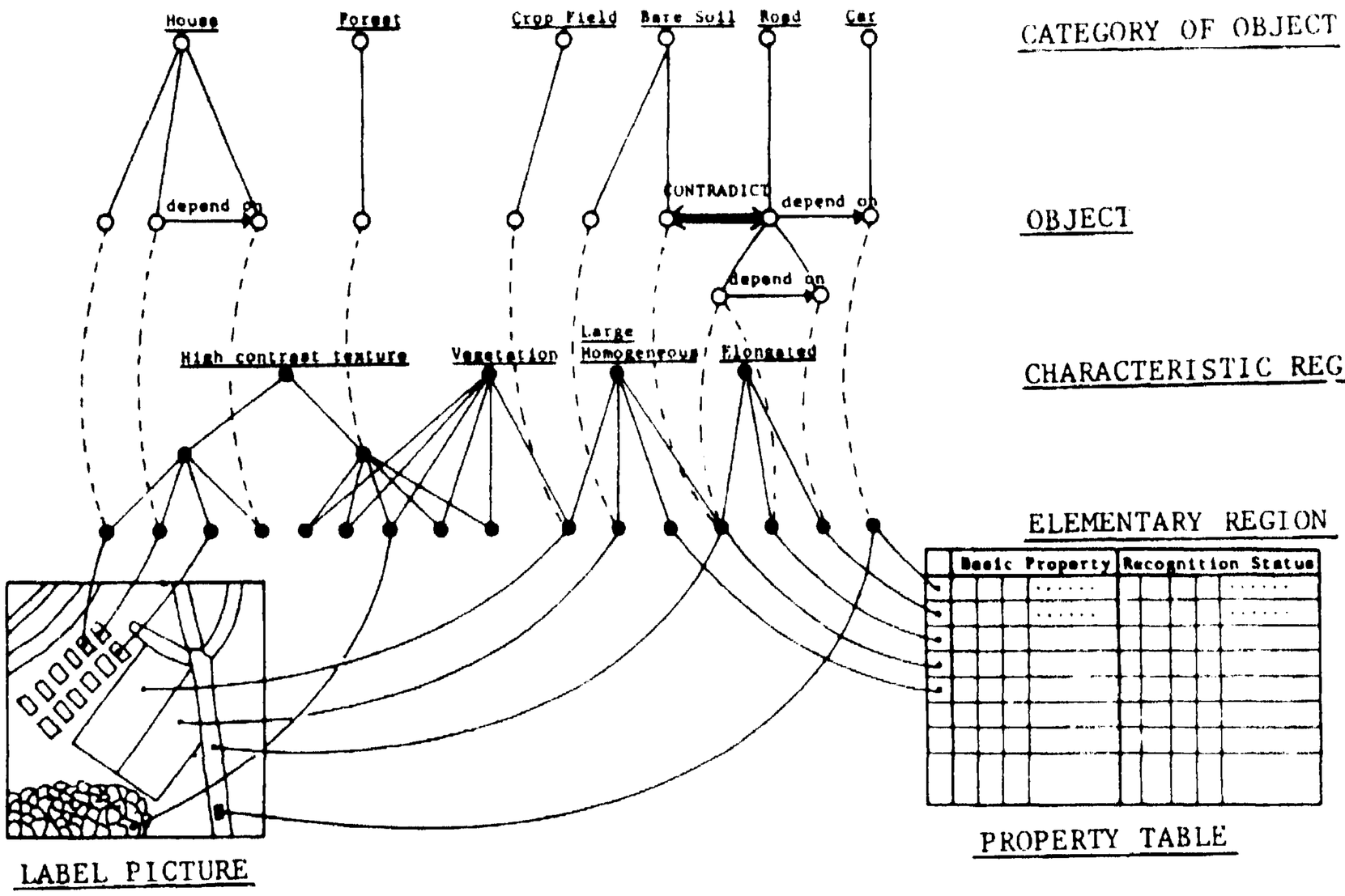


Fig.5 Structure of the blackboard

picture where each pixel in an elementary region is labeled with the same unique region number(Fig.6). The reason for this is:

The spatial relationships among regions used by object-detection subsystems are very different and depend on the properties of objects they want to find out. Therefore it is not economical, and is even sometimes impossible to calculate- all spatial relationships in advance. For example, when we want to estimate the location of a house by using the regurality of the spatial arrangement of already recognized ones, it will take a long time to find a candidate region of a house if we do not use the two-dimendional image.

As each pixel in LABEL PICTURE contains an unique region number,we can easily get the properties of the region to which it belongs. On the other hand, the location of a region in LABEL PICTURE is denoted by the two coordinate pairs,(BX,BY) and (EX,EY), in the property table(Fig.7). When one wants to calculate a new feature of a region, one only has to scan within the rectangle area specified by these coordinate pairs(Minimum Bounding Rectangle). This is very useful to save the processing time of picture processing programs.

Each characteristic region in the blackboard is represented by a characteristic region node which denotes a group of elementary regions. Two-dimensional images of characteristic regions can also be constructed from LABEL, PICTURE. These are very useful in locating clusters *of* elementary regions such as forest and residential areas.

When each object-detection subsystem recogni/es an object, it generates an object node in the blackboard, and the object node and its constituent elementary regions are connected by part/whole relations. If the recognition of an object depends on the properties of already recognized ones, the node of a new recognized object is linked with those of old ones(Fig.5). By storing the history of the. recognition process, the system c give back the state of the blackboard to the correct one when it finds out an error in it.

'3. CONTROL MECHANISM OF THE SYSTEM

As each object-detection subsystem recognizes objects independently of the others, the system incorporates the mechanism to solve conflicts between these subsystems.

The property table has the field where each object-detection subsystem returns one of the following recognition statuses: "unanalysed", "recognized", "irregular shaped" and "rejected", the system checks this field, and if some elementary region is recognized as different objects oy multiple subsystems, it evaluates the reliability value of each object to which that region belongs. Then the objects nodes except the most reliable one are deleted, and the corresponding recognition statuses of the region are changed from "recognized" to "rejected".

If there are other objects which have been recognized in connection with rejected objects, the system also deletes those object nodes by traversing the dependency links from rejected objects. In this case, the recognition statuses of their constituent regions are given back to "unanalysed", for they might be recognized by using the properties of the other objects of the same kind.

Errors in segmentation are also repaired by the system. Object-detection subsystems checks various properties of regions to recognize objects. They returns the recognition status, "irregular shaped", if the shape of a region is not suitable for an object while all the other properties

Fig.6 LABEL PICTURE: each pixel in an elementary region(enclosed by black lines) is labeled with an unique region number.

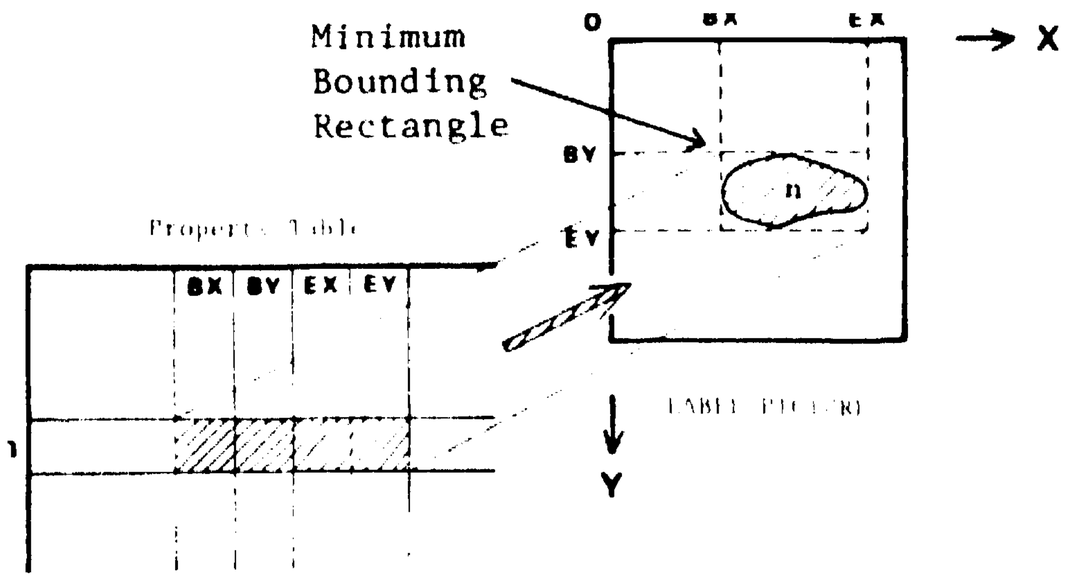


Fig.7 Specification of the location of an elementary region in LABEL PICTURE

are satisfactory. Then, the system re-analyses that region by applying the split/merge program. If the region has the bottle-neck as shown in Fig. 8, it is divided into small regions. If the boundary of the region is very rough and irregular (Fig. 9), neighboring small regions with the similar color are merged with it. These newly generated regions are added in the blackboard as temporary regions and analysed by object-detection subsystems. If a temporary region is successfully recognized, it is registered as a new elementary region in connection with its related object, and the original region is deleted from the blackboard If the result of the recognition of the new region contradicts with that of the original one, the system deletes one of them depending on the reliability. When the temporary region is not recognized, it is removed from the blackboard, and the corresponding recognition status ot the original region is changed to "rejected".

In the case of Fig. 8, the bottle-neck results from the error of mismerging two adjacent houses. When this region is splitted into two regions, the house detection subsystem comes to recognize them successfully. The region in Fig. 9 corresponds a crop field, but it is not recognized because of the irregularity of the boundary. After the merging process, it comes to take the smooth boundary, and is recognized as a crop field.

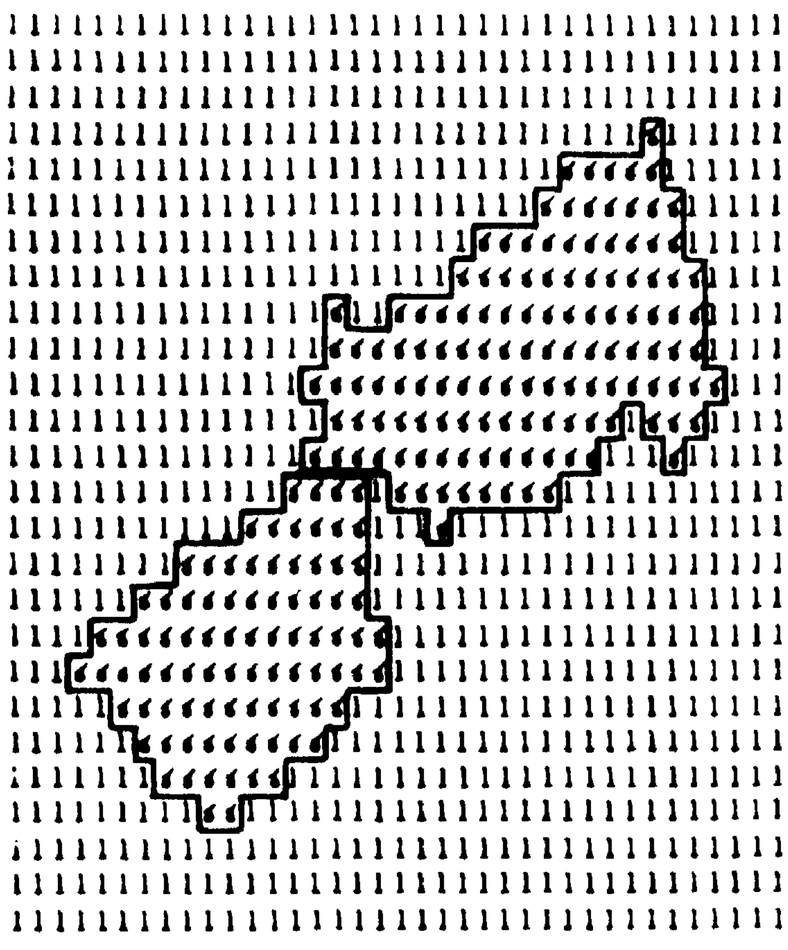


Fig.8 Splitting a region with a bottle-neck

By the benefits of the above-mentioned control mechanisms of the system, each object-detection subsystem can use the properties of already recognized objects without considering the results of recognition by the others. The system stops the analysis when no new objects are recognized.

Fig. 10 shows the final result of the analysis. Although white regions with no marks are left unanalysed, we can see that almost all objects which belong to clear semantic categories are successfully recognized. (As we do not have the ground truth data, the evaluation of the result is done by visual inspection.)

6. CONCLUSIONS

The system for the structural analysis of complex aerial photographs has been presented. The major conclusions on this system are the following:

(1) The focussing mechanism realizes the efficient analysis and successfully isolates objects. Table 1 shows the efficiency of this focussing mechanism.

(2) The production system architecture gives us the following benefits.

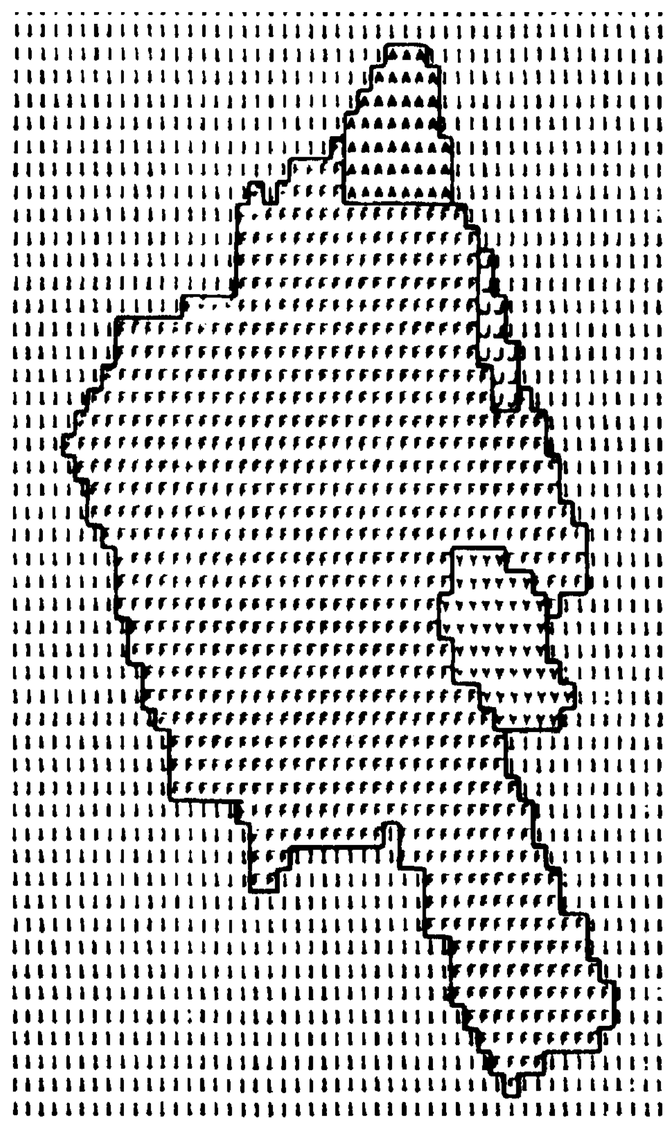


Fig.9 An irregular shaped region: the central large region is merged with neighboring saml1 regions.

A. Modularity : Diverse knowledge required to describe the structure of the ground surface can be individually Implemented in object-detection subsystems.
B. Model-driven analysis: We can use the proper ties of already recognized objects in order to analyse unrecognized areas and to find out contextual-dependent objects.
C. General control mechanism: The system takes the full responsibility for the maintenance of the blackboard. It solves the conflicts among object-detection subsystems and corrects the errors in segmentation. If necessary, it undoes the content of the blackboard to remove the effects of errors. These mechanisms of the system integrate mutually independent object-detection sub-systems.

This system is implemented on a large computer, FACOM M-190. The total CPU time was about 150 sec. in the picture of Fig.I. Experiments on several different aerial photographs have shown that this system works fairly well.

SCAN AREA	CANDIDATE REGION	TIME(sec.)
in MBR*	large homogeneous regions	0.14
whole area	large homogeneous regions	0.39
in MBR*	all regions	0.84
whole area	all regions	28.95

Table 1 Efficiency of the focussing mechanism:
Time denotes the processing time for the crop field detection subsystem to calculate straightness of region boundaries. As we focus only on large homogeneous regions, we can save process ing time very much.
* MBR denotes a minimun bounding rectangle(see Fig.7)

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Fig.10 Final result of the analysis:
White regions without mark are un-recognized (20% of the whole picture area)
BS: bare soil
(crop field without plantation)
CF: crop field
G : grass land
F : forest
RD: road
R : roof of a house
C : car
r : misrecognized roof
(these regions have similar multi-spectral properties to that of true roof)

S-NET : A FOUNDATION FOR KNOWLEDGE REPRESENTATION LANGUAGES

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A new knowledge representation scheme called S-Net is presented. The S-Net is a descendent of both semantic networks and recently developed AI languages. We are willing to introduce procedures into our network notations as FRL and KRL do. However, these languages have a serious disadvantage that the programmer should specify, explicitly by using indicators such as WHEN-FILLED, T0-F1LL etc., when the attached procedures are invoked. This results in the restriction of system's abilities of solving problems. To avoid this, the programmer should always pay attention to the overal control issues during the coding of his procedures. In our new formalism, the explicit specification is not necessary. The problem solver based on the S-Net dynamically determines which procedure is invoked when, according to the problem solving situations, not to the pre-specified indicators. We also discuss the problems of property inheritance through hierarchy. The inheritance mechanism provided so far is so restrictive that the programmer should do all things in his procedures. In the S-Net, the property inheritance is further augmented by the 'explicit path specification'. The detailed construction of the problem solver, which performs both forward and backward reasonings appropriately, is also given.

1 • INTRODUCTION

In this paper, we discuss a graphical notation called S-Net, which results in a foundation for recently developed AI languages. S-Net is a descendant of both semantic networks and recently developed AI languages. Semantic networks have been developed since the mid-sixties as a formalism for the representation of knowledge. Though the original idea of semantic networks is intuitively attractive, the recent formalisms of networks seem to lose the advantages which the researchers initially conceived. G. Hendrix [1975], L. Schubert[1976] and others have tried to formalize their networks based on predicate logic. As a result, their notations have become graphical analogues of logical formula. On the other hand, since the appearance of 'Frame' [Minsky 1975], great efforts have been made to develop programming languages and systems which realize the frame idea [Winograd 1977, Bobrow 1976, Goldstein 1977, Davis 1978]. They all have a certain data structure into which various sorts of knowledge, including both procedural and declarative ones, are integrated. However, their data structures are based only on the vague idea 'Frame', and, more seriously, lack rigidly defined semantics. Especially, the technique 'procedural attachment', though it is powerful tool for describing knowledge, makes the situation chaotic. There are no general mechanisms for managing the attached procedures appropriately. In most languages, the programmer must specify explicitly when an attached procedure should be invoked. Moreover, most aspects concerning the control of the interactions among the attached procedures are also left to the programmer. As a result, the programmer must always pay attention to the overall control issues during the coding of his procedures. We present in this paper a framework called S-Net on which descriptions and operations of these languages can be appropriately founded.

2. RELATED RESEARCH WORKS

Among others, FRL [Goldstein 1978] and KRL [Bobrow 1977] are the better known examples of recent AI languages. Because these two have both the advantages and disadvantages of recent attempts, we will consider them as typical examples and compare them with the S-Net notations throughout this paper.

As Goldstein said, FRL is a programming syster, rather than a language. It lacks the overall control mechanisms. It only provides a data structure and a programming package for manipulating it. The data structure, a frame system, consists of a set of mutually related knowledge units called *frame[1]. A frame, in turn, is an aggregation of descriptive data and procedures. The core of a FRL frame is a property list. FRL generalizes the LISP property list in the following ways:

1. FRL supplies a mechanism for inheritance of properties through a generalization hierarchy.
2. The property value in a frame can be a procedure which knows how to get the actual value.
3. Procedures can be associated directly with frames. The programmer is required to specify explicitly, by using facet indicators such as $IF-ADDED, $1F-REM0VED, $IF-NEEDED etc., what sorts of operations on the frames will invoke the associated procedures.

In short, the essential features of FRL are

1. Inheritance of properties through a hierarchy.
2. Procedural attachment.

Though these two ideas are intuitively attractive, there remain a lot of difficult problems before they can be realized. We will consider these problems in this section. Note that because we restrict the discussion in this paper to the topic of problem solving mechanisms and their foundations, we will neglect many characteristic features of FRL or KRL which are very interesting in their own right.

2.1 Property Inheritance Through a Hierarchy

Fig. 1 shows an example in [Goldstein 1977]. The frame MINSKY inherits the properties STREET, CITY, STATE and ZIP from the frame MIT-AI. In FRL, 'the AKO (A Kind OF) link establishes a mapping by which properties of one frame may be distributed to related frames. Semantically, the mapping can represent a set/subset, part/whole, or other relationships[Goldstein 1977].

```
(FASSERT      MIT-AI
   (STREET    ($VALUE  (  /545  Technology  Square/  )))
   (CITY      ($VALUE  (  /Cambridge/  )))
   (STATE     ($VALUE  (  /MA/  )))
   (ZIP       ($VALUE  (  /02139/)))      )

(FASSERT      MINSKY
   (AKO       ($VALUE  (  MIT-AI  )))
   (OFFICE    ($VALUE  (   821    )))
```

Fig. 1 Description of an AKO Hierarchy in FRL.

This approach seems very promising and appropriate. However, some properties can be inherited through set/subset relations but not through part/whole relations and vice versa. From the view point of logic, property inheritance is a specific mode of inference associated with a predicate. In a extreme case, for example, children may inherit their second names from their parents but not any other properties. This inheritance rule is associated with a predicate, say, CHILD-OF. In FRL, there are no explicit provisions for representing such a kind of restricted property inheritance. The only possible solution is to embed such a rule in a procedure (Fig. 2). This solution is not a real solution of the problem. The programmer should do all things in his procedures. Because property inheritance through hierarchy provides only a very restricted inference mechanism, we need additional frameworks for supporting other kinds of inheritance mechanisms.

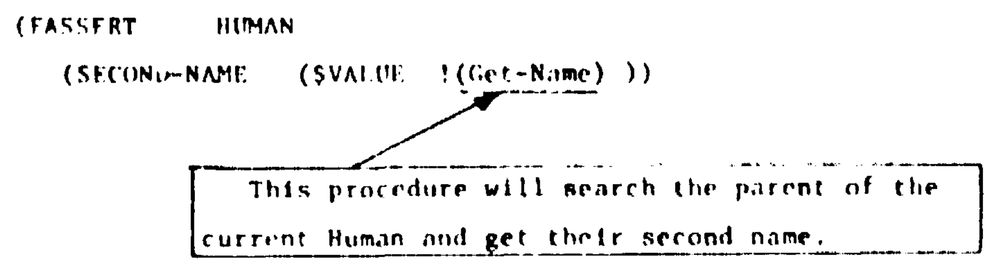

Fig. 2. Restricted Property Inheritance Embedded in a Procedure.

2.2 Procedural Attachment

One of the difficult problems in procedural attachment is how to decide when a procedure is evaluated, In most of the AI languages, the programmer should explicitly specify this.

```
DAY  Frame
     Year
     Monrh
     Day- Number        WHEN-FILLED
                          (CHECK-RELATION  day-number, month)
     Day-of-Week        TO-FILL
                          (APPLY  calender-lookup
                               TO year, month, day-number)
                          (APPLY  anchor-dnte-method
                               TO year, month, day-number)
     ASCII-form*        WHEN-FILLED
                          (FILL  year, month, day-number)
```

* ASCII-form for July 4, 1978 la 780704.

Fig. 3. Description for 'Day' in KRL.

$IF-ADDED in FRL and WHEN-FILLED in KRL indicators are used to indicate that the attached procedure should be invoked when a certain value is stored in the slot. However, this ;tyle of

specification is often inadequate. Some procedures should be triggered when more than one slot is filled. Fig. 3 is an example by Winograd [1975], The procedure Check-Relation, which checks the consistency between the Day-Number and the Month, will be triggered when the Day-Number slot is filled. Tf the Month slot has not been filled when the Day-Number is filled, the execution of the procedure should be suspended, and resumed again when the Month slot is filled. The control of such suspension and resuming of procedures may become very complicated, if it is implemented without any clear formalization. Moreover, the specification of TO-FILL and WHEN-FILLED indicators results in the restriction of the system's abilities. Consider a simple example in which we have two procedures which compute the slot-B's value from the slot-A's value, and the slot-C's value from slot-B's value respectively. There are four possibilities to embed such procedures by using TO-FILL and WHEN-FILLED indicators (Fig. 4]. In the first three, the slot-C's value can be obtained when the slot-A's value is given. However, it is not the case in the last representation.

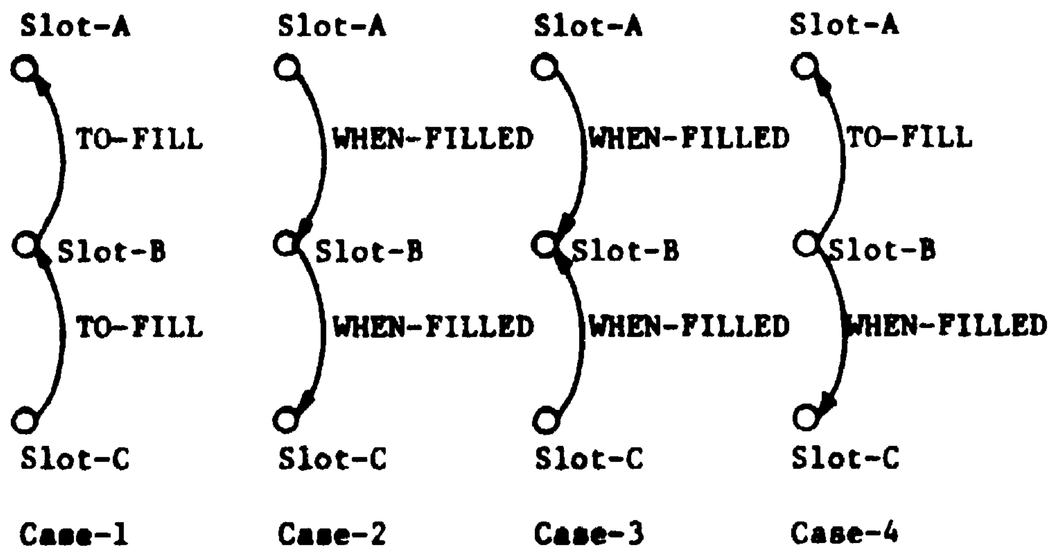

Fig.4 Explicit Pre-specifications of Invocation

To avoid this, we should carefully distinguish the two different kinds of knowledge: what logic al or conceptual relationships the attached procedure embodies, and when the procedure will be invoked. It is often known beforehand that the evaluation of a certain procedure requires much more resources (time or space) than the others or that a certain direction of searching often leads us to success. These sorts of knowl edge are called 'heuristics' and the programmer? have been encouraged to embed them in their representation. However, it is our contention that such heuristics are only heuristics, i.e., they may be reflected on the problem solving process only to the extent that they will not restrict the system's abilities. TO-FILL (WHEN-FILLED) indicators not only recommend the backward (forward) usages of the attached procedures but also inhibit their forward (backward) usages. In short, the pre-specification of the usages of attached procedures is too restrictive.

Our problem solver based on the S-Net alternately performs backward and forward reasonings. In that process, an attached procedure will be utilized either in forwards or backwards, according to the problem solving situations. In order to accomplish such mechanism, we introduce the concept of 'partially instantiated relationships' in the S-Net, which are dynamically created during the problem solving process [See 4.1 and 4.2].

3. S-NET REPRESENTATION

S-Net consists of several types of nodes and links. The node types which are used in the S-Net are shown in Fig. 5. The Disjoint node and the Condition node play the role of logical connectives. They are used for augmenting the generalization hierarchy (3.1). A property or a slot is represented in the S-Net by a node called Property node. All variable nodes in the S-Net are typed by certain data types. The definition of a type plays a central role in the S-Net.

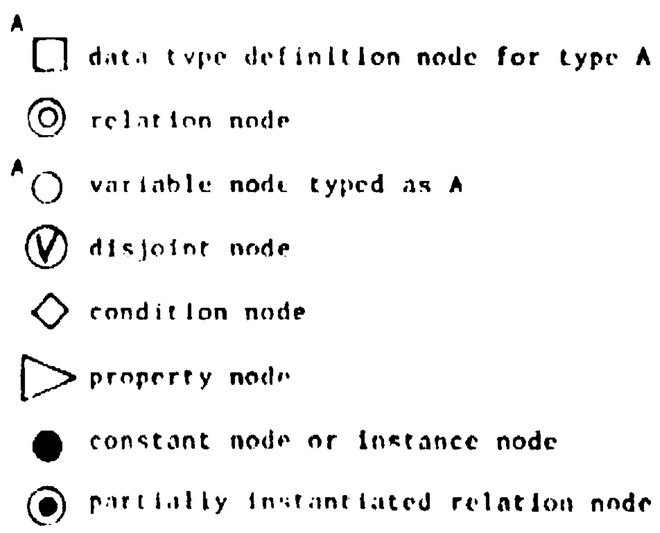

Fig. 5. Node Types in the S-Net.

A Type Definition node describes the basic-behaviour of a data type. It corresponds to an atom in LISP. In LISP, an arbitrary character string identifies an atom, and all occurrences of the same character string in LISP programs and data are represented internally by a pointer which points to the atom. The behaviour of an atom is described by the property list attached to the atom. According to this convention, a data type in the S-Net is identified uniquely by its name, and there is one type definition node for each data type.

3.1 Augmentation of Generalization Hierarchy

Data types can be organized in a hierarchical structure. We use the term SORT, instead of

AKO or ISA, to refer to the link. In our problem solving procedure, the hierarchy of data types plays the central role for distributing properties, though explicit path specification (See 3.3) will further augment the inheritance mechanisms. When a problem description is given, the instance nodes of the corresponding data types are created. Because each instance in a problem description has its own data type name, the initial position of the instance in the hierarchy is determined by its name. However, the position should be determined not only by its type name but also its whole descriptions. For example, the instance

(OBJECT-1 NAME = ALCOHOL

(! TEMPARATURE) - 28°C))

is identified with the data type ALCOHOL by its type name. Moreover, because ALCOHOL is a subsort of MATERIAL and because an instance of MATERIAL whose temparature is between the boiling point and the congelation point is an instance of LIQUID, it should be identified as an instance of LIQUID. All properties of LIQUID should be distributed to this instance. In order to accomplish such an identification process, we need a framework in the S-Net for specifying when an instance is located lower in the hierarchy. For this purpose we introduce in the S-Net a new link SUBSORT and a new type of node Condition Node (See Fig. 6). A SUBSORT link is a link from a higher data type to a lower one. A Condition Node holds a condition when the transition from the higher to the lower data type is permitted. Moreover, because new information about an instance may be derived during the problem solving process or accumulated through the dialogue with the user, the position Identification may be performed during the problem solving process.

We often find the following type of declarative sentences.

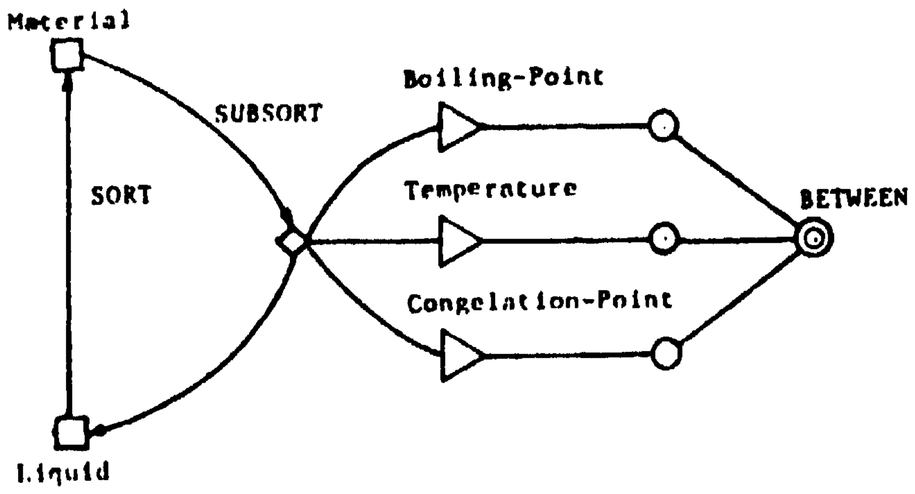

Fig. 6. SUBSORT Links with Condition Nodes.

Acid which dissolves copper is either Hydrochloric-Acid, Nitric-Acid or Sulphuric-Acid.

These statements describe mutually exclusive relationships among sets. A data type and a set do not necessarily correspond but they are close ly related.

We call a set of data types 'Disjoint Set', if the data types in the set satisfy the following conditions:

1. If an instance is a certain data type in the set, it can never be other data types in the set.
2. We can determine the data type of an instance by determining which data type it is not equal to, i.e. by elimination.

In the S-Net, we represent a disjoint set by a node called Disjoint Node (Fig. 7). Disjoint nodes are often useful to inhibit semantically irrelevant information from entering into the search space. By combining the Condition nodes and Disjoint nodes, the generalization hierarchy in the S-Net becomes very powerful.

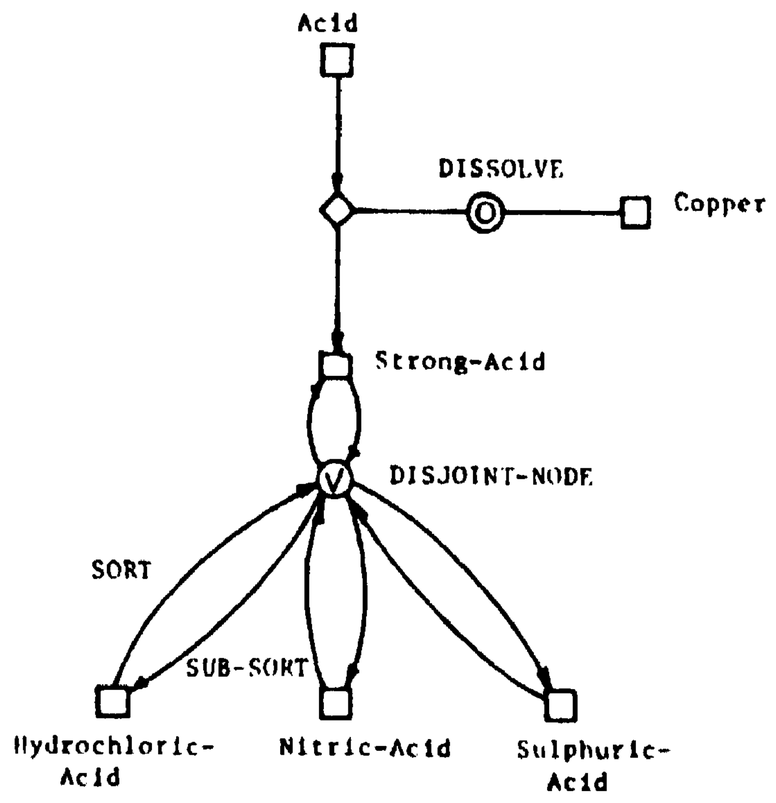

Fig. 7. DISJOINT-NODE.

3.2 Relation Nodes

A relation node in the S-Net expresses a certain dependency relationship among the slots, and also functions as entrance to some external procedures from the S-Net. Based on the dependency relationships, the S-Net problem solver determines how to solve a problem. For each relation node, a bunch of procedures is internally defined. The procedures embody how to utilize the relation in the problem solving. The problem solver decides which internal procedures is invoked,

based on both the dependency relationships and the problem solving situations.

Logical predicates of certain kinds, arithmetic operators, external data bases and procedures in general are all equally represented in the S-Net by relation nodes. , A relation node essentially corresponds to a logical predicate. A logical predicate extentionally specifies a set, possibly infinite, of tuples which satisfy the predicate. We assume that external data bases are constructed according to the relational data model. It consists of the tuples which satisfy a predicate or relationship, while a procecure in general expresses the mechanism for computing those tuples.

The description of a procedure in a relation node consists of two parts: Declaration part and Procedure body. The declaration part shows in which direction the procedure utilizes the relationship. This part, as demonstrated below, is fairly simple:

$$(arg_{i_1} \quad arg_{i_2} \quad \ldots \quad arg_{i_n}) : (arg_{i_{n+1}} \quad \ldots \quad arg_{i_m})$$

This means that if $arg_{i_{n+1}}, \ldots, arg_{i_m}$ are known, $(arg_{i_1}, \ldots, arg_{i_n})$ can be computed by the procedure. The declaration part can be interpreted both forward and backward by the S-Net problem solver depending on the situation, i.e. if one of $arg_{i_1} \ldots, arg_{i_n}$ is required, then try to get the values of $arg_{i_{n+1}}, \ldots, arg_{i_m}$ (in the backward mode), or if $arg_{i_{n+1}}, \ldots, arg_{i_m}$ are all known, then try to compute the values of $arg_{i_1}, \ldots, arg_{i_n}$ by the procedure (in the forward mode). As for the backward and forward mode, see 4.2.

In a special case, the left hand side of the declaration part can be null. In this case, the procedure body will be invoked when the arguments of the right hand side are all filled, and check the consistency among them.

Some examples of relation nodes are shown in Fig. 8.

3.3 Nesting of Data Types — Explicit Path Specification

A data type or a frame can be recursively defined. A data type may arise in the definition of another type. The description

(DT NAME = Aqueous - Solution

(! Solvent) = (DT NAME = Water))

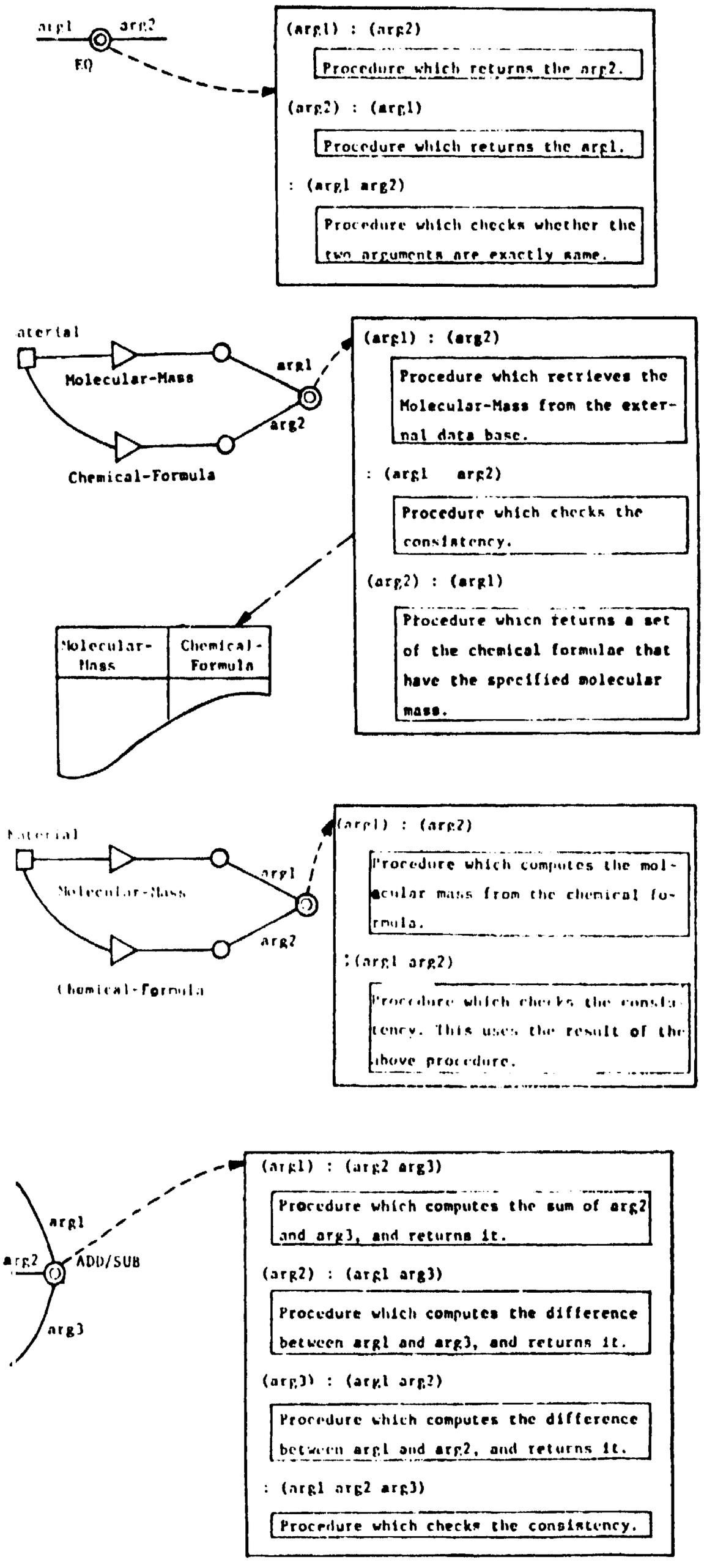

Fig.8 Examples of Relation Nodes and Their Internal Procedures

is a simple example of such descriptions. We treat an occurrance of a data type in the definition of another type as a variable typed by the data type. Thus, (DT NAME = Water) in the above example is represented as a typed variable. Since the variable is typed as Water, all information attached to Water is applicable to the variable. For example, we will have the value H20 when we retrieve the value of the property Chemical-Formula of the Solvent of a certain Aqueous-Solution. Moreover, a specific knowledge, which can be applied only to the water that is the solvent of a certain solution, but not to Water in general, is also attached to the variable.

```
(DT   NAME = Aqueous - Solution
      (!   Solvent) = (DT   NAME = Water)
      (ADD/SUB  (!  MASS) (!  Solvent MASS)
                (!  Solute Mass))
```

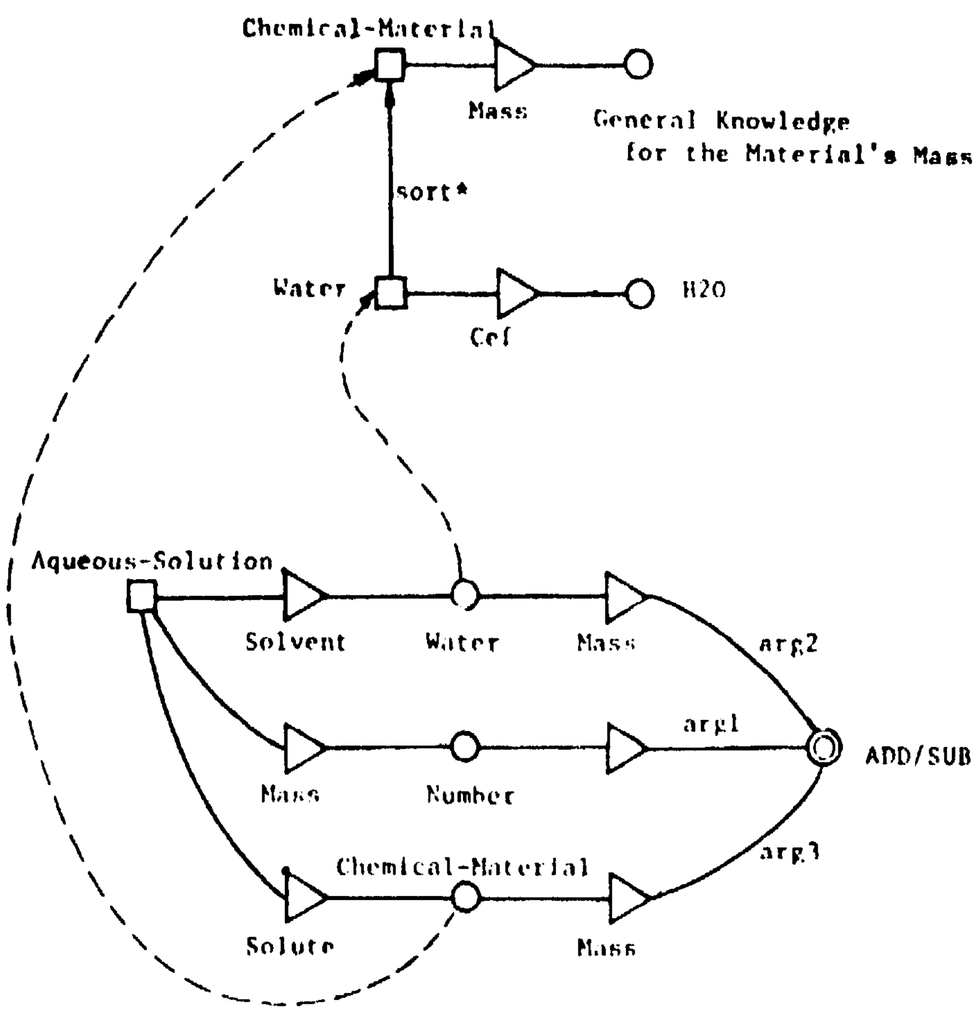

Fig. 9. Type Definition Node for 'Aqueous-Solutions[1].

The S-Net for the above description is shown in Fig. 9. Retrieval of a value through a path description such as (FGET Aqueous - Solution Solvent Mass) will cause the evaluation of a procedure which is defined as the 'internal' procedure of the relation node ADD/SUB that computes the Solvent's mass from those of the Solution and the Solute. Moreover, if the procedure fails to compute it, more general procedures which are attached to the data type Water or more general data types than Water will be invoked. Thus, unlike in FRL, a path description in the S-Net is augmented automatically by the system.

Such a path description can be emplyed not only in the query expression but also in the S-Net descriptions as follows. The general statement

'If a researcher is a member of an organization, he inherits the address from the organization'

can be expressed by

```
(DT   NAME = Researcher
      (!  Organization) = (DT   NAME
                           = Organization)
      (EQ  (!  Address) (!  Organization
                         Address))).
```

In the above examples, all path descriptions begin with !'s which show that the paths start from the current data type. A path which starts from a data type that is different from the current one is also allowed in the S-Net. Thus, the statement 'A MIT-Researcher inherits his address from MIT-Al-Lab' can be expressed directly by

```
(DT  NAME = MIT - Researcher
     (EQ  (!  Address)  ((DT  NAME =
                          MIT-Al-Lab) Address)).
```

The S-Net for this is shown in Fig. 10. By using this mechanism, called 'explicit path specification', property inheritance or distribution among different data types can be obtained in a very intuitive way. Because EQ is represented as a relation node, the above expression can be used not only for retrieving the researcher's address but also for checking the consistency when the address of a certain MIT-Researcher is given.

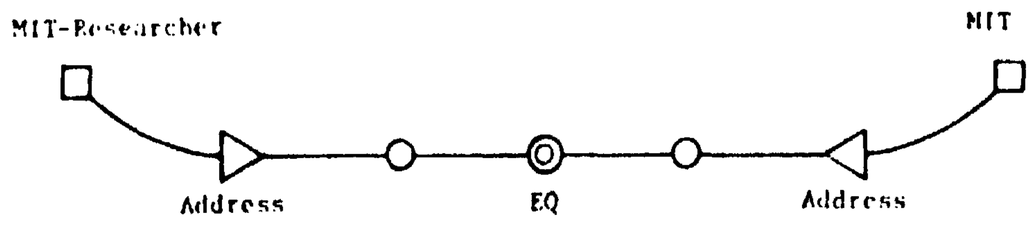

Fig. 10. Related Type Definition Nodes.

4. OPERATIONS ON THE S-NET

4.1 Creation of an Instance

A problem description may contain several instances. The description

```
(OBJECT-1   NAME = Solution
          (! Mass) = 100 gr
          (! Solvent) = (OBJECT-2  NAME = Water
                                (! Mass) = 98 gr)
          (! Solute) = (OBJECT-3
                                (! Cef) = Na-Cl))
```

contains three instances of different data types. They are instances of Solution(OBJECT-1), Water (OBJECT-2) and a data type without a name(OBJECT-3).

The type definition node for Solution contains various relationships among the properties. These relationships are also instantiated. For example, there may exist a relation node ADD/SUB that expresses the relationship among Solution's mass, Solvent's mass and Solute's mass. When the solution's mass is filled by 100 gr, the relationship is also partially instantiated, and the partially instantiated relation node is created (Fig. 11).

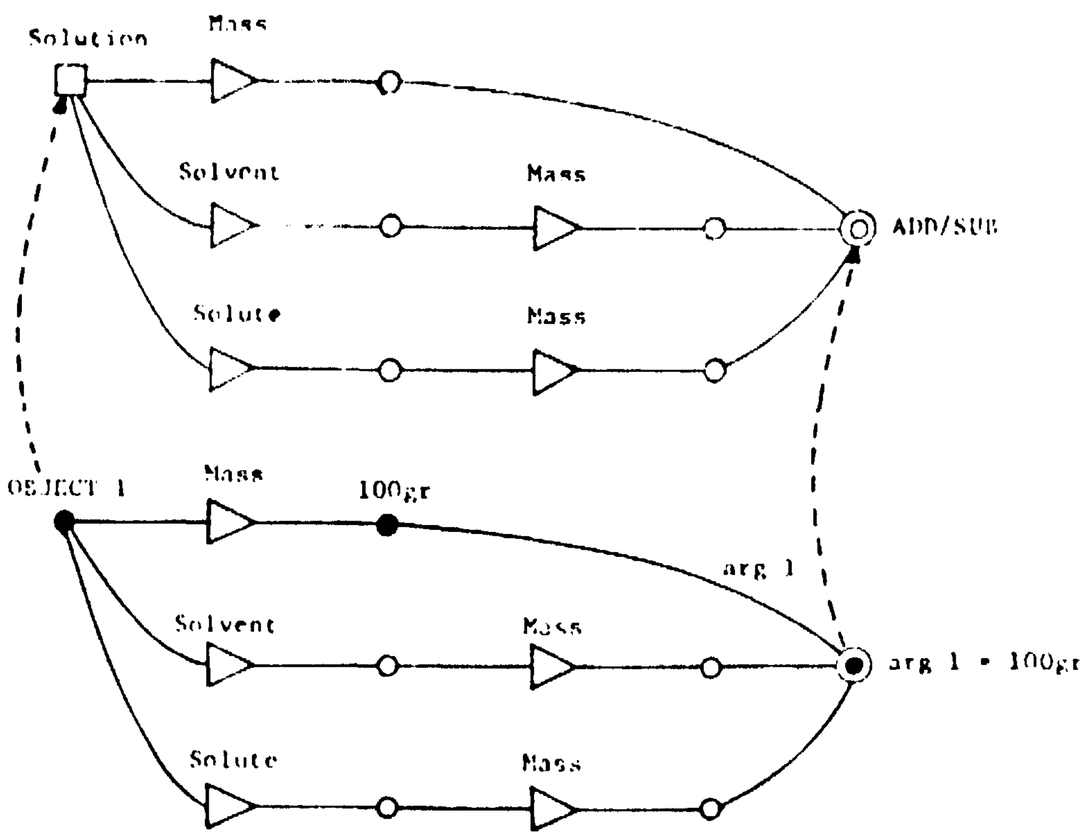

Fig. 11. Partially Instantiated Relation Node.

The instance OBJECT-2 is created as an instance of Water. Because the property Mass is filled by 98 gr, the relation nodes attached to Water's Mass are instantiated. Moreover, because OBJECT-2 is put in the property Solvent of OBJECT-1, the relation nodes attached to the Solvent's Mass are also instantiated. As a result, the instantiated relation node ADD/SUB is further instantiated, i.e., the arg-2 is bound to 98 gr. Since both arg-1 and arg-2 are known in this instantiated relation node, one of the procedures defined in this relation node which computes arg-3 becomes to be evaluable. The procedure is marked as evaluable and put into a list called EV-List (See 4.2). In the sequel, the final result will be such as shown in Fig. 12.

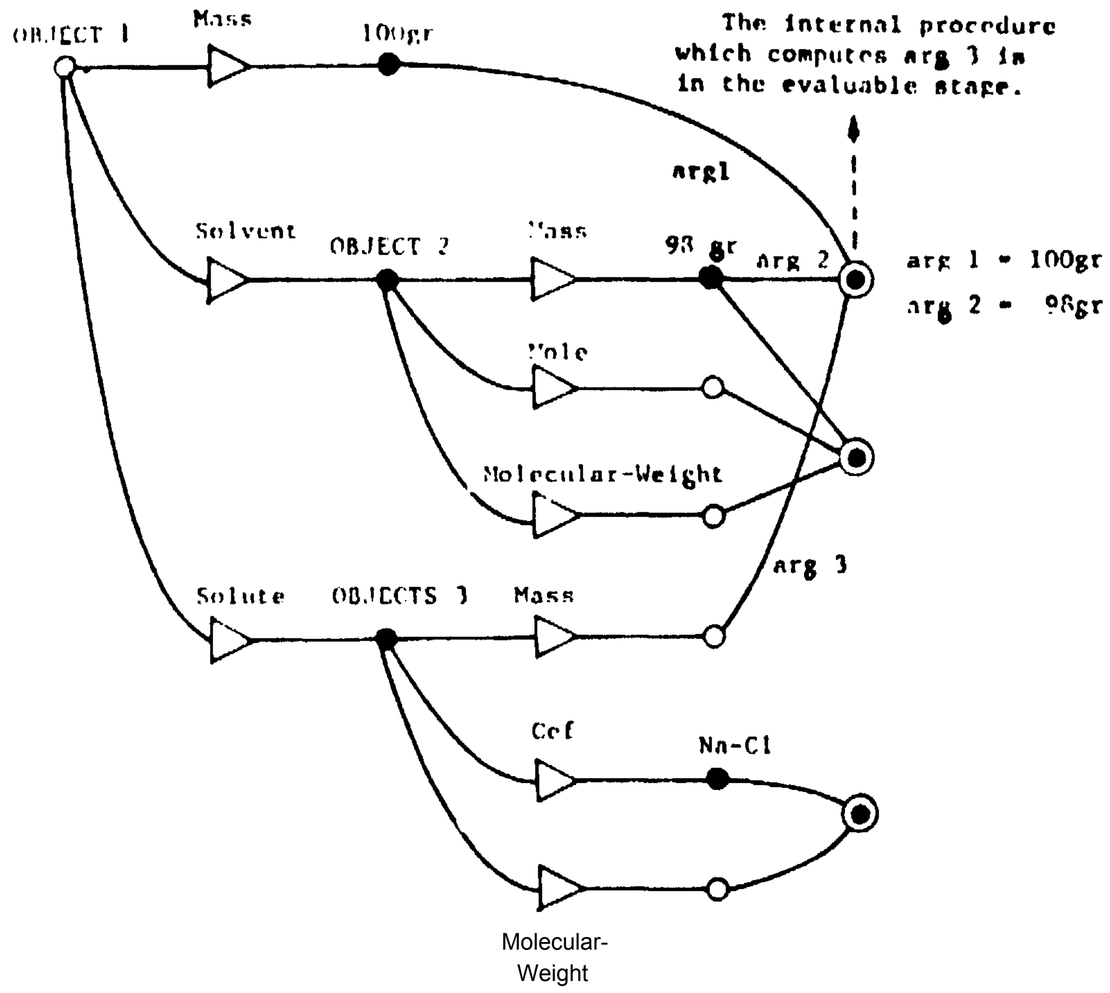

Fig. 12. Final Result of the Instantiation.

As described above, the instantiation of a data type recursively causes the instantiation of other data types. Some relation nodes are also instantiated during the process. The instantiation of relation nodes is propagated upward through the SORT-hierarchy: If a property of a certain data type is filled, the relation nodes attached to the same property of the higher data types in the hierarchy are all instantiated.

4•2 Backward and Forward Reasonings

As we described earlier, after the initial instantiation of variables, a certain set of procedures are only marked as immediately evaluable and put into the EV-list, because the immediate evaluation of these procedures will trigger the unlimited forward reasoning which may invoke many irrelevant procedures.

The next stage is performed backward. The initial goal, which is to solve the problem posed by the user, will be tried, and if not fulfilled, the goal will be further expanded into a set of subgoals. The expansion of a goal will be performed by utilizing the information attached to the instantiated data types, especially the declaration parts of internal procedures in the instantiated relation nodes. Because the instantiated relation nodes have already been

partially instantiated during the preceding forward mode, it is reasonable to expect that these instantiated relationships are relevant to the current problem more than those which have not been instantiated. We illustrate this process by considering a simple example. Suppose the problem description in 4.1 has been given and that the following problem is posed.

'Retrieve the Density of OBJECT-1'

The initial goal will not be achieved, because the mass of OBJECT-3 is not explicitly given. The initial goal is expanded into subgoals. Since the relation node which indicates the relationship among Solution's Mass, Solute's Mass and Solution's Density has been partially instantiated and attached to the instance OBJECT-1, this instantiated relation node will be used to expand the goal. The subgoal is

'Retrieve the Mass of OBJECT-3'.

The reasoning mode will be changed from the backward mode to the forward mode. In this mode, the procedures in the EV-list will be evaluated in turn. The evaluation will further instantiate some variables in the S-Net so that some other procedures will enter in the evaluable stage. They are also marked accordingly, and put in the EV-list. They will be evaluated in the next forward mode.

In the above example, the internal procedure in the relation node ADD/SUB, which computes the Solute's(0BJECT-3's) Mass, is evaluated. The result of the evaluation fulfills the above subgoal. This will be checked in the next backward mode. The success of the subgoal will result in the success of the initial goal.

Thus, the whole process is performed forwards and backwards. If there are no procedures in the EV-list, only the backward mode will be continued until a certain procedure will be entered in the EV-list. Note that an internal procedure in a relation node will be used in both directions, forwards and backwards. Moreover, the two mode works cooperatively in the sense that the backward mode prefers to operating the partially instantiated relation nodes proposed by the preceding forward mode.

5. A SIMPLE EXAMPLE

In order to give the reader some idea about the operation of the problem solver, we will give an example in this section. Suppose the following problem is given.

```
(OBJECT-1     NAME = Solution
      (!   Solute) = ( OBJECT-2)
      (!   Volume) = 200 cc )       )
(OBJECT-2     NAME = Sodium
      (!     Mass) -  2 gr  )       )
(RETRIEVE    OBJECT-1   Mol-Density) ?
```

In order to compute the Mol-Density, the problem solver should solve various subproblems such as computing the Solute's Mol-Number from the mass and the molecular-weight, retrieving the Molecular-Weight from the external data base, getting Sodium's Chemical-Formula for accessing the data base etc. The problem solver works fairly well and selects relevant knowledge appropriately even if there is much irrelevant knowledge in the S-Net.

6. CONCLUSION

In this paper, we have proposed a graphical notation called S-Net which provides a framework and a foundation for some of the operations of recent AI languages and systems. Especially,it is shown that the problems, 'when an attched procedure to be invoked' and 'how to represent restricted property inheritance in nonprocedural forms', can be solved in the S-Net representation. Moreover, various sorts of information about problem solving situations such as variable binding contexts etc. are distributively stored in the nodes(partially instantiated relation nodes etc.) so that the global controller, the problem solver, can be easily implemented. The current version is only one of possible constructions. We are now developing different problem solving strategies.

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LISP MACHINE NK3 AND MEASUREMENT OF ITS PERFORMANCE

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A LISP machine NK3 is presented. The machine has various special hardwares not only for executing ordinary LISP programs very fast but also for implementing flexible control structures such as co-routines. Special care is taken in the architecture to realize rapid transfer of the pointer information in the system. Automatic management of the stack area and the guarantee of high speed and flexible stack operations are the other important design issues. NK3 is provided with a hardware stack which contains the top part of the stack and transfers data from/to the main memory independently with the CPU. Various instructions for manipulating the stack, such as exchange the stack content[1] etc., are prepared. The constructions of the hardware architecture micro/macro instruction sets, and the software including the interpreter are described in this paper. Some results of performance evaluation are also shown.

1. INTRODUCTION

LISP is the most popular programming language in the research area of artificial intelligence. We have used LISP to develop natural language understanding systems and some problem solving systems. The most complicated systems among these is a programming language for natural language analysis called PLATON[NAGAO 1975], which is an extended version of Wood's ATN parser. It has the ability of pattern matching to check the applicabilities of the grammar rules. This makes the definition of a grammar very clear and easy to understand. However, because the pattern matching operation is very time consuming, it took a long time to analyze a sentence. The more power ful analysis we wish, the bigger the programs become, and require both a huge free cell area and high execution speed.

On the other hand, for natural language understanding systems the more flexible control structures are required than the recursive one the ordinary LISP systems provide. The idea of the 'society of experts'[HEWITT 1977] is also very important in natural language understanding systems. Implementing such a co-routine environment by an ordinary LISP may decrease the efficiency considerably. It is desirable that the hardware system supports such mechanisms.

From the above reasons, we decided, in 1975, to construct a special hardware system which can directly execute LISP codes. The LISP machine which we have developed is called NK3 and equipped with various hardwares such as a specially designed hardware stack. We have completed the hardware of NK3 and implemented the interpreter of LISP1.5 on it. We are now developping more sophisticated LISP interpreter, compiler, and micro coded instructions for the machine step by step in evolutional approaches. We have measured the performance of the machine from various view points: how often the data transfer between the hardware stack and the main memory occurs, how frequent each micro coded instruction is used etc. Based on these measurements, we are improving the constructions of the interpreter, compiler and micro coded instructions.

2. ARCHITECTURE OF LISP MACHINE NK3

Fig.1 shows the overall architecture of the LISP

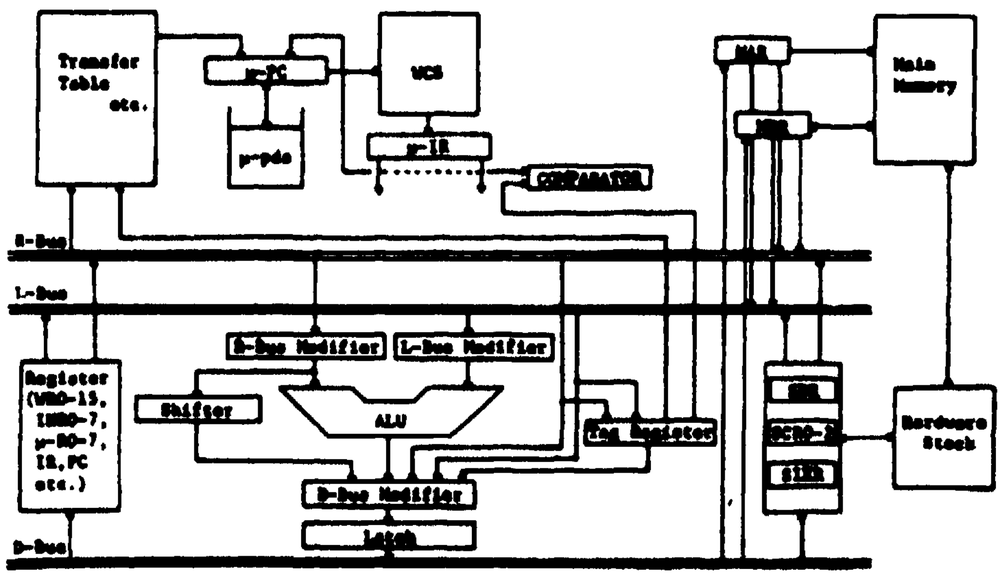

Fig.1 Architecture of NK3

machine NK3. NK3 is a micro-program machine. Micro-programs are stored in WCS(writable control store), and the macro-programs and LISP cells are stored in the main memory. The machine has three data buses, ordinary registers, ALU and some other functions. Special care is taken in the architecture to realize rapid transfer of the pointer information in the system. Automatic management of the stack areas and the guarantee of the high speed, flexible automatic pushing down and popping up operations are the other important design issues of the system. Some typical features of NK3 are the followings.

(i) Writable Control Store (4 kw, 42 bit/word)

This contains micro-programs of most built-in functions and most parts of the interpreter.

(ii) Main Memory (512kB, 800nsec)

The main memory is of the mini-computer INTERDATA 8/32 and is shared by NK3. Because of this memory sharing the access speed to the memory from NK3 takes about 2 /seconds, which is very slow. The input/output operations of NK3 are performed by INTERDATA 8/32. Since the OS is also shared, NK3 does not need to have any general facilities such as the file management.

(iii) Hardware Stack (16 words, 32 bits/word)

The top part of the stack is stored in these registers. The popping-up and pushing-down operations are generally performed in ordinary LISP programs alternately. Long consecutive popping (pushing) operations are rare. In such a situation, the usual double buffering technique is inadequate It causes frequent data transfer. To avoid this, we have adopted quadruple buffering for the hardware stack. The hardware stack is divided into four blocks, each of which consists of four words. By transferring data from/to the main memory asynchronously with the CPU by the unit of four words, the hardware stack is guaranteed to contain always at least four words of the stack and four word spaces for the push-down information. Special circuits are provided to detect the errors such as stack overflow and underflow. The data transfer is done by burst DMA mode independently with the LISP program. Any part of the main memory can be assigned to be the stack area, and any number of areas can be reserved for different stacks in the memory to realize co-routine environments. Some special instructions are prepared to switch the active stack from the current one to the other etc. Because frequent switching among stacks is expected to occur, it is not reasonable to have a larger hardware stack than the present one. It will cause a data transfer of large amount, when the active stack is changed.

We have measured how often the consecutive popping and pushing operations occur In the usual execution, and how often the data transfer is performed between the hardware stack and the memory (See Table 1).

	push-down(=pop-up)	PUSH-DMA	POP-DMA	DMA-RATE
TPU-1	196,240	7,470	8,009	0.158

$$\text{DMA-RATE} = \frac{4*(\text{PUSH-DMA} + \text{POP-DMA})}{\text{push-down} + \text{pop-up}}$$

Table 1. Stack Operations and Data Transfer

The bench marck problem here is the theorem prover based on 'resolution principle' [Chang 1973]. From this table, one can see more than 84% of stack operations are effectively carried out without any data transfer.

(iv) Transfer Table (1 kw, 15 bit/word)

The interpreter frequently checks the data types of the cells and determines the jump position in the program. The data types of cells are expressed in the tag parts of the memory words(Fig. 2). The Transfer Table is used by micro-programs to determine the jump position directly from the description of the tag parts.

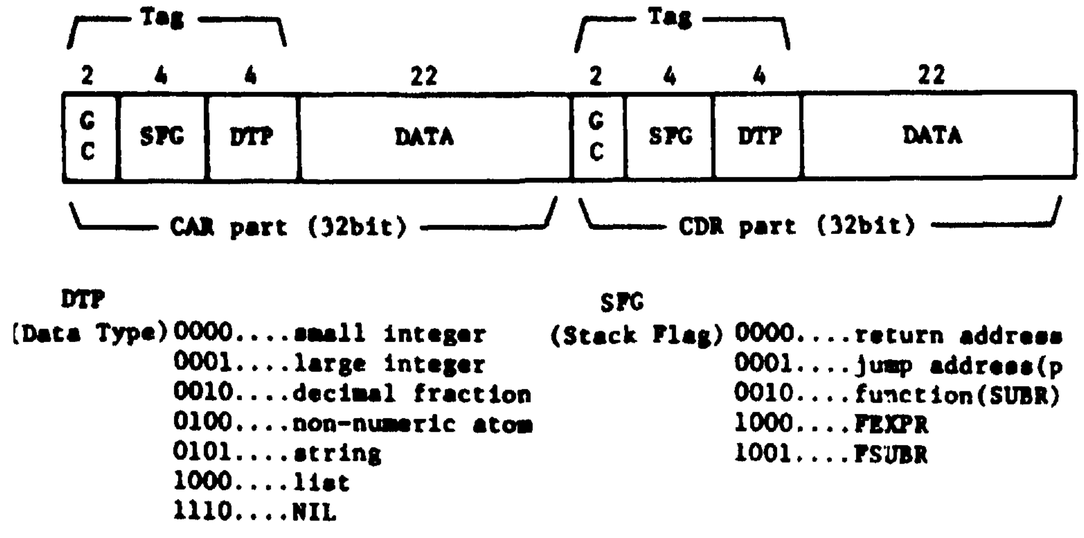

Fig. 2 Structure of LISP Cells

(v) Micro-Instructions

There are six types of micro-instructions. Those types are (1) Arithmetic and Logical operations, (2) Conditional Jumps, (3) Emit operations, (4) Transfer Table operations, (5) Patch operations, and (6) Shift operations. By Patch operations, we can patch arbitrary portions of L-Bus data and R-Bus data together. Combining this operation with the Shift operations enables us to manipulate the tag information efficiently. The format of the type 4 instruction is shown in Fig. 3.

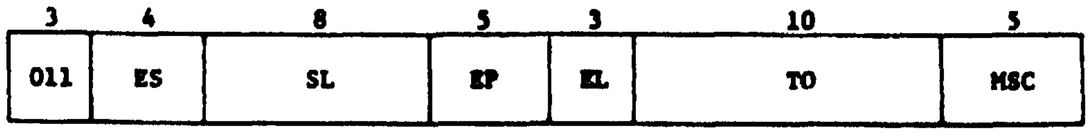

Fig. 3 Format of Type 4 Instruction

This instrution extracts the portion of the bus data (specified by ES - Extraction Source (R-Bus or L-Bus), EP - Extraction Position, and EL - Extraction Length), and adds it to TO (Table Offset). If the result is within SL (Search Length), it refers to the Transfer Table to determine the jump position. Otherwise, the instruction has no effect (See Fig. 4). This type of instruction is very useful for carrying out 'multi-way jump' in micro-programs, based on the tag information.

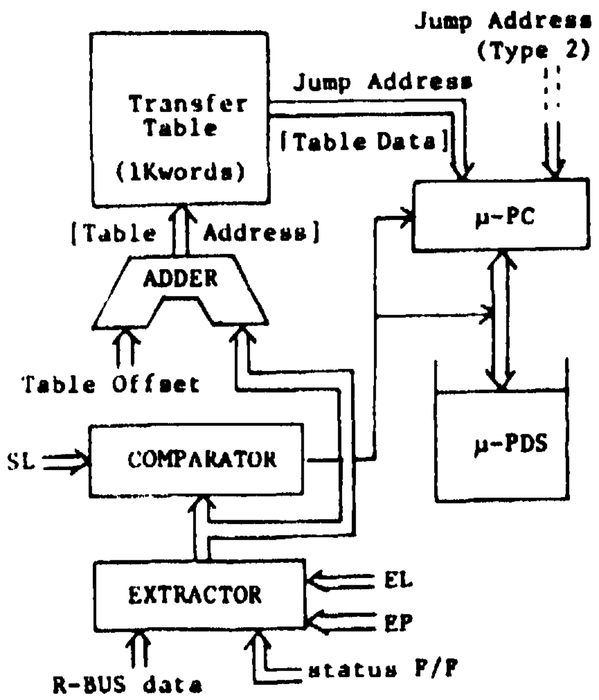

Fig. 4 Transfer Operation

3. HIGH LEVEL MACRO INSTRUCTIONS

NK3 is essentially a micro programmable computer which is equipped with various special hardwares. Therefore, in order to make the execution efficient, we should devise macro instructions which utilize these special hardwares well and are suitable for LISP operations. At present, most of built-in fuctions of LISP can be executed by single macro instructions. Moreover, some of them operates directly on the top of stack. Because of the hardware stack, these instructions are executed very fast.

A set of special macro instructions which facilitate the writing of LISP interpreters is provided. These are the parts of the interpreter which conceptually perform single tasks. For example, searching the value of a variable from the A-list, jumping to the appropriate locations in Eval or Apply according to the types of the arguments and so on are performed by single instructions. The instruction HASH is another example of high level macro instructions. The hashing operation on the atom's print-name is carried out by this instruction. It is very time consuming by the ordinary program to identify all the input character strings with the atoms already in the system. The HASH instruction performs this task very efficiently.

Some other special instructions have been devised to manipulate the hardware stack for implementing flexible control mechanisms directly. The instructions EXCHange and INITialize are the examples. The EXCH and TNIT enables us to implement co-routine environments. Because NK3 is equipped with a single hardware stack, only one of the co-routines can be active at a time and the stack information for the routine is stored in the hardware stack. The EXCH is used to exchange the content of the hardware stack, in order to activate another co-routine in place of the current one. The older context will be appropriately saved. The instruction INIT is for Invoking a new co-routine. It initializes a stack area and reserves a certain amount of memory area for that routine.

4. PERFORMANCE EVALUATION

We have written a LISP interpreter for LISP 1.5 by using the macro instructions described in 3, and have measured the performance and the effectiveness of these instructins. We are still seeking much more efficient set of macro instructions for LISP. Up to present we have experienced a drastic improvement of the execution times, for example two to three times, by setting up a good instruction set. On the other hand, another trial is in progress, which makes the macro instructions as big as possible in their functions. The limit in this direction is that the stack oprations cannot be realized by micro programs. Because of this weak point, the interpreter as a whole cannot be realized by micro instructions only.

We also compared the execution speed of NK3 with some other LISP systems on big and small computers. The bench mark problems were a sorting program, a theorem prover, and some other typical LISP programs. The performance of NK3 might be judged as : it has a half of the power of very large machines (i.e. M190), and has several times of the power of small computer versions of LISP. If NK3 can use the main memory exclusively without sharing with INTERDATA 8/32, and if the stack mechanism can be utilized freely from micro-programs, the execution speed will improve drastically. These may be the main improvement to be taken soon.

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A PARALLEL TREE SEARCH METHOD

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We describe a new tree search method which searches best few paths with backtracking in parallel by the following algorithm (α-β-γ search). Expand the best α nodes at one time. If the number of new nodes which have been expanded by a selected node exceeds a pre-set threshold (β), only the best β nodes are kept and others are pruned. If the total number of newly generated node sequences and non-expanded node sequences exceeds a pre-set threshold (γ), only the best y node sequences are kept, and others are removed. Repeat these consecutive processes until a complete sequence is generated. We evaluated this method by simulations and experiments, and obtained good performances both in the search efficiency and in the recognition rate.

1. INTRODUCTION

To recognize a perceptual input (ex. speech, image), all plausible candidates should be taken into consideration, because a system cannot know exactly what the input was, that is, the input is ambiguous. However, since the number of plausible candidate sequences becomes enormous in case of continuous speech recognition, image understanding and game, a system must select some best sequences and abandon the others. Therefore, the recognition of perceptual input contains the problems of tree search (pruning) and scoring mechanism.

In this paper, we describe a new tree search method employed in the LITHAN speech understanding system(I-4]. For convenience' sake, we would like to discuss the case of speech recognition as an example of recognition of perceptual input and the case of left to right parsing although various parsing strategies have been proposed[5,6].

2. SEARCHING STRATEGY OF ALTERNATIVE SEQUENCE

The aim of a speech recognition system is to determine,for an acoustic signal A and a task language L, a sequence of words W such that this sequence is consistent with the syntax, semantics and pragmatics of the task, and further that this sequence maximizes the a posteriori probability P(W/A,L). We assume an equal probability for the appearance of each sentence. Now $P(W/A,L) = P(W/L) \times P(A/W,L)/P(A/L)$. The term P(A/L) in the denominator is independent of W, and therefore does not have to be known. We assumed that P(W/L) was always constant for all correct sequences of words. Thus, P(W/L) does not also have to be known. Therefore, we can regard that P(W/A,L) is proportional to P(A/W,L). However, this algorithm consumes much computing time, because the approach is equivalent to searching all possible paths or words.

Seeing this difficulty, we coped with the problem by dividing the whole process into two stages: the acoustic signal-to-phoneme sequence and the phoneme sequence-to-word sequence. This division corresponds to approximating P(W/A,L) by $P(W/A,L) = \sum_{PH} P(PH/A,L) \times P(W/PH,L) \propto P(W/PH_0,L)$, where PH denotes a sequence of phonemes and PH_0 a recognized sequence of phonemes (that is, we assume the probability of recognized phoneme $\gg$ that of other phoneme). Furthermore, the maximum of $P(W/PH_0,L)$ is approximately obtained from tree search methods.

If an utterance is composed of s words, and t alternative words are identified for each of these, the number of sequences to be considered is s^t. Therefore the problem of continuous speech recognition can be seen as that of searching through a space of s^t word sequences to find the most acceptable sequence (that is, the sequence with the highest score), that does not contradict all the given knowledge; syntax, semantics, pragmatics, etc.

Fig.1 illustrates an example of a parsing tree. In this figure, the alphabetical symbol and numerical value on a branch denote an identified word and its likelihood, respectively. An encircled numeral on a node indicates the average likelihood for a word sequence corresponding to the path from the root node to that node. A double encircled numeral on a terminal node indicates the score of a complete sentence. The LITHAN system rejects words having a score below a pre-determined value, say, 80. It also rejects sentences below another value, say 85. Thus, in Fig.1, there are five complete sentences: BHM, BHN, CJO, CJP, and CK. If the best-first tree search is applied, the sentence BHN will be selected after the node selection sequence: B→BH→C→CJ→BHN. On the other hand, if we use the depth-first search, BHM will be selected (A→AE→AF→B→BG→BH→BHM). In the case of depth-first serach with ordering, BHN will be selected (B→BH→BHN). We would, however, like to select the sentence CJP. Now, the best-first search may guarantee the sequence with highest score, if the score of a word sequence has a true cost function for searching (namely the breadth-first search)[7]. However, such a method requires much computation time and many storage memories. Our searching scheme is not such a case. Although many techniques have been developed in artificial intelligence research[8,9], we will propose a new search technique and pruning method suitable for recognition of perceptual inputs.

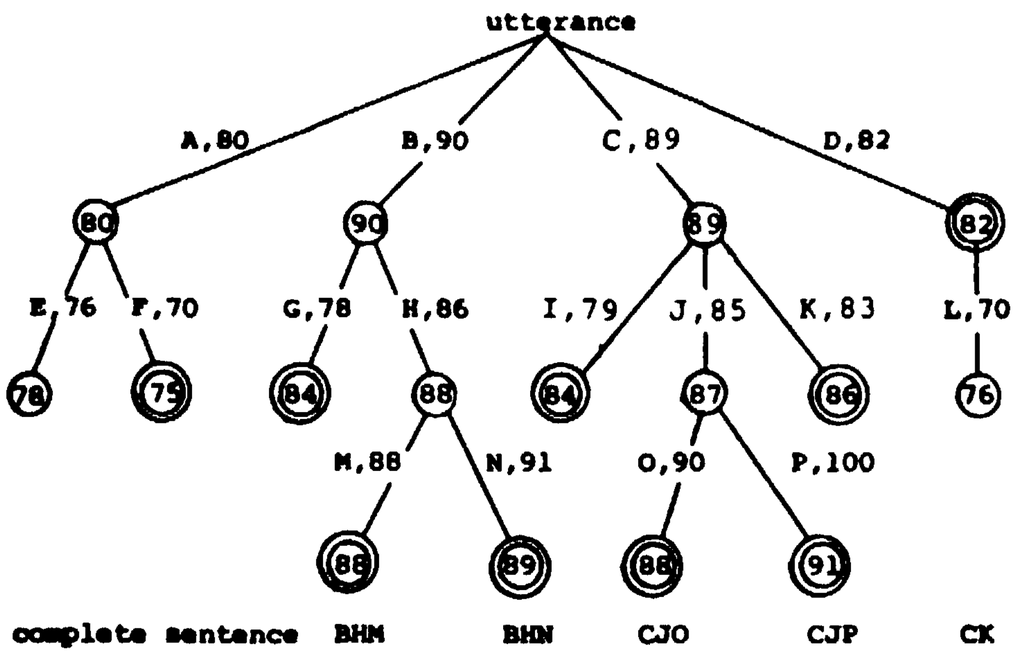

Fig. 1 An example of tree searching.

3. A PARALLEL SEARCH METHOD (α-β-γ METHOD)

We define the parameters which are used by this method.

α: number of nodes which are expanded in parallel at the same time.

β: number of nodes which are kept in all generated nodes at each branching point.

γ: total number of partial strings which are kept in a partial tree.

The score of a partial sentence is defined as the average of the score of words constituting this partial sentence.

Algorithm

step 1: Enter the root node into the set of OPEN NODE.

step 2: Expand α nodes in the set, each of which is the last node of one of partial strings with the highest α average scores. If the number of nodes in the set is less than α, these all nodes are expanded. If the expanded node is a terminal node, go to step 5.

step 3: Enter the β nodes with the highest β scores out of the generated nodes at each branching point into the set of OPEN NODE.

step 4: If the number of nodes in the set of OPEN NODE is more than γ, select the γ nodes, each of which is the last node of one of partial strings with the highest γ average scores, and the other nodes (or strings) are pruned. Go to step 2.

step 5: The string from root node to this terminal node is regarded as an input string. If the number of strings which are regarded as an input string is more than δ, stop. Otherwise, go to step 2.

We call the successive operations from the step 2 to the step 4 as one 'round'.

Although the method of Lowerre in the HARPY system (called beam search[10]) does not have the function of backtracking, our method has it implicitely in the case of α<γ. We call this method as α-β-γ tree search method (or best-α tree search) for convenience' sake.

For example, in Fig.1, let α, β, γ, and δ be 2, 3, 4 and 2, respectively. Here the following word sequences will be kept at each round (the two, α=2, underlined sequences are to be expanded at the next round).

Round 1: B, C, D
D may be a complete sentence in the case the score is less than 85, so it is rejected but may be reserved as a partial sentence.

Round 2: BH, CK, CJ, D
G and I are rejected. CK is a complete sentence.

Round 3: CK, BHM, BHN, CJO, CJP
These are all the complete sentences. In the end, CJP is selected as the recognized sentence.

Larger values of α, β and γ would bring a better recognition result, but such would also increase

the tree search time. Therefore, we have to decide the optimum thresholds of a, B and *y.*

4. COMPUTER SIMULATION

Our tree search method was evaluated by computer simulations. The evaluation of a tree search method depends on the depth of tree (DEPTH), branching factor (BRANCH), scoring mechanism and so on.

lor each |I)P,PTH, BRANCH), 100 trees and the score of each node were generated by a random generator of a uniform distribution |from 0 to 100). The score of a partial sentence was defined as the average score over all words in the partial sentence. We regarded the trees of DEPTH=5, BRANCHES | as the standard tree because a computer had the limitation of an amount of stored memories. The depth of all terminal nodes and the number of branches are same for a tree in this simulation. We define that the input sequence is the sequence with the highest average score. Thus, our problem is to find the sequence with the highest average score. Table .1 shows the kinds of trees which were generated by a random generator. LSSS shows the logarithm of the search space size of a tree. This value can be calculated from multiplying logarithm of DABF (dynamic average branching factor) by ASL (average sentence length)[4,11). The table 2 shows the set of parameters for tree search which were evaluated. We can divide these parameter sets into the two types. Although the type 1 ($\alpha=\gamma$) does not have the function of backtracking, the type 2 ($\alpha<\gamma$) has it implicitely. The parameter 6 was always set to 1.

Table 1 Kind of trees

type	number of branch	depth of a tree	LSSS	number of nodes
1	4	5	10.0	1364
2	5	4	9.3	780
3	5	5	11.6	3905
4	5	6	13.9	19530
5	6	5	12.9	9330

Table 2 Set of parameters

type	method	α	β	γ
1	1	1	1	1
	2	2	2	2
	3	3	3	3
	4	4	4	4
	5	5	5	5
2	6	1	5	10
	7	2	5	10
	8	3	5	12
	9	5	5	15

The simulation results are shown in Table 3 and Fig.2. The column '1' in the 'rank of recogni' n result' corresponds to the number of trees which were recognized correctly. This number associates with "recognition rate". The column '2' indicates that the input was recognized as the second best candidate. As a logical conclusion, the larger LSSS becomes, the worser the recognition rate becomes. From Fig.2, we find when the tree is small, the type 2 is inferior to the type 1. On the other hand, when it is large, the type 2 is superior to the type 1. And also we can say that the best-first search which is simulated by |α=1, β=5, γ=10| is inferior to anyone of parallel search (α≧2).

Table 3 Simulation result (DEPTH=5, BRANCH=5)

α	β	γ	number of expanded nodes	rank of recognition result										
				1	2	3	4	5	6	7	8	9	10	11~
1	1	1	25	23	11	5	2	6	6	0	3	3	0	41
2	2	2	45	52	12	4	7	2	2	4	3	2	1	11
3	3	3	65	71	9	9	5	2	0	1	2	0	0	1
4	4	4	85	78	12	5	2	0	0	1	1	0	0	1
5	5	5	105	82	13	3	1	0	0	0	0	0	0	1
1	5	10	66	58	12	10	4	3	3	2	1	1	0	6
2	5	10	78	74	13	7	1	2	0	0	1	0	0	2
3	5	12	95	80	11	8	1	0	0	0	0	0	0	0
5	5	15	130	83	13	3	1	0	0	0	0	0	0	0

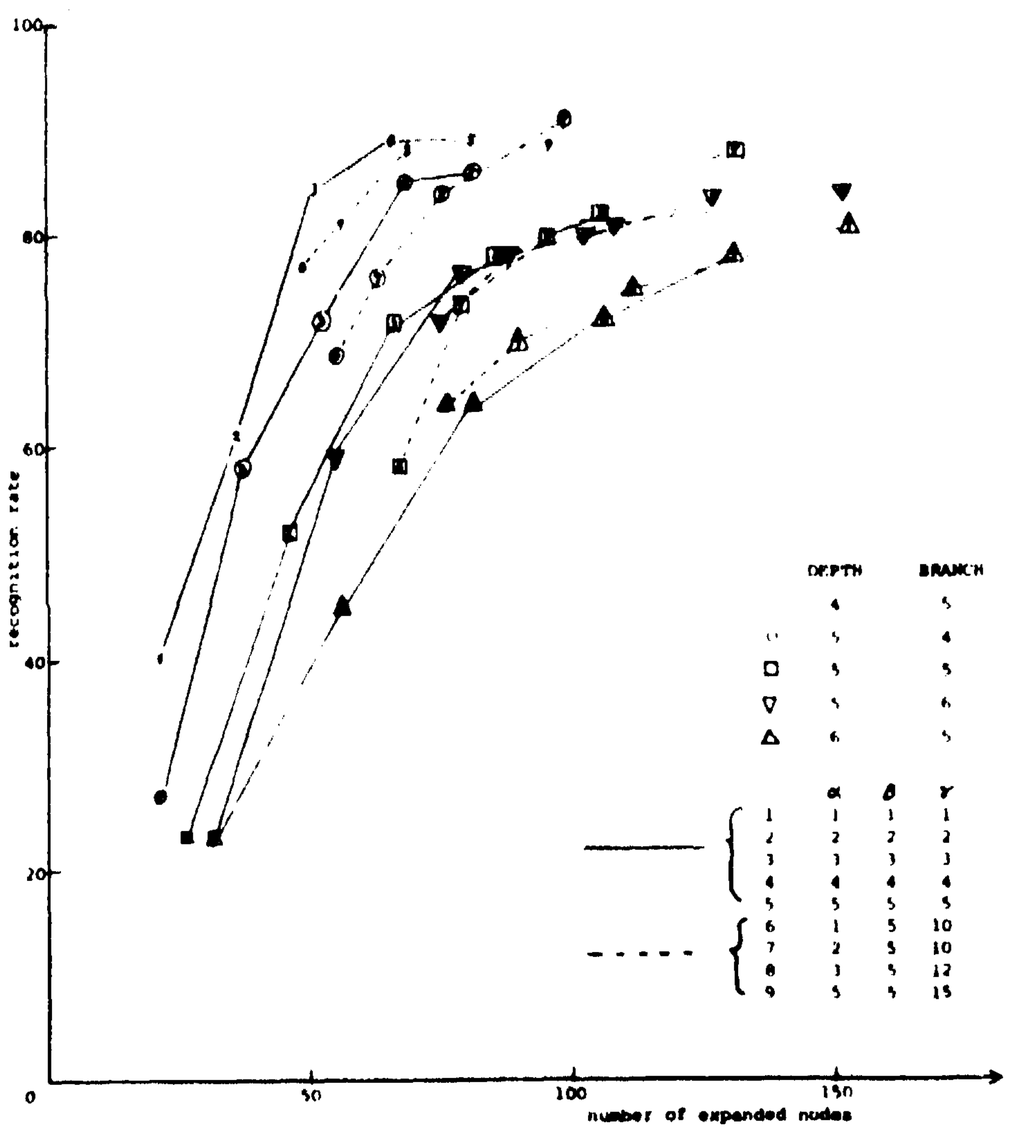

Fig.2 Relationship between recognition rate and number of expanded nodes.

This search method can control the search space size by taking the cost of search into consideration. That is, the scoring mechanism of a partial sentence is modified as follows. Let n be the number of words in a partial sentence and $S_1 \ldots S_n$ be the score of each word, respectively. The new score of this sequence is defined by average $[S_1 \ldots S_n] + W \times n$, where W is a weighting coefficient. If W is a negative value, the search space size becomes large and the recognition rate would be improved. In other wards, this leads that a string of short length is treated significantly than that of long length. If W is a positive value, the opposite results will be obtained.

Table 4 and !ig.3 show the results of this tree search method. Methods from 1 $[\alpha=1, \beta=1, \gamma=1]$ to 5 $[\alpha=5, \beta=5, \gamma=5]$, the type 1, are independent of this modification, because these methods always expand the partial sentences of same length in parallel. The simulation results are in approximate agreement with expected results. However, when W was smaller than -10, the recognition results became wrong. We found even if W is selected to an optimum value for the best first search, it is also inferior to any parallel search (refer to fig.4).

Next, we investigated the effectiveness of parameters: β and γ. The simulation results for $\alpha=1$, 2 are shown in ligs.4 and 5. In the case of these simulations |BRANCH=5|, the best of β was 3-5. The larger the value of γ becomes, the better the recognition rate becomes and then it is saturated. On the other hand, the number of expanded nodes also becomes larger dramatically. Therefore, we must set the parameters α, β and γ according with the purpose of applications.

At least, we think that a should be larger than 2 in pattern understanding systems, although a best-first search has been often adopted in the first stage of speech understanding systems[12].

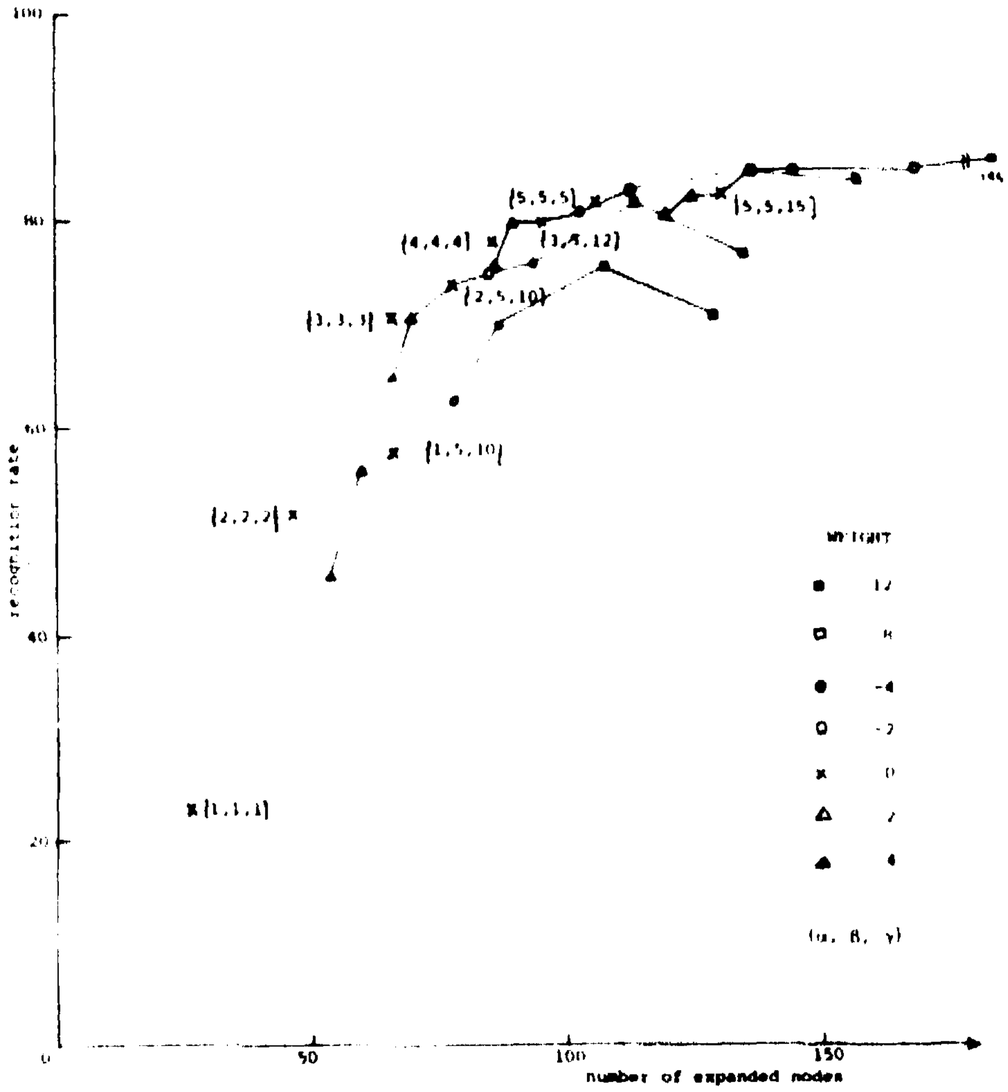

Fig.3 Relationship between recognition rate and number of expanded nodes. (DEPTH=5, BRANCH=5)

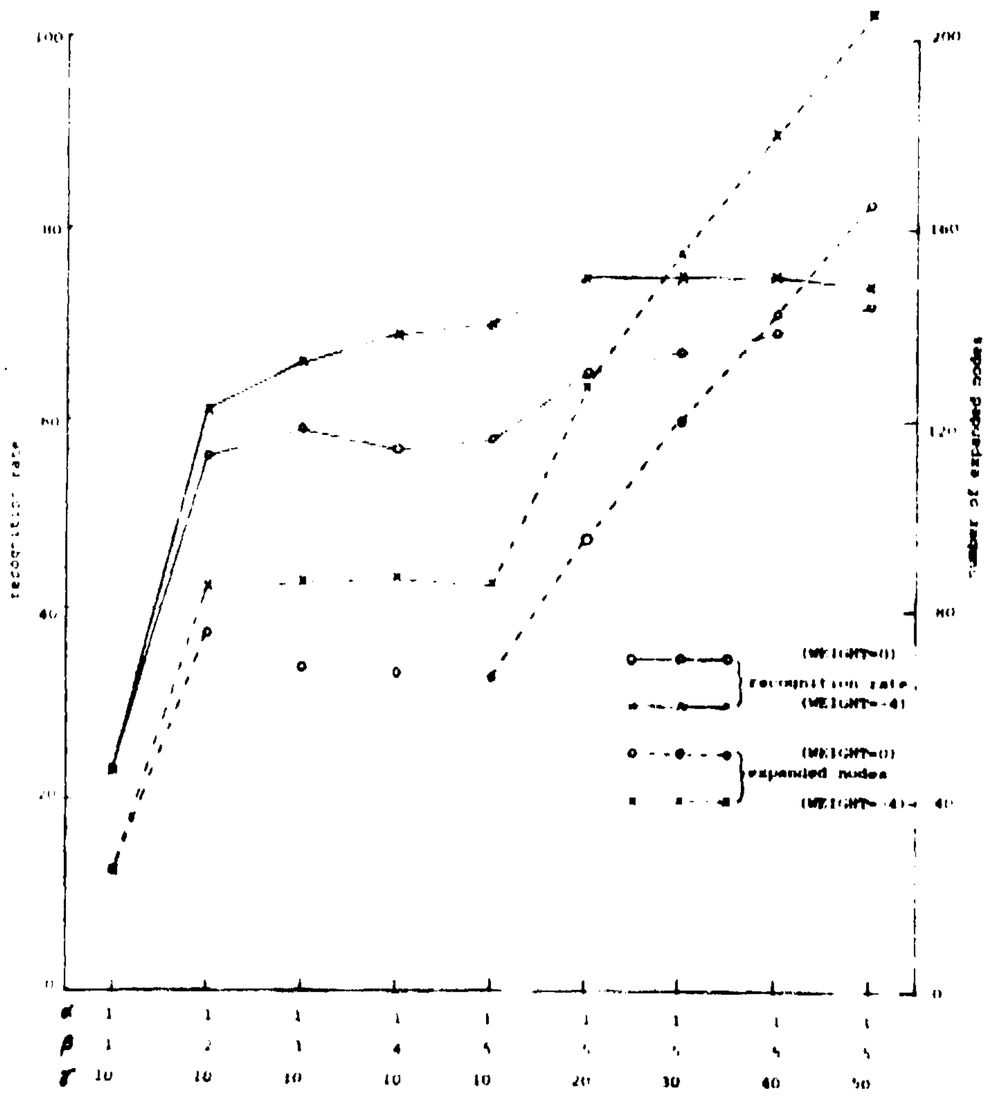

Fig.4 Relationship between recognition rate and number of expanded nodes. ($\alpha=1$, DEPTH=5, BRANCH=5)

Table 4 Simulation result (DEPTH=5, BRANCH=5, WEIGHT=-4)

α	β	γ	number of expanded nodes	rank of recognition result										
				1	2	3	4	5	6	7	8	9	10	11~
1	1	1	25	23	11	5	2	6	6	0	3	3	0	41
2	2	2	45	52	12	4	7	2	2	4	3	2	1	11
3	3	3	65	71	9	9	5	2	0	1	2	0	0	1
4	4	4	85	78	12	5	2	0	0	1	1	0	0	1
5	5	5	105	82	13	3	1	0	0	0	0	0	0	1
1	5	10	86	70	14	7	2	2	1	1	0	0	0	3
2	5	10	93	76	16	5	2	1	0	0	0	0	0	0
3	5	12	113	83	12	4	1	0	0	0	0	0	0	0
5	5	15	145	85	12	3	0	0	0	0	0	0	0	0

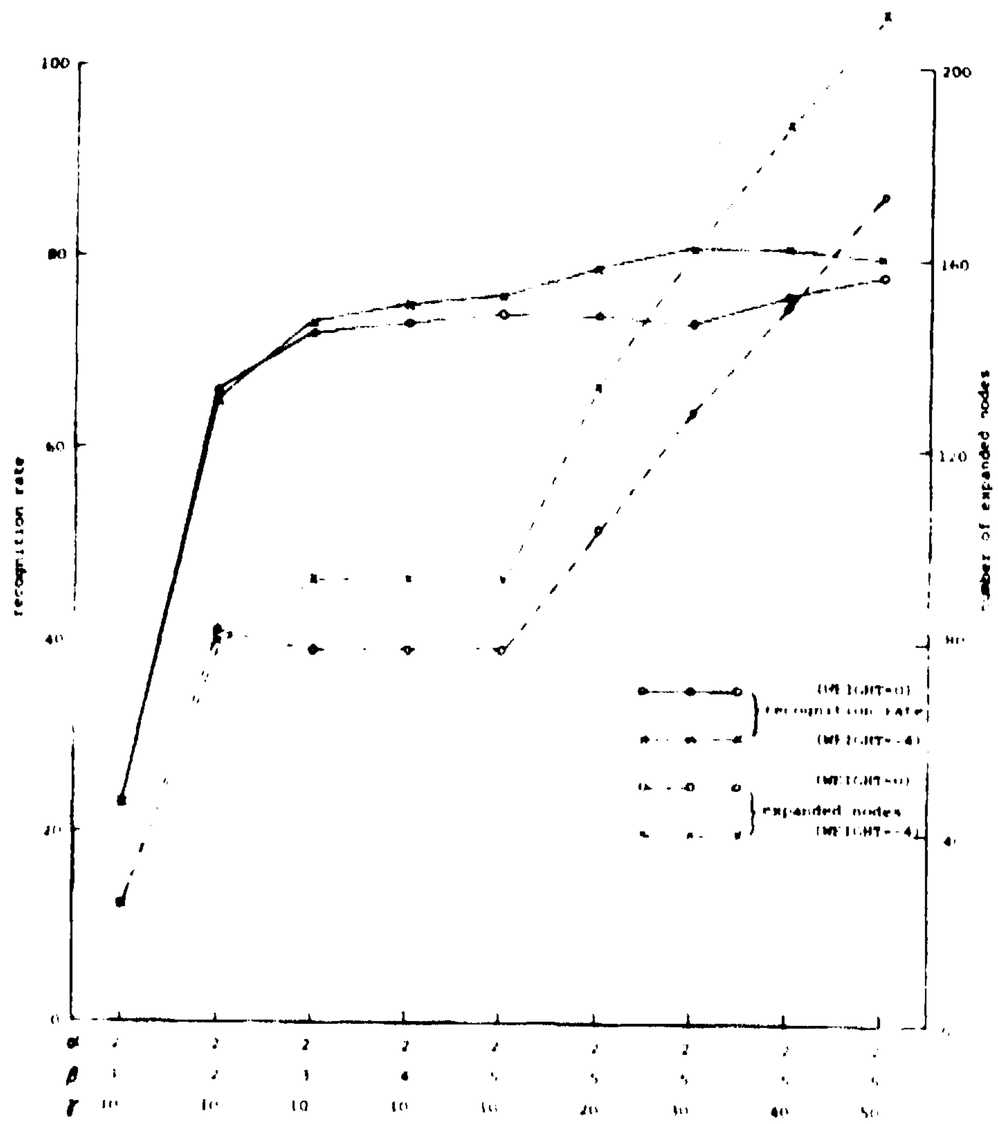

Fig.5 Relationship between recognition rate and number of expanded nodes. (α=2, DEPTH=5, BRANCH=5)

5. SPEECH RECOGNITION OF 'ARITHMETIC EXPRESSION'

We applied our tree search method to the speech recognition of 'Arithmetic Expression' as an example in a real world field[1,2]. In this task, the vocabulary size is 23, where each word has an average of 2.1 syllables. For example, this task accepts the sentence such as '1.2*(345 -6789.0)='.

The experiments of speech recognition of arithmetic expressions were tested on a total of 80 utterances containing 560 words, spoken by five male adults at a normal speed (these were uttered in Japanese). The reference patterns were common to all speakers. The DEPTH and BRANCH on the average were 7 and 10, respectively. The value of 8 is always pre-set at 5, because if a word really uttered belongs to one of predicted words probably it will be identified as one of the best five words (or candidates). The value of 6 was set at .2.

The relationship between recognition rates and parameters of the tree search is shown in Table 5. In this table, the search time column indicates for each case the ratio of the number of verified words to the case where a=1, 3=1 and *y=l. The results are in approximate agreement with simulation on the relative merits for nine search methods. However, the care is necessary to compare it with simulations, because the paths with highest scores in trees of these experiments are not always correct. From these results, we can also conclude that the best-few search (or parallel search) is superior to the best-first search.

Table 5 Recognition results of 'Arithmetic Expression'.

α	β	γ	search time	recognition rate word	recognition rate sentence	notes
1	1	1	1.0	80.1%	31.0%	no back tracking
2	2	2	2.0	88.4	47.0	〃
3	3	3	3.0	92.1	56.0	〃
4	4	4	4.0	93.1	58.0	〃
5	5	5	5.0	93.5	60.0	〃
6	5	6	6.0	93.8	61.0	〃
1	5	10	1.9	90.3	52.0	(nearly) best-first search
2	5	10	2.6	91.9	58.0	
3	5	12	3.3	93.2	60.0	
5	5	15	5.1	93.6	62.0	(rough) breadth-first search

6. CONCLUSION

We proposed a new tree search method which is suitable for the recognition of perceptual input. This is a parallel tree search method with backtracking implicitcly. We evaluated this method by computer simulations and experiments of speech recognition. From these results, we found that the parallel search was superior to the best first search. By taking a weighting function into consideration, we would control the recognition rate and search space size. Further, we found that the larger the tree becomes, the more the performance of parallel search becomes effective.

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MUSIC INFORMATION PROCESSING SYSTEM AND ITS APPLICATIONS TO COMPARATIVE MUSICOLOGY

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In the application of digital data processing techniques to comparative musicology, it is an interesting subject to determine the type *of* scale in folk music and to compare the similarities in melody and rhythm between different musics. This paper describes two subjects: data entry technique for the realization of a music database and its application to comparative musicology. The former deals with dictation of melody sound. The latter concerns a method to find what scale is included in the melody, using knowledge in the modern ethno-musicology, and describes a certain measure of similarity of music.

1. INTRODUCTION

Digital data processing techniques gave the ethno-musicologists a large capacity of data processing ability never before obtainable [1]. This paper deals with data entry method for realization of a music database and its applications to comparative musicology.

It is difficult to compare the music information by listening to the melody or by watching the note. It is troublesome, still more, to search what scale is included in the melody and to detect the similarity between two different melodies.

Figure 1 shows the music information processing system which has been developed for this reseach. Musical information is expressed by two types of pattern: one is audible pattern -sound - and another is visible pattern -music note-. Though it has analogy with the language, which has speech pattern and character, it is difficult to dictate the sound of melody and to read the music note. This system has two data entry functions: dictation of melody and recognition of music note. A synthesizer and a display are used for monitoring the music.

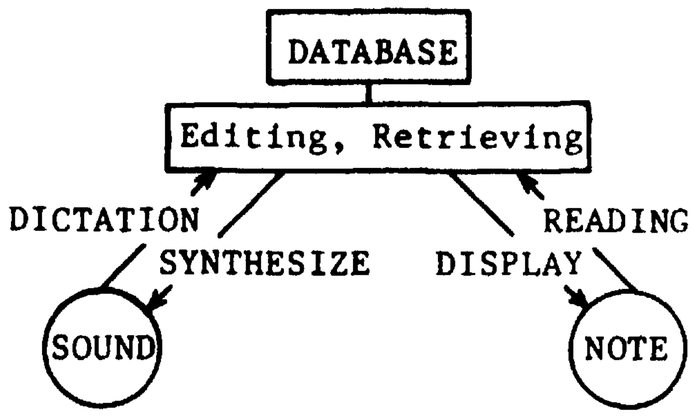

Fig.1 Music Information Processing System

2. DATA ENTRY AND DATABASE

• 1 Melody Analyser

In the early period, punched card or tape was used for comparative musicology [1]. In Japan there are a large number of folk musics which have never been collected before. So we have developed a melody analyser, which detects the pitch and the length of tone, for dictating folk music.

Pitch interval can be identified by detecting the fundamental frequency of sound. But the frequency difference ratio between the adjacent tones (semi-tone) is very small (21/12-0.059) and the duration of one tone may be very short, which requires that the measurement of the fundamental frequency should be done accurately during a short period [2],

As it is only fundamental frequency to be detected for pitch identification, a band-pass filter of Butterworth type ranging from 131 Hz (name of pitch: C_2) to 1047 Hz(C5) is used. Sound signal is sampled with the relatively low sampling rate (6kHz).

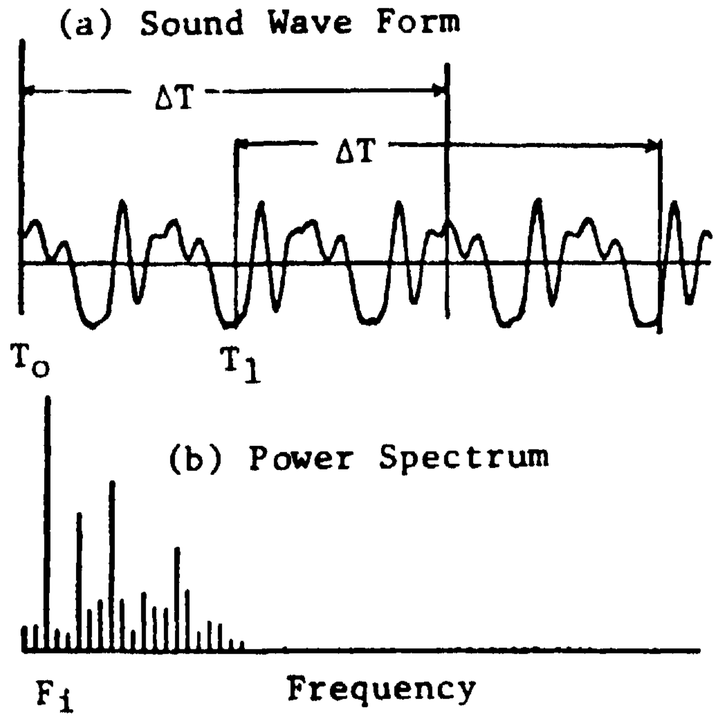

Fig.2 Frequency Analysis

For the identification of pitch, we transform the sound signal (a) in Fig.2 from T_o to $T_o+\Delta T$ into the power spectrum (b) using the FFT algorithm. In the discrete frequency analysis, the frequency difference ΔF between adjacent spectra, which is the inverse of data length ΔT, is too large. In order to obtain the accurate frequency F_p, we compensate spectral peak frequency F_i with the phase change as follows:

$$F_p = F_i + \left(\frac{\theta_1-\theta_o}{2\pi(T_1-T_o)}\right)$$

where θ_1 and θ_o are phases of F_i in the interval $[T_1,T_1+\Delta T]$ and $[T_o,T_o+\Delta T]$, respectively. Pitch P is expressed as follows:

$$P = 12\cdot\log_2(F_p/F_r)$$

where F_r is reference frequency.

The pitch obtained above has unstable frequency at the transition of tone. As the pitch of melody changes stepwise, a median filter gives good results rather than a moving averaging filter.

In case of vocal sound, F_p may vary over the range of semi-tone during the same tone because of the vibirato and the pitch scale may shift little by little for lack of absolute pitch. For the correction of them, the thresholding with hysteresis is carried out and the pitch is identified as the accumulation of the quantized pitch difference between the adjacent tones.

The segmentation is done at the time when one of the following conditions is satisfied: (1) Pitch changes stepwise, (2) Correlation of spectra between adjacent intervals becomes smaller than the predetermined value and (3) Power increases abruptly. Segmented length is quantized by using

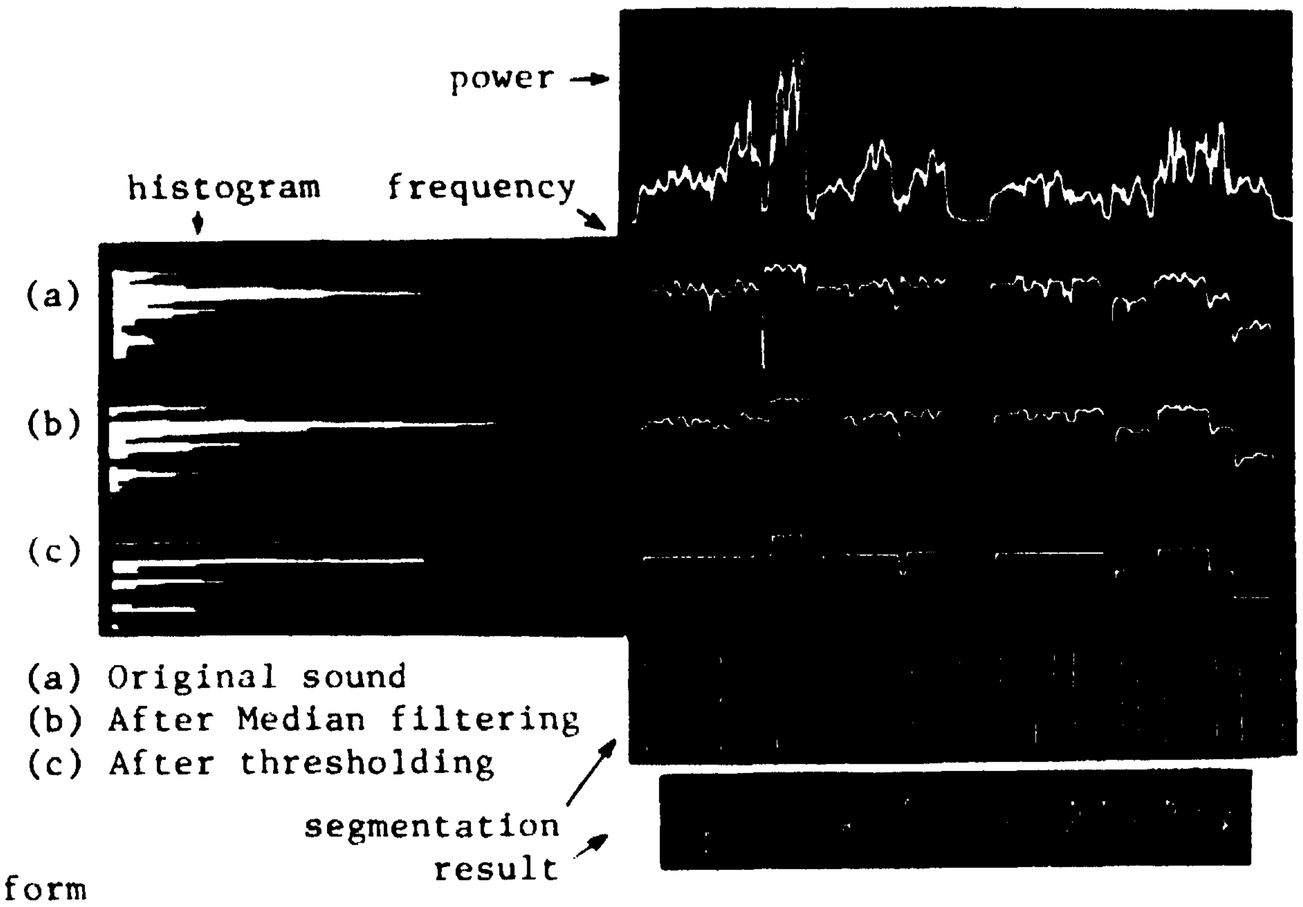

Fig.3 Dictation of Melody sound

its histogram partition. Figure 3 shows an example of dictation of a Japanese nursery song.

2.2 Music Database

Music data are encoded into a three-number code as shown in Fig.4. The m, n and l represent pitch name in octave, octave position and note length, respectively. The m and n are obtained as:

$$m = \mathrm{Mod}_{12}[P] \quad \text{and} \quad n = [P/12]$$

Notation of the music note is not unique but the pitch code in database described above is unique [3].

Music data can be entered into the database not only by the melody analyser but also by an optical note reader or a data tablet.

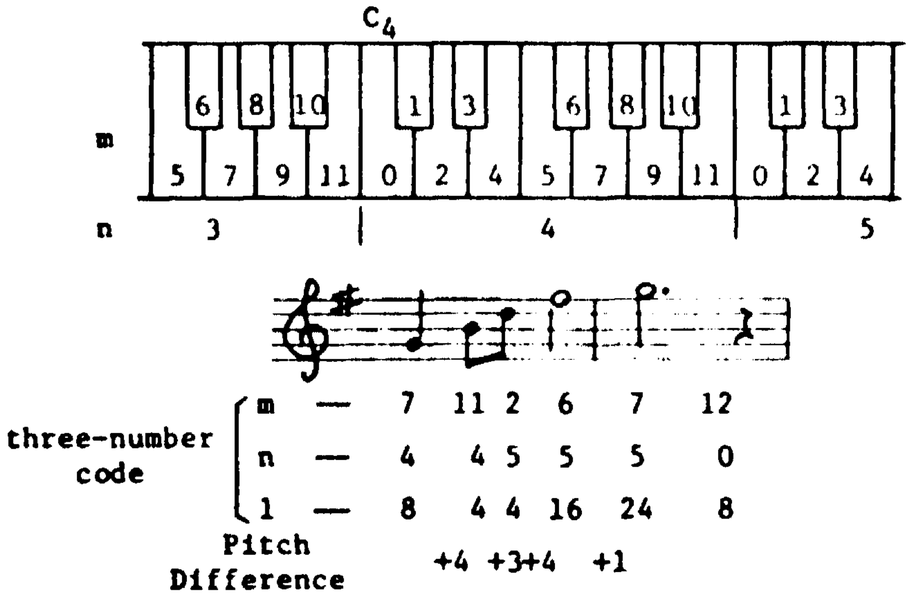

Fig.4 Data Format

3- APPLICATIONS COMPARATIVE MUSICOLOCY

3.1 Determinations of scale type

In the past, the scale of Japanese folk music was classified into Ritsu, Ryo, Yo and In scales, as the European music is classified into major scale and minor one. These scales, named after their origin, were partially illogical. In the modern Japanese ethno-musicology, Koizumi[4] claims that Japanese folk music, should be categorized into Minyo, Miyakohushi, Ritsu and Ryukyu scales as shown in Fig.5, where they are shown in the form of pitch difference sequence. And he also proposed that the type of scale should be determined by the type of tetrachord included in melody and the position of nuclear notes.

(1) Minyo scale +3 +2 +2 +3 +2

(2) Miyakobushi scale +1 +4 +2 +1 +4

(3) Ritsu scale +2 +3 +2 +2 +3

(4) Ryukyu scale +4 +1 +2 +4 +1

Fig.5 Scale Type of Japanese Folk Music
(Underlines indicate Tetrachord)

Tetrachords are the fundamental units to compose a scale and a melody, as structured with two Tetrachords conjuncted.

Nuclear notes, which mean the important notes of melody, have the following features:
(i) Basic note of tetrachord, (ii) Median note of three adjacent notes, (iii) Very often final tone of melody and (iv) Upper note in two-tone melody.

This knowledge makes it possible to categorize the type of scale by |1] Finding tetrachord and making its histogram and [2] Finding nuclear note and scoring it.

3.2 Similarity of Melody

The melody may be considered as a finite Markov chain process, in which the state k_i is the pitch note in scale. The pitch transition probability p_{ij}, the conditional probability that the pitch ki is followed by k_j, has the feature of the melody.

$$\mathbf{P} = \begin{array}{c} \\ k_1 \\ k_2 \\ \vdots \\ k_n \end{array} \begin{array}{c} \begin{array}{cccc} k_1 & k_2 & \cdots & k_n \end{array} \\ \begin{bmatrix} p_{11}, & p_{12}, & & p_{1n} \\ p_{21}, & p_{22}, & & p_{2n} \\ \vdots & & & \\ p_{n1}, & p_{n2}, & & p_{nn} \end{bmatrix} \end{array}$$

The weight of pitch note in scale can be expressed by its steady state probability **W**, which can be solved by the following equations.

$$\mathbf{W} = \mathbf{W} \cdot \mathbf{P} \quad \text{and} \quad \sum_{i=1}^{n} w_i = 1$$

The weight of pitch is effective to express the similarity between different melodies belonging to the same scale class.

3.3 Complexity of Rhythm and Melody

Let's assume the rhythm ratio R_i as:

$$R_i = \log_2(l_i/l_{i+1}) = \log_2(l_i) - \log_2(l_{i+1})$$

Its standard deviation σ_R indicates the complexity of rhythm.

$$\sigma_R = (1/n-1) \sqrt{\sum_{i=1}^{n} R_i^2}$$

The root mean square of pitch difference in melody can indicate the complexity of melody:

$$d_m = \sqrt{(1/n) \sum_{i=1}^{n} (Pi - P_{i+1})^2}$$

where P_i is the pitch of note (m + nx12).

On (σ_R, d_m) plane, horizontal and vertical axes indicate the complexity of rhythm and melody, respectively.

4. CONCLUSION

A method for dictating music sound was proposed for the realization of a music database. Regarding the applications of a Japanese folk music database, this paper described an algorithm for determining the type of scale using the knowledge about the modern ethno-musicology. And some measures of similarity in melody and rhythm were proposed for the comparison of folk music.

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AN AUTOMATIC THEOREM PROVER GENERATING A PROOF IN NATURAL LANGUAGE

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An automatic theorem prover which displays a proof in natural language is described. This system proves properties of recursive programs, and constructs a proof tree corresponding to the proof. Then it translates the tree into the proof text in English by means of the tree traverse. The proof written by this system is easy to read, because the English text is placed Instead of notations of logics, and some redundant and trivial statements are disappeared.

1. INTRODUCTION

Many automatic theorem provers have been implemented to verify programs or to prove properties of programs [2,5]. Some of them are based on a formal system in logics. However, users of such theorem provers are often confused by technical terms of logics appeared in the proof. And so it is desired that the system should display the proof in natural language without proper terms of logics. Chester [1] gives an algorithm which translates formal proofs into English. But we rarely find the systems which have such facilities. A_n algorithm to generate statements which are suitable to the context of a proof for a Gentzen-type formal system representing properties of functions is described.

TKP (Tsukuba-Keio Prover) is a family of theorem provers based on the formal system. As an ordinary prover, it combines a sequent calculus (decomposing a complicated theorem into parts which are easier to prove). The sequent is decomposed by applying the rules of inference. TKP displays a proof figure if the proof of a given theorem is completed. The proof figure consists of logical symbols and terms which are used properly in logics. Though these terms are Important tools to prove theorems automatically, they are regarded as codes which only logicians or experts in artificial Intelligence can read.

In this paper, we describe the method for displaying proofs in natural language without proper terms of logics.

2. OUTLINE OF TKP

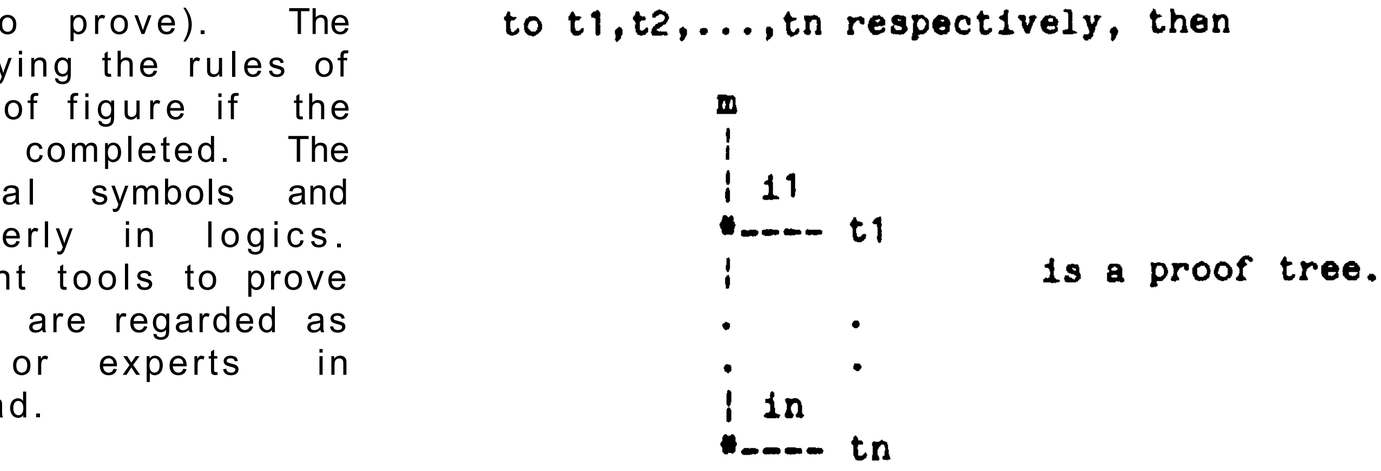
The original version, TKP1 [4], proves properties of recursive programs and generates the proof figures. TKP2, described in this paper, generates effective proofs in natural language furthermore. The formal system of TKP includes the propositional calculus of Gentzen's LK and additional rules to prove properties of recursive programs. Its completeness is shown by T. Nishimura [3].

Our processor accepts a sequent to be proved and user supplied knowledge, then it generates a tree of the proof of the given problem.

Def: A sequent is called a node.

Def: If A is a sequent decomposed from B by applying a rule, the name of the rule is the indicator from B to A.

Def: A proof tree is defined as follows.
1. A node is a proof tree.
2. If m is a sequent, t1,t2,...,tn are proof trees and i1,i2,...,in are indicators from m to t1,t2,...,tn respectively, then



is a proof tree.

3. The only proof trees are those given by 1 and 2.

If TKP proves the given problem, the proof tree will be generated (see APPENDIX in [4]). The later passes (analysis, reduction, generation), converts it into an English text.

3. ANALYSIS AND REDUCTION

In analysis, each proposition, called a P-type formula, is valuated and formulas of each node are simplified, and an analyzed tree is generated.

Def: An environment is a list of pairs of a P-type formula and the truth value. The initial state of the environment is empty.

The algorithm of analysis is as follows:

Traverse the given proof tree from its root.

When a sequent S Including the P-type formula p which does not occur in the environment, split the tree T whose root is S. Analyze T recursively in the new environment which is appended the pair of p and true to the environment E. Next, analyze T in the environment which is appended the pair of p and false to E. Construct a new tree T' whose root is S simplified in E and, whose subtrees are the above two analyzed trees (Fig. 1).

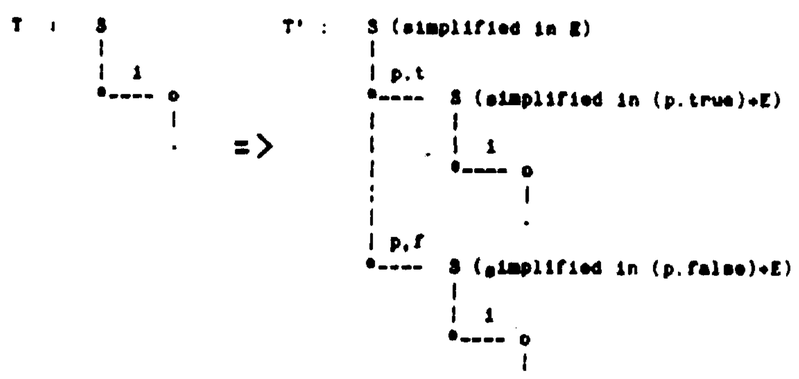


Fig. 1 Analysis (1)

When a sequent S including P-type formulas which occur in the environment is encountered, simplify S (the rules of simplification is in Fig. 3). However, if S is transformed from S1 by the user supplied knowledge or the induction hypothesis, and P-type formulas occur in S by the replacement, simplify S except the formula replaced. The new node is named S'. Next, analyze the tree whose root is S, append the indicator VAL and the analyzed tree to S' (Fig. 2).

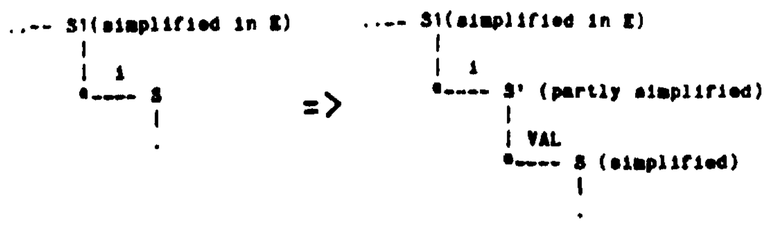


Fig. 2 Analysis (2)

In reduction, the analyzed tree is reduced and a final tree is recomposed by removing redundant nodes or subtrees from the analyzed tree.

The algorithm of reduction is as follows:

Traverse the analyzed tree.
If a node is identical to its son, remove the node together with the branch.
If a node satisfies either (I) or (II), remove the subtree connected with the node.
(I) The node becomes a logical axiom.
(II) Γ -> Δ is already proved and The node is Γ -> Δ1,Δ,Δ2

1: P-type formulas are replaced by their truth value, if exist in the environment.

2: Formulas and sequents

a) A&t,t&A,fvA,Avf ==> A
b) A&f , f&A , \t ==> f
c) Avt , tvA , \f ==> t
d) Γ1,t,Γ2 -> Δ ==> Γ1,Γ2 -> Δ
e) Γ -> Δ1,f,Δ2 ==> Γ -> Δ1,Δ2

Fig. 3 Rules of simplification

4. GENERATION OF A PROOF TEXT

Finally, the proof text in English is generated. A skeleton of the proof text is prepared for each type of tree. A skeleton is a rule of conversion of a tree to strings of characters. A typical skeleton Is shown in Fig. 5. Traversing the reduced proof tree, a proof text is constructed by applying the skeletons.

In principle, a tree is traversed from root to leaf. A tree free from branch, however, is traversed from leaf to root (Fig. 4).

APPENDIX II is generated from the final proof tree in APPENDIX I which is the reduced proof tree of the proof shown in [4].

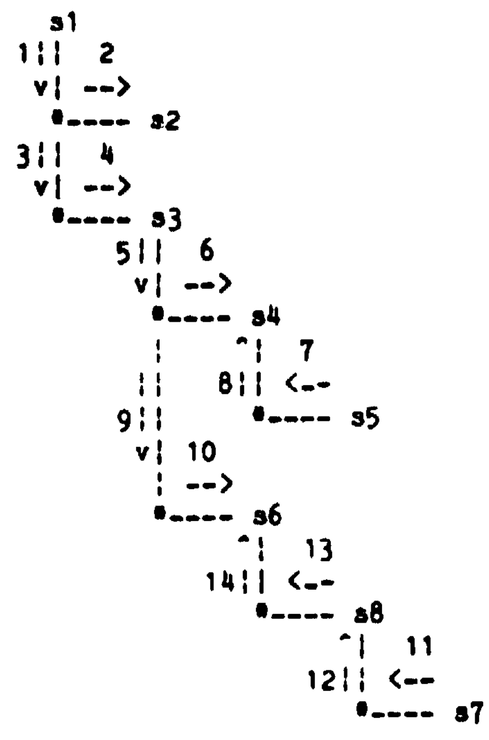


Fig. 4 Tree traverse

```
                    [ n ]   z.

z
|
|
| p.t
*---- T1          We distinguish two cases

                    CASE (1): Assume that P is true, the
                  following statement can be obtained.

                      <proof text of T1>

| p.f
*---- T2          Thus CASE (1) is proved.

                    CASE (2): assume that P is false, the
                  following statement can be obtained.

                      <proof text of T2>

                  Thus CASE (2) is proved.
```

Fig. 5 An example of skeleton

5. CONCLUSION

Our system is implemented in about 1000 lines of Lisp program. In actual program, analysis, reduction and generation are executed at the same time. These are implemented in about 600 lines. Our algorithm, except for the last pass, is independent of languages, then TKP2 can write in other language by changing the skeletons of the statements.

The proof written by this prover is very easy to read, because the English sentences are placed instead of the logical symbols, and some redundant or trivial statements are disappeared. We believe that this system will be used as a training tool of program verification.

ACKNOWLEDGEMENT

We would like to thank Prof. Toshio Nishimura for several very helpful comments.

APPENDIX I

```
F<?>(K) -> G<?>(K,1)
 |L-v
 *--F<0>(K) -> G<?>(K,1)
 |L-v
 *--F<N+1>(K) -> G<?>(K,1)
    |R-v
    *--F<N+1>(K) -> G<N+1>(K,1)
       |D-1
       *--P(K)&1 v \P(K)&KxF<N>(K-1) -> G<N+1>(k,1)
          |P.t
          *--1 -> G<N+1>(K,1)
          |  |D-2
          |  *--1 -> P(K)&1 v \P(K)&G<N>(K-1,Kx1)
          |     |VAL
          |     *--1 -> 1
          |P.f
          *--KxF<N>(K-1) -> G<N+1>(K,1)
             |HYP
             *--KxG<N>(K-1,1) -> G<N+1>(K,1)
                |D-2
                *--KxG<N>(K-1,1) -> P(K)&1 v \P(K)&G<N>(K-1,Kx1)
                   |VAL
                   *--KxG<N>(K-1,1) -> G<N>(K-1,Kx1)
                      |T-1
                      *--G<N>(K-1,Kx1) -> G<N>(K-1,Kx1)
```

APPENDIX II

```
Prove that
        if  a  F ? (K)  then  a  G ? (K,1)
where
        1   F-N+1-(X)  P(X)&1 v \P(X)&XxF N (X-1)
        2   G-N+1-(X,Y)  P(X)&Y v  P(X)&G N (X-1,Xx1)
using the theorem
        1   if  a  XxG N (Y,Z)  then  a  G N (Y,X,Z)
PROOF
 [1]    if  a  F ? (K)  then  a  G ? (K,1)
will be proved by induction on N
BASIS, F r N  0,
 [2]    if  a  F 0 (K)  then  a  G ? (K,1)
This is valid, because F 0 (K) is undefined
INDUCTION STEP  Assume (as the induction hypothesis)
that for every i  N+1,
        if  a  F i (K)  then  a  G i (K,1)
Now let's prove
 [3]    if  a  F N+1 (K)  then  a  G ? (K,1)
It is sufficient to prove that
 [4]    if  a  F N+1 (K)  then  a  G N+1 (K,1)
By definition 1, [4] is equivalent to
 [5]    if  a  P(K)&1 v  P(K)&XxF-N-(K-1)
           then  a  G N+1 (K,1)
We distinguish two cases
  CASE (1)  Assume that P(K) is true  The following
statement can be obtained,
 [6]    if  a  1  then  a  G N+1 (K,1)
Now, consider the following valid statement
 [7]    if  a  1  then  a  1
Since P(K) is true, [7] may be written as follows,
 [8]    if  a  1  then  a  P(K)&1 v  P(K)&Xx N (K-1,X1)
By definition 2,
 [9]    if  a  1  then  a  G N+1 (K,1)
Thus CASE (1) is proved
  CASE (2)  Assume that P(K) is false  The following
statement can be obtained
 [10]   if  a  Xx F N (K-1)  then  a  G N+1 (K,1)
Now, consider the following valid statement
 [11]   if  a  G N (K-1,X1)  then  a  G N+1 (K,1)
Since P(K) is false, [11] may be written as follows
 [12]   if  a  G N (K-1,X1)
           then  a  P(K)&1 v  P(K)&G N (K-1,Xx1)
By definition 2,
 [13]   if  a  G N (K-1,X1)  then  a  G N+1 (K,1)
By theorem 1,
 [14]   if  a  Xx G N (K-1,1)  then  a  G N+1 (K,1)
By the induction hypothesis,
 [15]   if  a  Xx F N (K-1)  then  a  G N+1 (K,1)
Thus CASE (2) is proved
This completes the proof
```

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LINEAR FEATURE EXTRACTION AND DESCRIPTION

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Abstract

A technique of edge detection and linking for linear feature extraction and its applications to detection of roads and runway like structures is described. Experimental results are included.

1. INTRODUCTION

The importance of effective early processing of visual input for a complete image understanding system is generally accepted. The early processing may consist of a description of image discontinuities, usually in the form of edges and lines, or segmentation into uniform regions. In this paper, we describe a technique for extracting linear features in an image by a process of edge detection and line linking and also of deriving higher level descriptions from the extracted lines. These techniques are aimed to be general. Applications to road detection and airport recognition tasks are described.

Edge detection and line finding techniques, of course, have been studied since the early days of this field. The literature is too numerous to list here; partial surveys may be found in [1-3]. In spite of the large amount of previous research in this area, no algorithms suitable for complex imagery are apparent. Here, we describe an edge detection and line finding technique with superior performance on a wide variety of images. Many of the steps in our process have been suggested by other researchers previously. However, due to limitations of space, we are unable to elaborate on these in this paper. More details may be found in [4].

2. EDGE DETECTION AND LINE FINDING

Convolution with Edge Masks

Edge detection starts by convolving a given image with masks corresponding to ideal step edges in a selected number of directions. The magnitude of the convolved output and the direction of the mask giving the highest output at each pixel are recorded as edge data. We have found 5 x 5 masks in six directions to be suitable for most images of interest.

Thinning and Thresholding

The presence of an edge at a pixel is decided by comparing the edge data with some of the 8 neighboring pixels. An edge elements is said to be present at a pixel if:

1. the output edge magnitude at the pixel is larger than the edge magnitudes of its two neighbours in a direction normal to the direction of this edge. (The normal to a 30 degree edge is approximated by the diagonals on a 3 x 3 grid);
2. the edge directions of the two neighboring pixels are within one unit (30 degrees) of that of the central pixel; and
3. the edge magnitude of the central pixel exceeds a fixed threshold.

Further, if the conditions 1 and 2 above are satisfied, the two neighboring pixels are disqualified from being candidates for edges. This algorithm produces results independent of the order in which the pixels are examined.

Linking

The first step in boundary tracing is to determine the continuing neighbors on the boundary for each edge point. Typically each point has two neighbors, known as a predecessor and a successor, except for the end-points, isolated points and where two boundary segments join or intersect. This connectivity information is stored in two files, called p and s files, of the same size as the input image. Each element in these files contains an integer corresponding to the proceeding (or succeeding) eage among the 8 neighbors. Forks are indicated by an extra bit as explained later.

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Our criteria for connecting two edge points is that they be neighbors, in the 8-neighbor sense, ana that they have edge directions differing by not more than a certain value, set at 30 degrees for masks described previously. Due to the nature of thinning, only three locations are potential candidates for predecessor or successor elements as shown in Figs. 1(a) and (b) for edges of u and 30 degree directions respectively. The determination of successor (predecessor) pixels is elaborate due to the several cases that are possible at each pixel:

1. Only one element is an acceptable successor. In this case the successor (predecessor) is recorded in the s(p) file as an integer corresponding to its location.
2. Two candidates are acceptable successors. If they are not 4-neighbors, a fork is present as shown in Fig. 2(a). If they are 4-neighbors, a fork exists only if their directions differ by more than 2 units (60 degrees), as in Fig. 2(b). Otherwise no fork exists and the nearer of the two (using Euclidean distance), forms the successor (predecessor), as shown in Fig. 2(c). These rules are for smooth continuation of lines and were derived by complete enumeration of such configurations. In case of a fork, the stronger of the two candidates in edge magnitude forms the main stream. The fact that a fork exists is noted in the s(p) file by marking one bit. This information is sufficient to trace both streams of a fork by examining the p and s files simultaneously.
3. Three candidates are acceptable successors. Fig. 3 shows all possible such configurations for a vertical edge (no three successor configurations occur for 30 degree edges). In these cases, a fork exists. The main stream is formed by the nearer of the two edges having the same direction, and the other candidate with different direction froms the other branch.

The predecessor-successor representation of the linked edge elements is in contrast to explicit lists of elements forming a connected segment. For larger images, not entirely resident in core, it is more convenient to form predecessor and successor matrices first, as the processing requires only a sequential scan of the image file. Further, this representation is "iconic" and certain proximity computations can be made more easily.

Tracing Boundary Segments

Boundary segments containing ordered lists of edge elements are computed from the predecessor-successor (p-s) files. An edge point with no predecessors determines the starting point. A boundary segment is traced by following the successor elements until an element with no successors is reached. At a point with multiple successors, the "main" fork is chosen. The secondary branches of forks are picked up on a second pass that starts tracing at such points. A third pass is required to trace circular or closed segments. This pass begins arbitrarily at an edge point that has not been thus far visited, i.e. included in a segment. (A temporary binary file is used to store this information).

Linear Approximation

Each boundary segment is approximated by a series of piecewise linear segments. The algorithm used is a variation of the well known iterative end-point fit algorithm (see *I'D]* pp. 33b-339). Results of processing an airport image are shown in Figure 4.

3. OBJECT DESCRIPTION

A major goal of this research is to compute descriptions of objects useful for their recognition. Certain classes of objects, such as roads ana airport runways, are characterized as being bounded by elongated parallel lines. lhese lines have opposite contrasts and we call them "anti-parallel" lines, abbreviated as "apars". These apars are conveniently described by a medial line and width of the pair. These descriptions were motivated as being two-dimensional special cases of Binford's "Generalized Cone" representation 16]. Finding apars in facilited by sorting line segments by their orientations.

Proper choice of apars that correspond to objects can be difficult and is like resolving figure-ground relationships However for many applications, such as for roads and runway detection, a choice of the closest pairs may suffice and be aided by knowledge of the desired objects being brighter or darker than the background.

Fig. 4(c) shows the axes of the apars computed from the segments in fig. 4(b). Only the closest pairs were retained. Work is in progress to recognize specific airports from the spatial relationships of the partial axes of the runways and taxiways as shown here.

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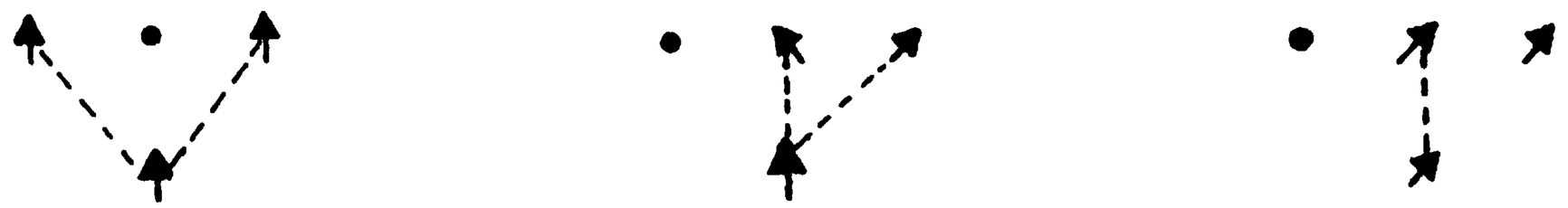
a) 0^{O} Edge b) 30^{O} Edge

Fig. 1. Possible Successor Locations for Two Edges.

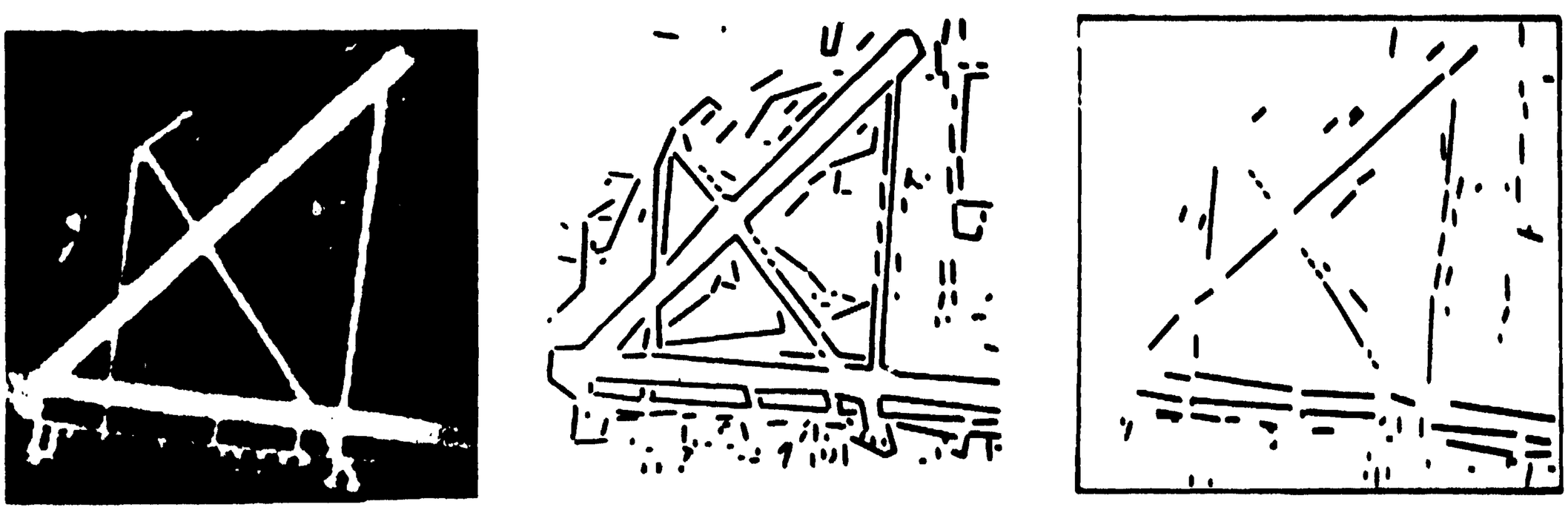


a) Non-neighboring Successors b) Successors Directions Differ by 60^{O} c) Successors of Same Direction

Fig. 2. Three Instances of Two Successors.

a) b)

Fig. 3. All Instances of Three Successors.



a) Image b) Linear Segments c) Anti-Parallel Axes

Fig. 4. Processing of an Airport Image.

DESCRIBING NATURAL TEXTURES

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ABSTRACT

There have been many different approaches to texture description, primarily statistical techniques although there has been some work on structural texture analysis all along. We present here a technique which can be used to easily derive parts of the structural description - the regularity information in particular. Some limits on this method and its use in an overall texture description system are discussed.

1. INTRODUCTION

Areas of an image may be better characterized by their textures rather than by pure intensity information. Texture is the pattern of the spatial arrangement of different intensities. The different textures in an image are usually very apparent to a human observer, but automatic description of these patterns has been difficult. We wish to describe the texture in the same terms *as* a human observer, rather than by a purely statistical method.

Many statistical textural measures have been proposed and studied in the past [1-4], including analysis of the discrete Fourier transform 14], analysis of generalized gray-level co-occurence matrices [1], and analysis of the micro-edges in a subwindow [3]. We are not interested in finding one texture measure which will distinguish between all areas, but in finding a texture description to use in conjunction with many other features [9].

The work in structural texture description has been more limited. Maleson [5] used simple regions as the basic elements and used relations between regions and shape properties in his analysis. Tamura et al. [6] developed a set of operators to rate textures on several scales, comparable to their ratings by human subjects. The proposals of Marr [7] for texture analysis based on the primal sketch are similar to some of the analysis which we perform.

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2. ANALYSIS OF TEXTURE

We have chosen to first explore the description of regular patterns (e.g. street patterns of certain cities shown in the top of Fig. 1). Other attempts to derive much of the structural information from the Fourier transform were only partially successful [4], so we felt other methods should be attempted. The individual textural elements could be located ard analyzed [5], but the simple regions are unreliable when the textural elements are very small. Another option is to analyze an edge image to find the structure. The patterns in the original image will cause related patterns to appear in the edge image, which should be more consistent and easier to analyze than the original image data.

We are interested in the edges between adjacent textural elements and not so much in edges between adjacent textural patterns or extended regions. The edge operator has been applied to other types of analysis lb], and is applied over a 3 x 3 window to generate an edge magnitude and direction (1 of 8). Fig. 2 shows the edge output for the subwindows in Fig. 1.

The edge images retain the regularity of the initial image, but now the regularity is in the spacing of edges not texture elements. A Fourier transform applied to this binary edge image may indicate the repetitive nature of the edges, but is obscured by the degeneracies introduced by the binary nature of the input.

3. EDGE CO-OCCURRENCE ANALYSIS

Generalized gray level co-occurrence matrix analysis is a basis for much of the statistical texture analysis 11]. Basically a set of matrices are computed where the (I,J) entry of a

matrix is the probability that a point with value J occurs at a given spacing and angle from a point with value 1. Usually the image values are partitioned into a small set of values (8 rather than 25b), so that it is even possible to compute the initial matrices. Also the computation is made for several spacings (1,2,J,8, etc.) and airections (U°, 4b°, 90°, etc.). Because of the large number of matrices that are generated by this method, various measures are computed on the matrix values, and the classification is performed using these measures [1]. The common measures do not capture the important feature in the edge images: the tegular spacing of edge elements. The measure we use is one that indicates the probability of edges occurring at two points at a certain distance and angle from each other, given that an edge occurs at one of the points.

There are several ways to determine if an edge occurs at two points, with different features indicated by the different comparison methods. Using all edges for every direction presents severe problems in the analysis of the output since long lines running in the same direction as the co-occurrence computation will be included along with lines running perpendicular to the direction. (Tamura et al. [6] used this feature to indicate linear patterns in their texture experiments.) The first limitation is to consider only those edge elements perpendicular to the direction of search, that is in the computation of co-occurrences in a horizontal direction, only vertical edges are considered. The variations on this basic restriction include: allow some freedom in the edge direction (45° either way), accept only perfect matches (up and up, down and down), and accept only opposites (up and down, not up and up).

4. DISCUSSION

None of this analysis would be worthwhile if it did not ease the task of describing regular textures. The highly regular patterns of the urban area (the top row of the image, and Fig. 3) and raffia (the bottom row and Fig. 4) produce strong periodic patterns in the plot of the co-occurrence measure. A high value in the graphed measure indicates that pairs of edges frequently occur at that particular spacing and angle.

The spacing of pairs of textural elements is given by the peak to peak spacing in the measure which matches edges only in the exact same direction (see Fig. 3). The size of individual elements is best given by the measure which allows edges in the opposite direction (see Fig. 4). The solid line in the graph indicates the size of dark objects and the dotted line the size bright objects. The size is from the first major peak, the succeeding peaks are caused by the repeated pattern. The patterns usually do not line up with one of the 4 directions, so there will be some response in 2 directions. When these directions are 45° apart the dominant direction is probably between them (urban, Fig. 3). But when they are 90° apart there should be a regular pattern in two directions (Raffia, Fig. 4). Thus, from the data we can say that the urban subwindow has a regular pattern of bright and dark regions oriented in one direction, near 45°, with the bright regions being larger (width about 10 pixels) than the dark ones (width about 4). Note that the size of the blocks in the other direction is near the size limit of the co-occurrence computation and also that few of the relevant edges are detected.

The irregular textural patterns (e.g.the suburban areas of the second row of Fig. 1, and the grass, sand, and wool of the third row,) do not produce the same clearly periodic patterns of raffia. But it is possible to derive certain useful features from the results, primarily that of the size of the textural elements.

This is not a complete description of the textures, but serves as a good initial description of the patterns. There are still other important features of the textures which are not derived by this method, but may be computed by other techniques. The simple edges are not intended to be the final elementary object in the texture description, others such as extended edges, lines and regions may be required for complete analysis. This procedure has been applied on many other less regular patterns with similar results [10].

5. CONCLUSIONS

General texture analysis is a very difficult problem, but this analysis of edge images appears to be an effective method to extract many important structural features from the textural patterns. One major unanswered question is whether or not all of the information derived by the human user can be reliably derived by a program. We are still working on the automatic extraction of this information from the data which is produced by this textural analysis method.

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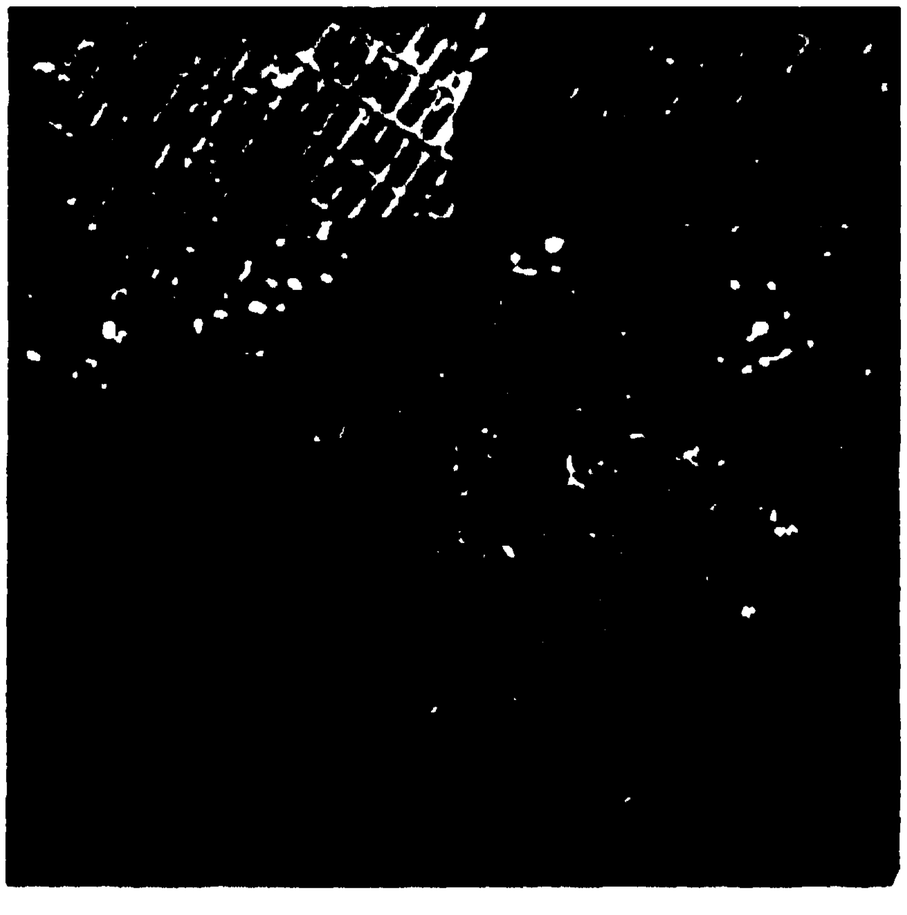

Fig. 1. 16 Subwindows for Texture Analysis.

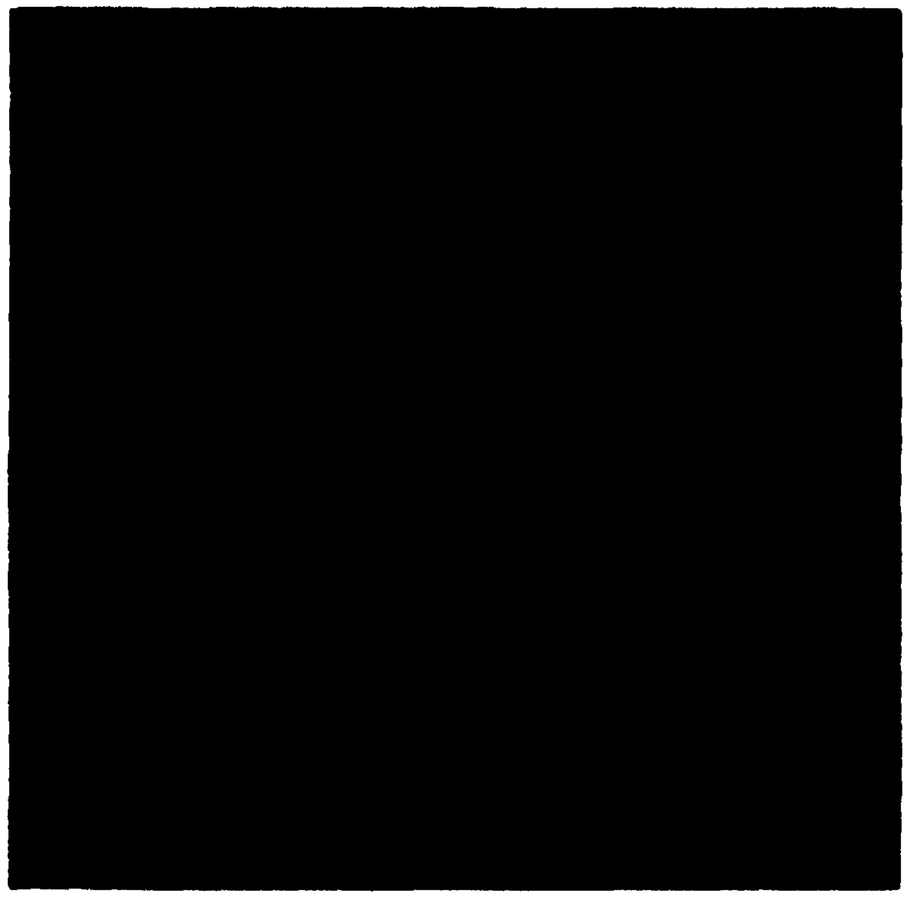

Fig. 2. Edges from Fig. 4.

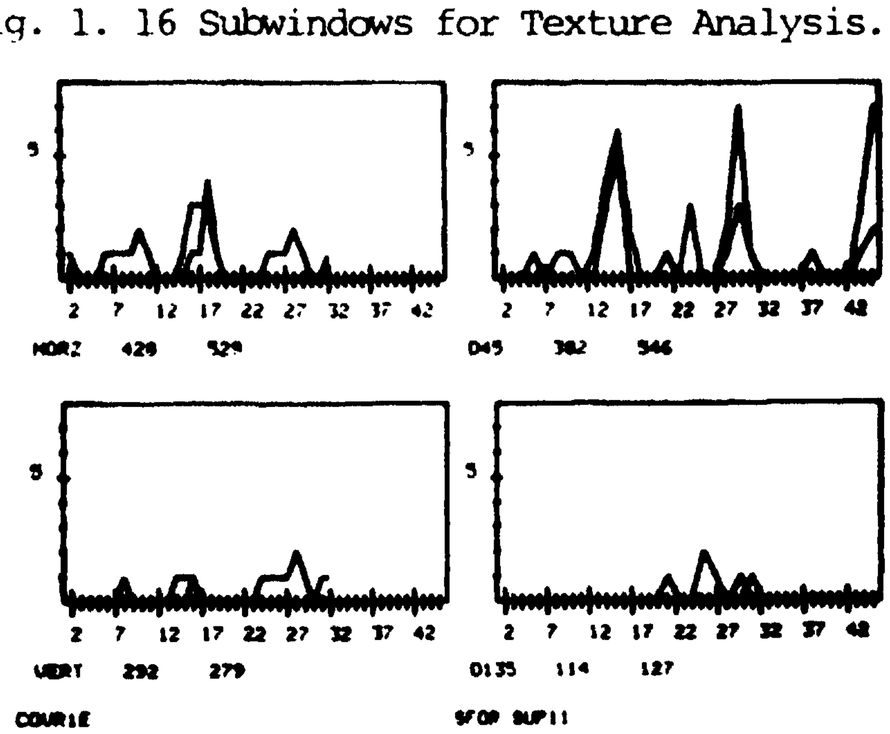

Fig. 3. Co-occurrence Results for San Francisco Exact Edge Direction Matches Only.

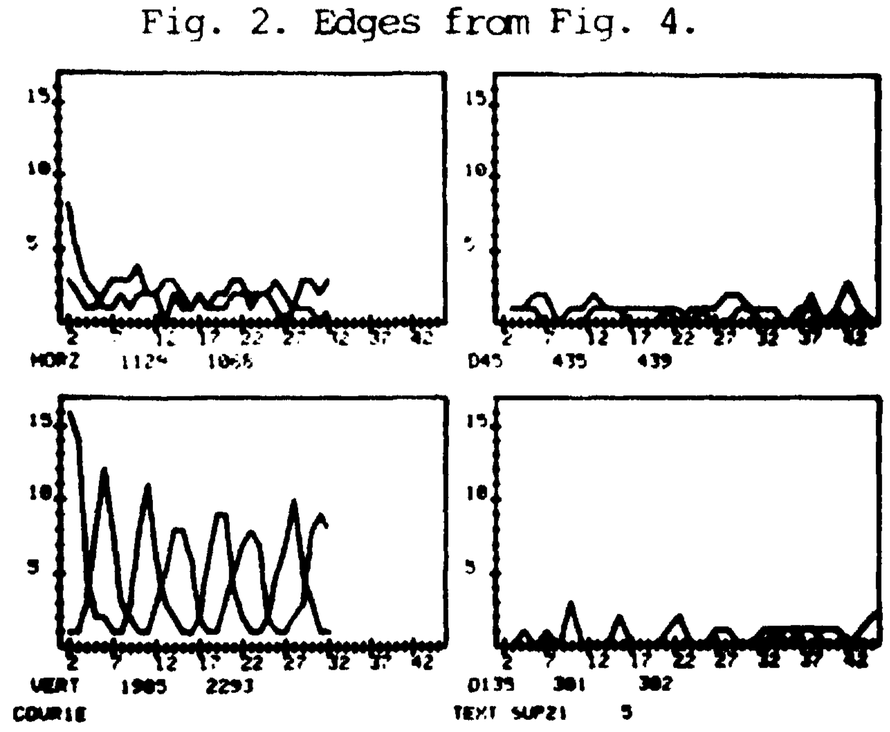

Fig. 4. Co-occurrence Results for Raffia Opposite Edge Direction Matches Only.

AGE (Attempt to Generalize): A Knowledge-Based Program for Building Knowledge-Based Programs

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The goal of the ACE project is to demystify and make explicit the *art of knowledge engineering.* It is an attempt to formulate the knowledge that knowledge engineers use in constructing knowledge-based programs and put it at the disposal of others in the form of a software laboratory. To achieve this goal, the task for ACE is divided into two main sub-tasks: (1) isolating techniques used in knowledge-based systems and programming those that are general and useful (2) building an intelligent agent to guide in the use of these techniques. Currently AGE has a facility to build programs using the Blackboard Model [8,131

1. INTRODUCTION

This paper reports the goals and the current status of the ACE project." Appendix I contains a protocol of a user solving a specific problem using ACE. The intent of the protocol is to show ACE from the user's point of view. The main body describes the motivations for and the description of the facilities in ACE.

1.1 @bjectives

The general goal of the ACE project is to demystify and make explicit the art of knowledge engineering. It is an attempt to formulate the knowledge that we knowledge engineers use In constructing knowledge-based programs and put it at the disposal of others in the form of a software laboratory.

The design and implementation of the ACE program is based primarily on the experience gained in building knowledge-based programs at the Stanford Heuristic Programming Project in the last decade. The programs that have been, or are being, built arc: DENDRAL, meta-DENDRAL, MYCIN, HASP, AM, MOLCEN, CRYSALIS [9], and SACON [21 Initially, the AGE program will embody artificial intelligence (AI) methods used in these programs. However, the long-range aspiration is to integrate methods and techniques developed at other AI laboratories. The final product is to be a *collection of building-block programs* combined with an *intelligent front-end* that will assist the user in constructing knowledge-based programs. It is hoped that ACE will speed up the process of building knowledge-based programs and facilitate the dissemination of AI techniques by: (I) packaging common AI software tools so that they need not be reprogrammed for every problem; and (2) helping people who are not knowledge engineering specialists write knowledge-based programs.

The task of building such a software laboratory for knowledge engineers is divided into two main sub-tasks:

1. *The isolation of techniques used in knowledge-based systems.* It has always been difficult to determine if a particular problem solving method used in a knowledge-based program is special" to a particular domain or whether it generalizes easily to other domains. In existing knowledge-based programs, the domain specific knowledge and the manipulation of such knowledge using AI techniques are often so closely coupled that it is difficult to make use of the programs for other domains.

2. *Guiding the user in the initial application of these techniques.* Once the various techniques are isolated and programmed for use, an intelligent agent is needed to guide the user in the application of these techniques.

1.2. User Profile

The design of the ACE system would depend, to a great extent, on the type of users we expect will benefit most from using ACE. *Initially, ACL is designed for AI scientists familiar with current problem solving techniques, and who can program in the* INTERLISP *language* [19] *(since* ACE *is implemented in* INTER LISP); *and are familiar with production-rule representations of knowledge* [51 In other words, ACE is initially aimed at people who could conceivably write knowledge-based programs themselves.

For the person in this category, the advantages of using AGE are twofold:

1. The basic system components are already programmed (e.g., rule interpreters and other control mechanisms, traces, explanation modules, and other components basic to many systems).
2. ACE allows the user to experiment with different problem solving techniques without extensive reprogramming.

Eventually, ACE will be able to help the less knowledgeable or less experienced person.

1.3. Outline of the Paper

The term "knowledge engineering" is being used more frequently to refer to the process of writing application programs using primarily AI methods. The historical context in which knowledge engineering arose and the nature of the work are described by Feigenbaum [91 Section 2 contains a brief description of the task for the AGE program within the context of knowledge engineers' work. It is followed by an overview of the facilities in the current version. Section *i* contains a short description of an organizational method by which frameworks are decomposed to form a basis for a software laboratory. It is followed by a summary section.

2. TASK FOR THE ACE SYSTEM

Currently there are several projects that aim to provide prepackaged tools for knowledge engineers (UNITS [18],

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EMYCIN [2]) or to provide programming languages (KRL [4] AIMDS [17]). In preprogrammed packages, all, or most, of the paradigm, system design, and implementation choices have been made by the package designers. In languages none, or very few, decisions have been made for the user. Neither approach guides the user in the design and the construction of knowledge-based programs. AGE has been conceived to bridge the gap between these two extremes—to provide some guidance in the *what, why,* and *how* of programming; plus some preprogrammed problem-solving frameworks.

Ideally then, AGE is an attempt to define and cumulate knowledge-engineering tools, with rules to guide in the use of these tools. It must itself be a knowledge-based system containing knowledge about building knowledge-based programs, combined with a facility that allow the user to explore and experiment with various concepts and techniques. It must provide the user with a variety of preprogrammed modules, allow her to modify them and to add her own. And above all, it must be able to produce running programs. How the AGE system itself is organized for modularity will be described in Section 4. In the next section we describe a framework currently available to the user to construct her knowledge-based program.

3. PROFILE OF THE CURRENT AGE SYSTEM

To correspond to the two general research goals described in the Introduction, the AGE program is being developed along two separate fronts. The first of these fronts is the development of tools to help the user build a variety of knowledge-based programs—the *generality* front. The second front is the development of *intelligence* in the interaction between the user and the AGE program; i.e., moving from dialogues on *how to use the tools* in AGE to *what tools to use*—the *how-to-what* spectrum described by Feigenbaum [91

3.I. Currently Implemented Tools

The building-block components currently available to the users have been carefully selected and modularly programmed to be useable in combinations. The current AGE system aims to provide the user with a framework useful for incremental hypothesis formation, known as the *Blackboard Model* [8, 131 It can be described as follows:

1. There is a global data base (the blackboard) that is used as a means of communication and interaction among the KSs;
2. There are diverse knowledge sources (KSs) that are kept separate and independent; and
3. The KSs respond to changes in the blackboard.

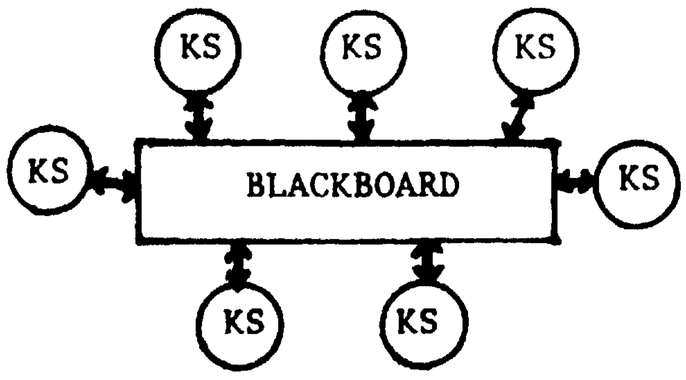


Figure I. The Blackboard Model

The paradigm itself does not specify the structure of the data base, the representational form of the KSs, nor the response mechanisms. When a model is translated into a program, various architectural and implementation decisions are made by the designers, and programs that use the same paradigm may have different organization and behavior. For example, although HEARSAY-II [13] and CRYSALIS [7] use the Black . .d model, the basic architecture, knowledge representation, and knowledge utilization techniques differ. The differences can be attributed to many factors: the nature of the problem (understanding speech signals and interpreting x-ray crystallographic data); implementation language; real-time constraints; noise level of data; quality and amount of available knowledge; and, last but not least, the designers' tastes.

In AGE the Blackboard-based program design has been implemented to allow flexibility in representation and in the application of other problem solving methods within the framework. It consists ot three major components:

1. The Blackboard: The blackboard contains hypotheses in a hierarchical data structure; it represents the task domain in terms of a hierarchy of analysis levels of the task.
2. The KSs: The KSs contain the knowledge of the task domain (which the user must provide) that can perform the analysis. The KSs are represented as sets of production rules.
3. The Control: The control component contains mechanisms that allow the user to (a) specify the conditions for the invocation of the KSs and (b) to select items on the blackboard for focus of attention [10]

In the remainder of this section these components will be described in more detail.

3.1.1. Blackboard

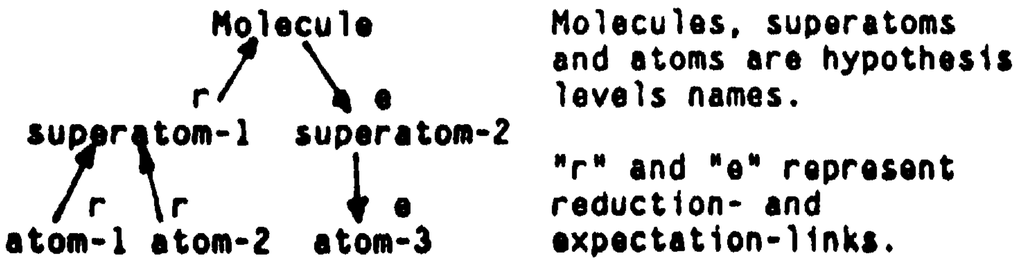
The combined process of KS selection and incremental changes to the blackboard is viewed as a general process of hypothesis formation consistent with the following definition:

An hypothesis can be generated [11]:

1. deductively, using *support from above*—this support can be
   a. *theoretical* support (or model-based support),
   b. *support* from more Inclusive hypotheses that have Independent evidential support; or
2. Inductively, using evidential *support from below.*

This definition suggests that the most natural way to represent hypotheses is in some form of a hierarchy The structure of the hierarchy may be strict; it may be flat consisting possibly of only two levels—input data and its translation; or, it may be complex, consisting of many related hierarchies (often referred to as blackboard planes [7]). Currently AGE can represent all of the above forms of hierarchy. An hypothesis is represented as hierarchically organized hypothesis elements integrated by links that represent support from above—called the *expectation-link,* or support from below—called the *reduction-link* (see example 1).

EXAMPLE 1: **Hypothesis structure in CRYSALIS [7]**



An *hypothesis element* is a named node in the hypothesis structure that represents an aggregation (summary,

interpretation, etc.) of lower level hypothesis elements. Each element contains information In the form of attribute-value pairs that are meaningful at that particular hypothesis level (see example 2). These information are inferences generated by the rules in the KSs and can, in turn, be used for further hypothesis formation.

EXAMPLE 2: A possible hypothesis element in CRYSALIS

```
Hypothesis level: ATOMS
Hypothesis element name: ATOMS-18
Inferred attribute-value pairs:
  Atom.name    Sulfur
  Location     (12.3 13.6 24.2 +- .02)
  Partof       (OR CYS14 CYS17)
  Bonded to    HEME-1
  Bondtype     Hydrogen
```

In some problems all the hypothesis elements needed to solve the problems are known *a priori.* In other problems the number of hypothesis elements in the solutions are not known in advance. For example, in PUFF (a program to diagnose pulmonary function disorder [12]) all the possible disease states which account for specific patient data are known in advance. On the other hand, in cryptogram problem (see Appendix I) the number of letters, words, parts of sentence, etc. are not known until a specific cryptogram is being solved. To accommodate both types of solution space, AGE allows the user to generate and name hypothesis elements in advance, generate and name them dynamically, or generate them in some combination.

The hypotheses are generated by inference rules in the KSs. What the KSs look like and how they work are described next.

3.1.2 Knowledge Representation

Knowledge representation in ACE is based on the premise that there are at least four broad categories of knowledge that are needed to solve problems:

1. knowledge of specifics,
2. knowledge of ways and means of dealing with the specifics,
3. knowledge of universals and abstractions in the task domain [3], and
4. knowledge of problem solving and knowledge utilization methods in the task domain.

Within the framework of incremental hypothesis formation using the Blackboard model, an attempt has been made to help the user identify, represent, and utilize these diverse types of knowledge.

Domain knowledge in ACE represents the knowledge necessary to accomplish the goals of the user's program. This knowledge reflects the *knowledge of specifics* and the *knowledge of ways and means of dealing with the specifics.* The knowledge is represented as production rules [51 These rules are organized into sets called the Knowledge Sources (KSs).

Knowledge Sources

A *Knowledge Source* is a *mega-chunk of knowledge* consisting of a labeled set of rules that are *a priori* deemed to belong together. *How* the rules within a KS is organized and *what* rules are included in a KS depend on, the intended role of the KS in the overall problem solving plan. For example, a KS may be organized to represent models—in which case all rules are grouped around some objects or concepts, much like schemata or frames. Or, a KS may be organized around events—in which case all rules which, for example, process input data, are grouped together. In order to solve problems within the framework of the Blackboard model, KSs must place their inferences on the Blackboard. In other words, KSs must generate hypotheses using rules that:

1. add or modify hypothesis element(s), or
2. add or modify relationships between elements by
   a. analyzing data (support from below),
   b. specializing or instantiating a more inclusive hypothesis element (support from above), or
   c. generating expect at ion(s) from
      1. models, or
      2. more inclusive hypothesis elements that must be verified by data.

Each KS has associated with it: (a) preconditions (a list of events) for its invocation; (b) a list of dotted pairs of hypothesis levels that it spans; (c) list of links generated by it; (d) "single" or "multiple" hit strategy to be used for the rules, and (e) a facility for variable bindings to set local context, to simplify expressions in the rules, to avoid multiple evaluations of the same expression, and to allow communication between the condition and the conclusion halves of a rule.

AGE allows the use of just one KS in the user's program if desired. Whether a single KS is sufficient to solve a problem or not, depends on the characteristics of the problem and on the formulation of the KS. MYCIN [16] is an example of a program that has an equivalent of one KS; all the rules are chained in a goal-directed fashion to represent a line of reasoning meaningful in that domain.

The set of domain-specific KSs may be manipulated in many ways by other higher level KSs [6, 14] The higher level knowledge may reflect both the knowledge about *ways and means of dealing with the specifics, knowledge of problem-solving methods useful in the task domain,* and *knowledge about other knowledge* in the domain. These higher-level KSs are often integrated into the Control component described later.

Rules

A *rule* in ACE is a *chunk of knowledge* written in a syntax comprehensible to ACE. Each rule consists of a left-hand-side (LHS) and a right-hand-side (RHS). The LHS specifies a set of conditions or patterns for the applicability of the rule (i.e. premises). The RHS represents the implications or conclusions to be drawn under the situation specified in the LHS.

To be consistent with the various ways in which hypothesis elements can be generated, the current implementation of the RHS can:

1. add elements to the hypothesis; or add or modify the values of the attributes of elements or the relationship between elements;
2. generate expected elements or values of (or relationship between) elements in the hypothesis;
3. generate goals to establish some elements, or values or links, within hypothesis elements.

Rule Credibility

The domain rules that generate hypotheses are, more often than not, judgmental and uncertain. A *credibility value,* or *weight,* can be associated with the rules to reflect uncertainty. AGE provides means of associating weights (certainty values.

probability, etc.) with inferences generated by the RHS of rules. It also provides some pre-programmed procedures for the manipulation of these weights, for example, an algorithm to compute Certainty Factors (CF) from MYCIN. For users who need different algorithms, ACE provides mechanisms for integrating user-provided algorithms.

EXAMPLE 3: Integrating weights

Note: The rules used in this example, and some others, are based on PUFF rules [12]. From pulmonary function test data, the PUFF program determines if a patient is normal, has obstructive airway disease (OAD), restrictive lung disease (RLD), or other pulmonary function-related diseases; and the severity of the diseases. It further determines if OAD is of type emphysema, asthma, or bronchitis. ("RV" in the example refers to a measurement--residual volume.)

```
Weight-adjuster: $ADJWT (MYCIN algorithm)
Rule to be evaluated:
   if (TYPE = OAD) & (RV > 220) then (PROPOSE
      (SEVERITY SEVERE .8))
Hypothesis element before rule evaluation:
      hypo-element name:  DISEASE-05
      type:  (OAD .8)
      severity:  (SEVERE .6)
Hypothesis element after rule evaluation:
      hypo-element name:   DISEASE-05
      type:  (OAD .8)
      severity:  (SEVERE .92)    <-----
```

Rule Evaluators

The applicability of a rule is determined by how the premises in the LHS are evaluated. The term "applicability" can have a different definition for different problems--it may mean that all or some of the premises in the LHS need be TRUE, or that the premises require more complex evaluation. The user can define this "applicability" in the form of a function to serve as the "LHS evaluator." Some pre-programmed LHS evaluators are available; for example, a type of threshold evaluator used in MYCIN.

EXAMPLE 4: LHS Evaluator: $ANDMIN (This function is similar to the one used in MYCIN where evidence with less than .2 value is ignored.)

```
Hypothesis element name:  DISEASE-03
      disease:  (OAD .8)
      subtype:  (EMPHYSEMA  .1)
      severity:  (SEVERE  .6)
Rule 1: if (isa disease OAD) and
                (isa subtype EMPHYSEMA) then...
Rule 2: if (isa disease OAD) and
                (grdeg severity MODERATE) then...
```

Using $ANDMIN, only *Rule* 2 is found applicable within the context of the given hypothesis state.

Example 5 shows how the features described thus far are represented within a KS. Note that some relevant features (e.g. credibility computation) reside outside the KS, because they are relevant to all the KSs in the user program.

Example 5: A KS Summary (ACE version of PUFF)

```
--Knowledge Source: OAD-SUBTYPERULES
Precondition:  (OAD-DEGREE)
Inference levels:  (from . to)
    (DISEASE . DISEASE)
Links between levels:  NONE
Hit strategy:  (MULTIPLE)
Local variable bindings:  NONE
[other relevant information
  LHS-evaluator:  $ANDMIN
  Wt-adjuster:  $ADJWT]
        ----------------------------
if
  (GREQDEG ($VALUE OAD DEGREE) MILD)
  (GREQDEG ($VALUE PATIENT DIF-DEF) MILD)
  (GREQ    ($DATA TLC-BB:OBS/PRED) 110)
  (GREQ    ($DATA RV/TLC:OBS/PRED) 10)
then PROPOSE
  change.type  MODIFY
  hypo-element OAD
  attr-val/link  (SUBTYPE EMPHYSEMA .9)
   (FINDINGS "OAD, diffusion defect, elevated
     TLC and RV together indicate Emphysema")
  event.type  OAD-SUBTYPE
  comment  (Rule 31 of EMYCIN version)
```

3.1.3. Knowledge Utilization and Control Mechanisms

As mentioned earlier, the invoking of higher level knowledge about the appropriate use of problem solving methods and the invoking of other domain-specific knowledge appropriate to the situation, are both accomplished in the Control component. Until recently, very few attempts had been made to express *control* information explicitly. Davis [6] addressed the problem of expressing knowledge about other knowledge in production rule form and called *it meta-knowledge.* Nii [14] attempted to distinguish inference-generating KSs and knowledge-utilization KSs by organizing the KSs themselves into a hierarchy. In ACE, we have tried to provide concepts and mechanisms whereby users can express different types of higher level knowledge. The structure of the Control component is described below very briefly (see Appendix II for more detailed description). Whether the whole structure is sufficiently general to handle a variety of problems is still under study.

There are several system components grouped under the heading of *Control.* The various sub-components can be individually specified or programmed by the user. In order to simplify the designing process for the user, AGE provides pre-programmed components where appropriate. The control components that need to be specified are.

1. input data format,
2. initialization function,
3. processing method to be applied to each inference step,
4. rules or procedure to select the next step to be processed,
5. rules to select the relevant KS to process the selected step,
6. termination condition, and
7. post-processing function.

Components 1 and 2 deal with getting input data and performing setup operations in the user's program. The data can be brought in from a file or typed in from a terminal. The data elements are bound to names prespecified by the user. Within the initialization function the user may preprocess the data or perform other initialization activities—the only requirement for ACE is that the initialization function return a name of the first KS to be invoked.

Components 3-6, called the *control kernel* (Figure 2), constitute the core of the Blackboard control component. The primary functions of the control kernel are to select and invoke the appropriate KSs and to select the focus of attention within the blackboard. The control in the user's program is a simple loop:

1. *Rule evaluation:* In the invoked KS each rule is evaluated according to the user specified LHS-Evaluator (sec. 3.1.2). When the LHS meets the evaluation criteria, i.e. evaluates to True, the rule is *find.*

2. *Inference generation-.* Fired rules either (1) PROPOSE change in the hypothesis (this change is made in the hypothesis and is also placed on the Event-list), (2) indicate that some change in the hypothesis is EXPECTed to occur (this expectation is placed on the Expectation-list), or (3) indicate that the hypothesis needs to ACHIEVE a particular value or a state (this goal is placed on the Goal-list). Each of these actions is called a *Step.*

3. *Focus of attention:* Within the Step-selection module, select a step (an event, an expectation or a goal) and a hypothesis element or data to process next. Within the KS-selection module, choose a KS relevant to the selected step, and invoke that KS. (The KS may have associated with it a *processing method;* e.g., a KS may require a backward-chaining mechanism for the rules to achieve a goal.) *[go to*

Components 5 and 6 deal with terminating the kernel control loop and processing the completed hypotheses. One characteristic of the Blackboard model is that there is no prescribed way that the incremental hypothesis formation process terminates short of running out of relevant KSs. Thus, the user needs to specify the conditions under which the processing is to terminate; ACE monitors for the occurrence of these conditions. In the postprocessing function, the user may perform any further processing she wishes, for example, print the current hypothesis.

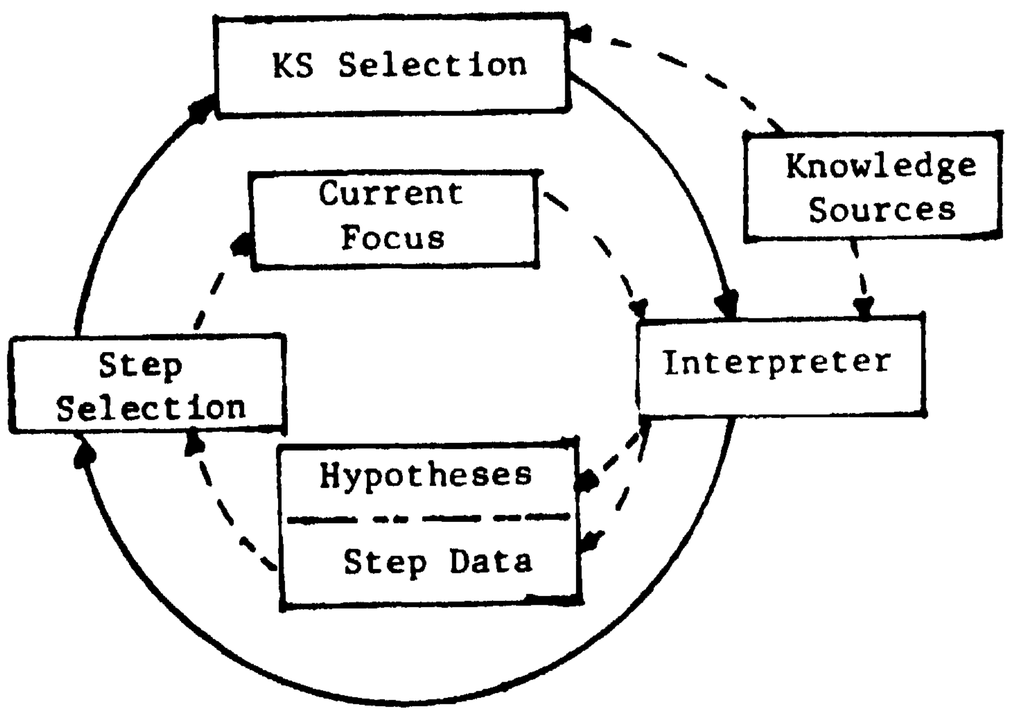


Figure 2. Control of Blackboard Model in ACE

Control Macros

Since the specifications required for the control kernel are quite complex, ACE provides control macros, currently one for event-*drivin control* and one for *expectation-driven control.*

Event-Driven Macro: Event-driven hypothesis formation is characterized by incremental formation of hypothesis elements from evidence found in data or in lower level hypothesis elements. The elements can be processed by rules either on the basis of first-in-first-out, first-in-last-out, or best-first. These correspond roughly to breadth-, depth-, and best-first processing of the hypothesis space. When an element is chosen to be processed, it is called a *focused element.* The event-type associated with the focused element helps determine which KS Is to be invoked in the future.

The control loop for the Event-driven macro is:

1. <rule> modifies the hypothesis and causes an event (with associated event-type).
2. If <event-type> ■ <KS-precondition> then invoke the KS. [Co back to 1]

Expectation-Driven Macro-. Within an expectation-driven system, expectations in the hypotheses are generated by the rules. These rules are normally grouped around objects and their properties, similar to a schema (frame) organization. They usually form models of objects from which other properties can be inferred or can be expected to occur. For example, a rule of the form:

```
if (isa disease oad) & (isa severity severe)
   then (expect RV >200)
        (expect RV/TLC.RATIO >20)
             etc.
```

has a schema-like flavor and produces expectations that need to be verified.

In order to determine if an expectation has been met, or can be met, the user must provide an *expectation matching function.* ACE always checks to see if the expected situation has occurred either in data or in the hypothesis (i.e. performs a passive match of expectation).

The control loop for the Expectation-driven macro is:

1. <rule> generates an expectation.
2. If an expectation is met, then modify the hypothesis as specified. This action generates an event.
3. If <event type> - <KS precondition> then invoke the KS. [Co back to step 1]

For most problems, both the expectation-driven (or model based) and the event-driven (or data-driven) methods are needed in some combination. For the sake of completeness the control components from which the macros were created are described in Appendix II.

3.2. The Intelligent Front-end in ACE

ACE assumes that the user neither knows nor understands the concepts and implementations of the various program components described above. It is the task of the front-end to guide the user in constructing a program using the component parts. Currently the *intelligence* in the front-end is limited to: (a) a tutor subsystem that allows the user to browse through the textual knowledge base, and (b) a design subsystem that guides the user through each step of program specification. An unfamiliar" user is always introduced to ACE by way of the tutor subsystem.

The textual knowledge base contains (a) a general description of the building-block components at the conceptual level, (b) a description of the implementation of these concepts within ACE, (c) a description of how these components are to be used within the user's program, (d) how they can be constructed by the user, and (e) various examples. The information is organized in a network to represent the conceptual hierarchy of the components and to represent the functional relationship among them.

The design subsystem guides the user in *design and*

construction. The knowledge necessary for ACE to accomplish this task is represented in a data structure in the form of an AND/OR tree that, on one hand, represents all the possible structures available in the current AGE system; and, on the other hand, represents the decisions the user must make in order to design her program. Using this schema, the design subsystem can guide the user (in the *guided* design mode) from one design decision point to another. At each decision point, the user has access to the textual knowledge base, to advice on the decisions to be made at that point, and to acquisition functions that aid the user in specifying the appropriate component. The user also has direct access (in the *unguided* design mode) to various acquisition and editing functions.

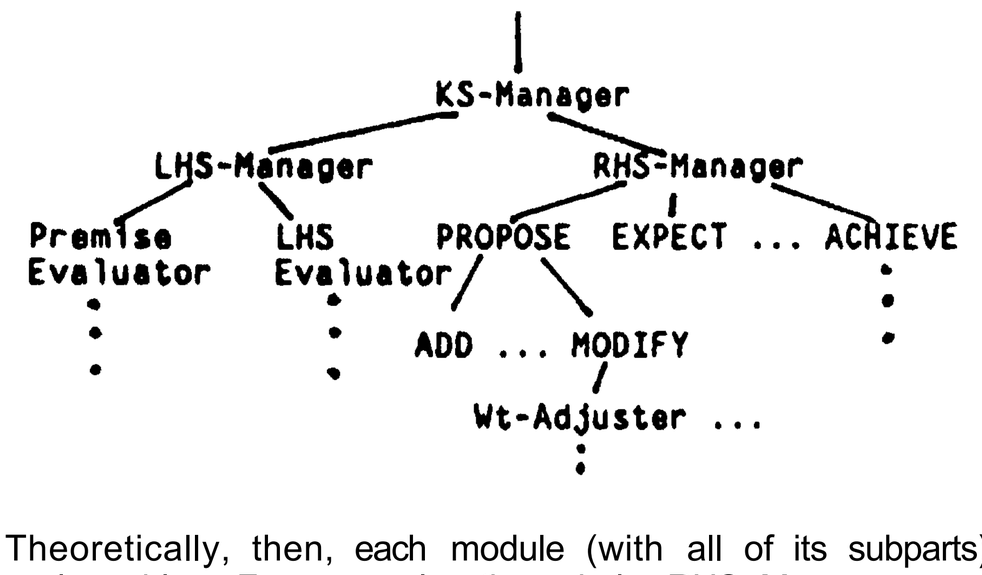
The reader is referred to Appendix I which contains extensive examples of the various interactions currently possible in AGE.

4. DECOMPOSITION OF FRAMEWORKS

Although the intention of this paper does not include discussion of the architecture of AGE itself, we briefly describe some of the motivation behind the decomposition of problem-solving frameworks into interchangeable parts.

Our concept of a software laboratory is a facility in which the users are provided with a variety of *preprogrammed problem-solving frameworks*—similar in spirit to designs of prefabricated houses. The user augments and modifies a framework to develop her own programs. In order to provide such a facility, a framework must be built with parts that can be "unplugged" and replaced. Each framework is decomposed into self-contained modules, creating a hierarchically organized set of component parts. These parts in turn are interpreted or evaluated by "various" managers. As an example, a part of the decomposed Blackboard framework is shown below:

EXAMPLE 6: **Blackboard Model Decomposition**



Theoretically, then, each module (with all of its subparts) is replaceable. For example, the whole RHS~Manager can be replaced *if* the user wants a definition of the RHS of rules different from the one we currently provide.

However, complete modularity is not achieved, because some of the modules are not independent. From a practical stand point the greatest barrier to replacing some of the modules is in their inaccessibility. Nevertheless, as in prefabricated houses, every module can be modified or replaced—some changes are more costly than others in terms of time and detailed knowledge of the implementation needed. In general, those parts nearer the bottom of the hierarchy are more accessible and easier to change. For example, the definition of ADD (add a new hypothesis element) can be changed by simply redefining the ADD function. Or, another function that makes changes to the hypotheses in a different way can be added. On the other hand, the LHS- and the RHS-Managers are not independent. For those components that are independent, and easily modified or replaced, ACE provides some aids for making changes-acquisition functions and descriptions in the textual knowledge base. For those more difficult to change, we provide less aid with the Intention of discouraging novice users.

In order to have a useful software laboratory, we need to provide the user with diverse tools—some tools need to be flexible in their utility while others need to be fine-tuned for specific use; and some tools require substantial skill in their use while others do not. By organizing the program modules by their utility and providing easy access to those that arc general and easy to use (but allowing skilled users access to all modules), we hope that the laboratory can be useful to a wide range of users.

5. SUMMARY AND CONCLUDING REMARKS

ACE is an experimental program currently running on PDP-10 at the SUMEX-AIM Computing Facility at Stanford University. The immediate goal of the project is to provide software tools with which a knowledge engineer can reduce the time it takes to build knowledge-based programs. The longer range goal *is* to aid people less knowledgeable in AI methods to build knowledge-based programs. We have taken a small step toward reaching these goals by exploring the various ways in which Blackboard-based programs can be built, and by implementing a set of parts from which such a program can be built.

In the process of building AGE, we have used it to write some programs: CRYPTO, a program that solves cryptogram problems; a portion of a bidding strategy problem in bridge games; two different versions of PUFF [9,12]--one using the Event-driven control macro and another using the Expectation-driven control macro [15]. Since the domain-specific knowledge for PUFF already existed and was being used in EMYCIN, the AGE version took about a week to bring up—time to reorganize the existing rules into KSs and to rewrite the rules in AGE rule syntax. Currently, the CRYSALIS program [7] is being rewritten using AGE.

To the extent that we have been able to use AGE to develop some programs, we feel encouraged to continue with further development. However, there are still many issues that need to be explored in the current work—the adequacy of the user interface and debugging facility; generality of the current functional breakdown of the Blackboard model; sufficiency of the current rule syntax and semantics to express a wide range of knowledge, adequacy of the production rule representation itself for a variety of tasks; reliability of the system, etc. We have made no progress in providing a facility for explanation within the object program; we need more basic research in this area before such a facility can be implemented.

APPENDIX I: Building Knowledge-Based Program with AGE

Introduction

This appendix shows the ACE system from an user's point of view. We have included an example program with parts of actual protocols to illustrate various facilities.

Cryptograms

The problem used as an example is translating cryptograms. The cryptogram solution consists of a four level hierarchical

hypothesis structure. The rules to solve cryptograms were provided by a human "expert". The task for CRYPTO is to take a "newspaper" cryptogram (10 to 20 words long, about 100 letters) and using a set of heuristics, translate it into an English sentence. For example, the cryptogram "CSHSUO CI DXDV BSS CLESVBFCB BS HD NCCU HJB ISLD JCNCCU EDSEYD EVSXD BZFB BZDVD'I IBCVY F RDP SR JI PZS FVD BSS ILFYY." translates to "Nobody is ever too important to be kind but some unkind people prove that there's still a few of us who are too small." The word boundaries and punctuation are given. There is a one-to-one correspondence between the cryptletters and their translation, and no letter translates to itself.

Typical run

An AGE user typically builds a knowledge-based program over a period of time, conducting many *hands-on* sessions. In the first session the user gets acquainted with the system, learning the different components available and the system conventions, and discovering what information she must provide (i.e., what to think about before the next session). During the next few sessions the user designs and builds her program. Finally, the user iterates on checking out the program, running it, and modifying it.

TUTOR: *The TUTOR subsystem is described in Section S.2.*

[after the user logs on, AGE begins by determining if the user needs a tutorial]
Are you already familiar with this system?: No
This and all subsequent sessions will be recorded.
The record will go on your directory as DRIB<namexdate>.

Following is a list of AGE conventions which may be useful.
[description of ACE user conventions)

[canned text on other topics]
What follows is a tutorial session to acquaint you with AGE.
[The following text describes the organization of the ACE on-line manual]
Each topic in the AGE system has one or more modifiers attach to it. A modifier may be a descriptive word (e.g. Hypothesis.-element) or it may be one of the following:

ISA: Definition or definitional description.
FOR MIS: Representation or structural description.
FORMEDBY: How <topic> is generated or created internally during the user program execution.
TOSPECIFY: Description of the acquisition function.
GEN: generally accepted description.
AGE: definition or description as interpreted for AGE.

[canned text on further topics]

[The following interaction shows cross-referencing]
—There are some pre-assembled control structures available for convenience. (See CONTROL.MACRO)

References are: Hypothesis.structure Control.macro
Do you want to see them now?: y
HYPOTHESIS.STRUCTURE Y/N::y
The hypothesis structure in AGE is hierarchically organized. There may be more than one hierarchy in the hypothesis (generally known as blackboard planes). Each hierarchy consists of linked hypothesis elements, HYPOTHESIS.ELEMENT, grouped into levels of abstractions.

[Tutorial session is eventually terminated.]
This ends the AGE tutorial session. From this point on you will be given a menu of tasks to select from. To start, I suggest you begin with the DESIGN task.

DESIGN: *Refit to section S.2 for a detailed description of the Design subsystem.*

What do you want to do next?
Tasks available are: *[These are top level tasks in ACE)*

name	description
Tutor-	System explanation.
Browse	Browse thru the AGE manual.
Design	Create the user program.
SAve	Save the user program on a file.
Getsys	Get the user program from a file.
Check	Check syntax of the user program.
Run	Execute the user program.
SYsout	Save everything (1e. SYSOUT)

:: design
Create the user program.
What is the name of your system?:: CRYPTO
[AGE determines if there already exists a program by that name]

Do you want a Guided design session, or Unguided session?

[Only a minimal number of consecutive letters that uniquely identifies the prompt is needed.)

Beginning DESIGN and ACQUISITION: You will need to design and specify three major components of your program: the hypothesis structure, the domain-specific rules, and some control information.

You may begin working on Hypothesis.structure Knowledgc.domain-rules Control

During this design session, in addition to specifying or editing components of the system, you may also ask for ADVICE, more INFORMATION from the manual, or to QUIT the session.

What do you want to do next?
Your options are: Hypothesis.structure Knowledge.domain-rules Control Advice Information Quit
Type H/K/C/U/A/I/Q,: a *[asking for advice]*

Specify the hypothesis structure first; it will aid you in structuring your problem. Then enter some domain rules, followed by control information. Within the control specification, choose system-provided control methods to see how your rules work. More rules can be added or more sophisticated control can be specified later.

HYPOTHESIS: *See Section S.J.I for a general discussion of the Hypothesis.*

CRYPTO uses a four-level structure, as shown in Figure Ai At the highest level (SENTENCE) there is one named node CRYPTOGRAM, where information inferrea about the whole cryptogram will be stored. At the WORD level, elements WORD1 to WORDn are created dynamically for each word of the cryptogram; and at the LETTER level, elements LETTERl to

LETTER1 to LETTERm for each letter.

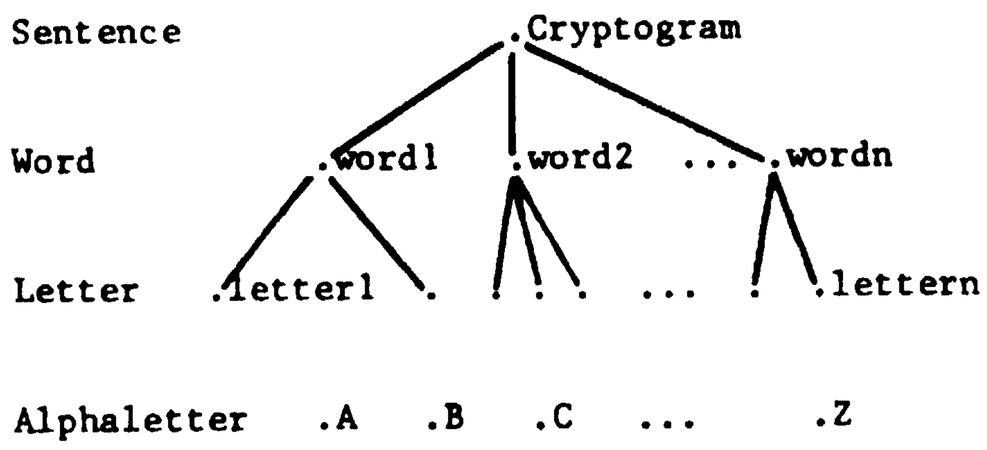


Figure A1. CRYPTO Hypothesis Structure

What follows is an example protocol of the acquisition of the hypothesis structure for CRYPTO.

What do you want to do next?
::Info [*ask for information*]
Select a topic.
::hypothesis.tospecify
Function: (HYPO)
The user is asked for the names of levels of hypothesis elements, and for the names of the attributes at each level. The level names must be unique; the attribute names need only be unique within a level. When AGE asks for attributes, only attributes should be given and not the names of the links between two levels. AGE will start from the highest level, LEVEL1.

Do you want to work on Hypothesis.structure?:: y
Aquiring HYPOTHESIS.STRUCTURE
Name of LEVEL1 ?
A level name can be any literal atom not already used for the name of another level. Type Done to quit.
:: sentence
Attribute?
Attributes must be unique within a level.
:: words
Attribute?
[*etc.*]
Name of LEVEL2 ?
:: wurd [*misspelled name--to be corrected later*]
Attributes?
:: letters
[*The remainder of hypothesis acquisition and editing deleted.*]
:: print [*print the hypothesis structure*]
LEVEL1 - SENTENCE
WORDS - NIL
ENGLISHWORDS - NIL
LETTERS - NIL
LEVEL2 - WURD [*mispelled level name*])
LETTERS - NIL
ENGLISHWORD - NIL
ORDREINSENTENCE - NIL [*misspelled*]
POSSIBLEWORDS - NIL
LEVEL3 - LETTER
CRYPTLETTER - NIL
ORDERINWORD - NIL
RELFREQ? - NIL

KSs: *Refer to Section 3.1.2 for a general description of the KSs*

as used in AGE. The protocol shows the partial acquisition of two KSs. The specification of each KS begins with some declarative information needed to evaluate the rules in the KS. Then the user is prompted for parts of the rules. The first KS is a set of rules that look at the whole cryptogram. It is called once after initialization and any time thereafter to find a new part of the cryptogram to focus on. This KS assumes that certain information already exists in the hypothesis structure as a result of initialization. The first rule looks for one-letter words which could either be A or I, with A more likely than I.

You need to specify: Rule.evaluator Knowledge.sources Control
You may modify: Hypothesis.structure
[AGE keeps track of what has and has not been specified]
What do you want to do next?
:: kn
What is the name of the KS you want to create or add rules to?
:- wholesentencerules
[New knowledge source]
What events invoke this knowledge source?
:: always *[Always means any event can be a precondition to this knowledge source)*
Between which Hypothesis levels does this KS make inferences?
From?
:: letter
To?
:: alphaletter
From?
::none
Which links are used to record inferences made by this KS?
:: possiblevalue *[Possiblevalue links will connect elements from the letter level to possible values in the alphaletter level]*
Inverse link?
:: possiblevalue/of
Link?
:: assigned value *[Assignedvalue links will connect positively assigned values from the alphaletters to the cryptletters on the letter level]*
Inverse link?
[etc.]

Do you want to use multiple or single hit strategy for this KS?
You can specify Onceonly with Single or Multiple.
:: single onceonly *[Single to fire only one rule and Onceonly to mark that rule so that it won't be fired again)*

Local variables can be defined as (variable value) or (variable).
Define a local variable.
:: (wordnodes (lvalue 'cryptogram part))
[Store the node names for the word nodes in WORDNODES. The function $VALUE retrieves those names by following the "part" link from the CRYPTOGRAM node)
Define a local variable.
:: (word)
Define a local variable.
[etc.]

What is the first condition? Type None when done.
[This problem involves searches which are awkward with the current rule syntax and requires extensive Lisp code. See Example 5 for the more usual use of rules.)
:: (setq word (for wd In wordnodes therels
(and (eg (length ($VALUE wd letters)) 1)

(null (Svalue wd englishword]
Hooking for a word of length I, not already assigned a value}
Next condition?
:: none

Next, you will be prompted for the RHS of the rule.
PROPOSE, EXPECT, COAL, or LOOP?
::? propose *[ask about PROPOSE]*
PROPOSE is used to change the hypothesis structure.
:: prop *[specification of PROPOSE follows)*
ch.type;: supersede *[replace current value)*
hypo-element:: word *[of word element)*
attr-value:: (englishword *a) *[with* V]
link-node:: none
event.type:: assignword *[name of the event it generates)*
comment:: (a one letter word is most likely 'a')

PROPOSE, EXPECT. COAL, or LOOP?
:: propose *[more than one action allowed in the RHS]*
[etc.]
link-node:: (assignedvalue 'a) *[change the relational link]*
event.type:: assignletter
comment:: (assign the letter V to the cryptletter)

PROPOSE, EXPECT, COAL, or LOOP?
:: none
More rules?:: no
What is the name of the next KS you want?
:: fill-inrules
[New knowledge source]
[some declarative infcrmation deleted]
PROPOSE, EXPECT, COAL, or LOOP?
::? loop *[ask about LOOP]*
LOOP is used to indicate an iterative action, either PROPOSE, EXPECT, or COAL. If LOOP is used, you will be prompted for the name of an iteration variable and the name of a list of values on which to repeat the action.
:: loop
Iteration variable?
:: of
Name of the list to be iterated on?
:: otherletters
PROPOSE, EXPECT, or COAL?
:: propose
[remainder of rule acquisition delete)

CONTROL: *Refer to Section 4 and Appendix II for discussion of knowledge utilization and control mechanisms. The overall strategy for solving cryptograms is to focus on a particular word or a combination of letters that has potentiar; work on the focussed item and follow through on all the ramifications, which in turn may generate a new focus.*

:: control

Control specification: Currently there are three methods of specifying the control information. Two are macros which require minimal specification, EVENT-DRIVEN-MACRO and EXPECTATION-DRIVEN-MACRO. The third method, DETAILCONTROL, involves detailed specifications of several subcomponents.

New additions to design component: (Detailcontrol Control.macro. Event-driven Controlmacro-expectation-driven)

[When a node is chosen, it opens other *nodes that require further specification)*

What do you want to do next?
:: detail
Detailed Control Specification: There are several components grouped under the heading of DETAILCONTROL. To simplify the designing process, ACE provides default specification where appropriate. The components that need to be specified are:
1. input data format: INPUTFORMAT,
2. initialization function: INITIALIZATION.
3. processing method to be applied to each step-type,
4. rules to select a step to be used as the current focus,
5. rules to select relevant KS (or procedure) to process the selected step: (3,4,5 part of KERNEL),
6. termination condition: TERMINATION, and
7. post processing function: POSTPROCESSING.

New addition to design component: (Inputformat Initialization Control.Kernel Termination Postprocessing)

What do you want to do next?
:: inputform
The input data you use in your system will be stored on an implicit level of the hypothesis structure called INPUTDATA. A function tDATA is available to access the data. At the beginning of each run you will be asked to input (from a file or TTY:) the actual data associated with each data name.
First name?
:: inputcryptogram
Next name?
:: done

What do you want to do next?
:: initial
You must provide a function that will return, as its value, the name of the first KS to be invoked. Within this function you may do any processing you whish.

[NEW FUNCTION]
What would you like to call your initialization function?
:: crypto-initialization
Your initialization function must return the name of a KS.
Please define CRYPTO-INITIALIZATION

(CRYPTO-INITIALIZATION (LAMBDA NIL
[This line provided by AGE]
(prog (eg)
(eg <- (Sdata Inputcryptogram))
(f1ll-1nlevals)
(computerel freqs)
(return 'wholasentenctru1es]
What do you want to do next?
:: terminate
You must provide a function which will determine when to terminate vour program.

What *is* the name of your termination function?
:: crypto-quit
[define CRYPTO-QU IT function in the same manner at above)

What do you want to do next?
:: post

you can provide functions for printing
the results, translating the results into a more readable form.

Take up this option or bypass it? *[optional component)*
:: take
What would you like to call your postprocessing function?
:: decodedprint
[Define DECODEPRINT)

What do you want to do next?
:: control.k
This function allows the user to specify various options which determine how events, expectations, and goals will be processed. First we will look at the event processing information.

Do you want to enter kernel information now?:: y
Which event selection method would you like to use? LIFO and FIFO are available or you can write your own function. Type LIFO, FIFO, or function name.
:: ?
The Event-selection is used to decide which event from the event list to process next. LIFO chooses the last event added. FIFO chooses the earliest event. You can provide your own function. For example, bestfirst might depend on the weights associated with each event.
:: lifo

Name an event type to be collected.
:: fill-in
:: done

The control rules are used to determine what step type to proces next. Each control rule consists of a condition and a step type.

STEPTYPE:: event
CONDITION:: expectation list
STEPTYPE:. expectation
CONDITION:, none

USER FUNCTIONS: *The final information the user must provide is the names and definitions of the functions used in the rules or called from other user-defined functions. The user can name and define functions one at a time or load them from files.*

EDITING: *There are two ways to edit: (I) by calling the appropriate editing function from Unguided design session or (2) during the Check-out session. The Check subsystem described below.*

SYSTEM CHECKOUT: *The Check subsystem does a syntax check on the user created program. It finds errors in the designed structures and points out missing, but required, information. Check also allows the user to edit the errors as they are found by calling the appropriate editor.*

What do you want to do next? : check
Check syntax of the user program,
checking hypothesis levels - ALPHA LETTER ...
checking knowledge sources -FILL-INRULES ...
Warning: 2 events not used as preconditions
ASSIGNWORD FILL.IN
[they will be used by KSs to be defined later)
\ syntax errors in the user program.
Do you want to edit the errors now?:: n

RUNNINC: *Once all the information is specified, the user can run her program in two modes, debugging mode or normal mode. In debugging mode, ACE prints a trace of the control flow showing the rules evaluated, the actions taken, and the steps and focuses selected. In normal mode, ACE only prints the input data and the results.*

A complete run will begin with a request for input data. Next the user's initialization function which returns a KS name is evaluated. That KS is the first to be interpreted and starts the control loop, which will continue until the termination condition is met. Finally, the postprocessing function is called. The following is a sample run of the CRYPTO program. We have deleted a large section of the protocol to save space.

What do you want to do next?:: run *[top level prompt)*
Execute the user program.
Do you want to input data from a file or from a terminal? (filename or TTY:):: crypto-datal *[input from a file)*
((INPUTCRYPTOGRAM (GSHSUO CI DXDV BSS CLESVBFGB BS
HD NCGU HOB ISLD JGNCGU EOSEYD EVSXD BZFB BZDVD'I IB
ROP SR JI PZS FVD BSS ILFYY)))

Knowledge source Invoked - WHOLESENTENCERULES
[WHOLESENTENCERULES is the KS name returned by the initialization function.]

Left hand side of applicable rule -
((SETQ WORD (for WO 1n WORDNODES therels (AND ...
[first rule to fire, word!17, letter7S, is probably "A".
Two events result, ASSIGN LETTER and ASSICNWORD)

NAME OF NEW EVENT: ASSIGNWORO
NAME OF NEW EVENT: ASSIGNLETTER
. . . . . .
NEXT STEP: EVENT *[choose the next step - EVENT)*

FOCUS EVENT-(ASSIGNLETTER(LETTER73)(ASSIGNEDVALUE A
WHOLESENTENCERULES EV2 NIL)
[Since the ASSIGNLETTER event was added to the EVENT LIST last, it is the next focus event under the depthfirst (LIFO) selection method. When there are no further ramifications of ASSIGNEDLETTER, ASSICNWORD will become the focus event.]

Knowledge source Invoked - FILL-INRULES
Left hand side of applicable rule -
((SETQ OTHERLETTERS (for L 1n CRYPTLETTERNODES Join
[find other letters with same cryptvalue as letter 73
FILL-IN those letters with value "A")

NAME OF NEW EVENT: FILL-IN
. . . . . .
NEXT STEP: EVENT

FOCUS EVENT - (FILL-IN (LETTER92) (ASSIGNEOVALUE A)
(ASSIGNEDVALUE A) EV13 NIL)
[letter92 was assigned last, thus with a depthfirst selection method, it becomes the new focus.]

[The rest of the protocol continues in the same manner until terminated.]

Summary

One common question asked about the CRYPTO system is, "When CRYPTO makes an incorrect assignment, can CRYPTO back up?" The answer is no. There is no back-up or alternative hypothesis capability. In CRYPTO we believe

that with enough rules and with the POSSIBLEVALUE attributes and weights, the system will always make the correct assignments. This belief stems from the sessions recorded with the expert newspaper cryptographer, who never needed to "back up." The expert never guessed at a value or tried to confirm or contradict a guess by looking at its ramifications. However, we do recognize that the concept of alternative hypotheses is a powerful one, and we expect to add facilities to AGE to allow them in the future.

APPENDIX II: SUMMARY OF THE CONTROL KERNEL

The Control Kernel consists of several components (Figure BI) each of which must be specified by the user. The sequence of actions which are taken within the Kernel is described below.

1. Invoke rules (CONTROLRULES) to select the next step-type to process--EVENT, EXPECTation,or GOAL;

2. If the selected step-type is EVENT,
   then
   (a) Select an event, (SELECTIONMETHOD provided by the user);
   (b) Collapse the EVENTLIST by deleting/merging events referring to identical attributes and values of the events specified by the user (COLLECTIONRULES);
   (c) Select a KS (EVENTRULES generated by AGE from the KS preconditions).

3. If the selected step type is a goal (ACHIEVE), then
   (a) Select a goal (SELECTIONMETHOD);
   (b) Evaluate to determine if the goal has been met (MATCHER).
   (b) If not, apply a goal-seeking method (SEEKMETHOD).
   (d) If the goal has been met, execute the remainder of the RHS of the rule that generated the goal.

4. If the selected step-type is EXPECT,
   then
   (a) Select an expectation (SELECTIONMETHOD);
   (b) Evaluate to determine if the expectation has been met (MATCHER),
   (c) If so, process the expected event by executing the remainder of the RHS that generated the expectation.

Step-type	Event	Expectation	Goal
SELECTION METHOD	FIFO | LIFO | ⟨fns name⟩	FIFO | LIFO | ⟨fns name⟩	FIFO|LIFO | ⟨fns name⟩
COLLECTION RULES	⟨KS name⟩ | ()	---	---
MATCHER	[EVENTRULES]*	⟨fn name⟩| passivematch	⟨fn name⟩| nil
SEEKMETHOD	---	---	⟨fn name⟩

Figure BI. Summary of Control Kernel Components and Options

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EXTRACTION OF ITEMS FROM ABSTRACTS

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This paper presents a method of extracting prescribed items from a summary or an abstract of technical papers. An experimental system is now under development. The internal expression of an input sentence is transformed into a standard form which has the standard case-labels for extraction of items. The part of remaining sentences is combined with the adjacent sentence into an item section every main item. [1] And the prescribed items are extracted efficiently.

1. EXTRACTED ITEMS

This paper is primarily concerned with a textual analysis from the viewpoint of extraction of items in a specified form for filing. The kind of texts is chosen to a summary of some technical papers, the length of which is rather short. The first thing to be done will be the determination of the specification table of the extracted items rather than the construction of the rewriting rules. The main items to be extracted are generally chosen to the labels of main frames appearing in many summaries of technical papers which can be also considered to produce their respective detailes of the main frames of summaries by various transformation. For the whole of various kinds of technical papers, however, it is a difficult and significant problem to choose the main items and to construct a well organized tree or graph of these summaries. Hence, we confine the file of the main object to a specific one, for example, one of software systems such as language processing systems. In this scheme, a choice of main items is taken as shown in Table 1.

PRED-F: _ (PRED-F: *, AG-S: $t_1 \cup t_2$, PAT: _##,
SO: _##, G: _##, M: _##)
AG-S: t_1 (OBJ-S: *, COMP-S: t_2)
INSTR-S: _ (PRED-F: _, AG-S: *, PAT: _, SO: _,
G: _, M: _, INSTR-S: _#, USED-S: $t_1 \cup t_2$)
USED-S: _ (PRED-F: _, AG-S: *, PAT: _, SO: _,
G: _, M: _, INSTR-S: $t_1 \cup t_2$, USED-S: _#)

Table 1. A Specification Table

In the above, two capital-letter sequents connected with a hyphen '-' are a case-label and a category of a term inserted to the case respectively. The specification of the category of a case is assumed optional. The abbreviated large symbols denote OBJect, COMPonent, PREDicate, AGent, PATient, SOurce, Goal, Modal or manner, INSTRument, USED system or location, PARTicipant, Characteristic, System, Function and Process. Each underline denotes a slot of a case and a small letter t denotes a term. Each term takes a form

C: t
or C: t (--, K: t, C_1: t_1, C_2: t_2, --),

which means a term t plays the role denoted by a case or a case-category label C in a specified upper case frame and it is sometimes modified by several terms in a case frame enclosed by parentheses.

In a modifying frame, the modified term and the case frame are described together with a predicative term when it is necessary to show the role of the modified term clearly. In the Table 1, the symbol * in a modifying frame denotes the modified term prefixed to the frame. The double underlined term specifies or defines the main case-label of the term prefixed to the modifying frame and are used for identification of the term. In a completed form for output, however, they are deleted for efficiency. The nested modification of a term is restricted to specified terms with the symbol '#' or '##' in order to avoid to store duplicated information and non-essential one. The term with the symbol '#' can be modified by a modifying frame which involves a term in the same case-label as the prefixed case-label recursively. The term with the symbol ' ##' can be modified by any modifying frame so long as it is not duplicated information.

A main item is defined as a pair of a case-label and the characterized term with a number instead

of modifying frames appearing in the leftmost of the specification table. For a case-label, there are sometimes several terms in a union or serial form, where the union form is an unordered set of terms with a form ' C: tiut2U———' ,while the serial form is an ordered set of terms with a form ' C: t1At2/\——', placed by a temporal or causal relation.

2. NORMALIZATION

Prior to extracting some specified items from summaries, it is preferable that each sentence of a summary is normalized to some axtent. First, each input of a summary is transformed into the internal form by parsing. Each word of a pronoun or a common noun is characterized by attaching a number by means of the anaphoric analysis though the attached number is omitted except section 4 for simplicity. Then the internal form is transformed into the standard form which takes i concrete predicate word as a governor at every partial predicate or function expression and dose not involve any term of the same name as a case-label. Every transformation is done by refering to case-labels and categories of terms though the precise conversion procedures are omitted for simplicity. The outline of the conversions is described as follows.

2.1 Transform To Predicate-governor Forms

This is a form of a predicate expression every part of which generally takes a concrete predicative word as a governor if the part involves a concrete predicative word. For example, let us take an example of an internal form which involves a term of a function form that contains a predicative word p corresponding to a clause or a phrase.

(PRED: p_1, ---, K_0: t_1(K_1: p_2(K_2: t_2, --))).

The predicate-governor form of the above is

(PRED: p_1,---, K_0: t_1(PRED: p_2, K_1: *, K_2: t_2, --)).

If a function form lacks a predicative word, the term of the pseudo case of a predicative word is left empty.

[Example 1]
K: t_1(COMP: t_2) → K: t_1(OBJ: *, COMP: t_2),

where the symbole '→' shows the left side is to be replaced by the right side.

A term of the same name as a case label K is also transformed to an expression using the case-label K.

[Example 2]
K (OBJ: t) → $(OBJ: t, K: $),

where the symbol '$' denotes a certain term to be replaced by a concrete term if it appears later.

2.2 Transform To Non-complementary Forms

A predicate part of a complement form is transformed to a non-complementary form by a case-transformation.

[Example 3]
(PRED: make, AG: t_1, PAT: t_2(PRED: *, **t**), G: t_3)
→ (PRED: t_2, **t** , INSTR: t_1, M: t_3),

where a bold letter **t** denotes a sequence of pairs of case-labels and terms.

2.3 Removal Of Formal Predicative Words

A formal predicative word such as 'be based on' or 'comprise' is removed, and the case-labels prefixed to the dependant terms are replaced by a more concrete case label implied by the removed predicative word.

[Example 4]
(PRED: use, AG: t_1, PAT: t_2,
PURPOSE: t_3 (PRED: *, **t**))
→ (PRED: t_3, **t** , AG: t_1, INSTR: t_2).

The conversion rules in article 2.2 and 2.3 are implemented for each word in a word dictionary.

3. EXTRACTION OF ITEMS

From the normalized sentences of a summary the items in the specification table are extracted. First, the subject sentence is taken from a sentence of the summary which involves a predicative word of category 'process' and contains several terms involved in the main items of the specification table as well as in the title. The cases of these items are identified using the method described in section 1 and several case-transformation rules such as

(OBJ-S: t_1, COMPOSITE-S: t_2)
→ (OBJ-S: t_2, COMP-S: t_1),
(PRED-F: t_1, AG- S: t_2, INSTR-S: t_3
(PRED-F: t_4, AG-S: *))
→ (PRED-F: t_4, AG-S: t_3, USED-S: t_2

(PRED-F: t_1, AG-S: *)).

Thereafter, the details of the main items are arranged as indicated in the specification table, combined with the main items and put into the edition area for output.

Subsequently, the remaining sentences are processed from the first sentence. First, the main item to which the current sentence belongs is identified. Second, the part to be extracted is arranged to the specified form. For example, if a sentence contains a serial relation, it is arranged as followes;

(PRED-F: t_1, AG-S: t_2, PAT: t_3,
MEANS-F: t_4(PRED-F: *, t) → (PRED-F: t_4, t) ∧ (PRED-F: t_1, AG-S: t_2, PAT: t_3).

Then, the following sentence is taken and it is asked whether or not this sentence belongs to the same main item as the preceding one. If it does, the part to be extracted is arranged, combined with the preceding extracted part as an item section and rearranged using some temporal relations or combined rules such as

$(K_0: t, K_1: t_1) \cup (K_0: t, K_2: t_2)$
$\rightarrow (K_0: t, K_1: t_1, K_2: t_2)$.

If the following sentence dose not belong to the same item as the preceding one, the extracted part of the preceding item section are marked for later scanning, and its copy is combined and rearranged with the data in the edition area for output. Then the current sentence is processed as a new item sentence. At the end of the summary, the scanning restarts from the beginning of the summary for extracting the specified detail from the remaining parts *of* each sentence. Each term is stored from the output form into a tree-like file of categories together with several sequents of the prefixed case-labels and the document number.

4. EXAMPLE

4.1 An Example

(1) This paper describes TORUS, a natural language understanding system which serves as a front end to a data base management system in order to facilitate communication with a casual user. (2) TORUS uses a semantic network for understanding input statements and for deciding what information to output in response. (3) The semantic network stores general knowledge about the problem domain. (4) A number of functions of TORUS make it possible to integrate the meaning of an input statement to the semantic network, and to select a portion of the semantic network which stores information that must be output.

4.2 Standard Forms

```
(1) (PRED-P: describing, AG: paper'1,
  PAT: TORUS
    (PRED-F: understanding, AG: *,
             PAT: natural-language'1)
    (PRED-F: communicating, INSTR: *, M: easy,
             COAGENT: casual-user'1)
    (AG: *, USED: front-end'1 (AG: *,
        USED: system'1 (PRED-F: managing,
              AG: *, PAT: data-base'1)))),
(2) (PRED-F: understanding, AG: TORUS, INSTR:
     semantic-network'1, PAT: input-statement'1)
 ∪(PRED-F: deciding, AG: TORUS, INSTR: semantic-
    network'1 PAT: information (DET: what)
      (PRED-F: output, PAT: *,
               ENVIRONMENT: response)),
(3) (PRED-F: storing, AG: semantic-network'1,
    PAT: general-knowledge'1
       (OBJ: *, PART: problem-domain'1)),
(4) (PRED-F: integrating, AG: TORUS, PAT:
    meaning'1 (CH: *, OBJ: input-statement'2),
    G: semantic-network'1, M: possible)
 ∪(PRED-F: selecting, AG: TORUS, PAT: portion'1
    (OBJ: *, COMPOSITE: semantic-network'1
      (PRED-F: storing, AG: *, PAT: infcrmation'1
        (PRED-F: output, PAT: *, M: must)))
    M: possible).
```

4.3 Extracted Items

```
(PRED-F: understanding (PRED-F: *, AG: TORUS,
   PAT: natural-language)
∪ integrating (PRED-F: *, AG: TORUS,
   PAT: meaning (CH: *, OBJ: input-statement),
   G: semantic-network, M: possible)
∪ slecting (PRED-F: *, AG: TORUS, PAT: portion
   (OBJ: *, COMPOSITE: semantic-network))
∪ deciding (PRED-F: *, AG: TORUS, PAT: informa-
   tion (DET: what) (PRED-F: output, PAT: *,
    ENVIRONMENT: response)),
AG-S: TORUS,
INSTR-S: semantic-network (PRED-F: storing,
  AG: *, PAT: general-knowledge, USED: TORUS)
  (PRED-F: storing, AG: *, PAT: information),
USED-S: front-end (AG: *, USED-S: system
  (PRED-F: managing, AG: *, PAT: data-base),
  INSTR: TORUS)).
```

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PROBLEM SOLVING OF ELEMENTARY ALGEBRA BY HIERARCHICAL ABSTRACTION

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This paper presents a hierarchical problem-solving method which searches some applicable transformation rules to the precondition of the problem at various abstract levels using a tree-like address table and finds a global solving policy which reduces the difference between the current state and the goal. The frame of the problem is chosen from the field of elementary algebra.

1. INTRODUCTION

The abstraction of a problem and a relation which retains only their key characteristics will be indispensable for global solving of complicated problems. Many researches of mechanical problem solving using this concept have been actively done, but a lot of problems to be solved seem to remain for practical use.[1],[2]. This paper develops the method of EAPS(Elamentary algebraic Problem Solver) of the previous paper[3] by adding (i)a tree-like address table of theorems and global relations for the efficient access to them and (ii)a mixed abstract notation of problems for flexible representation.

2. ABSTRACT EXPRESSIONS

In mechanical problem solving, it is considered indispensable to introduce an abstraction or an abbreviation method of expressions at least in complicated quantitative relations. Along this idea, we introduce an abstract form for quantitative terms and relations as follows;

idname-k(C-name:value,···,C-name:value), (1)

where 'idname' takes a term 't', a literal 'rq' or a set of literals '$\overline{rq}$'. k is the identification number though it is omitted in Table 1 for simplicity. The C-names('C-' is the abbreviation of the word 'characteristic' in this paper) are a variable 'var', a function class 'fc', a form of a literal 'form' and a sign of terms 'sgn'. The value of 'var' is a set of variables in an expression. The values of 'sgn' are {p,z,n} and the combinations of them. The item 'form' takes the values 0,1,2 and 3 for a solution form q(x, t(var:ϕ)), a semi-solution form q(y,t(var:{x})), a transposed form q(t(var:{x}),0) and the general form q(t(var:{x}),t(var:{x})) respectively. An abstract form eq.(1) is obtained by parsing an objective expression by the aid of the rewriting rules shown in Table 1.

```
/ar:φ) ::= const
/ar:{x},fc:(x:{fs})) ::= fs(x)
/ar:{x,y},fc:(x:{fs1,fs3})(y:{fs2,fs3}))
:= fs3(t(var:{x},fc:(x:{fs1})),t(var:{y},fc:
   (y:{fs2})))
num:2,var:{x,y},fc:(x:{fs1})(y:{fs2}))
:= t(var:{x},fc:(x:{fs1})),t(var:{y},fc:(y:
  {fs2}))
::= =|>|<
(var:{x,y},fc:(x:{fs1})(y:{fs2}))
:= q(t(var:{x},fc:(x:{fs1})),t(var:{y},fc:(
   y:{fs2})))
(num:2,var:{x,y}) ::= rq(var:{x}),rq(var:{y})
::=∧|∨|∧∨
```

Table 1. A part of rewriting rules.

Table 1, fs1, fs2 and fs3 are function symbols, and $\overline{rq}$ denote sets of terms and literals respectively and num is the number of the elements a set. The values of function classes about riables are polynomial 'poly', fractional ract' and so on. L is the abstraction of a mpound logical operator.

The quantitative expressions in a given problem are reduced to three abstract forms; q(term,term), rq(C-name:value,•••,C-name:value) and L(rq(C-name:value,*••,C-name:value)). They are called the objective-based literal expression OBL, the characteristic-based literal expression CBL and the abstract compound-literals expression ACL. These three forms are constructed at the general identification and are permitted to appear in an expression as a mixed form.

In addition to the general identificaiton, several special identification routines are implemented which identifies the C-value if the transformation rule to be applied contains a special kind of C-name such as the degree of a polynomial.

Problem descriptions take the following forms. Problems such as a proof-problem (Qx)(P(x)→R(x)) are expressed as ((Qx)P(x)|(Qx)R(x)) based on the state space representation, where Qx is a sequence of quantifiers and both P(x) and R(x) are predicates and called the precondition and the goal respectively. Value-finding problems are also expressed in a similar format to proof problems as follows;

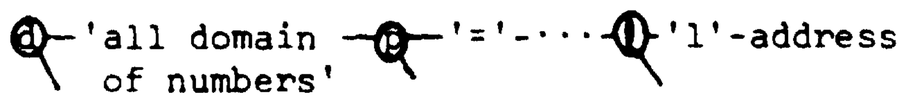
((∃?x)P(x)‖(∃?x)Obj(L(x=t(var:Φ)))),

where '‖' stands for an equivalence relation, and the goal part denotes to require an objective form corresponding to the ACL expression L(x=t(var:Φ)).

3. THEOREMS AND TRANSFORMATION RULES

Mathematical theorems are classified into several subsets by their characteristics and can be accessed by means of a tree-like address table shown in Fig.1.

```
Tree 1:d-p-pf-q-l          }(a) Classification
Tree 2:{fc,npf}-d-p-q-l    }     items
```



(b) A part of Tree 1.

Fig.1 Address trees.

Tree 1 concerns primitive functions pf's such as addition, while Tree 2 concerns function classes fc's such as polynomials and also non-primitive functions npf's such as the absolute function. The C-item d means the domain where a theorem holds, p is the item that indicates an equality or inequality relation, p indicates the kind of quantifiers and l is the number of literals included in a premise of a theorem.

In addition to theorems, some relations called transformation rules 'TR's are introduced in order to find a global solving policy. There are two kinds of TRs, one of them is C-TRs and the other is P-TRs(i.e. problem-TRs). The form of a C-TR takes an implication form (Qx)(r(x)->'s(x)) (OP:S), where r(x) and s(x) are conjunctive normal forms of some abstract expressions of literals. The symbols 'P' and 'P' represent probable relations. The OP part indicates location areas of supporting theorems, TRs or procedures of the TR. Some of the TRs are shown in Table 2.

(1) Characteristic-TRs

① rq(var:{x},fc:poly)
⇄L(r̄q(var:{x},fc:poly(deg:{1,2})))(OP:TR ②)

② t(var:{x},fc:poly)
⇄ Π(t(var:{x},fc:poly(deg:{1,2})))(OP:PROC factorization)

③ (∀x) (∄(t(var:∀u{x},fc:poly(deg:(x:2))),0)
⇄(∄(Σ(t̄(sgn:pz,var:ȳ)),0))(OP:TH ①,TH ②)

④ Σ(t̄(sgn:pz)) = t(sgn:pz)

(2) Problem-TRs

① (T|Q)⇔(Q‖T) ② (Q₁|Q₂)⇔(Q₁→Q₂‖T)

Table 2. Transformation rules.

The universal quantifier of TRs are omitted for simplicity. The logical connective symbol L, the predicate symbol q and the variable symbols x and y in the TRs are variables for which any corresponding instance or variable can be substituted. The predicate symbol q denotes equality or inequality. TR ① means that a polynomial relation will be reducible to a combined logical form which consists of several linear or quadratic relations. TR ② suggests that a polynomial term will be factorized into several linear or quadratic terms by a procedure. TR ③ shows an absolute inequality which contains quadratic terms about a variable can be transformed to a sum of definite sign terms such as definite positive terms, where TH ① and TH ② are

a≠0→a*x**2+b*x+c=a*(x+b/(2*a))**2+c-b**2/(4*a)

and

a>0∧c-b**2/(4*a)≥0
⇄(∀x)a*(x+b/(2*a))**2+c-b**2/(4*a)≧0

respectively.

In P-TRs, the symbols Q, Q_1 and Q_2 are variables for which any logical formula can be substituted. The symbol T denotes a tautology such as t(sgn:p)>0.

The access to TRs is performed by the aid of a tree-like address table a part of which is shown in Fig.2.

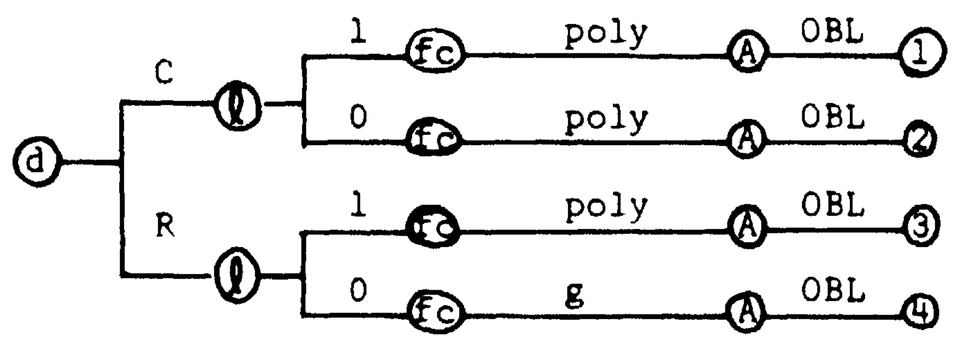


Fig.2. A part of address table of TRs.

In the address table, the items d, l and fc have the same meanings as in Fig.1. The value C denotes the complex number domain, while R denotes the real number domain. l0, l1 and l2 mean l=0, l=1 and l≥2 respectively. A TR with l=0 is a no-premise relation. The value g of the item fc denotes the general-function class. 'A' indicates the abstraction levels of premises of TRs. If a TR involves several literal expressions of different abstraction levels, its address is recorded at the respective abstraction levels.

The following describes the main part of application procedures of TRs to the conjunctive nor-

mal form of the precondition of a problem.
At the first step of application procedures, if the abstraction level of a TR is lower than that of a problem, the abstraction level of the TR is raised to that of the problem by the identification of the TR, otherwise the usual unification algorithm is adopted. Let $P_1' \wedge \cdots \wedge P_n' \cdots$(a) and $P_{i1} \wedge \cdots \wedge P_{im} \rightarrow Q \cdots$(b) be a precondition of a problem and a TR respectively, where P' means an instantiation of P and $\{i1, \cdots, im\}$ is a subset of $\{1, \cdots, n\}$, then the result of the application of (b) to (a) is $P_1' \wedge \cdots \wedge P_n' \wedge Q'$. If the implication symbol is replaced by the equivalence symbol in eq. (b), $P_{i1}', \cdots, P_{im}'$ are removed from the result.

4. SOLVING PROCEDURES

The solving procedures of EAPS are divided into three phases;(i)the identification of the current problem at the three abstract levels, ACL, CBL and OBL,(ii)the breadth-first search of a relevant global solving policies by the aid of the tree-like address table and (iii)the depth-first solving in a concrete form according to the suggestion of the obtained global solving policies.
A part of a solving tree generated by EAPS is shown in Fig.3, where the forms of PB, PB_i and PB_i' are (P|G), (P|Q) and (Q|G) respectively.
The global solving policies are placed in the ascending order of the difference between the precondition and the goal of PB_i' which is evaluated based on the assigned values to the fundamental C-items.

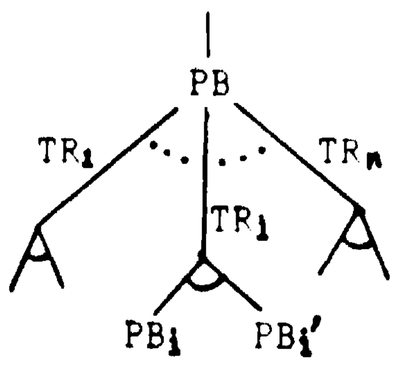


Fig.3 A part of a solving tree.

If no global solving policy is found, EAPS searches applicable theorems by the aid of the tree-like address table of theorems. If EAPS fails to find applicable theorems, it applies P-TRs to the current problem then retries to solve the problem.

[Example] 'Prove that if k is a real number, the equation x**2-2*k*x+2*k-2=0 of x has real roots'.
The expression of the problem is

(k∈R|(∃x)root(var:x,rel:x**2-2*k*x+2*k-2=0)⊂R) (1)

Since there is no applicable TR or TH to the precondition of eq.(1), the problem transformation is tried. The application of P-TR ① to eq.(1) yields

((∀k)(∃x)(~k∈R∨root(var:x,rel:x**2-2*k*x-2*k-2=0)⊂R‖T). (2)

After finding no applicable TRs, one candidate of applicable theorems

(∃x)(root(var:x,rel:a*x**2+b*x+c=0)⊂R) ⇄ b**2-4*a*c≧0

is found from the address area fc:poly-d:real-p:nq-q:∀-∃:1 involved in the address table of THs.
The application of the above theorem to the precondition of eq.(2) results in

((∀k)~k∈R∨k**2-2*k+2≧0‖1≧0). (3)

The CBL form of eq.(3) is

((∀k)~k∈R∨rq-3·2(var:{k},fc:poly)‖ rq-3·3(var:φ,form:2)). (4)

The numbers 3·2 and 3·3 in eq.(4) denote the second and the third literals of eq.(3) respectively. The candidates of applicable TRs are ① and ③. The application of TR ① fails in the adoption of TR ② which is suggested by TR ①. The application of TR ③ to the OBL form of eq.(3) results in

((∀k)~k∈R∨≧(Σ(t̄(sgn:pz,var:{k})),0) ‖≧(t(sgn:pz),0)).

The application of the theorem TH ① suggested by TR ③ to eq.(3) leads to the result;

((∀k)~k∈R∨(k-1)**2+1≧0‖1≧0). (5)

The highest level of abstraction of applicable TRs to the precondition of eq.(5) is OBL, that is;

((∀k)~k∈R∨q-5·2(Σ(t̄(var:{k},fc:poly,sgn:pz)), 0)‖≧(t(sgn:pz),0)). (6)

The number 5·2 denotes the second literal of the precondition of eq.(5). The application of TR ④ to the precondition of eq.(6) yields

((∀k)~k∈R∨≧(t(sgn:pz),0)‖≧(t(sgn:pz),0))

which leads to the completion of the proof.

6. CONCLUSION

The first version of EAPS[3] implemented on a mini-computer in an assembly language solved problems such as those which involve a simultaneous linear equation symbolically in about ten seconds. The new EAPS with additional facilities presented in this paper is under development on a computer with a 768 kB memory in LISP 1.5.

ACKNOWLEDGMENTS

The authors wish to thank Mr. K.Imori for his help in the implementation of EAPS.

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THE FRAMEWORK OF KNOWLEDGE REPRESENTATION AND 1' RETRIEVAL IN LGS — THE LITERATURE GUIDE SYSTEM

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This paper describes the framework of knowledge representation and the techniques for information retrieval in a program called LCS (the Literature Guide System). LGS will answer questions about scientific literatures in natural language. Model theoretic approach is employed to represent the meanings of sentences in the abstracts of literatures. The knowledge base is a set of interpreted logical formulas, and is partitioned into possible worlds, User!s own view to the knowledge base can be incorporated into objects called script frames. A script frame is defined in terms of logical formulas. A query to the knowledge base is presented as a pattern. A list containing all items which match the pattern will be returned as the result. A set of rules for pattern matching are defined in terms of logic, and are designed so as to cover the cases of paraphrases and categorical implications. LGS is composed of an accommodator, a retriever, and a natural language interface. It is under development on the personal LISP system.

1. INTRODUCTION

LGS [1] is an experimental system which integrates knowledge about scientific literatures and which will answer questions about them, LGS is toward a natural language data base system (NLDB system). In any NLDB system, the problems of knowledge representation and information retrieval are crucial.

We employ the model theoretic approach to a NLDB system. The model theory gives the formal semantics to the knowledge representation in a NLDB system. The meaning of a sentence is described as a logical formula of the intensional logic. Many aspects of natural language expressions such as modalities can be clearly explained by the concept of a possible world. Our approach to a NLDB system can be summarized in the following schema;

NATURAL LANGUAGE EXPRESSION
(STEP1) syntactic analysis
LAMBDA EXPRESSION
(STEP2) lambda calculus
LOGICAL FORMULA OF INTENSIONAL LOGIC
(STEP3) interpretation
DOMAIN DESCRIPTION BY META-LANGUAGE
(STEP 4) accommodation
THE KNOWLEDGE BASE

The idea about STEP1 and STEP2 is formalized in MG (Montague Grammar) [2] which is implemented in the natural language interface. In this paper, we concentrate on STEP3 and STEP4. In STEP3, meta-language expressions are created from logical formulas, and in STEP4, they are accommodated into the knowledge base with some auxiliary data objects which are called frames.

Information retrieval plays an important part in question answering. Pattern matching among meta-expressions is a basic technique in information retrieval. Rules for pattern matching are defined in terms of logic. The concept hierarchy is defined as logical implications between concept predicates. The rules are presented to cope with the cases of paraphrases and categorical implications.

We are implementing those ideas as LGS. Currently, we have a limited version, LGS-0, where simple dialogs are available using Japanese or query commands.

2. KNOWLEDGE REPRESENTATION AND THE KNOWLEDGE BASE

2.1 Meta-language Expressions

In general, the interpretation of natural language, that is, the proper generation of domain description from a given natural lan-

guage expression, is accompanied with much difficulty, especially when treating quantifiers. So, by employing some conventional expressions in meta-language to leave ambiguity in translation, we shall put aside those problems temporarily. Here we show some of those representations. (Representations in natural language are enclosed by "...".)

(E1) indef[x; program(x)] for "a program"
(E2) def[x; program(x)] for "the program"

Def and indef are a definite operator and an indefinite operator, respectively.

(E3) love("she","he") in a possible world P, for "he believes that she loves him."

Where the possible world P Is the one which is "believed by him."

2.2 The Knowledge Base

Conceptually, the knowledge base is a set of meta-expressions which are partitioned into possible worlds. In the actual implementation, the knowledge base is constructed from data structures, called paragraphs, units, and frames. A paragraph is a possible world management block. A unit is a data structure for internal representation of a meta-expression. There are four types of a unit, I-, P-, F-, and O-unit. An I-unit (Individual-unit) is used for an object, which includes a set of references to the object. A P-unit (Predicate-unit) is for a predicate. Not only a set of references but also a list of 'case slot and filler[1] pairs for the predicate are Included. A F-unit (Function-unit) is for a function. An O-unit (Operator-unit) is for an operator.

A frame is a data structure for representing more complicated but stereotyped knowledge. Two levels of a frame, a basic frame and a script frame are defined. A basic frame is a data structure defined for each predicate symbol and function symbol. It includes the definition of the symbol and the index of its occurences in the knowledge base. The concept hierarchy, which plays a key part in inference on the knowledge base, is embedded in the collection of basic frames as implication relationships among predicate symbols. A script frame is a data structure defined for more complicated situation. It includes case structure, frame definition, and knowledge base search strategies. Users can define script frames with their own case structure and knowledge base search strategies. Here we shall show an example of a script schema about a "natural language understanding system."

```
script-name:*
    NATURAL-LANCUAGE-UNDERSTANDING-SYSTEM;
    1) VARIABLE DECLARATIONS:
      DCL x,y,z,w objects;
      DCL P,Q,R,S,T,U predicates;
    2) INSTANTIATION CONDITIONS:
      P:understand(x,y) & Q:written-in(y,z) &
      R:natural-ianguage(z) & S:system(x);
    3) CASE DEFINITIONS:
      name:=w such that name(x,w),
      theme:=y,
      method:=T such that method(P,T),
      performance:=U such that actor(U)«x;
```

Script frames will be created for all knowledge structures that fill the instantiation conditions.

2.3 Interpretation and Accommodation

In this section, we shall overview how the meta-expression is created from a given logical formula, and accommodated into the knowledge base. First, a paragraph is created for the actual world. Then the knowledge structure construction program reads logical formulas one by one. Let a given formula be f, then the construction process proceeds as follows;

1) set a pointer (WP) to the actual world.
2) seek a possible world which is related to the actual world by a modal operator or an intensional operator in the formula. If it is found, move WP to the possible world, and if not, create a new possible world corresponding to the operator and move WP to the new world. Remove the operator from f.
3) remove indef and def operators if possible. It f is a predicate P(...indef[x;q(x)]...), and P is an extensional predicate, create a new object c in the possible world pointed by WP, and generate internal structure corresponding to P(...c...) and q(c). If f is a predicate P(...def[x;q(x)]...), search the object that satisfies q(x), and if it is found, replace def[x;q(x)] by the object.
4) construct a network structure for the resulting formula and put it into the world pointed by WP.
5) add an index to the related basic frames.

Steps 2-5 may be called recursively when the given formula is nested. Script frames may be instantiated for the generated knowledge structure if the instantiation conditions are filled.

3. INFORMATION RETRIEVAL

An important type of an information re-

trieval request may be "for the given predicate P, find all objects (x's) such that P(x) is true in some possible world." Any object y should be retrieved if D(y)->P(y) holds in some possible world, where D(y) is the conjunction of all descriptions about y. In LGS, the pattern matching method is used to test the implication, since the direct proof of the implication by a resolution-based theorem prover is inefficient and inflexible. Each formula is regarded as a symbolic pattern. The predicate match[P*,y] is tested instead of D(y)->P(y), where P* is indef[x;P(x)].

The retriever consists of an index searcher, a matcher, and a modality generator. The index searcher examines the index structure of basic frames to produce a list of candidates. Then for each element y in the list of candidates, the matcher tests if the pattern matches y. Any candidates that do not match the pattern are removed from the list. Finally, the modality generator may add appropriate modal operators to the remaining candidates so that they may be the predicates in the actual world.

A set of rules are defined for pattern matching. Especially,

(RULE1) categorical implication rule:
a pattern P matches another pattern D if

$$D \vdash P.$$

(RULE2) paraphrasing rule:
a pattern P matches another pattern D if there exists a predicate Q such that

$$P \vdash Q \text{ and } D \mid\!- Q,$$

where natural deductions are used with the set of axioms for the concept hierarchy.

RULE1 covers the cases of categorical implications. For example, the pattern "animal" matches "human-being". RULE2 covers the cases of paraphrases. For example, a predicate

give(actor=A,object*B,direction=C)

can match the predicate

get(actor=C,object=B,source=A)

where the predicate Q is

transfer(object=B,source=A,direction=C).

The range of the applications of deductions in RULE2 should be limited for plausibility.

4. EXPERIMENTS

LGS is under development on the personal LISP system (LISP1.7) [3]. We currently have a limited version of LGS (LCS-0). LGS-0 can integrate the knowledge about the literatures and answer questions. The interactions can be done in natural language. LGS-0 consists of three program modules (the natural language interface, the accommodator, and the retriever) and the knowledge base. The natural language interface is used (1) to translate both sentences of literatures and queries into logical formulas of intensional logic, and (2) to generate natural language outputs as the replies to queries. The details are described in [1].

LGS-0 can perform simple dialogs like below in Japanese.

U: do you know any literature about a question answering system?
(Information retrieval is done.)
S: YES, I KNOW 20 SUCH SYSTEMS.
U: take one of them!
U: what is the name?
S: LGS
U: what kind of questions can it answer?
S: IT WILL ANSWER QUESTIONS ABOUT SCIENTIFIC LITERATURES,
(Question answering about the found object.)
U: which papers describe it?
S: THE PAPER THAT IS SUBMITTED TO THE 6TH IJCA1.
(A literature is guided.)
U: what aspects does it describe?
S: THE FRAMEWORK OF KNOWLEDGE REPRESENTATION AND INFORMATION RETRIEVAL IS DESCRIBED.
... (U: a user, S: the system)

5. CONCLUSION

In this paper, we have attempted to show our model theoretic approach to a NLDB system. We think LGS is a good example for such an approach. Of course, there are lots of problems to be solved in future. Especially, the problem of inferences in the possible world domain [A] is important.

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THE THEOREM PROVER USING A PARALLEL PROCESSING SYSTEM

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1. INTRODUCTION

An AND/OR graph is often used to solve problems. It abstractly expressed the concept of dividing one problem into several sub-problems which are independently solved. This makes it possible that the sub-problems are solved in a parallel process. In this paper, D-graph deduction is proposed, which is based on a reductio ad absurdum using D-graph (a kind of directed AND/OR graph). The D-graphs are corresponded to the predicate logic formulas which represent the axioms and the negation of the theorem proved.

If several sub-problems share the same variables in problem solving, then the way in which one problem is solved may affect the solution of the others. This prevents sub-problems from being solved independently. There is the same issue in the D-graph deduction. The use of micro -actors settles such an issue. The micro-actors are the modules which compose basic structure for the knowledge representation. They can be applied to search a D-graph, because the D-graph basically consists of OUT-AND arcs. It will be shown that the sub-problems are solved independently in a micro-actor system in which the micro -actors correspond to the nodes in the D-graph and the common variables.

2. D-GRAPH DEDUCTION

2.1 First Order Predicate Logic and D-graphs

The authors will propose a formal deduction method using a directed AND/OR graph, called D-graph deduction, which is based on a reductio ad absurdum argument for the first order logic using D-graphs. Nodes in the D-graph are corresponded to the predicate symbols, their negations, TN (which means true), and FN (which means false), A set of arcs indicates a clause (a predicate logical formula).

[Definition 1] A label (α,β) is attached to arc (A,B) corresponding to the formula $A(\alpha) \rightarrow B(\beta)$, as shown in Fig. 1. α and β are the arguments of the predicates A and B, respectively. Thus, a label to an arc is an ordered pair of variable vectors, whose components are the variables and Skolem functions of predicates corresponding to the start and the goal nodes.

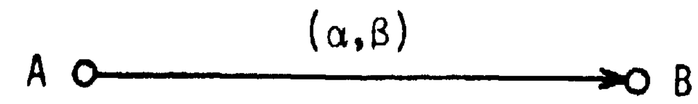


Fig. 1 D-graph representing $A(\alpha) \rightarrow B(\beta)$.

Let Greek lower-case letters express the tuple of constants, variables and Skolem functions.

[Definition 2] (Rules for translating clauses to a D-graph)

(1) Select a clause from a set of support, where the set of support is a non-empty subset K of the initial set S of clauses such that S - K is satisfiable. Let the clause be represented $L_1(\lambda_1) \vee \ldots \vee L_h(\lambda_h)$.

The clause may be modified as follows:

$$\text{True} \rightarrow L_1(\lambda_1) \vee \ldots \vee L_h(\lambda_h)$$
$$= (\text{True} \rightarrow L_1(\lambda_1)) \vee \ldots \vee (\text{True} \rightarrow L_h(\lambda_h)).$$

Nodes $L_1, \ldots, L_h$ in the D-graph are regarded as OUT-AND nodes concerning TN, and arcs (TN, L_1), ..., (TN, L_h) are grouped by a linking symbol. Attached to the arcs are the labels $(\ ,\lambda_1), \ldots, (\ ,\lambda_h)$ (See Fig. 2 (a)).

(2) Let $L_1(\lambda_1) \vee \ldots \vee L_m(\lambda_m)$ be a clause which has more than one literal, excluding the clause chosen at (1). This clause can be translated as follows:

$$\neg L_i(\lambda_i) \rightarrow L_1(\lambda_1) \vee \ldots \vee L_{i-1}(\lambda_{i-1}) \vee L_{i+1}(\lambda_{i+1}) \vee \ldots \vee L_m(\lambda_m)$$

$= (\neg L_i(\lambda_i) \rightarrow L_1(\lambda_1)) \vee \ldots$
$\vee (\neg L_i(\lambda_i) \rightarrow L_{i-1}(\lambda_{i-1})) \vee (\neg L_i(\lambda_i) \rightarrow L_{i+1}(\lambda_{i+1}))$
$\vee \ldots \vee (\neg L_i(\lambda_i) \rightarrow L_m(\lambda_m))$.

The D-graph representing this formula consists of OUT-AND arcs and nodes conserning $\neg L$ as shown in Fig. 2 (b). The above operation must be performed for all i (i = 1, ..., m).

(3) A unit clause $L(\lambda)$, which is not selected at (1), may be modified to $\neg L(\lambda) \rightarrow$ False. $L(\lambda)$ is therefore represented as the D-graph illustrated in Fig. 2 (c).

(4) $L(\lambda)$ and $\neg L(\lambda)$ are always inconsistent, so the clause set containing them is unsatisfiable. They are indicated by IN-AND arcs and nodes concerning FN, as shown in Fig. 2 (d).

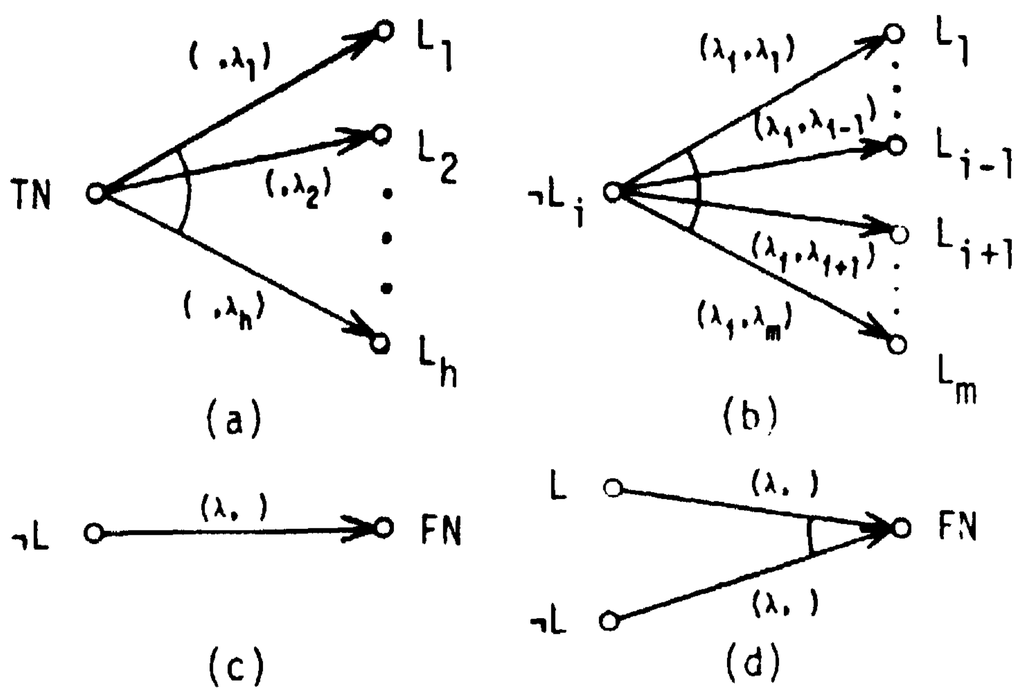


Fig. 2 D-graph
(a) True $\rightarrow L_1(\lambda_1) \vee \ldots \vee L_h(\lambda_h)$
(b) $\neg L_i(\lambda_i) \rightarrow L_1(\lambda_1) \vee \ldots \vee L_{i-1}(\lambda_{i-1})$
$L_{i+1}(\lambda_{i+1}) \vee \ldots \vee L_m(\lambda_m)$
(c) $L(\lambda)$
(d) $(L(\lambda), \neg L(\lambda))$.

2.2 Completeness of D-graph Deduction

D-graph deduction is carried out by communicating the state of a node to its successor and by referring to the labels. The following define the state of a node and its communication rule, and the relation between a node and FN in the D-graph.

[Definition 3] Suppose e, with lable (α, β), denotes the arc from node A to node B, and that γ represents the state of A. If there exists the most general unifier (m.g.u.) π of α and γ, the state γ of A is said to satisfy the label condition and e is said to be abailable. Then the state of B is $\beta\pi$. When the state γ of A does not satisfy the label condition of e, nothing is conveyed to B, i.e., this is equivalent to that saying arc e does not exist.

[Definition 4] (Achievability for a D-graph) Achievability is defined between any node and FN as follows:

(1) If a node A is connected to FN by an arc (A, FN) which is not an IN-AND arc and is available, then A $\stackrel{*}{\rightarrow}$ FN.

(2) Suppose that the set of arcs $(A, N_1), \ldots, (A, N_m)$ forms an OUT-AND arcs concerning A. If each of the arcs is available and $N_j \stackrel{*}{\rightarrow}$ FN (i = 1, ..., m), then A $\stackrel{*}{\rightarrow}$ FN.

(3) If there is a sequence of arcs $(\neg A, N_1), (N_1, N_2), \ldots, (N_n, A)$ (or $(A, N_1), (N_1, N_2), \ldots, (N_n, \neg A)$) and all arcs are available together with the most general unifier π for the states of A and $\neg A$, then A $\stackrel{*}{\rightarrow}$ FN ($\neg A \stackrel{*}{\rightarrow}$ FN). If there are nodes $M_1, \ldots, M_m$ which have an OUT-AND relation with $\neg A$ (A), FN must be achievable from them and the state of M_i (i = 1, ..., m) applied must satisfy the label condition.

(4) A $\stackrel{*}{\rightarrow}$ FN is only generated by applying the above rules.

The D-graph deduction is carried out to determine whether FN is achievable from TN in D-graph which represents the axioms and the negation of the theorem. The states of nodes and the labels of arcs are employed to deal wit the arguments of the predicates. The completeness of the D-graph deduction is guarenteed by Theorem 1.

[Theorem 1] Let G be the D-graph representing a set of S of clauses. S is unsatisfiable if and only if TN $\stackrel{*}{\rightarrow}$ FN in G.

3. PARALLEL PROCESSING SYSTEM

In this section, a parallel processing system is described to solve the problem usingmicro-actors. The micro-actors are the modules for the knowledge base. The micro-actor is composed of a script and an acquaintance. The script consists of the pairs of the message pattern and the action corresponding to the pattern. The micro -actor has the acquaintance as a memory space to hold the data and the names of the other micro -actors it directly knows about. Since only message passing is the interactive method between the micro-actors, the action of a micro -actor never affects the other micro-actors. This enable us to construct a parallel processing system.

3.1 Node Micro-Actors and Variable Micro-Actors

We will define two kinds of micro-actors. One is a node micro-actor (NMA), which corresponds to a node in a D-graph. Scripts of NMAs are the same. That is, they have a program which sends messages to the other NMAs according to their acquaintances. An NMA stores the relation between the node indicated by the NMA and the other nodes, in ELI5T in its acquaintance. An example of ELIST is as shown in Fig. 4 (a).

Another is a variable micro-actor (VMA), which corresponds to a common variable and is made under searching a graph. Since a micro-actor is independent of the other micro-actors except for message sending, a VMA is independent of the other VMAs and NMAs. However, several NMAs must be able to refer to one VMA. There *are* two kinds of actions of a VMA:

(1) Add the sent data to the aquaintance.
(2) Reply the data which have flag sent.

The basic data of the acquaintance is in form of (F V), where F is a set of flags which are similar to sentence number, and V is a value. (When the value is not given, V is NIL.)

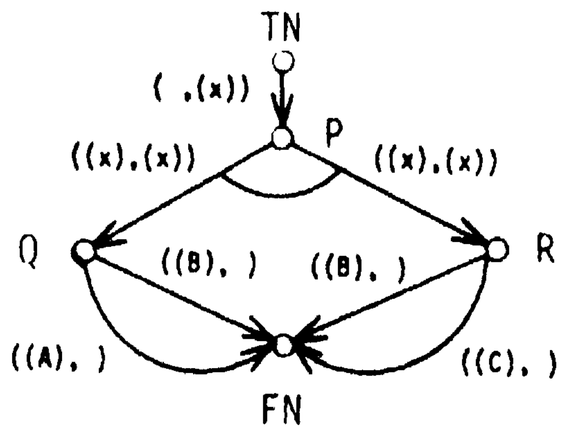
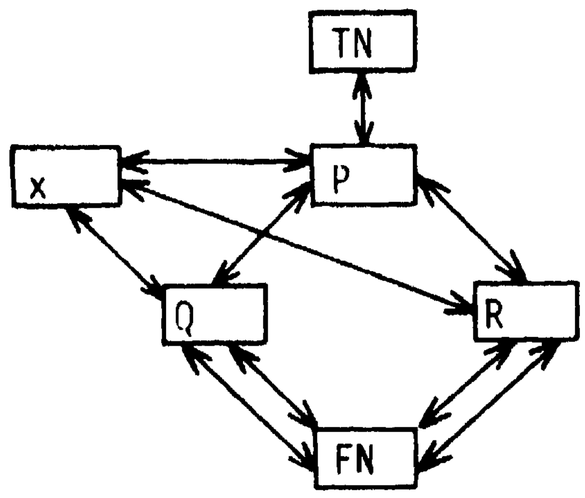


Fig. 3 A part of D-graph in Example 1.

```
TN-ELIST = ((NIL P (x)).
 P-ELIST = (((?x) Q (x) R (x))).
 Q-ELIST = (((A) FN NIL) ((B) FN NIL)).
 R-ELIST = (((B) FN NIL) ((C) FN NIL)).
```

(a)



(b)

Fig. 4 ELISTs (a) and micro-actors (b) in Example 1.

[Example 1] The D-graph illustrated in Fig. 3 is a part of D-graph representing the following clauses:

axioms: $\neg P(x) \vee Q(x) \vee R(x)$, $\neg Q(A)$, $\neg Q(B)$, $\neg R(B)$, $\neg R(C)$.

negation of theorem: $P(x)$.

Where A, B and C are constants, and x is a variable. Fig. 4 (b) shows a micro-actor system corresponding to the D-graph in Fig. 3. Fig. 4 (a) shows ELISTs in the micro-actors. Graph searching begins when TN sends the messages and is carried out by sending message from NMAs to NMAs. NMAs perform one of three operations: expansion (sending the messages to successors), merging (merging several messages into one) and partial refutation (which is similar to ancestor resolution). FN replies to its ancestor. When a NMA receives a reply, the NMA checks the consistency of it. So the result of the system does not depend on the order of replies the messages which are sent concurrently. The system is stopped when a reply is sent to TN. Sending message from NMAs to NMAs makes the coroutine control, while sending message from NMAs to VMAs makes the subroutine control.

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AN ACTIVE FRAME FOR THE KNOWLEDGE REPRESENTAION

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This paper describes micro-actors which construct the knowledge representation in which the modularity was established without sacrificing the interaction. The behavior of the micro-actor is defined in terms of only one kind of action: sending message to another micro-actor. The micro-actor is composed of a script and an acquaintance. The script consists of the pairs of the message pattern and the action corresponding to the pattern. The micro-actor has the acquaintance as a memory space to hold the data and the names of the other micro-actors it directly knows about. As a result of using the micro-actors, we can deal with knowledge about the actions as well as knowledge about the world states. The information about an action sent from a micro-actor is effective only in the micro-actor which received it. This guarantees the modularity of micro-actors.

An example shows that the continuation in a message make both the subroutine control and the coroutine control possible. The other indicates a dialogue in the question-answering system using the micro-actors.

1. INTRODUCTION

Artificial Intelligence is a branch of computer science which is mainly concerned with the problem solving, the cognition, and the comprehension of natural languages. Many approaches to the problem solving have been developed; forexample, the algorithm A* (Hart) [4] for searching trees, the resolution principle (Robinson) [13], GPS [2] and its application: STRIPS (Fiks, Nilsson) and so on. The resent approach is the development of the programming language for artificial intelligence. The cognition is the intelligence process to acquire knowledge in the image understanding and the speech understanding. The comprehension of natural languages needs the integration of many approaches in artificial intelligence.

The common issues of the above mentioned themes are the knowledge representation and the mechanism of understanding and inference. In this discussion, "Knowledge" does not mean only the facts about a world state but also the techniques dealing with the facts. The artificial intelligence system obtains information from the scene and/or the statements in natural language. The system, then, acquires new knowledge by comparing the obtained information with the knowledge the system has. Therefore, the knowledge representation is necessary, in which it is easy to specify knowledge, modify it and refer to it. There have been two types for the representation of knowledge: the declarative one and the procedural one [17]. The modularity is emphasized in the former; e.g., the logical formulas. On the other hand, the interaction is stressed in the latter; e.g., PLANNER [5], QA4 [16], CONNEVER [9] and so on. The declarative representation has several benefits: The separation of knowledge into data and procedures brings the flexibility and economy of the declarative representation. The independence of the axioms or facts leads to the understandability and learnability of them. On the contrary, in the procedural representation, a frame axiom need not be specified. Furthermore, the heuristic knowledge can be treated in it. To utilize both benefits of the declarative representation and the procedural one, it is necessary to develop the method in which the modularity is established without sacrificing the possibilities for interaction.

KRL (Bobrow, D.G. & Winograd, T.) [1] and FRL (Roberts, R.B. & Goldstein, I.P.) [14, 15] are developed as the approaches to the problem mentioned above. Both KRL and FRL are based on frames, and attempt to integrate procedural knowledge with a broad base of declatative forms. By the way, there is some knowledge about the action; for example, the control of the reasoning mechanism, the data base processing and so on.

Such knowledge is preferable to be expressed by the procedures rather than the declarative forms. If declarative knowledge is integrated with the procedures which deal with it, and the procedures have the modularity, then we can freely use both declarative knowledge and procedural one.

This paper describes a micro-actor* as a method for knowledge representation. The script of a micro-actor contains procedural knowledge to deal with only the acquaintance of the micro -actor. The acquaintance has declarative knowledge in the form of frame.

2. REPRESENTATION OF WORLD-STATE

2.1 Frame Representation In Acquaintance

A micro-actor is composed of a script and an acquaintance. The script describes the behavior which the micro-actor should take when it receives a message. The acquaintance is the memory space for the micro-actor. The acquaintance stores the data that the micro-actor knows; for example, its native values, its attributes, the names of the other micro-actors it directly knows about, and the relation with them. The followings are the reason why the concept of Frame Theory [8, 10] is used for construction of an acquaintance:

(1) A frame is a data-structure representing a stereotyped situation.

(2) Several kinds of information can be attached to each frame, and some of this information is about how to use the frame.

(3) Frames enable us to represent knowledge in a hierarchical structure.

Fig. 1 shows a slot array representation to indicate a frame intuitively. A frame is, however, represented by the nested association lists as shown in Fig. 2 in its implementation. The respective substructures of a frame are named; Slot, Facet, Datum and Comment. A slot shows which property the data in it are connected with. A facet shows kinds of the data; e.g., values, constraints, procedures and so on. A datum is elementary information associated with the facet, and a comment is additional information

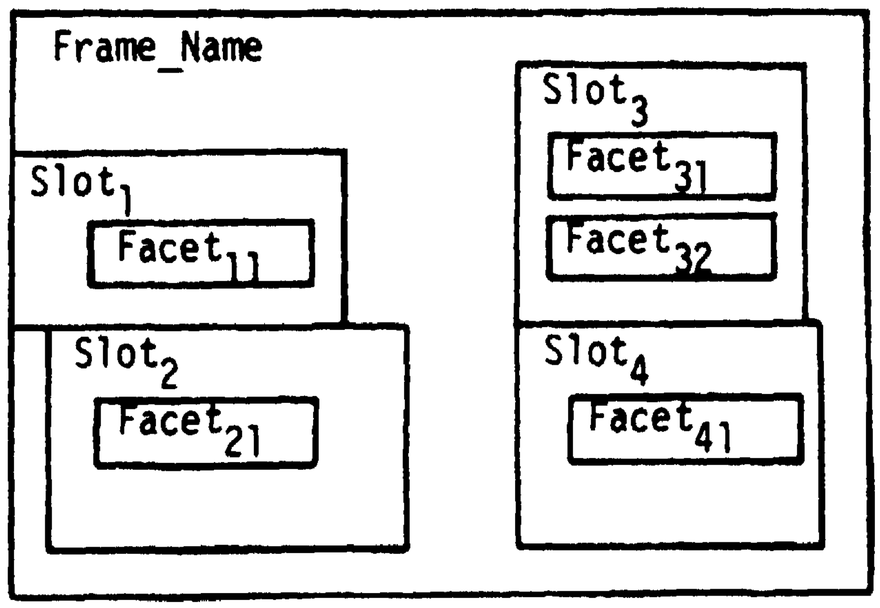

Fig. 1

Slot array representation of a frame.

```
(Frame Name
 (S1 (F11 (D111 C111) ... (D11h C11h)))
 (S2 (F21 (D211 C211) ... (D21i C21i)))
 (S3 (F31 (D311 C311) ... (D31j C31j))
     (F32 (D321 C321) ... (D32k C32k)))
 ......
 ......
 (Ss (Fs1 (Ds11 Cs11) ... (Dslm Cslm)))
)
```

Fig. 2

Nested list representation of a frame.
S: slot, F: facet,
D: datum, C: comment.

for the datum.

2.2 Effect On Other Frames

An addition of procedures to a slot of a frame enables the frame to acquire information from other frames and to change the contents of the other frames. This may make it possible to combine the declarative knowledge and the procedural knowledge; that is, the modurality and the interaction. However, a question still remains to be solved.

A frame is freely dealt with using three basic functions; obtaining something from the frame, putting somthing to it, and removing from it. The use of only the three functions is, however, inconvenient and uneconomical when a frame is dealt with in several ways. New functions should be made either in advance or afterward. We will try to put box A on box B in a block world.

Assume that there are frames which correspond to box A and box B. To put box A on box B is

* The micro-actor was proposed as the implementation of some of abilities of actor (Hewitt, C.) [6, 7] in 1977 [11]. A new version of a micro-actor described in this paper has similar abilities of actor. Parallel process and coroutine control are possible in a micro -actor system. There is a slight difference between the micro-actor and the actor in point of notation.

executed by the following process; If both box A and box B are a kind of Block and Cleartop*, and box B is Supportable**, then let box A be supported on box B and let box B support box A. The knowledge concerning the process mentioned above is represented in three methods: (1) Function ON is made in order to put an object on another, and is added to the basic fuctions. (2) The process is distributed to the frames corresponding to box A and box B. (3) A new frame is created corresponding to the function ON.

In (1), there exists the chunk of procedures dealing with frames. A slight change of a procedure often affects the other procedures. As a result, (1) is not good to represent the knowledge about actions in A.I. system. General functions can be used in both (1) and (3). On the contrary, a procedure depends on a particular frame in (2). (2) is convenient to describe the procedure closely depending on the frame, and to establish the modularity among procedures. It is, however, wasteful when several frames have the similar function. (3) is equal to (1) in essence. So there remains the possibility of the unlimited and unrestricted interactions. However, the application of the idea of actor to (3) leads the module for representing knowledge with proper interaction method.

The actor model is suitable to control and describe the interaction between the modules. Namely, the action of an actor is defined in terms of only one kind of action; sending messages to the other actors, and any other side effect is not permitted. When the actor receives a message, it becomes active and tries to play its role. The authors think that the actor model is useful for parallel processing.

3. REPRESENTATION OF ACTION

The chapter 2 said that a frame is good for representing the knowledge about a world state, but not so good for representing the knowledge about an action. On the other hand, a micro-actor is very suitable for representing the action. The micro-actor, which is a procedure, is a basic module in order to construct the knowledge base. This chapter describes the form of script which represents the behavior, and illustrates how to deal with the knowledge about the world state using message passing.

* Cleartop means the state in which the box supports nothing.

** The box which is supportable can suppor another box.

3.1 Micro-Actor

The script of the micro-actor precisely represents the message passing, the parallel computation and the coroutine control. The form of the script is similar to Yonezawa's notation[19]. But the micro-actor is based on LISP whereas his notation is based upon PLASMA.

(i) Script

The script is specified with a set of pairs of message patterns and rules as follows:

((message_pattern$_1$ rule$_{11}$ ... rule$_{1m}$)
(message_pattern$_2$ rule$_{21}$ ... rule$_{2n}$)
:
(message_pattern$_p$ rule$_{p1}$ ... rule$_{pq}$)).

(ii) Message Pattern

There are two types for pattern:
(1) (MES: ?%N *content* TO: ?CONT).
(2) (RE: ?%N *content*).
?%N is only matched with the message number %n, where n is a positive integer. A message number is assigned to an input sentence or a message for distinguishing it from the others as a tag. The message number is also used to distinguish a datum from the others stored in the same micro-actor. The atoms prefixed by "?" (e.g., ?CONT) are the variables for pattern matching. The prefix "!" is used instead of the prefix "?" to refer to the pattern matching variables for their values; for example, !CONT. "MES:" means a message and "RE:" means a reply. "TO:" means that the continuation is !CONT. The continuation is the micro-actor which is sent a reply. Assign "NO-ONE" to !CONT in the case that the answer is not required. Assign "ME" to !CONT when the reply is demanded. This is equal to the subroutine control.

(iii) Rule

A rule is a set of programs, which carries out a job. The rule consists of three parts as follows:

((P-C: program$_{p1}$ ... program$_{pq}$)
(N-C: program$_{n1}$ ... program$_{nr}$)
(C-E: program$_{c1}$ ... program$_{cs}$)).

"P-C:" is an abbreviation for pre-condition. "N-C:" means next-condition which is an option. "C-E:" is an abbreviation for caused-events in which the messages are sent to the other micro-actors when both the pre-condition and the next-condition are satisfied. The form of the rule is given by Dr. Yonezawa, and it is sug-

gested that the form of the rule is useful to deal with the parallel computation. The programs should be carried out 1n order of the appearance of them in the pre-condition and the next-condition. On the other hand, the programs in the caused-events can be executed concurrently.

(iv) Program

A program is written in the restricted LISP notation. The user can freely use the LISP functions which don't have influence upon the pointers to lists and atoms; e.g., MEMBER, ASSOC and so on. The variables are restricted to the form !m or !!n (Both m and n are positive integers.) for the LISP functions which have influence upon the pointers; e.g., SETQ and so on. This restriction prevents the behavior of a micro-actor from giving unitentional effect to other micro-actors. The variable !m is used as well as PROG variable, whicle !!n can be used in a special way as mentioned in the next section.

A specification for message passing is as follows:

(-> *the_n(xme_ of_micro_actor a_messages*).

The user uses the basic function (FGET, FPUTand FREMOVE) to deal with the acquaintance. These functions differ from those of FRL in point of the necessity of the frame name. The functions in this paper do not need the frame name because the micro-actor deals with only its acquaintance. Therefore, the execution of the basic function does not affect the other micro-actors.

(v) Behavior of Micro-actor

A micro-actor tries to find a message pattern which is matched with a messge M1 when it receives M1. If the message pattern P1 is found, a rule R1 is searched for, which is one of rules making a pair with the pattern P1 and whose pre-condition should be satisfied. When there is the next-condition in R1 all programs in the next-condition should be evaluated. If the next-condition is satisfied, the caused-events are executed. If there is no rule whose pre-condition is satisfied concerning the pattern P1, the micro-actor tries to find another message pattern which is matched with M1.

Since the system holds the COMMON-SCRIPT which is necessary for all micro-actor, the users may specify the micro-actor by the peculiar script. The COMMON-SCRIPT has the message pattern (MES: ?XN ?X TO: ?CONT) and acts as follows:

(a) If the variable !X (corresponding to ?X) indicates one of the basic functions (FGET,FPUT and FREMOVE), then it is put into practice.

(b) If !X shows one of the extension functions (i.e., there exists a micro-actor corresponding to it), the rules are obtained from the micro-actor corresponding to the extension function, and they are performed. The variables !!n (n = 1, ..., 5) are corresponded to the arguments; for example, !!1 means the first argument.

(c) If !X indicates a set of rules, then !X is accomplished.

3.2 Example

A block world gives us good examples to illustrate the representation of the script and the acquaintance of a micro-actor, and message passing. The following discussion concerns with the micro-actor PROPERTY. It is used in the implementation of putting an objict on another. The script of the micro-actor BOX! is NIL, because it needs just only the COMMON-SCRIPT. The acquaintance is expressed by one slot as follows: ((AKO (:VALUE (BOX))). This means that boxl is a kind of box. The AKO slot has a higher level concept of boxl as the value marked by the :VALUE facet. Concerning the micro-actor BOX, the script is NIL as well as boxl, and the acquaintance is as follows:

```
((AKO          (:VALUE (BLOCK)))
 (INSTANCE (:VALUE (B0X1 B0X2 B0X3)))
 (PROPERTY (:VALUE (SUPPORTABLE))) ).
```

This shows the following facts: (1) Box is a kind of block. (2) The instances of box are boxl, box2 and box3. (3) The native property is supportable which means that the box can support another box.

Fig. 3 gives the script and the acquaintance of the micro-actor PROPERTY which deals with the rules about the properties. In the rest of this paper, a variable prefixed by "!" indicates its value until it is quoted. The script hasarule to ask the micro-actor !B if it has the property !A. According to the rule, PROPERTY sends !B the rules in which !A is substituted for ''!!1''. The AKO slot means that PROPERTY is a kind of E-FUNCTION (which is an abbreviation of extension function). The CONTENT slot shows the rules which contain the following algorithm. If the micro-actor which executes the rules has the value SUPPORTABLE in its PROPERTY slot,then it sends the reply OK to !CONT. Otherwise, if it has the value A in the AKO slot, then A is sent the message to ask if A has the property SUPPORTABLE. If A has it, A sends the reply OK to !CONT; otherwise, A sends NIL to !CONT. Note that A need not answer the micro-actor which sent the message to A. This means the possibility of a coroutine control.

```
((MES: ?%N ?B PROPERTY ?A TO: ?CONT)
 ((P-C: (SETQ !1 (FGET CONTENT :VALUE)))
  (N-C: (SETQ !1 (*SUBS !1 (LIST (CONS
                    (QUOTE !!1) !A)) )))
  (C-E: (=> !B (MES: !1 TO: !CONT)))
))
```

(a)

```
(AKO     (:VALUE (E-FUNCTION)))
(CONTENT (:VALUE
  ((P-C: (SETQ !5 (FGET PROPERTY :VALUE))
         (ASSOC !!1 !5))
   (C-E: (=> !CONT (RE: !%N OK)))
  )
  ((P-C: (NOT (ASSOC !!1 (FGET PROPERTY :VALUE)))
         (SETQ !4 (FGET AKO :VALUE))
         (SETQ !4 (CAAR !4)))
   (C-E: (=> !4 (MES: !%N PROPERTY !!1
                      TO: !CONT)))
  )
  ((P-C: (NULL (FGET AKO :VALUE)) )
   (C-E: (=> !CONT (RE: !%N NIL)))
)))
```

(b)

Fig. 3

(a) The script of the micro-actor PROPERTY.
(b) The acquaintance of PROPERTY.

Fig. 4 shows the diagram of the message passing for the process to see 1f boxl is supportable. The user can communicate with the micro-actor system using the special micro-actor * as shown in Fig. 4. For example, when the user wants to know whether boxl is supportable or not, he may write as follows:

(* PROPERTY B0X1 PROPERTY SUPPORTABLE).

The first argument of * is the target of the message whose content follows the first argument. The micro-actor * composes the message and sends it to the micro-actor PROPERTY (See linel and line 2 in Fig. 5).

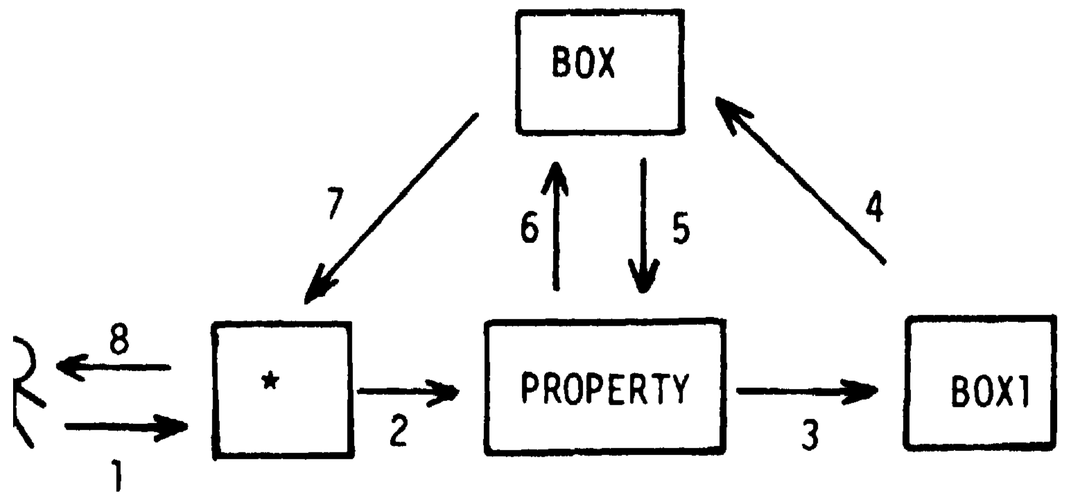

Fig. 4
The diagram of the message passing.

```
1 (* PROPERTY BOX1 PROPERTY SUPPORTABLE)
2 (* PROPERTY <= (MES: %2 BOX1 PROPERTY SUPPORTABLE TO: ME))
3 (*+ BOX1 <= (MES: %2 (((P-C: (SETQ !5 (FGET PROPERTY :VALUE))
                               (ASSOC SUPPORTABLE !5))
                          (C-E: (=> !CONT (RE: !%N OK)))  )
                         ((P-C: (NOT (ASSOC SUPPORTABLE (FGET PROPERTY :VALUE)))
                               (SETQ !4 (FGET AKO :VALUE))
                               (SETQ !4 (CAAR !4)) )
                          (C-E: (=> !4 (MES: !%N PROPERTY SUPPORTABLE TO: !CONT)))  )
                         ((P-C: (NULL (FGET AKO :VALUE)))
                          (C-E: (=> !CONT (RE: !%N NIL))) ) )
                   TO: ME))
4 (*++ BOX <= (MES: %2 PROPERTY SUPPORTABLE TO: ME))
5 (*++* PROPERTY <= (MES: %2 FGET CONTENT :VALUE TO: ME))
6 (*++* REPLY: (RE: %2 (((P-C: (SETQ !5 (FGET PROPERT :VALUE))
                               (ASSOC !!1 !5))
                          (C-E: (=> !CONT (RE: !%N OK)) ))
                         ((P-C: (NOT (ASSOC !!1 (FGET PROPERTY :VALUE)))
                               (SETQ !4 (FGET AKO :VALUE))
                               (SETQ !4 (CAAR !4)) )
                          (C-E: (=> !4 (MES: !%N PROPERTY !!1 TO: !CONT)) )  )
                         ((P-C: (NULL (FGET AKO :VALUE)) )
                          (C-E: (=> !CONT (RE: !%N NIL))) )
                   )))
7 (* REPLY: (RE: %2 OK))
8 (* RE: %2 OK)
```

Fig. 5
Messages and Targets shown in Fig. 4.

Fig. 5 gives us the messages and the targets illustrated in Fig. 4. Each line in Fig.5 shows the message passing which is represented by the arrow attached the same number that the line has. The front atom in each list (i.e., *, *+, etc.) illustrates the level of message passing. The symbol "*" means the subroutine control, and "+" means the coroutine control. Each line will be explained.

Linel: The user communicates to the system the message (* PROPERTY B0X1 PROPERTY SUPPORTABLE).

Line2: The micro-actor * composes and sends it to the micro-actor PROPERTY.

Line3: The micro-actor PROPERTY sends the B0X1 the message including the rules to see if the target has a datum SUPPORTABLE in its property slot. The continuation of the message on the line3 is the same one on the line2. In other words, "ME" means the micro-actor *

Line4: BOX! puts the rules into practice according to COMMON-SCRIPT. As BOX1 does not have a property slot, BOX1 sends the message to the BOX which is the higher level concept of boxl. The continuation "ME" is BOX in this case, and this means the subroutine control.

Line6: PROPERTY returns the rules to BOX.

Line7: BOX carries out the rules. As BOX has the value SUPPORTABLE in the property slot, BOX sends OK to the micro-actor *.

Line8: * replies OK to the user.

This example shows about the method of the coroutine control and the subroutine control, and explains how the extension function defined as the micro-actor is used and is executed, furthermore, it gives the preferred inference about the knowledge represented with frames.

4. QUESTION ANSWERING SYSTEM

In the question answering between a machine and a human, one of most important things is a topic of conversation and a context to understand what the partner said. We assume that the speaker and the listener have the common knowledge about the discourse. Consequently, the inference plays a great role to understand the partner's intention. The micro-actor can get a good policy from the acquaintance in which the facts of the world state are expressed by a frame.

4.1 Mapping From World

The authors consider that the knowledge about a world is a "snapshot (Bobrow, D.G.) of world state. The followings show the difficulty of mapping data from a world state to a knowledge state. What part of a house one directs his attention to when he sees it? Someone might direct his attention to the door. A gardener

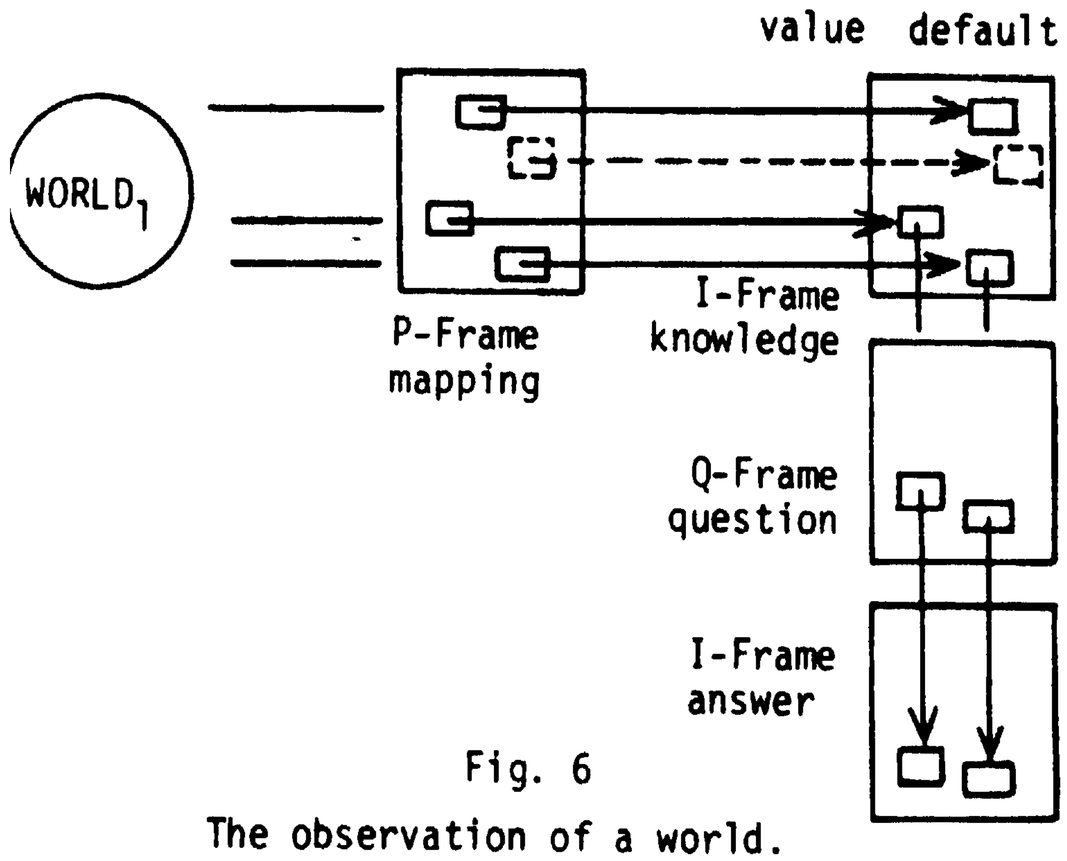

Fig. 6

The observation of a world.

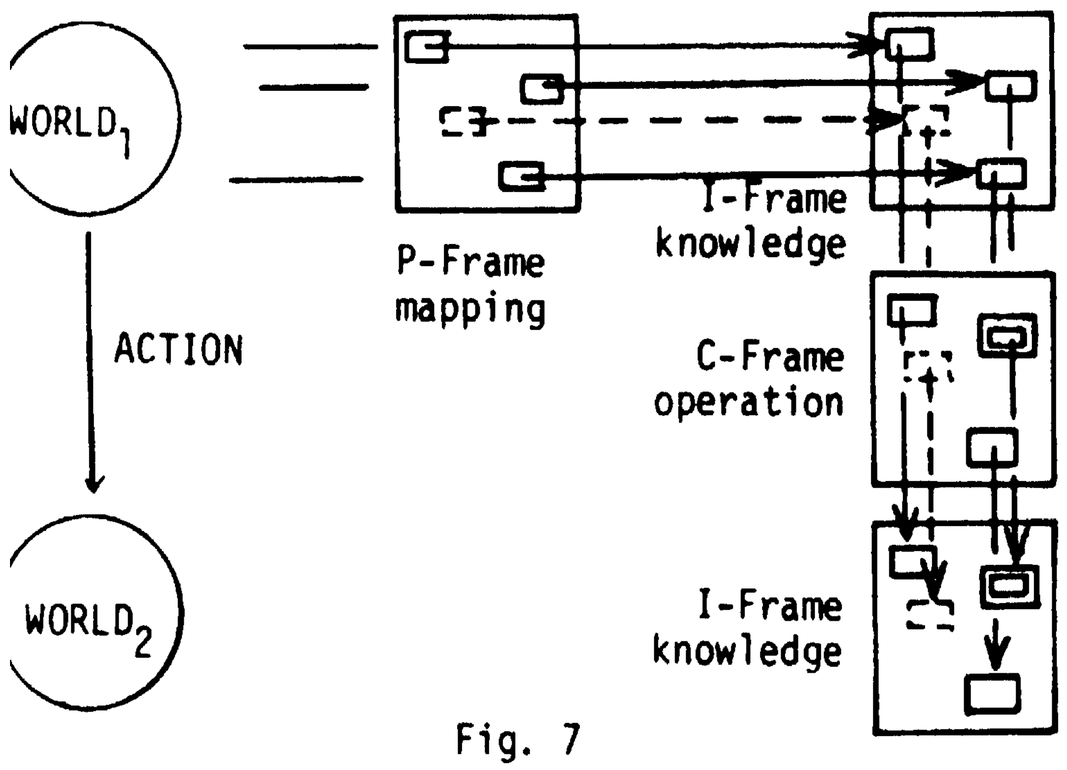

Fig. 7

The change of a world.

might be interested in the trees and flowers in the garden. An architect might look the style of the house. Consider another example. When we hear "John is like a frog", what individuality do we assume about John? The answer depends on the context and the topic of the discourse. If one heard that Mike was a handsome boy just before, then he considers that John is ugly. If one heard that Mary was gentle then thinks that John is noisy.

The frame representation is suitable for extracting information from the world. The mapping method using the frame is to move a part of the world state to a slot of the frame. The data acquired by the mapping must satisfy the condition of the slots which depend on the topics and the context. So, we will use the frame called P-Frame (Prototype Frame), which has the slots to fill out. The P-Frame is used to compose an I-Frame (Instance Frame) which

represents the knowledge state. The P-Frame has the default values which are communicated to the I-Frame if necessary. In the same way, using a Q-Frame (Quary Frame) whcih corresponds to "question", the I-Frame for the answer obtains the data from the I-Frame for the knowledge. A Q-Frame means such an action as human observes a world and gets the data (See Fig. 6). In Fig. 6, the knowledge is indicated by a frame for brevity. The knowledge is, however, represented by several frames in practice.

Fig. 7 gives two I-Frames which correspond to the worldl and the world2 changed from the worldl. A C-Frame (Change Frame) represents the action which affects the world, or which changes the observer's situation (In the latter case, the world is not changed.). A C-Frame transfers the data from an I-Frame to another frame, and changes the data if necessary.

4.2 Conversation Examples

The question answering system about the geometrical figures is constructed with the micro-actors according to the consideration in 4.1. The user communicates with the system in the limitted Japanese for the present. The authors are developing a Japanese analyzer. After it is accomplished, the user will be able to converse with the system in Japanese. Fig. 8 presents the examples in the conversation. The sentences in the figure are written in English for the readers to understand. The user's sentences are marked by "*", and the replies are marked by

```
1.  * Build a house.
2.  ! What is a house.
3.  * It is the composition in which a triangle
     is on a rectangle.
4.  ! OK.
5.  * I prefer an isosceles triangle for the
     roof.
6.  ! Is the roof the triangle of the house?
7.  * Yes, it is.
8.  ! OK.
9.  * The house is like a tower.
10. ! OK.
11. * What a kind of house is it?
12. ! It is a tall house.
```

Fig. 8

Examples of the conversation.
*: user, !: computer.

The system has the geometrical world as the context in advance. The context, of course, is changed during the conversation. The system also has the knowledge about several kinds of triangles, the rectangle and square. The system tries to associate the input sentence with the knowledge. If it fails, the system asks the user about the sentence as shown in line2.

When the micro-actor build receives the sentence (linel), it tries to make the micro-actor house. As "house" is still undefined and the other parts of linel are not associated with the knowledge, the system asks the user about a house (line2). The user defines the house as shown in line3, then build can create the micro-actor house (line4). The context plays a great role to decide kinds of slot in the acquaintance of house and to fill the slot with the data. In this case, build is regarded as P-Frame. As the world "roof" on line5 is not defined yet, the micro-actor prefer will associate an isosceles triangle with the knowledge as follows. Since the topic is about the house, prefer investigates the relation between the nouse and the isosceles triangle. The triangle is in the AKO slot of the micro-actor isosceles triangle. The house is in the PART-OF slot of triangle. Then prefer infers that the roof is a "part of the house, and asks the user if the result of the inference is correct (line6). If the user answers yes (line7), prefer creates roof and adds the PREFER facet into the PART slot of house (line8). In this case, prefer acts as aC-Frame. The above process is smoothly performed using message passing between the micro-actors as mentioned in the chapter 3.

There have been several studies of metaphors using transfer frames [18]. Our system makes use of these studies (lines9,10,ll and 12). The like behaves like a P-Frame. That is, like receives the slot which has an extremal value from the tower, and communicates it to house.

5. CONCLUSION

This paper presented the micro-actors which construct the knowledge representation in which the modularity is established without sacrificing the interaction. The micro-actor is also suitable to represent the knowledge about the actions. The micro-actor mainly consists of the message patterns and the actions corresponding to them in the script. The micro-actor acts according to the script, refers to and modifies the acquaintance, and sends the messages to the other micro-actors if necessary. Since only message passing is the interactive method between the micro-actors, the modularity is established. The message can communicate enough information to the micro-actor. Furthermore, the continuation in a message makes both the sub-

routine control and the coroutine control possible. This is *very* useful for obtaining the data from another micro-actor, in particular, acquiring information from the higher level concept.

The acquaintance is a memory space whcih stores the data and the names of the other micro-actors. Since the frame is employed to represent the acquaintance, the data in the acquaintance is used smoothly. The acquaintance is treated by only the micro-actor which has it. This prevents the acquaintance from being affected by acother micro-actor.

The chapter 4 presented examples of the question answering system using the micro-actors. The dialogues show the following abilities: the creation of new micro-actors, the association using the higher level concetpt, the comprehension of metaphors, and the recognition of the constructed figures. These abilities greatly depend upon the frame representation. On the other hand, the form of the micro-actor is *very* useful to implement the system.

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THEORETICAL BASIS FOR A KNOWLEDGE REPRESENTATION SYSTEM

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Theoretical basis for a system named the SBDS (Structure Based Deduction System) including a formalism for representation of knowledge and an inferential algorithm is presented. This system is designed as a part of an intelligent interactive system to support man carrying out such the intelligent activities as engineering design, decision making, scientific research and so forth. The major emphases on the system are : (1) high processing efficiency, (2) high expressive power so that user can represent any knowledge he wishes and (3) easy access to databases.

1. INTRODUCTION

A system named the SBDS (Structure Based Deduction System) including a formalism for representing knowledge and an inference algorithm is presented. It is a subsystem of a total knowledge system named the KAU (Knowledge Acquisition and Utilization) system that is designed as an intelligent interactive system intended to support man's intelligent activities such as engineering design, decision making, scientific research and so forth. Thus the motivation for the research resides in what is called the intelligent agent view point by E. Feigenbaum [6].

SBDS adopts, as its basic framework for representation of knowledge, an extended form of the first order predicate logic, because it is, we think, suitable for converting to and/or being converted from any of three major forms of information used in computers today, i.e., (1) languages, (2) databases and (3) programs. In this paper, relations of (1) and (2) to SBDS are discussed. That of (3) to the first order logic has been discussed in [5] and [10).

As a matter of course, a knowledge system is required to have high expressive power in representation of knowledge. Though there have been some approaches adopting the first order logic in AI problems [5], [7], [10] and also in the more practical problem of databases [3],[9], the first order logic shows a shortage of expressive power for many real applications. The adoption of the higher order logic in its general form [81 as the main framework instead of the first order logic, however, is not good solution because it is too a general form for the practical purpose and therefore the inference is inefficient to be used in a real environment.

We therefore adopt a simpler form that is obtained by defining, first, a formalism to define the predicate and a deductive inference algorithm and, then, extending the first order logic towards higher order within the framework until the extended form can accommodate most of the language expressions that are almost sufficient to represent knowledge in many applications. The formalism for defining the predicate is combined with the hierarchical structure of entities defined in the universe. A fast deductive algorithm has been developed so as to use effectively the property of the structure.

On the other hand, for users working in the real applications, the use of databases is becoming inevitable. So far a number of databases and their management systems have been developed [4]. These DBMS's, however, are very inconvenient to be used for such the intelligent works as mentioned above. For an engineering designer, for example, the objective is to reach a final model through the repetitive processes of a model construction and its evaluation. He will require the data structure to be dynamically managed. But the conventional DBMSs can hardly do so because in these systems the structures of data are almost

fixedly defined. Therefore it is desirable that the knowledge system takes over the dynamic restructuring of information and can accesses to databases only when the values of data are necessary. SBDS possesses such the capability. Thus the KAU of which the SBDS occupies the central part is intended to serve as an intelligent interface between users and DBMS's [12], [13].

A number of different approaches have been made and have also been developing for the problem of knowledge representation [1], [15]. The approach proposed in this paper is still different from them as seen from the system's point of view though it implies some concepts common to the others in part. Theoretical basis of our approach is on the first order predicate and the resolution principle [2], [14]. However as the SBDS also contains the concept of network, there are also some ideas in common between our method of deductive inference and methods developed for performing deductive inference on the knowledge represented in the network [15].

In this paper, we describe the SBDS with its mathematical foundation. A universe is defined as the collection of all concepts that can be referred through the language. Over this universe, the first order-logic is defined and then extended toward higher order to the limited extent. A classical predicate logic is used rather than the resolution logic not only because it is intuitively understood by many people but, rather, because it is convenient to extend the first order logic and also to convert the predicates to the database operations.

An inference algorithm has been developed in which the information contained in user's query is effectively used for searching information and for deduction. The algorithm is also applicable to the extended form by slightly modifying its control mechanism.

2. INTERFACE TO LANGUAGE FOR EXPRESSING KNOWLEDGE "

A problem world is described in many cases by means of language, and, therefore, we consider only the world that is describable by the language.

In reality, a vocabulary allowed to be used in the knowledge system is finite in which some words, -nouns- designate sets of entities or individual entities while the order words -verbs, adjectives, propositions, some nouns, etc.- represent the attributes of entities or the relations amongst entities. We call the former the entity words and the latter the relational words.

The syntax of the language defines sentences. There are a set of basic patterns of sentences or basic sentences in short such that all sentences can be analysed to the combination of some of them. If a system can understand the meaning of each basic sentence and also is given a parsing algorithm for analysing the compound / complex sentence to the logically connected set of basic sentences, then the system can understand the language. Here, by the term "understand" we mean that the system can process the information given in the form of language based on its meaning so that it responds correctly to users requests.

The set of basic patterns of sentences is finite in ordinary languages. In this paper, twenty-five patterns as shown in Table 1 are considered almost enough in case of English for expressing knowledge used in most of applications.

The vocaburaly, on the other hand, is different in every application. Though some common words can be defined independent of applications, some jargons are to be added in each application. Therefore the dictionary in the system must be an open set.

3. DATABASE

A relational model is considered exclusively in this paper [3],[4] though the system is not restricted to it. In this model a relation is defined as a set of n-tuple records, (t1, t?, '*** tn), where ti is an occurence value in the domain Ti. A relation is represented in the form of a flat table with n colums and a relation name is given to it.

4. FIRST ORDER PREDICATE LOGIC IN A CLASSICAL FORM

In the classical predicate logic, an atomic formula or atom in short, is defined as $F(t_1, t_2, \cdots, t_n)$ where F is an n-place predicate symbol and $t_1, \cdots, t_{n-1}$ and t_n are terms. Then a well formed formula, or a formula in short is defined recursively as follows [2] :

a. An atom is a formula.

b. If F and G are formula, then ~F, F∪G, F∩G, F⇒G and F⇔G are formulas where ~, ∪, ∩, ⇒ and ⇔ are read as "negation", "disjunction",

"conjunction", "imply" and "equivalent" respectively.

c. If F is a formula and x is a free variable in F_1 then $(\forall x)F$ and $(\exists x)F$ are formulas.

d. Formulas are generated only by a finite number of applications of a through c.

A formula can be written in the prenex normal form. In the following, it is written in a vector form as :

$$(\mathbf{Q}\,\mathbf{x})[S\{F_i(\mathbf{x}_i)\}], \qquad \text{- - -(1)}$$

where $(\mathbf{Q}\,\mathbf{x}) = (Q_1x_1)(Q_2x_2)\cdots(Q_nx_n)$ with each Q_i being either $\forall$ or $\exists$, $S\{\ \}$ stands for a logical structure composed of atoms, $F_i, (i = 1 \cdots m)$, by means of logical connectives shown in the above definition of the formula, and $(\mathbf{x}_i) = (x_i \cdots x_{ini})$.

In the resolution logic [2],[4], the formula is standardized by being converted to the conjunctive normal form and Skölemized. In this paper, instead of the standardization, the formula is modified in another way.

Firstly, no function symbol appears in the formula. In general, n-place function is a mapping from D^n to D where D denotes a domain of a variable. It is represented in the SBDS by an n+1-place atom $*F_f(z;x_1 \cdots x_n)$ that is defined true iff $f(x_1 \cdots x_n)=z$ holds. Since to each of this kind of atoms corresponds a procedure that evaluates it procedurely, these atoms are called the procedural type atoms. The procedural type atom is identified by a symbol * on the left shoulder in the paper. An example is, *(ADD 5;2 3):"2 plus 3 is 5".

Secondly, in the resolution logic, Herbrand universe is defined as a set of which the elements are generated successively by means of the constants and function symbols appearing in the formula(s) while, in the SBDS, the universe **U** is first defined as the set of all objects that can be referred by the language.

Thirdly, the concept of sets is explicitly included in a formula. In the following, a variable free formula is called a ground formula. Any subset I of the set of all ground atoms, $F(t_1, \cdots, t_n)$, of which $t_1, \cdots, t_n$ are in the universe determines an interpretation where the meaning of an n-place predicate symbol F is a n-ary relation over the universe : $\{(t_1, \cdots, t_m) : F(t_1, \cdots, t_n) \in I\}$. I is said to be a model of the formula if the truthhood of the formula is determined by the rules : F is true iff $F \in I$ and $\sim F$ is true iff $F \notin I$. When I is a model, the set of the tuple $\{(t_1, \cdots, t_n) \mid F(t_1, \cdots, t_n) \in I\}$ is denoted $\mathbf{D}_I$. Then $F(x_1, \cdots, x_n)$ is true iff $(x_1, \cdots, x_n) \in \mathbf{D}_I$. This fact is written as

$$(\forall \mathbf{x})[(\mathbf{D}_I \ni \mathbf{x}) \Rightarrow F(\mathbf{x})] \quad \text{where } \mathbf{x} = (x_1, \cdots, x_n) \text{ --(2)}$$

In many cases, $\mathbf{D}_I$ is a Cartesian product of X_i, $(i=1, 2, \cdots, n)$, i.e., $\mathbf{D}_I = X_1 \times \cdots \times X_n$ where each X_i denotes a domain of the variable x_i. In this case, the formula (2) is rewritten as

$$(\forall x_1) \cdots (\forall x_n)[(X_1 \ni x_1) \cap \cdots \cap (X_n \ni x_n) \Rightarrow F(x_1, \cdots, x_n)] \qquad \text{- - - (3)}$$

or, equivalently,

$$(\forall x_1) \cdots (\forall x_n)[X_1^*(x_1) \cap \cdots \cap X_n^*(x_n) \Rightarrow F(x_1, \cdots, x_n)] \qquad \text{- - - (4)}$$

where $X_i^*(x_i)$ is a predicate meaning "$X_i \ni x_i$". On the other hand, a fact that $F(x_1, \cdots, x_n)$ is true for some value $(t_1, \cdots, t_n)$ in $\mathbf{D}_I$ is written as

$$(\exists \mathbf{x})[(\mathbf{D}_I \ni x) \cap F(\mathbf{x})]. \qquad \text{- - - (5)}$$

If $\mathbf{D}_I$ is a product set, then

$$(\exists x_1) \cdots (\exists x_n)[X_1^*(x_1) \cap \cdots \cap X_n^*(x_n) \cap F(x_1, \cdots, x_n)]. \qquad \text{- - - (6)}$$

If both $\forall$ and $\exists$ appear in a formula, then a recursive relation is obtained:

$$(Q_1x_1) \cdots (Q_nx_n)[(X_1^*(x_1) \overset{\circ}{1} (X_2^*(x_2) \overset{\circ}{2} (\cdots X_{n-1}^*(x_{n-1}) \overset{\circ}{n-1} (X_n^*(x_n) \overset{\circ}{n} F(x_1, \cdots, x_n)) \cdots)] \qquad \text{- - - (7)}$$

where $\overset{\circ}{i}$ represents either $\Rightarrow$ or $\cap$ depending on Q_i being $\forall$ or $\exists$. For example, if $\mathbf{D}_I = X \times Y \times Z$, $Q_x = \forall$, $Q_y = \exists$ and $Q_z = \forall$, then

$$(\forall x)(\exists y)(\forall z)[X^*(x) \Rightarrow (Y^*(y) \cap (Z^*(z) \Rightarrow F(x,y,z)))] \qquad \text{- - - (8)}$$

In these representation of formulas, each variable is defined over **U** of which $X_i, (i=1, \cdots, n)$, is a subset. Then the formula can also be written in an abbreviated form as

$$(Q_1x_1/X_1) \cdots (Q_nx_n/X_n)F(x_1, \cdots, x_n) \qquad \text{- - - (9)}$$

meaning that the formula is true for assignment to each variable x_i of all or some values of X_i depending on the quantifier Q_i being $\forall$ or $\exists$, but otherwise it is not true. It is further simplified by abbreviating the variable symbols and moving F into the parenthesis as

$$(Q_1X_1) \cdots (Q_nX_n)(F, X_1, \cdots, X_n) \qquad \text{- - -(10)}$$

With this formalism, (2) and (5) are written as $(\forall \mathbf{D}_I)(F\ \mathbf{D}_I)$ and $(\exists \mathbf{D}_I)(F\ \mathbf{D}_I)$ respectively. A ground atom $(F, t_1, \cdots, t_n)$ is a reduced form of (9) in which every domain has only one element. It shoud be noted that the formula (10) can be transformed easily to a set-of-clauses form of the resolution logic.

Example:

$$(\forall X)(\exists Y)(\forall Z)(F\ X,Y,Z) = (\forall x)(\exists y)(\forall z)[(\sim X^*(x) \cup (Y^*(y) \cap (\sim Z^*(z) \cup F(x,y,z))))] = (\sim X^*(x) \cup Y^*(f(x))) \cap (\sim X^*(x) \cup \sim Z^*(z) \cup F(x,f(x),z)) = \{C_1, C_2\}$$

$$C_1 = \sim X^*(x), Y^*(f(x)),$$

$$C_2 = \sim X^*(x), \sim Z^*(z), F(x,f(x),z) \qquad \text{- - -(11)}$$

where f(x) is the Skölem function.

The general form of the formula, then, is
$(Q\ \mathbf{X})[S'\{(F_I\ \mathbf{X})\}]$ - - -(12)

5. THE UNIVERSE AS AXIOMATICALLY DEFINED SET

A predicate symbol of a formula corresponds to a relational word in a vocabulary set. Let the simple collection of all predicate symbols be $\mathbf{R}$. Then since the vocabulary is a finite set, $\mathbf{R}$ is also finite. Each F_i in $\mathbf{R}$ acts on $\mathbf{U}$ to define a basic pattern of atomic formula of which the predicate symbol is F_i. In other words, to each F_i, an ordered set $\{t_1,\cdots,t_{ni}\}$ is specified where each t_i is in $\mathbf{U}$ such that the ground atom $(F_i\ t_1,\cdots,t_n)$ is in a model I.

The universe $\mathbf{U}$ is not so simple as $\mathbf{R}$. Many different types of elements must be included in $\mathbf{U}$. Consider, for example, two atomic formulas; (FATHER t_1,t_2):"t_1 is father of t_2" and (CARD-NO t_3,t_4):"cardinal number of t_3 is t_4". Both t_1 and t_2 are of the same type in a sence that they can be the elements of a set, say, PERSON. On the other hand, t_3 is a set while t_4 must be an integer. In this case t_3 is said being of the different type and is one level higher than t_4. Each t_i in an atom can be of the different level as was seen in the case of CARD-NO.

These examples shows that any set of the elements in $\mathbf{U}$ must be an element of $\mathbf{U}$ too. Each predicate symbol specifies the level of each term to be an argument of the ground atom. Such a term is called a ground term for the atom and a symbol # is attached in the following.

On the other hand, in the atomic formula (10) defined as the collection of all ground atoms, X_i is a set of t_i's, and therefore is an element of $\mathbf{U}$ that is one level higher than t_i's. Thus an atom and its ground atom are defined over two levels of elements in $\mathbf{U}$ for each argument.

This definitions of formula requires the universe $\mathbf{U}$ being of multi-layers structure. For example, the concept of the power set is necessary to represent a formula such as : $(VT_3)(\exists$ INTEGER)(CARD-NO T_3 INTEGER)?:"For every set is there an integer which is the cardinal number?", where T_3 is a set of all sets. Fortunately such the set has been studied as an axiomatic set theory. We can use the Zermelo/Frankel axioms of set theory [11] as the universe though we don't touch on them here. We only point out that the set thus defined satisfies all conditions mentioned above $\mathbf{U}$ and, still further, such the set contains n-tuples, $(t_1,\cdots t_n)$ too, as it elements.

Based on this structure of the universe, a simple formalism for defining formula is obtained. That is, a formula is a pair $(F_i\ \mathbf{D}_I)$ attached by the information for quantification, $\mathbf{Q}$ where $F_i \in \mathbf{R}$ and $\mathbf{D}_I$ is a mapping of F_i into $\mathbf{U}$.

6. INFERENCE ALGORITHM

Inference algorithm is defined to the formula in the form of (12). This algorithm is logically equivalent to the resolution principle [2] but is designed to have high physical performance. It consists of the selection rule (SR), the test for implicative condition (TIC) and the replacement rule (RR). TIC corresponds to the unification algorithm and RR the resolution in the resolution logic respectively.

Suppose a formula P of the form
$P:(Q_p\mathbf{X})[(B_1,\mathbf{X}_1)\cap\cdots\cap(B_k,\mathbf{X}_k)\Rightarrow(A,\mathbf{X}_0)]$ - -(13)
exists in the knowledge base where $(Q_pX) = (Q_{p1}\ X_1)\cdots(Q_{pm}X_m)$, $\mathbf{X}_i = \{X_{i1},\cdots,X_i\alpha_i\}$ and $\mathbf{X} = \{X_1,\cdots,X_m\} = \overset{\vee}{}_{i=1}\mathbf{X}_i$, and a query Q of the form
$Q:(Q_q\mathbf{Y})[(C_1,\mathbf{Y}_1)\cap\cdots\cap(C_1,\mathbf{Y}_1)]$ - - -(14)
is presented where $(Q_p\mathbf{Y}) = (Q_{q1}\ Y_1)\cdots(Q_{qn},Y_n)$, $\mathbf{Y}_j = \{Y_{j1},\cdots,Y_{j\beta j}\}$ and $\mathbf{Y} = \{Y_1,\cdots,Y_n\} = \overset{\vee}{}_{j=1}\mathbf{Y}_j$.

Then a non-procedural type literal C_j is selected from Q by SR and the relation
$(Q'_p\mathbf{X}_0)(A,\mathbf{X}_0)\Rightarrow(Q'_q\mathbf{Y}_j)(C_j\ \mathbf{Y}_j)$ - - -(15)
is tested by TIC where $(Q'_p\mathbf{X}_0)$ and $(Q'_q\mathbf{Y}_j)$ are the partial sequences of $(Q_p\ \mathbf{X})$ and $(Q_q\ \mathbf{Y})$ comprising only the variables included in $\mathbf{X}_0$ and $\mathbf{Y}_j$ respectively. Implicative condition (15) is tested by the following two steps:

(A) For each pair of corresponding variables, say X_{pi} and Y_{qi}, of left hand term and right hand term of (15), either of the set theoretical relations shown in Table 2 should hold depending on the combination of quantifiers of variables. This rule applies to all variables in the atoms of (15).
(B) There should not be such indices pair (i,j) that, in $(Q'_p\mathbf{X}_0)(A,\mathbf{X}_0)$, i-th variable is universally quantified and is preceding to j-th existentially quantified variable while, in $(Q'_q\mathbf{Y}_j)(C_j,\mathbf{Y}_j)$, corresponding i-th universally quantified variable is preceded by j-th existentially quantified variable.

If the implicative relation (15) is certified by TIC, then a new formula R of the form
$R:(Q_r\mathbf{Z})[(C_1,\mathbf{Z}_1)\cap\cdots\cap(C_{j-1},\mathbf{Z}_{j-1})\cap(B_1,\mathbf{W}_1)\cap\cdots\cap(B_k,\mathbf{W}_k)\cap(C_{j+1},\mathbf{Z}_{j+1})\cap\cdots\cap(C_1,Z_1)]$- -(16)
is generated by RR where $(Q_r\ \mathbf{Z}) = (Q_{r1}Z_1)\cdots(Q_{ri}\ Z_n)$, $\mathbf{Z}_j = \{Z_j,\cdots,Z_{jrj}\}$, $_1\mathbf{W}_i = \{W_{i1},{}_k\cdots,W_{i\alpha i}\}$, and $\mathbf{Z} = \{Z_1,\cdots,Z_v\} = (\overset{\vee}{}_{i=j}\mathbf{Z}_i)\ V\ (\overset{\vee}{}_{i=1}\mathbf{W}_i)$. Each Z_i and its quantifier Q_i is decided by its corresponding variables, X_i and Y_i, in P and Q

respectively, and their quantifiers as shown in Table 3.

Q_{pi}	$Q_{qi}(\overline{Q}_{qi})$	CONDITION
$\forall$	$\forall(\exists)$	$X_i \supset Y_i$
$\forall$	$\exists(\forall)$	$X_i \wedge Y_i \neq \phi$
$\exists$	$\exists(\forall)$	$X_i \subset Y_i$

Table 2 Implicative condition between single 1-atom formula

	Q_{pi}	Q_{qi}	Q_{ri}	Z_{ri}/W_{ri}
$X_i \in (X_0 - Y_j)$	$\forall$	$\forall$	$\forall$	Y_i
	$\forall$	$\exists$	$\exists$	$X_i \wedge Y_i$
	$\exists$	$\exists$	$\forall$	X_i
$Y_i \in (Y - Y_j)$	-	$\forall$	$\forall$	Y_i
	-	$\exists$	$\exists$	Y_i
$X_i \in (X - X_0)$	$\exists$	-	$\forall$	X_i
	$\forall$	-	$\exists$	X_i

Table 3 Replacement rule

It is not difficult to show that above rules of TIC are equivalent to the condition for the unification algorithm to terminate successfully in the resolution logic.

The set theoretical relations appearing in Table 2 can be represented in the logical form as

$(X \supset Y) \equiv (\forall x)[Y^*(x) \Rightarrow X^*(x)]$ - - -(17)

$(X \wedge Y \neq \phi) \equiv (\exists z)[X^*(z) \wedge Y^*(z)]$ - - -(18)

The relation (15) is proved by showing that the negation of the relation, i.e.,

$\sim[(Q'_p X_0)(A\ X_0) \Rightarrow (Q'_q Y_j)(C_j\ Y_j)] \equiv (Q'_p X_0)(A, X_0) \wedge (\overline{Q}'_q Y)\sim(C_j, Y)$ - - -(19)

does not hold where $\overline{Q}_q$ is obtained by exchanging $\forall$ and $\exists$ of each Q_{qi} in Q'_q. (20) is transformed to the set-of-clauses form. Let it be denoted S. S is different to each assignment of quantifiers to variables. To avoid the notation becoming too complicated, let's pay an attention for a particular pair of variables (X_i, Y_i). The quantifiers of (X_i, Y_i) is denoted $(Q_{pi}, \overline{Q}_{qi})$. Then four different forms of S are derived according to the different specification for $(Q_{pi}, \overline{Q}_{qi})$. Then the validity of conditions listed in Table 2 is tested by applying a refutation process to these conditions combined with S. Here, only a case, $(Q_{pi}, \overline{Q}_{qi}) = (\forall, \exists)$, is shown.

In this case, $S=\{\cdots, \sim X^*_i(x_i), \cdots, A(\cdots x_i \cdots)\}, \{\cdots Y^*_i(f_{yi}(*))\cdots\}, \{\sim C_j(\cdots f_{yi}(*)\cdots)\cdots\}$ where $\cdots$ represent terms concerning to variables other then x_i and y_i. $f(*)$ is a Skölem function where * represents a set of universally quantified variables preceding to y_i in the prefix $(\overline{Q}_q\ Y_j)$.

These set of clauses are put together with (17) in the standard form, $\{\sim Y^*(x), X^*(x)\}$. x_i can be substituted by $f_{yi}(*)$ because by the second law of TIC it is ensured that * does not include x_i. Then $A(\cdots x_i \cdots)$ and $C(\cdots f_{yi}(*) \cdots)$ is unifiable if A and C is the same. Thus it is easy to show that the empty clause is deduced from the set of these clauses. The other cases are also proved by the similar procedures.

Example :

P: $(\forall X)(\forall Y)(\forall Z)[(BROTHER\ X\ Y) \wedge (PARENT\ Y\ Z) \Rightarrow (UNCLE\ X\ Z)]$ "For every x, y, z, x who is brother of z's parent y is z's uncle"

Q: $(\exists U)[(UNCLE\ U\ \#Tom) \wedge (ILL\ U)]$? "Is there any uncle u of Tom, who is ill?"

where X, Y, Z and U represent the set PERSON and $x \in X$, $y \in Y$, $z \in Z$ and $u \in U$.

At the deduction SR selects $(\exists U)(UNCLE\ U\ \#Tom)$ from Q and TIC tests for

$(\forall X)(\forall Z)(UNCLE\ X\ Z) \Rightarrow (\exists U)(UNCLE\ U\ \#Tom)$ - -(20)

It holds because $X \wedge U \neq \phi$, $Z \supset \{\#Tom\}$. Then RR generate,

R: $(\exists U)(\exists Y)[(BROTHER\ U\ Y) \wedge (PARENT\ Y\ \#Tom) \wedge (ILL\ U)]$ - - -(21)

R is regarded as a new query.

The deductive procedure is repeated until either the formula of which the Boolean value can be obtained or the formula consisting only of the procedural type literals is reached. Further consideration is necessary to make the algorithm logically complete though it is abbreviated here. Refer [13] for the detail.

7. STRATEGY FOR SEARCHING THE CANDIDATE FORMULA

There may be a number of formulas stored in a knowledge system and, at a time only part of which participate to deducing the query. Therefore, quick selection of the relevant formula is very important.

The universe is represented by a hierarchical structure in which each node represents a set of objects. In the following a set is denoted by the upper case letter. A node is connected to another node by either of two types of arcs representing the set—theoretical inclusion and disjointness. The former is called the I-type arc and the latter the D-type arc. For instance, the set LIVING-THING(LIVTH in short), MAMMALIA, FISHES, BIRDS, MANKIND, DOGS,CATS etc are in the set-theoretical relations such as LIVTHDMAMMALIA, FISH, BIRD, INSECT,-- MAMMAIL MANKIND, DOG, ••• and so on. We say "X is upper to Y" or "X is larger than Y" when XDY and Y is connected to X by the I-type arc. On the other hand, the set MAN and WOMAN are disjoint to each other and are connected by the D-type arc. By applying the processes of linking by means of these arcs successively, a hierarchical structure of universe, called the semantic skeleton structure, or the skeleton in short, is formed. Some node is connected to more than two other upper nodes by the 1-type arcs. Such a node represents a set defined as an intersection of the other sets. For instance, a set BOY is represented as the intersection of MAN and CHILD.

A formula that includes a set Xi as an argument is linked to the node Xi in the skeleton and is accessible from this node. Accordingly the formula (10) can be accessed from any of nodes Xi, X2, •••, Xn.

Suppose a query (14) includes a constant or a variable, say Yj, that is universally quantified. It is ordinary the case because a query of which every argument is existentially quantified variable is nothing else but a damp command. Then the formula P that satisfies the relation (15) to this query, if any, must be linked to some node Xj that is over Yj in the skeleton from the rule (A) of TIC. Therefore, it is reachable by following the I-type arcs upward starting from Yj. Since the skeleton expands downward, it reduces the search space considerably and formulas of which the predicate symbols are the same with the query but the variables are out of above condition are disregarded.

The formula thus found is called the candidate which satisfies the condition of TIC only with respect to the variable Yj. It must be tested for the condition (Table 2) for the other variables too. The skeleton is used again. Since, this time, both left and right hand formulas of (15) are in hand and, therefore, both domains (sets) of corresponding arguments can be specified in the skeleton, the tests for the set theoretical relations of Table 2 are achieved by the test for the positional relations between nodes in the skeleton. Since its algorithm is very simple it can be implemented by the special but simple wired logic and therefore the test can be performed very fast. The SR selects a literal among all literals in the query that contains most constants / universally quantified variables.

The system further reduces the possibility of fruitless test being achieved. In case of conventional first order logic, the set of formulas such as

$B_1 \Rightarrow A, \quad B_2 \Rightarrow A, \cdots, B_e \Rightarrow A$ ---(22)

often arises in the definition of the meaning of words. For instance, the relations between sets mentioned above are represented as

$$\left.\begin{array}{l}(\forall x)[MAMMALIA^*(x) \Rightarrow LIVTH^*(x)] \\ (\forall x)[FISH^*(x) \Rightarrow LIVTH^*(x)] \\ (\forall x)[BIRD^*(x) \Rightarrow LIVTH^*(x)]\end{array}\right\} \quad ---(23)$$

Suppose A->Q is satisfied to a query Q. Then the resolution logic will make an exhaustive test looking for a path leading to the empty clause. It is exhaustive because the refutation process proceeds in the direction from A to Bi in each formula (22) in a sense that A is unified with the query and Bi is remained for the next test.

In the SBDS every formula of the type(23) is represented by an arc in the skeleton. Searching the formula by following the I-type arcs upward in the skeleton corresponds to searching the refutation path proceeding in the reverse order of the resolution logic. Thus, as far as such the formulas as (23) are concerned, the exhaustive test is avoided.

8. ACCESS TO DATABASES

The formula (2) means that if a tuple x=(xi, •••, xm) is included in D, a relation F holds among xi, •••, xm. Suppose then that a set of n-tuples, D, is given as a data file in a table form. Then, the condition (D9i) for some n-tuple, t=(ti, •••, tm), is tested by a special procedure that searches t in the file. That is, the premise of (2) is represented by a kind of procedural type atom. Let it be denoted as *(FGET, D:xi, •••, xn) and be called the file type atom where D indicate the file name. Then the formula (2) is written as

$(VXi) \ldots (VX_n)[*(FGET\ D : Xi, \cdots, X_n)*F(Xi, \cdots, X_n))$ ---(24)

This formula gives a definition/description of a table type file D. A user input the system a set of data in the table form accompanied with a formula (24). After then, any user can use this file without any knowledge on it. The

system determines itself how and when to access the file through the deductive operation and converts the formula to the relational algebra [4]. Only the outline of the conversion is shown without proof.

Suppose, a formula consisting only of the file type atoms.

$(Q\ \mathbf{X})[S\{*(FGET\ D_i : \mathbf{X}_i)\}]$ - - -(25)

is obtained as the result of deductive operation$_k$where $\mathbf{X}_i=(X_{i1}, \cdots, X_{ini})$ and $\mathbf{X}=(X_1, \cdots, X_n)=\bigvee_{i=1}^{k}\mathbf{X}_i$. Suppose each file D_i is the set of mi-tuples and each domain X_i is a finite set. Let $\mathbf{X}_i^*=\mathbf{X}-X_i$. Then (25) is equivalent to

$(Q\ \mathbf{X})[S\{*(FGET\ D_i \times \mathbf{X}_i^* : \mathbf{X})\}]=(Q\ \mathbf{X})[*(FGET,\ \hat{S}\{(D_i \times \mathbf{X}_i^*)\},\ \mathbf{X})]$ - - -(26)

where $D_i \times \mathbf{X}_i^*$ means a cylinder set in the n-dimensional space, $X_1 \times \cdots \times X_n$, $\hat{S}$ is a structure of the set theoretical operations that is obtained from S by replacing every $\cap$ and $\cup$ in S by $\wedge$ (intersection) and $\vee$ (union) respectively, and $\hat{S}\{(D_i \times \mathbf{X}_i^*)\}$ means that the structure of the set operations $\hat{S}$ are applied to $(D_i \times \mathbf{X}_i^*)$. Since all the $(D_i \times \mathbf{X}_i^*)$'s, (i=1, 2, $\cdots$, k), are the set of n-tuples, $\hat{S}\{(D_i \times \mathbf{X}_i^*)\}$ is reduced to a set of n-tuples. Let it be denoted $\mathbf{D}^*$. Then the formula (26) results in

$(Q\ \mathbf{X})[*(FGET\ \mathbf{D}^* : \mathbf{X})]$ - - -(27)

Here the following two file operations are introduced.

$DIV(\mathbf{D}^*, X_i)=\{\mathbf{x}=(x_1, \cdots, x_{i-1}, x_{i+1}, \cdots, x_n) \mid \mathbf{x} \times X_i \subset \mathbf{D}^*\}$ - - -(28)

$PRJ(\mathbf{D}^*, X_i)=\{\mathbf{x}=(x_1, \cdots, x_{i-1}, x_{i+1}, \cdots, x_n) \mid (x_1, \cdots, x_{i-1}, x_i, x_{i+1}, \cdots, x_n) \subset \mathbf{D}^*\}$ - -(29)

These operations correspond to division and projection operations respectively of the relational algebra in the relational data base. Then the following relations between logical view and set-theoretical view hold.

$$\left.\begin{array}{l}(Q_1X_1) \cdots (Q_{n-1}X_{n-1})(\forall X_n)[*(FGET\ D^* : X_1, \cdots, X_n)]=(Q_1X_1) \cdots (Q_{n-1}X_{n-1})[*(FGET\ DIV(D^*, X_n):X_1, \ldots, X_{n-1})] \\ (Q_1X_1) \cdots (Q_{n-1}X_{n-1})(\exists X_n)[*(FGET\ D^* : X_1, \cdots, X_n)]=(Q_1X_1) \cdots (Q_{n-1}X_{n-1})[*(FGET\ PRJ(D^*, X_n):X_1, \cdots, X_{n-1})]\end{array}\right\} \quad (30)$$

These relations and operations are repeatedly applied to the formula (27) until finally $*(FGET\ T : \phi)$ is obtained where T is either 1 or 0 depending on if the operations can be continued to the end or these operations result in an empty file. If T=1, the original query formula proved true.

In practice, user must be able to designate some data to be output. Such the data must be saved during the above processes. When the other procedural type atoms besides the file type are included in a formula, a further consideration is necessary. For the details refer [13].

9. EXTENTION OF THE SYSTEM

9.1 Predicate Symbol as Variable

A hierarchical structure can be introduced in the set of predicate symbols. Consider, for example, two atoms, (BROTHER X Y) and (SIBLING X Y). When the same terms are substituted into the corresponding variables, then (Brother, t_1, t_2) ->(Sibling, t1 t2). In this case "Sibling" is said larger than "Brother". On the other hand, (Natural, X)fi(Artificial, X) shows an inconsistancy. The predicate symbols being in such relations are said disjoint to each other. Based on these relations, the skeleton is formed for the predicate symbols and the predicate symbol can be dealt with as if it were a variable because it can be processed by the same algorithm as the other variables at the deduction. Then the atom can be rewritten as

$(Q\ X)(X),\quad X=(X_0, \underline{Xi.---.Xn})$ ——————(31)

where the predicate symbol is denoted Xo. With this modification, the system can accept the query which asks the value in X_0, i.e., the predicate symbol. For example, a query Q:(3 RELATION) (RELATION //Tom //Mary) ?: "What is the relation holding between Tom and Mary?" can be answered by using P: (FATHER //Tom //Mary) if the relation FATHERPRELATION is given in advance as is the case of the other variables.

9•2 Recursive Form

Let the atom of the form (31) be called the n-atom when it comprises n terms including Xo. In ordinary predicate, n is larger than or equal to two. Suppose it can be extended to the case n*I. There are only two 1-atoms of the form, (V X)(X) and (3 X)(X) with meanings "for all x6X, x€X" and "there is some x in X such that xgX", respectively. Thus (X) shows the logical aspect of the set X. The applications of TIC rules to the 1-atoms reveala the rule (A) of TIC being just the implicative condition itself for two 1-atoms.

The SBDS has been described as including the concepts both of sets and of logic. It is for the purpose of taking advantage of the strength of each at the implementation. We can obtain the logical description of it by replacing X by (X) and the rule (A) of TIC by the implicative relation between 1-atoms. Then the universe is regarded as a collection of 1-atom'formulas and the formula (31) is rewritten as the relation among n 1-atom formulas to which the rule(A) of TIC, rephrased as the followings, is applied ' (A^1) To each pair of corresponding inner 1-atom formulas, the implicative condition should hold.

These concepts are extended. Assume that the universe can include not only 1-atoms but general formulas, by adding all possible formulas definable by R and U to U resulting in U_1, then by adding all possible formulas definable by R and U_1 to U_1 resulting in U_2 and so on. For many applications the extended universe U_k with finite K may be enough. The mechanism for defining the atom (ref. Sec.5) is unchanged. Then the SBDS has atoms in recursive form as

$((FML)^*_0, (FML)_1 \cdots (FML)_n)$ - - -(34)

where $(FML)^*_0$ denotes a 1-atom corresponding to the predicate symbol and $(FML)_i, (i=1, \cdots, n)$, is a formula. The rule (A') is extended to :

(A") For each pair of corresponding inner formulas, the implicative condition should hold.

The rule (A") is applied recursively to the formulas in form of (34) at the deduction.

As the result of this extention the SBDS acquires a large power of expression. But the extension is based on the assumption that any 1-atom formula can be replaced by a general formula. Further study on its validity is necessary.

Example: (VX)(VU)[(INTEND X (DO X U))∩(CAN X(DO X U)) ⇒ (DO X U)] :"Every one does thing if he intends to and can do it."

where X;PERSON, U;UNIVERSE,

(CAN X (DO X U)) : X can do U,

(INTEND X (DO X U)) : X intends to do U.

10. CONCLUSION

An outline for the SBDS, a central part of a knowledge system (KAU) designed as an intelligent support system, has been presented. Mathematical foundation for the formalism for representing knowledge, the deductive algorithm and the interface with databases has been mainly described. The major emphases on the SBDS design are : (1) high processing efficiency, (2) high power of expression so that user can represent any knowledge he wishes and (3) easy access to databases. The core of SBDS has been implemented and is being tested for its usefulness.

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1) S-V-Direct Object 2) S-V-to-Infinitive 3) S-V-Noun-to-Infinitive 4) S-V-Noun-(to be) -Complement 5) S-V-Noun-Infinitive 6) S-V-Noun-Present Particle 7) S-V-Object-Adgective 8) S-V-Noun 9) S-V-Past Particle 10) S-V-Adjective 11) S-V-that clause 12) S-V-Noun-that clause 13) S-V-Conjunctive-to-Infinitive 14) S-V-Noun-Conjunctive-to-Infinitive 15) S-V-Conjunctive Clause 16) S-V-Noun-Conjunctive Clause 17) S-V-Gerund 18) S-V-Direct Object-Preposition-Prep.Object 19) S-V-Indirect Object-Direct Object 20) S-V-(for)-Complement 21) S-V 22) S-V-Predicative 23) S-V-Adverbial Adjunct 24) S-V-Preposition -Prepositional Object 25) S-V-to-Infinitive

Examples: 1) X likes Y :(LIKE X Y)

2) X intends to do- : (INTEND X (DO X ••))

12) X tells Y that Z does ••• :(TELL X Y (DO Z ...))

17) X enjoys doing Y •• :(ENJOY X (DO X Y ••))

19) X gives Y Z .(GIVE X Y Z)

Table 1 Basic patterns of sentences

A PRODUCTION SYSTEM FOR REGION ANALYSIS

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Production system architectures are useful for knowledge representation. We have applied the architecture to image analysis in the framework of region growing and developed an outdoor-scene analyzer. In this paper, the following three problems are addressed to make production systems workable in scene analysis. I) Appropriate size of knowledge represented in a. production rule. *2)* Reduction of computation. 3) Control of the analysis toward goal.

1. INTRODUCTION

A production system consists of a set of production rules and a database. A production rule is the unit of knowledge representation and the database records the facts about input image. The control structure of production systems is heterarchical. Each production rule is a pair of a condition and an action and is "watching" the database. Whenever the predicate in the condition part is satisfied, the system evaluates the action part and modifies the database. Because of this, it is easy to add or modify knowledge in production systems. This is a useful feature to organize an analysis system for complex scenes, such as outdoor scenes, which include various kinds of objects.

We have made an outdoor-scene analyzer in the framework of region growing using production system for knowledge representation and control structure[1]. In this paper, we describe the outline of our scene analyzer and discuss production systems from the view point of image analysis.

2. OUTLINE OF ANALYSIS MECHANISM

Figure 1 shows the schematic diagram of the analysis mechanism in our system. The system receives, an input color image as digitized red-green-blue intensity arrays and constructs a semantic description of the scene.

Preliminary segmentation - The primary objective of the preliminary segmentation process is not the reduction but the structuring of raw image data into usable information; The input color image is segmented into a set of coherent "patches" and organized into a fully structured symbolic description. In the higher-level processes, all picture-processing operations are performed on this structured description rather' than the raw image data. The "patch" is an important element to describe the input image and to build a production system in our region analyzer.

Plan generation - The plan generation process extracts the overall structure of the scene to obtain clues concerning which knowledge should be applied to what part of the scene. First, patches with large area are selected as key-patches from the segmented image. It is reasonable to assume that most of them correspond to large parts of objects in the scene. Labels of objects are assigned to each of the keypatches and the degree of correctness is computed using

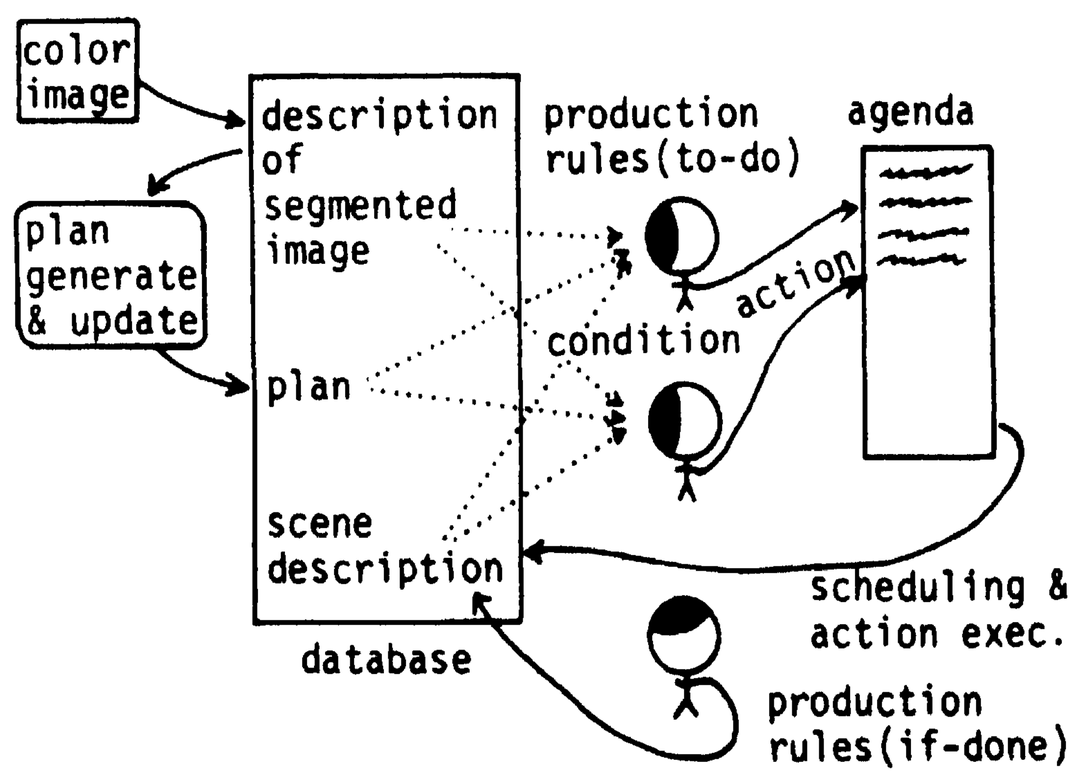

Fig. 1. Outline of the Analysis Mechanism

knowledge, which is represented as a collection of knowledge-blocks[2], about the properties of and the relations between objects. The result of the interpretation, called a plan, is a set of labels and their correctness values assigned to each keypatch, e.g. (sky=0.6, buiiding=0.2, tree=0.1, road=0.l), etc. The plan is updated whenever significant fact, such as the position of scene horizon, is found by the production rules in the analysis process.

Database - The structured description of a segmented image, the plan, and the scene description so far obtained are all stored in the database. Figure *2* illustrates the structure of the scene description built as the result of analysis. Scene, object, region, sub-region, patch, and pixel are the important concepts which constitute the hierarchical structure of our description. The patch corresponds to the result of the preliminary segmentation. All the descriptive elements are organized into the hierarchical structure by "part-of" relation. Relations between parts of objects, such as "adjacent" or "occluded", are described between corresponding regions.

Production rules and agenda = There are two types of production rules in our system; to-do rules and if-done rules. They correspond to consequent and antecedent theorems of PLANNER[3], respectively. A to-do rule performs basic operations in region growing process. It examines each patch which is not yet interpreted in the segmented image by the fuzzy predicate in its condition part and determines whether the action can be executed for it. The executable action is given a score to indicate its priority, and added into the agenda. The agenda manages those actions which are executable in the present context through their scores. The action with the highest score is executed and as the result the agenda is updated. An if-done rule is triggered by the execution of a certain action of the to-do rules. It performs an additional operation in making the scene description, such ac extracting the position of scene horizon, etc.

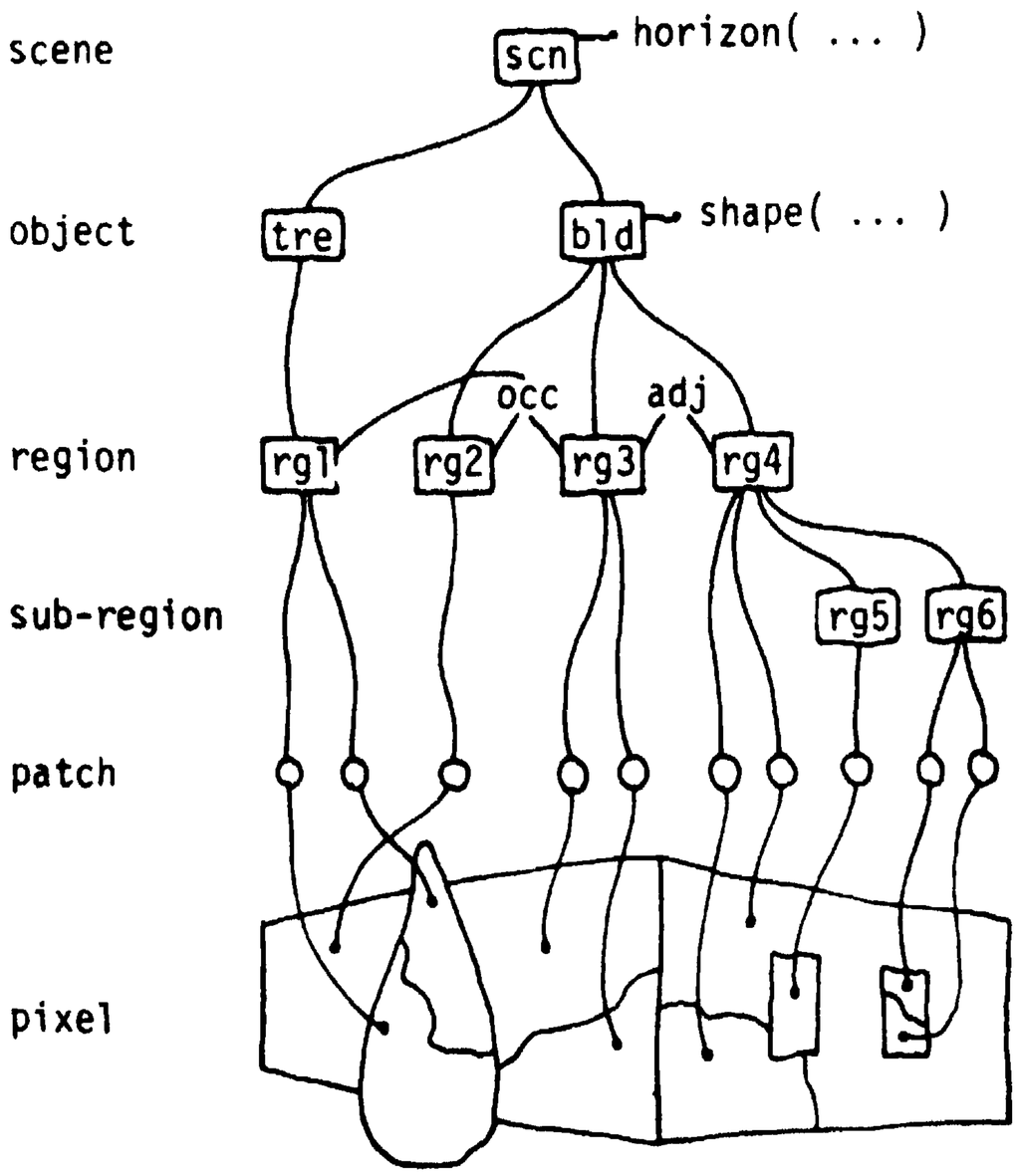

Fig. 2. Structure of the Scene Description.

3. DISCUSSIONS

We have to solve three problems to import the production system architecture to image analysis. The first is the problem of what "size" of production rule is appropriate for region analysis, the second is the problem of how to reduce the amount of computation, and the last is the problem of how to direct the analysis to goal.

° What "size" of production rule is appropriate?

What size of knowledge should be represented by one production rule? As an example of "large" knowledge size, it is possible that each production rule corresponds to one object to be extracted and has whole knowledge about the object. This scheme enables to perform skillful analysis according to the characteristics of each object. On the other hand, the rules become large and complex and it is difficult to manage them.

Small sized knowledge - In our system the size of knowledge represented by a rule is fairly small. Each rule is described as a combination of basic operations in region growing: selecting an un-interpreted patch from the segmented image, assigning a label to it, and assembling it into the scene description. This scheme has the following merits: each rule is simple and easy to modify, and the interaction among rules can be performed in a clear way because the access method to the database is simple.

Reinforcements - Because the analysis proceeds patch by patch in our scheme, it is difficult to deal with global constraints such as object shape or relation between objects. We took three steps to cope with this situation. First, a plan is generated as rough interpretation of the input scene. This enables the production rules to catch information about global structure of the scene. Secondly, patches can be dealt with as a set at a time, and it becomes possible to extract

object which is defined as a combination of mutually constrained patches such as windows of a building or a car on road. Lastly, we have devised special rules which extract information from the segmented image without sticking to the patch-by-patch analysis. This kind of rules, for example, is used to extract the shape of a building.

° How to reduce the amount of computation?

In production systems the control program must grasp the state of executable actions at any moment in the analysis process. The agenda must be updated whenever the database is changed. Roughly speaking, the number of tests to be done each time is estimated as:

(the number of un-i interpreted patches)
X (the number of production rules).

It becomes several thousand and it is too many. Furthermore, the predicate in the condition part, of the production rules includes time-consuming picture-processing functions. It is necessary to reduce the number of the patches and production rules which must be actually examined at a time. For this, the structure of scenes must be taken into consideration.

"Globaiity" and "Locality" - A scene usually has two different properties from the view point, of image analysis: "Globaiity" and "Locality". Analysis results such as determination of scene horizon or detection of objects may have significant influence on the analysis of overall structure of the scene. This property is called "Globaiity". On the other hand, the results of analysis in a small part, of an object scarcely has influence on the analysis of other parts in the scene. This property is called "Locality". These two properties are utilized in the control structure- of our scene analyzer.

Scene phase and object phase - In order to deal with such two properties, of scenes, two phases are net up in the control program. They are scene phase and object phase. The task of the scene phase is to analyze overall structure of input scene without sticking to details. So, it is almost meaningless to examine small patches in the scene phase analysis and only the key-patches are examined. Whenever a keypatch is labeled, the scene phase is activated and all un-interpreted keypatches are re-examined. In the object phase, analysis of detailed structures are performed under the context of the results in the scene phase analysis. When a patch which belongs to a object is labeled, the object phase corresponding to the object is activated and the patches touching the patch just labeled are examined or re-examined.

Dividing rules into subsets. - The set of production rules can be divided into subsets to be used in the scene phase and the object phases corresponding to each object. In each phase, only the subset corresponding to that phase is activated by the control program to examine the un-interpreted patches.

Consequently, the number of tests to be done at a time is reduced to several 10's.

° How to direct the analysis to goal?

It is an import,ant, feature of production systems that each production rule independently checks the database and modifies it whenever the condition is satisfied. However, two problems need to be considered to make this mechanism actually work; a method to direct the analysis to goal and a method to resolve the conflict among the executable actions which are inconsistent with each other.

Score - As was described, every executable action is registered in the agenda with its score and the action which has. the highest score is executed to change the database. Then the score plays an important role t,o direct the analysis, toward goal. The value of seore associated to each executable action is calculafed as the sum of a base value and a premium value. The base value- is a constant given to each production rule, and it plays a role to specify the order of analysis. The premium value is given as the degree of satisfaction of the condition of production rule at, the situation the rule was examined, and it plays a role to guide the analysis toward the correct interpretntiun. To sum up, the analysis proceeds toward goal guided by the premium values following the strufegy specified by the base values.

Conflict resolution - In our system, the basic operation which changes the database is very simple: to assign an object label to a patch. This makes the detection of the inconsistent actions quite straightforward. Whenever a patch is interpreted by executing an action registered in the agenda, every action which is going to give a different interpretation to the patch just interpreted is decided to be inconsistent and deleted from the agenda.

In this paper, we described a production system which was applied to region analysis. Some problems and their solutions were discussed.

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AN INFINITE-CONNECTED WORDS RECOGNITION SYSTEM FOR MALE SPEAKERS USING TIME-SPACE DYNAMIC PROGRAMMING

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A new algorithm of pattern matching for time-space speech feature using Dynamic Programming is proposed for recognizing infinite-connected words spoken by male speakers without adaptation of speakers before the utterance. The new algorithm carries out frame-wisely two kinds of normalizations : the time normalization for removing speed variation of speech and the space normalization for removing speaker-dependence. This algorithm is realizable by a simple cellular automaton. The recognition rate 85.7% is obtained for 50 categories, *h* male speakers and 440 samples (connected words).

1. INTRODUCTION

The purpose of this paper is to propose a recognition system based on a new dynamic programming algorithm for recognizing continuous speech spoken by male speakers. This system is realizable as a simple cellular automaton.
Recently, recognition systems dealing with isolated words spoken by many speakers are proposed [l], [2]. Other systems dealing with several connected words spoken by a speaker are also proposed [3], [4]. The following abilities are desirable for a system; l) dealing with infinite connected words in an utterence, *2.)* allowing for many speakers without speaker adaptation before the utterance, 3) working in real-time. We propose a system with these abilities.

2. RECOGNITION PRINCIPLE

The principle is based on a new pattern matching algorithm using dynamic programming called Time-Space Dynamic Programming (TSDP), With regard to speech feature with the time and space axes such as spectrum and vocal tract area function, TSDP is applicable for normalizing two kinds of variations occured in time-space axes of the feature. The one is time normalization for removing speed variation *oV* speech and the other one is space normalization for removing speaker-dependence. Two normalization parts of TSDP are carried out frame-wisely without segmentation of a continuous speech. Segmentation problem of continuous speech is maintained to the final stage of recognition process. Two kinds of normalizations of TSDP are separable.

3. OUTLINE OF THE SYSTEM

The recognition of words is carried out frame by frame. We can divide this frame-wise recognition process into three stages as follows.

1) Extraction of a vocal tract area function.
2) Application of Time-Space Dynamic Programming.
3) Frame-wise decision of category.

4. VOCAL TRACT AREA FUNCTION EXTRACTION

We use a vocal tract area function as a parameter. The reason is that a vocal tract area function is more stable for different male speakers than other parameters such as spectrum. The pre-experimental results revealed this conclusion.
The extraction technics of a vocal tract area function from speech waveform have already developed by Wakita [6] and Nakajima et al [7] by using inverse filter technic to remove glottal wave. We used an improved technic of Nakajima's one that is a frame-wise inverse filtering method of second order critical damping with a positive or a negative pole. The used one is a frame-wise inverse filtering method with the only positive pole. This method is more suitable because it does not carry out over inverse filtering for the frames in the consonant part of speech waveform.
The analysis condition is as follows ; 10 kHZ

sampling, 20 msec window for analysis, 10 msec frame interval, 12 sections for a vocal tract area function and a vocal tract area function is normalized with regard to its volume.

5. TIME-SPACE DYNAMIC PROGRAMMING

5.1 Time Normalization Part

Let $\{ f(t,x) : 1 \le x \le L \}$ be a vocal tract area function of the time t, where x indicates the space axis, i.e. vocal tract, and L is the length of vocal tract. Let $\{ Z(\tau,x) : 1 \le \tau \le T, 1 \le x \le L \}$ be a standard pattern representing a word, where T indicates the length of the standard pattern and τ corresponds to the time axis of speech feature. We define a function A(t) representing the temporary minimum distance between a past input pattern with the optimum length and a standard pattern, i.e.,

$$A(t)=\frac{1}{J^*(t)} \min_{(\zeta_j,\tau_j)\ j=1,2,..,T}\left\{\sum_{j=1}^{T} K_j \left(\sum_{x=1}^{L} | f(t-\zeta_j,x)-Z(\tau_j,x)| \right)\right\},$$

where $K_j=\zeta_{j-1}-\zeta_j+\tau_{j-1}-\tau_j$, $\zeta_1 \ge \zeta_2 \ge \cdots \ge \zeta_j \ge \cdots \ge \zeta_T \ge 0$, $\tau_1 \ge \tau_2 \ge \cdots \ge \tau_j \ge \cdots \ge \tau_T = 1$.

and J*(t) is the sum of Kj's determined from the optimum pairs $(\zeta^* j, \tau^* j)$ from j equals one to j equals T. We will propose an algorithm for calculating A(t) frame-wisely using Dynamic Programming. When we calculate A(t) by the following method, we call it the time normalization part of TSDP. This idea is suggested by so-called Max-Product Parallel Machine proposed by Y.Isomichi [5]. Three variables are necessary for describing the time normalization part of TSDP. The variable $Q(t,\tau)$ indicates the local distance, $P(t,\tau)$ indicates the optimum value obtained from integration of the values of $Q(\cdot,\cdot)$'s, and $C(t,\tau)$ indicates an integrated value of Kj's which are embedded in the value $P(t,\tau)$. The variable $C(t,\tau)$ is necessary for normalizing the length of the optimum pass.

$$P(0,\tau)=P(-1,\tau)=M \quad (1 \le \tau \le T)$$
$$P(t,1)=2Q(t,1)$$
$$P(t,2)=\min \begin{cases} P(t-2,1)+2Q(t-1,2)+Q(t,2) & (a)\\ P(t-1,1)+2Q(t,2) & (b)\\ P(t,1)+Q(t,2) & (c)\end{cases}$$

$$P(t,\tau)=\min \begin{cases} P(t-2,\tau-1)+2Q(t-1,\tau)+Q(t,\tau) & (d)\\ P(t-1,\tau-1)+2Q(t,\tau) & (e)\\ P(t-1,\tau-2)+2Q(t,\tau-1)+Q(t,\tau) & (f)\end{cases} \quad (3 \le \tau \le T)$$

$$C(0,\tau)=C(-1,\tau)=0 \quad (1 \le \tau \le T)$$
$$C(t,1)=2$$
$$C(t,2) = \begin{cases} C(t-2,1)+3 & \text{if (a)}\\ C(t-1,1)+2 & \text{if (b)}\\ C(t,1)+1 & \text{if (c)}\end{cases}$$

$$C(t,\tau) = \begin{cases} C(t-2,\tau-1)+3 & \text{if (d)}\\ C(t-1,\tau-1)+2 & \text{if (e)}\\ C(t-1,\tau-2)+3 & \text{if (f)}\end{cases} \quad (3 \le \tau \le T)$$

where $Q(t,\tau)=\sum_{x} | f(t,x)-Z(\tau,x)|$ and M is the fixed value. Then the following equations hold.

$$P(t,T)=\min_{(\zeta_j,\tau_j)\ j=1,2,..,T}\left\{\sum_{j} K_j \left(\sum_{x} | f(t-\zeta_j,x)-Z(\tau_j,x)| \right)\right\}.$$

$$C(t,T)=J^*(t). \qquad P(t,T)/C(t,T)=A(t).$$

The detail discussion about these derivations is described in a paper [8].

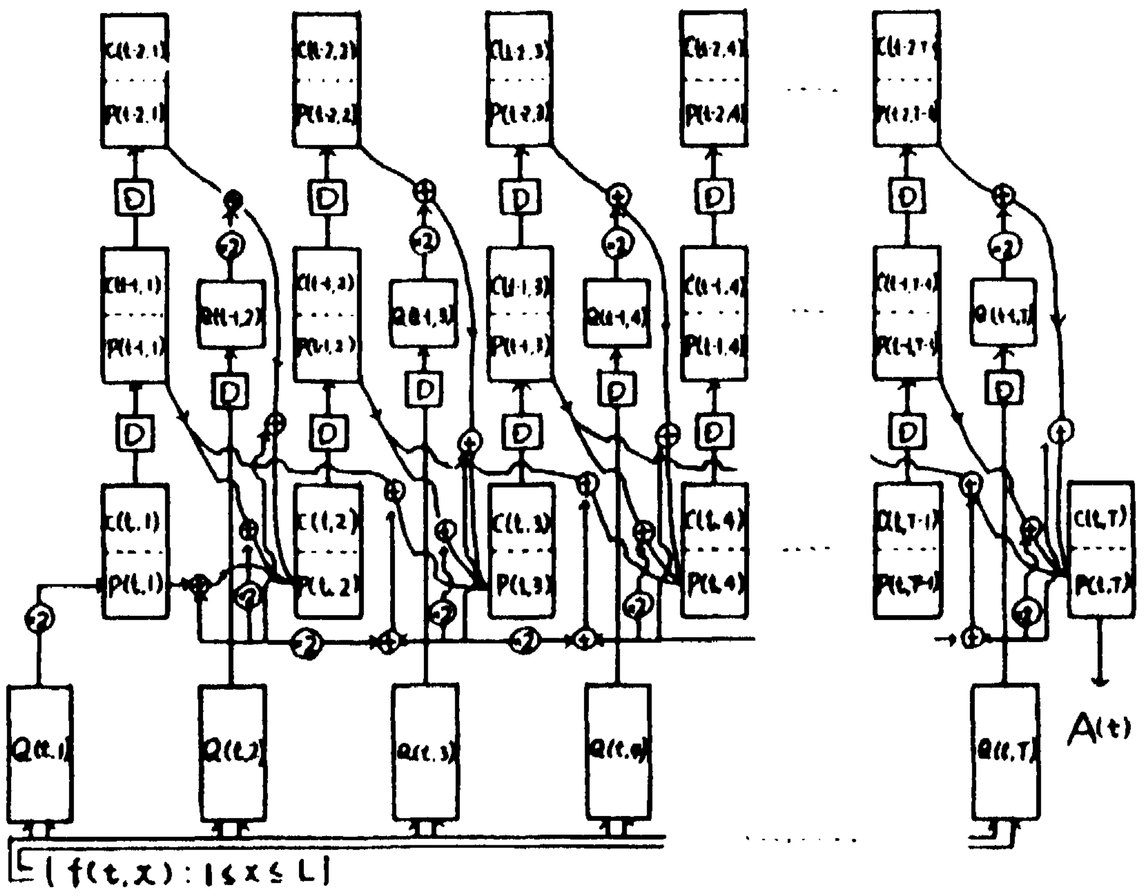

Fig. 1 Cellular Space Realization.

5.2 Space Normalization Part

The space normalization is applicable to the determination part of the value $Q(t,\tau)$ of the time normalization algorithm.
If we introduce a new variable $g(t,\tau,x,\xi)$ and suppose $1 \le \xi-1 \le x \le \xi+1 \le L$, then the space normalization algorithm is described as follows.

$$g(t,\tau,1,1)=2 | f(x,1)-Z(\tau,1)|$$
$$g(t,\tau,x,\xi)=\min[\ g(t,\tau,x-1,\xi-2)+2|f(t,x)-Z(\tau,\xi-1)| + |f(t,x)-Z(\tau,\xi)|,\ g(t,\tau,x-1,\xi-1)+2|f(t,x)-Z(\tau,\xi)| ,g(t,\tau,x-2,\xi-1)+2|f(t,x-1)-Z(\tau,\xi)|+|f(t,x)-Z(\tau,\xi)|].$$

If the time normalization part has $Q(t,\tau)$ defined by $Q(t,\tau)=g(t,\tau,L,L)/2L$, then the algorithm is called TSDP. The value $Q(t,\tau)$ indicates the local distance normalized with respect to the space x in f(t,x). The following equation holds about the output of TSDP A(t).

$$A(t)=\frac{1}{2L\ J^*(t)}\min_{(\zeta_j,\tau_j)j=1,2,..,T}\left\{\sum_j K_j\left(\min_i \sum_l W_i\left|f(t-\zeta_j,x_i)-Z(\tau_j,\xi_i)\right|\right)\right\}$$

where $K_j = \zeta_{j-1} - \zeta_j + \tau_{j-1} - \tau_j$, $W_i = x_i - x_{i-1} + \xi_i - \xi_{i-1}$, $x_1=1$, $x_L=L$, $\xi_1=1$, $\xi_L=L$.

6. CATEGORY DECISION ALGORITHM

Let $\{A_i(t): i= 1,2,..,n\}$ be n values determined from TSDP, where i is the category number. Let tF be the end time of a word in a continous speech. We never use tF in the recognition system. Section 5. reveals that the value of $A_i(tF)$ is the smallest among those of $A_j(tF), j\neq i$, $A_i(t)$ $(t<tF)$, and $A_i(t)$ $(t>tF)$. We define $i1^*(t)$, $i2^*(t)$ so that $A_{i1^*(t)}(t)= \min A_i(t) \leq \lambda$, $A_{i2^*(t)}(t)= \min A_i(t) \leq A_{i1^*(t)}(t)+h \leq \lambda$ for $i\neq i1^*(t)$, where λ and h are the positive constants. Then we define the decision category number $i^*(t)$ by

$$i^*(t) = \begin{cases} i1^*(t) \text{ if } L_{i1^*(t)} \geq L_{i2^*(t)} \\ i1^*(t) \text{ if no } i2^*(t) \\ i2^*(t) \text{ if } L_{i1^*(t)} < L_{i2^*(t)} \end{cases}$$

where $L_{i1^*(t)}$, $L_{i2^*(t)}$ are the lengths of the standard pattern $i1^*(t)$, $i2^*(t)$. If $i1^*(t)$ does not exist, we set $i^*(t)=0$. The variable $i2^*(t)$ is the candidate category number of the second minimum distance. In general, further algorithm is necessary since there is a time sequence whose frames indicate the same nonzero recognition category number.

7. EXPERIMENTAL RESULTS

Recognition experiments were carried out for 50 words making weather forecast sentences (25 Japanese-city names and 25 Japanese words about weather forecast), The standard patterns are isolated utterances of the words spoken by a male speaker who is out of the tested 4 speakers. The uttered connected words take a form of a sentence with natural speed. Three types of error existed, i.e., confusion: the system decides an uncorrect category at the time when a word mu9t he recognized, missing: the system decides no word at the time when a word must be recognized, ghost: the system decides a category at the time when no word must be recognized. Table 1 shows the two kinds recognition results of connected words (application of TSDP and the time normalization only of TSDP).

8. CONCLUSIONS

A new speech recognition system has been developed and evaluated from the viewpoint of continuous words recognition for male speakers without segmentation and speaker adaptation. The recognition system is realizable as a simple cellular automaton. We obtained 85.7 % as the recognition rate for 440 connected samples, 4 speakers and 50 categories using the standard patterns spoken by a male speaker who was out of the tested speakers.

ACKNOWLEGEMENTS

The auther would like to thank Dr.S.Mori and Dr.T.Nakajima and the menbers of the Speech Recognition Section for supporting this work.

SPEAKER NAME	STAND. NAME	CONNECT SAMPLES	CORRECT	ERROR C	M	G	RATE
I.M	R.O	109	93	13	2	6	85.3 %
S.Ishi.	R.O	113	101	7	4	2	89.4 %
S.Ita.	R.O	111	97	10	3	3	87.4 %
T.S	R.O	107	86	11	8	3	80.4 %
TOTAL	R.O	440	377	41	17	14	85.7 %
TIME-SPACE DYNAMIC PROGRAMMING							
R.O	R.O	500	466	15	19	28	93.2 %
9 males	R.O	48	30	5	12	7	62.5 %
ONLY TIME NORMALIZATION PART OF TSDP							

Table 1

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SUPP: UNDERSTANDING MOVING PICTURE PATTERNS BASED ON LINGUISTIC KNOWLEDGE

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This paper presents a system for understanding moving picture patterns based on linguistic knowledge. In order to deal with the difference of knowledge level between picture pattern and natural language, a hierarchical structure is adopted for the representation of knowledge. At a certain level knowledge data is organized as frame centred around the concept of verb. The concepts of approximately five thousand Japanese verbs were systematically classified to construct such a knowledge system.
The program reads a picture pattern sequence. Pairing a picture pattern with the successive one in the sequence, it recognizes primitive pictures in the pair. Then, checking dynamic relations among primitive pictures , it organizes the relations into verb-centred events . It makes inferences about similarity between two concepts of verbs . Finally it describes each event in Japanese and English.

1. INTRODUCTION

It is a matter of course that image and natural language understanding are very important aspects of artificial intelligence researches . The research works in both areas have remarkably increased in number in recent years , but the results obtained in one area have not been sufficiently used for the research works in the other area . There is much difference of the present knowledge level between image , especially real world image , and natural language understanding: the knowledge level for the former is low while one for the latter is high.
In the last decade or more we have worked at constructing a system named SUPP(System for Understanding Picture Patterns) in order to raise the level of image understanding up to the linguistic knowledge level and to fill the gap between the works in the two areas. This paper is an overview of SUPP[1]-[7). The theory developed there agrees with much of Minsky's frames idea[8], SUPP can be viewed as a specialization of frames idea in the domain of linguistic understanding of image sequence . It has the following two characteristics:
a. A systematic and exhaustive investigation of the meaning of image is made from the linguistic viewpoint.
b. A theoretical basis is given for dealing with the structure and the meaning *of* change, be it motion, deformation or so forth, occuring in image sequences.

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2. CONCEPTUAL TAXONOMY OF JAPANESE VERBS

When an image or image sequence is given , infinite number of static or dynamic events can generally be observed in it . Suppose that the meaning of each event is described In natural language, the description sentences will amount to infinite number. An ordinary sentence is decomposed into simple sentences , each of which is governed syntactically and semantically by a verb . Since there are only finite number of verbs in each language , meanings of infinite number of events are roughly divided into meanings of those verbs and their interrelations.
An object in the real world which is identified by a verb is called "matter." It arises acompanying things, events and attributes , which are called "constituents," so its concept can be regarded as the concept of dynamic or static relation among constituents.
After due consideration about correspondence with the real world , the concepts of approximately 5,000 Japanese verbs were classified according to an algorithm . The concepts are divided into two large classes : "simple matter concept" and "non-simple matter concept." The former can not be decomposed into elementary matter concepts while the latter can be decomposed. They can further be classified according to their structural patterns and semantic contents. The results are described in (21 and [3].

3. THE KNOWLEDGE SYSTEM

The knowledge system contains a visual , a conceptual, a linguistic and a thesaurus component.

3.1 The Visual and the Conceptual Component

The visual component contains models of primitive pictures and syntactic rules among them . An example of model is shown in Fig. 4-(b). The rules are applied to picture pattern pairs , which Minsky called "before-after" frame-pairs. The conceptual component contains conceptual features, concepts and networks of concepts . A matter concept is expressed by [V : C1C2....'C1 d1(E;)d2(E2)••-d_m(Em)) where each CI denotes a feature of matter itself and corresponds to a syntactic rule mentioned above . Each d;( ) denotes the case or role of a constituent and must be filled by specific instance or concept of constituent. Features Ej (= ej1e_2••.ein) specify the conditions its assignment must meet . Networks are constructed among similar matter concepts.

3.2 The Linguistic and the Thesaurus Component

The linguistic component consists of dictionaries for the production of Japanese and English sentences. The thesaurus component contains all the classified concepts in Chap. 2 and supports to develop other components.

The knowledge system is discussed in detail in [I],|5|,|b | and |7|.

4. THE UNDERSTANDING PROCESS

The process of understanding a sequence of two-dimensional line drawings (handwriting is allowed) is described . The overall system is indicated in Fig. 1.

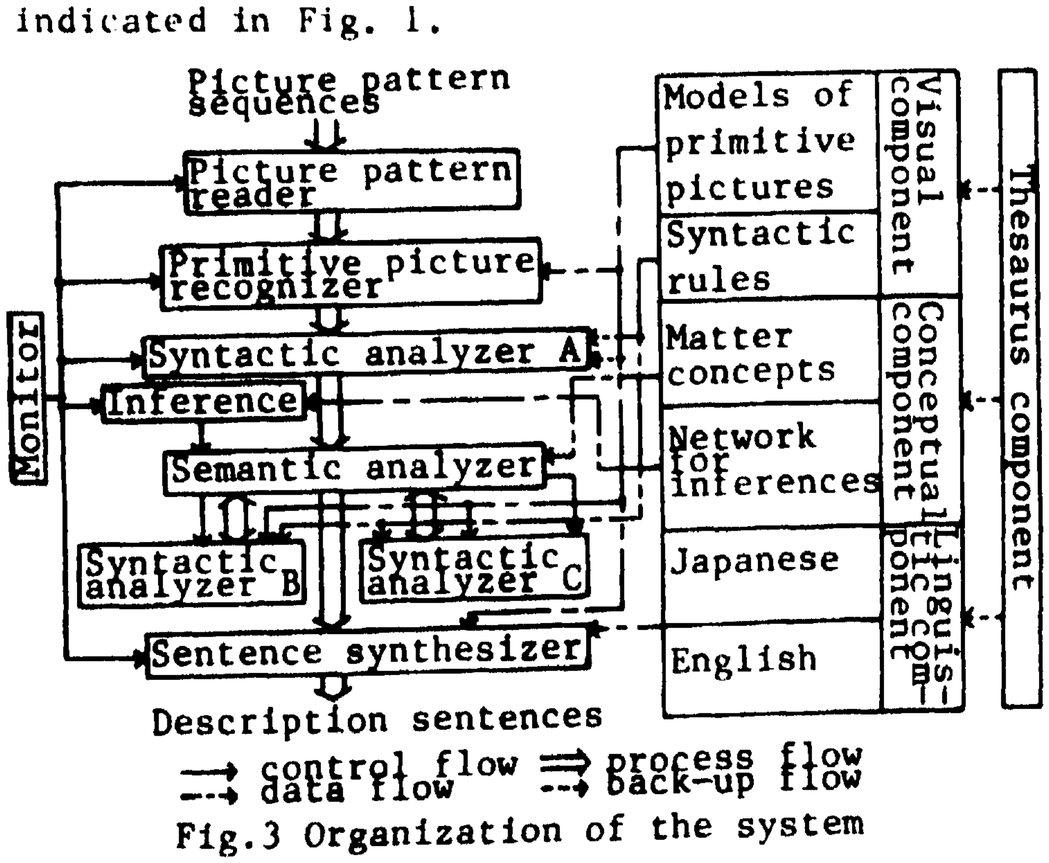


Fig.3 Organization of the system

4.1 Primitive Picture Recognition and Syntactic Analysis

The picture pattern reader is a curve follower that traces line segments by octagonal scanning. The recognizer is based on Evans's matching program[9] for graph-like line drawings but is improved to handle noisy ones.

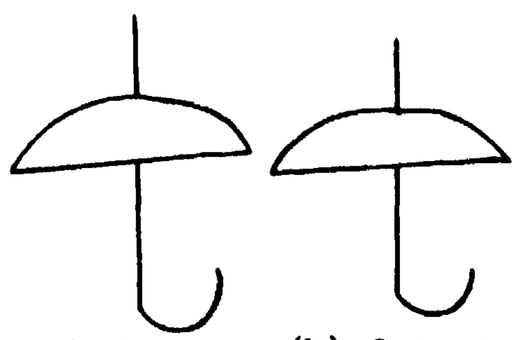
The syntactic analyzer A decomposes the complex picture , in which two or more primitive pictures may intersect or touch each other , and recognizes them according to Gestalt criteria. The syntactic analyzer B performs Boolean operations on quantized primitive pictures to check uch a relation as "MAN INSIDE HOUSE." The syntactic analyzer C performs numerical operations on the data such as coordinates and transformational coefficients of primitive pictures. The programs mentioned above are described in detail in [4] and [5].

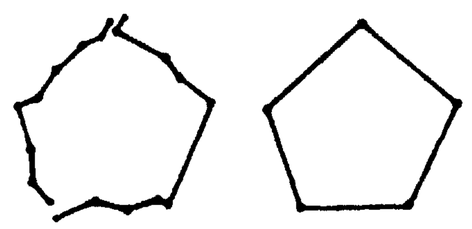
4.2 Semantic Analyzer and Inference

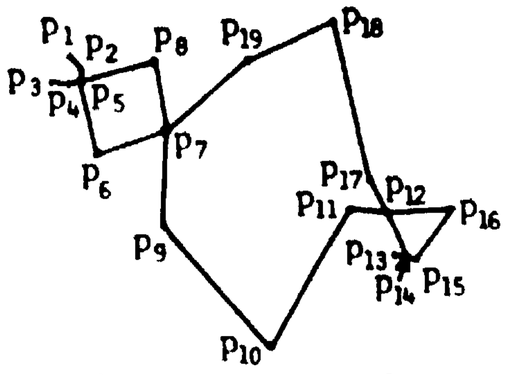
The semantic analyzer detects the meaning of matter-centred change in picture pattern pairs by top-down analysis . Suppose that matter [$V(s,o_\alpha):c_1c_2\cdots c_1 d_s(e_s)d_{o_\alpha}(e_{o_\alpha})$] is directed by the Inference. The analyzer assigns the role of s to one of the primitive pictures , say P_s , after checking whether P_s meets e_s. It assigns the role of o_α to another primitive picture $P_{o\alpha}$ in the same way. Then it analyzes each c_i by calling a correspondent sub-program in the syntactic analyzer B or C. If all the analyses end in success, the meaning of $V(s,o_\alpha)$ is detected. The present Inference makes inferences about all the similar concepts in the network in depth-first order , directing each matter concept at a node to the semantic analyzer. Finally , the synthesizer produces Japanese and English simple sentences.

5. EXPERIMENTS

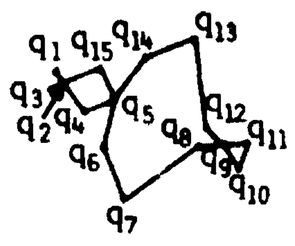
Almost all the programs were written in FORTRAN to run under the OSII/VS of the FACOM 230-38S medium scale computer at the Department of Information Science and Systems Engineering at Oita University. Experimental results [4]-[7] are shown in Fig. 2-5.


(a) Input (b) Output
Fig. 2-Reading of "umbrella"


(a) Unprocessed (b) Preprocessed
Fig. 3-Noise cleaning of pentagon



(a) Preprocessed input picture



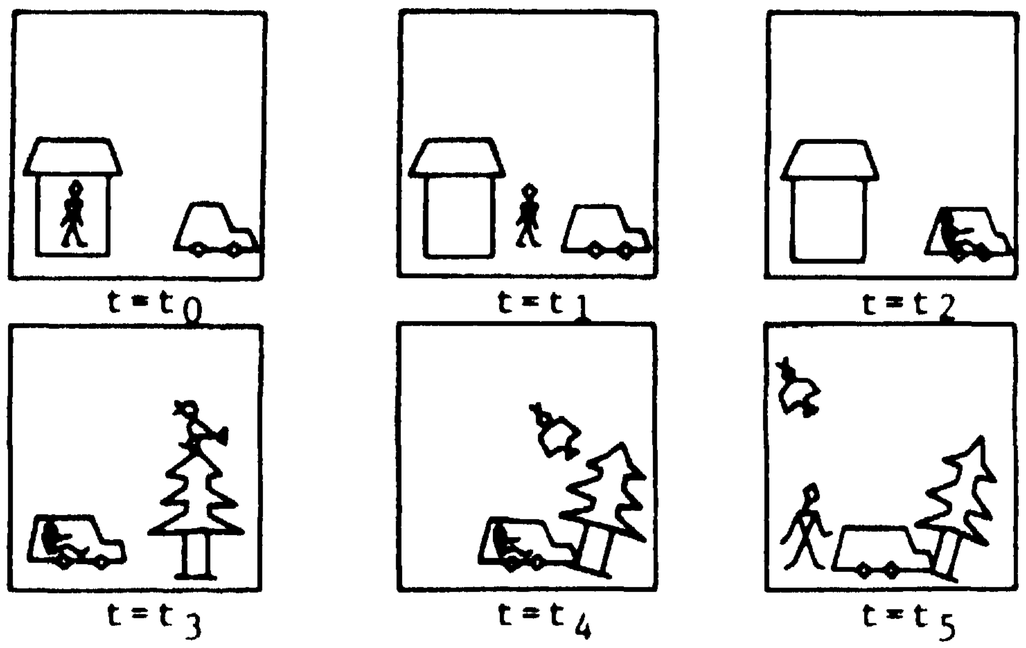
(b) The model of "bird[1]"

1. Pattern matching

$[p_7:q_5],[p_9:q_{14}],[p_{19}:q_6],[p_8:q_4],[p_6:q_{15}],$
$[p_{10}:q_{13}],[p_{18}:q_7],[p_5:q_2],[p_{11}:q_{12}],$
$[p_{17}:q_8],[p_{12}:q_9]$
$[p_{16}:q_{10}],[p_{12}:q_9],[p_{15}:q_{11}]$

2. Transformation and similarity
Translation : (524.4, 483.7), scaling : 2.173 times, rotation : 2.290 radian, reflection : in Y-axis. Similarity : 0.718(≤ 1)

Fig. 4-Recognition of "bird[1]"



(a) Input sequence

$t=t_0$ * *OTOKO(4) GA IE NO UCHI NI ITA.*
* THE MAN[4] WAS IN THE HOUSE.

$t=t_1$ * *OTOKO(4) GA IE KARA DETA.*
* THE MAN[4] WENT OUT OF THE HOUSE.

$t=t_2$ * *OTOKO(4) GA KURUMA NI NOTTA.*
* THE MAN[4] RODE INTO THE CAR.

$t=t_3$ * *KURUMA GA HASHITTA.*
* THE CAR RAN.

$t=t_4$ * *KURUMA GA KI NI BUTSUKATTA.*
* THE CAR COLLIDED AGAINST THE TREE.

$t=t_5$ *TORI(1) GA KI KARA SATTA.*
THE BIRD[1] LEFT THE TREE.
* *OTOKO(3) GA KURUMA KARA ORITA.*
* THE MAN[3] ALIGHTED FROM THE CAR.

(b) Output sentences

1. Description of $t=t_0$ is for the picture pattern at $t=t_0$.
2. Description of $t=t_i$ ($i \geq 1$) is for the picture pattern pair at $t=t_i$ and t_{i-1}.
3. The * marks were assigned by man.

Fig. 5-Understanding of a picture pattern sequence

6. CONCLUSIONS

A system has been surveyed that understands moving picture patterns linguistically. Badler's approach[10] basically agrees with ours in handling verb-centred events but differs in that SUPP is based on a systematic analysis of almost all the verbs used for everyday Japanese while he notes only motion verbs in English. By SUPP image understanding research has come closer to natural language understanding research.

ACKNOWLEDGEMENT

The author started to develop SUPP some ten years ago when he was at Kyushu University. The author wishes to express his gratitude co Prof. T.Tamati of Kyushu University for kind guidance and material support.

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COMPUTER CONTROL OF MULTIJOINED FINGER SYSTEM

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This paper treats computer control of multijointed fingers. First, we discuss optimum operational direction of multijointed fingers. The direction is determined from motional structure of the fingers and is important in the control stage of arm part. second, general description about, software system is presented with primitive program:; to control hardware system. These have been implemented on the ETL object-handling system for manual industry. Third, experimental results of nut-turning task are[1] presented which verify the feasibility of manual task by computer control,

1. INTRODUCTION

Multijointed fingers are useful not only for automation of manual industry but also for animal-like assistant robot from the standpoint of human welfares since they are suited to realize flexible motions that give us not fear but familiality. Further, the fingers provide a research tool for investigation of new modes of servoing, intelligent manipulation, interactive real-time real-world system and AI. Under this philosophy, we treat fingers with complicated structure in our research.

Most of multijointed fingers are not competent for manual task since they are not on a level of programmable manipulation. Hanafusa [1] performed flexible manipulation by using elastic fingers which have coil springs. The ETL object-handling system [3] of which the hardware is overviewed in a reference [2] realizes the flexible manipulation with multijointed fingers.

In this paper, an optimum operational direction of a finger part is discussed with generality. Then, Fundamental ideas for programming manual task are presented with primitive programs about the ETL finger system. Experimental results of nut-turning task by computer control are also shown.

2. OPERATIONAL DIRECTION OF A FINGER PART

Multijointed fingers have an adaptability to grasp an object and handle it from various direction in general. But it is reasonable to fix an operational direction for a finger part to have much flexibility in handling an object. We consider a volume in which the finger terminal can be located. We call the surface of it an envelope. Shape of the envelope depends on structure of the finger. In most cases, the shape is like an ellipsoid as shown in Fig.1. It is mathematically expressed in the coordinate system (X_p, Y_p, Z_p) that has an origin at the center of the palm plate as

$$\frac{\{(X-x_j)\cos\psi_j-(Z-z_j)\sin\psi_j\}^2}{A_j^2}+\frac{Y^2}{A_j^2}+\frac{\{(X-x_j)\sin\psi_j+(Z-z_j)\cos\psi_j\}^2}{B_j^2}=1,$$

where j is a subscript related to finger number, $(x_j, 0, z_j)$ denotes the coordinates of the finger root, A_j means effective finger length concerned with bend-in and bend-out joint, and B_j means that concerned with abduct and adduct joint. Mostly, the value of A_j is greater than that of B_j $(A=\ell_1+\ell_2+\ell_3+\ell_4,\ B=\ell_2+\ell_3+\ell_4)$.

We have determined an optimum operational direction of a finger part as the direction toward which a common point of multiple envelopes is viewed from the center of the palm plate (In Fig.1, W shows this direction). Even if the finger part is composed of a lot of fingers, the optimum operational direction of the finger part would be fixed on the finger system according to its structure. On the other hand, an object has

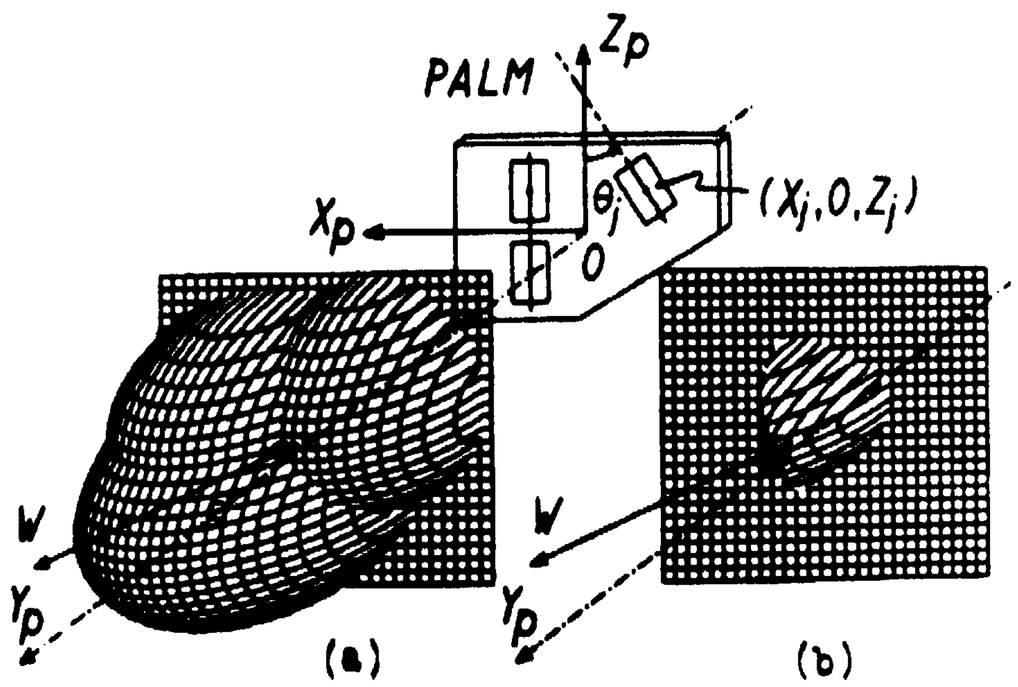

Fig.1 Total envelope related to three fingers

its own optimum operational direction as its property. Tt can be expressed by an axial line which is peculiar to the object. Therefore, adaptability of the finders would be created by controlling the arm so that these operational directions might accord with each other.

3. SOFTWARE SYSTEM

3.1 General description

At present, the software system for manual task is on a low level since it is not described in the form like manipulator language or hand language. We consider the symboric notations [3] that are defined to fundamental motions of a finger are useful to develop the language. Finger operation for manual task would be programmed by applying these motions to a geometric model of an object. The use of sensors; is; important to make adaptable handling in real-world. As shown in Fig.;', our system has a short-range finding sensor (SRFS) *[4]* at the palm area for local inspection of the object. This sensor reduces complexity of programming since it augments the capabilities of the system so that it can find and acquire unindexed workpieces and cope with unexpected events in performing object handling and assembly operations. For example, in nut turning, it monitors the fixation between screw and nut, and provides the resulting displacement of a nut along a screw axis. Therefore, fingers' pushing or pulling operation is sensor-controlled according to the amount of its displacement.

3.2 Primitive Programs

Primitive programs control the hardware of the object-handling system. The next program is common to finger part and arm part.

TAFCON(IAF,IFMODE,XAF,YAF,ZAF)

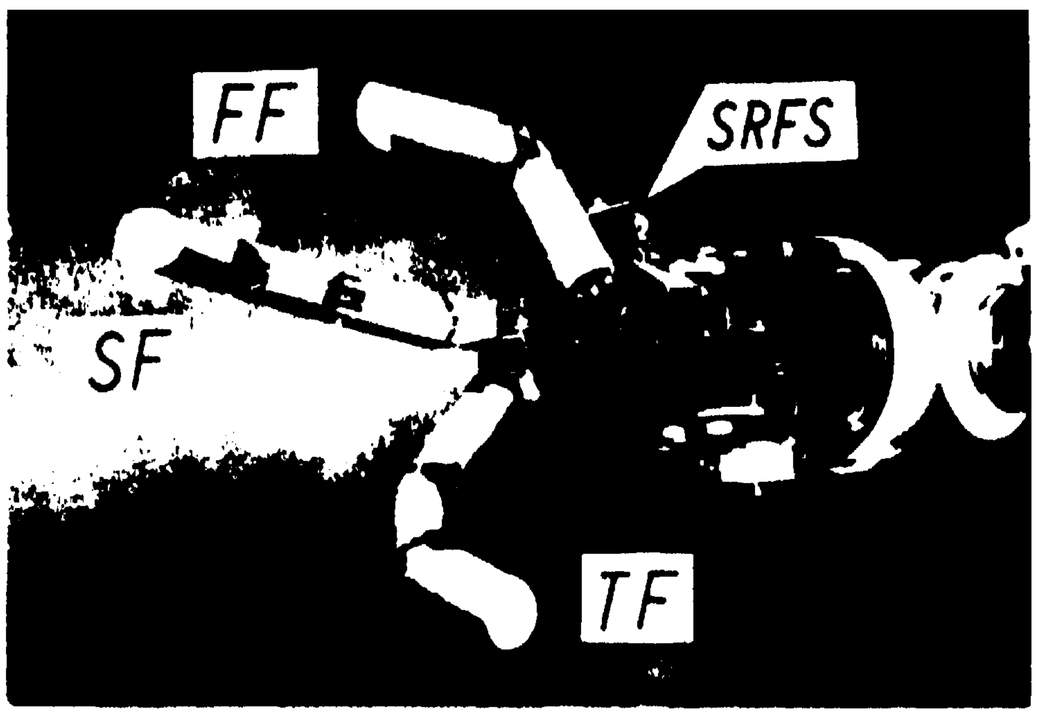

Fig.2 View of finger part

The argument- IAF designates the part to be controlled. The meaning of it is

IAF = } 0 ; Arm
1 ; First Finger
'2 ; Second Finger
3 ; Third Finger

IF MODE is the argument concerned with the control mode about the finger terminal direction. This is effective when the value if IAF is not equal to zero. When IFMODE takes the value of 1, only the position of a finger terminal is controlled. But when the value of *?* or 3 is assigned to IFMODE, not only the position but also the direction of the finger terminal is controlled. Especially, when the value of 3 is assigned to TFMODE, the direction is controlled to be optimum. (XAF,YAF,ZAF) are the coordinates of the palm point for arm control or the terminal point f*or* finger control in the coordinate system (X,Y,Z) that has an origin at the shoulder joint. When the value of IAF is equal to zero, the next, program is used.

ARMS0L(XAF,YAF,ZAF,,6,Y,IFLAG)

This program calculates an arm solution by using the parameters (cx,B,Y) that are concerned with the optimum operational direction of the finger part. The argument, 'IFLAG notifies whether the arm solution is obtained or not,.

As far as the fingers are concerned, coordinates (XAF,YAF,ZAF) are the values expressed in the coordinate system (X,Y,Z). In order to obtain the coordinates (XF,YF,ZF) expressed in the coordinate system (X_f,Y_f,Z_f) that has an origin at the root of the finger, the next program for coordinates transformation is used:

TRANSF(J,XAF,YAF,ZAF,XF,YF,ZF)

The argument J takes the value equal to that of IAF and designates the finger to be controlled. Control values (P1,P2,P3,P4) for finger joints

are obtained from programs FINSL1, FINSL2 and FINSL3 that are prepared according to the values of IFMODE. The command format to use these programs is written as follows:

FINSLn(J,XF,YF,ZF,P1,P2,P3,P4,IFLAG)

when the value of IFMODE is 2 or 3, the unit vector $\mathbf{V}_{jn}$ $(=u_{j1}X+u_{j2}Y+u_{j3}Z)$ which denotes the direction of the finger to be controlled is referred. Finger solution in FINSL2 and FINSL3 are obtained by hill-climbing method and exhausting method, respectively.

4. EXPERIMENTAL MANUAL TASK

Nut-turning task is performed in the experiment. In order to adapt the fingers to the task, arm part is controlled so that the optimum operational direction of the fingers accords with axial line of the screw. Then, each terminal point of the fingers is controlled to move along the contour which is assumed to be circular in mathematical model of the nut. Results of the task are shown in Fig.3. The values of IFMODE in (a) and (b) are equal to 1 and 2, respectively. In (b), both directions of the finger SF and TF are equal to screw axis, namely, $u_{21}=u_{23}=u_{31}=u_{33}=0$ and $u_{22}=u_{32}=1$. Time required to accomplish one cycle of turning for (b) is about 2.3 times long as compared with that for (a) under such condition that the resolution angle of the joint is 2 degrees. Incidentally, the time for the case of IFMODE=3 is about 3.5 times long. The fact shows that the more precisely the finger direction is controlled, the more time it takes. But the time required to obtain control values for the case of IFMODE=2 is not so long as we have supposed. We could hardly find the difference in the results between the cases of IFMODE=2 and IFMODE=3. This means the capability of real-time control of both the position and the orientation of multijointed fingers in IFMODE=2. In (a), finger supports the nut with a point. But in (b), it tends to support the nut with a line. The fingers would realize stable operation when the orientation of the fingers are controlled to fit to a surface of an object.

5. CONCLUSIONS

Nut-turning task has been carried out smoothly by computer control without influence of shape and size of the nut. This would show the feasibility of manual tasks by multijointed fingers with flexibility.

Each fingertip is assumed to be an ideal point. But in real, it is extended like a ball. Therefore, the extension of the nut should be considered in fine operation of an object. Further the fingers might be controlled not only in position but also in torque. We have just started to develop intelligent manipulati with cooperated control of these.

(a) IFMODE=1 (b) IFMODE=2

Fig. 3 Nut-turning task

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A MEASURE OF CLOSENESS OF WEAK IMPLICATION TO STRICT IMPLICATION

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The concept of weak implication introduced by R.Boudon is relevant to approximate reasoning which is a subject of the study in AI. The weak implication can be interpreted by the fuzzy material implication which is a binary fuzzy relation. A measure of closeness of weak implication to strict implication is defined as the maximum of distances within the given fuzzy relation,but constructed in the 2x2 contigency table. This measure agrees with the absolute value of Boudon's index f of closeness of weak implication to strict implication under some conditions.

1. WEAK IMPLICATION

1.1 Approximate Reasoning

In real-world domain in which reasoning is often judgemental and inexact,it is required to be able to say that " A suggests B" or "C and D tend to rule out E". As an application of AI to real-world problem a model of approximate implication has been already used,with a certainty factor which indicates the strength of implication,in the knowledge-based medical consultation system in [2]. On the other hand,it seems that we have no knowledge-based system in any field of social science as an application of AI, However approximate implication was discussed firstly by R.Boudon on sociological implication in [1]. He criticized the transitive implication on the approximate reasoning that H. Zetterberg have done in [7] and he proposed the concept of "weak implication" against strict implication. He also introduced some measure of closeness of weak implication to strict implication with a certain probabilistic measure.

1.2 Weak Implication as Fuzzy Implication.

R.Boudon's weak implication is fuzzy implication in a sense,because it is implication that has fuzzy truth value. Membership function which defines a fuzzy subset is different from probability as indicated in [3],thus it may be preferable to give another measure of closeness of weak implication to strict implication by the use of the fuzzy implication rather than probabilistic measure. This paper shows that weak implication can be well expressed with a binary fuzzy relation which gives the fuzzy material implication on the fuzzy linguistic variable given by L.A.Zadeh in [4], [5], [6] and another measure of closeness of weak implication to strict implication is newly defined by the maximum of some distances between of fuzzy binary relation which is fuzzy material implication.

2. FUZZY RELATION MATRIX OF WEAK IMPLICATION

2.1 Construction of Fuzzy Relation Matrix

We now construct a fuzzy relation matrix for a given 2x2 contigency table,in which the observed frequencies are shown under classification with the two attributes A and B, However it actually occurs that the classification is not proper because of ill-defined of A and

B or not-fitted in practice for that criterion of classification. Thus it is more natural to regard A,B (or S,E) as fuzzy subsets of possible universe of discourse X and Y,respectively. We assume that normalized frequencies in rows in the 2x2 contigency table (Table 1) are values of membership function of fuzzy subset A or $\bar{A}$; this table may

Table 1. Contigency table normalized in rows.

	B	$\bar{B}$	
A	$n_{11}/n_{1.}$	$n_{12}/n_{1.}$	1.0
$\bar{A}$	$n_{21}/n_{2.}$	$n_{22}/n_{2.}$	1.0

expess a fuzzy relation R in AxB $\subset$ XxY. This procedure intends to determine the grade of fuzzy subsets by empirical data.

2.2 Fuzzy Material Implication

The extension of the notion of material implication to fuzzy subsets is given by L.A.Zadeh in [6] as follows,

IF A THEN B ELSE C = AxB + $\bar{A}$xC

IF A THEN B = IF A THEN B ELSE V

=AxB + ~|AxV

where U,V are two possible different universe of discourse;A,B and C are fuzzy subsets of U,V and V,respectively. The material implication is a binary fuzzy relation in UxV and here we simply denote them A -> B. From the assumption that the normalized 2x2 contigency table is a fuzzy relation matrix,the fuzzy material implication is obtained for the given 2x2 contigency table. For example,we obtain fuzzy implication for a not strict but strong implication as follows;fuzzy subsets A=[1/1,0.2/2],B=[1/1,0/2],relation matrix

$R=\begin{bmatrix}1 & 0\\ 0.2 & 0.8\end{bmatrix}$, fuzzy implication $A \Rightarrow B$

$=AxB + \neg AxV=\begin{bmatrix}1 & 0\\ 0.2 & 0\end{bmatrix}+\begin{bmatrix}0 & 0\\ 0.8 & 0.8\end{bmatrix}=\begin{bmatrix}1 & 0\\ 0.8 & 0.8\end{bmatrix}$

The several examples of fuzzy implication from strict to very weak implication are shown in Table 2.

Table 2. Examples of fuzzy implication.

STRICT IMPLICATION

A=[1/1,0/2],B=[1/1,0/2]

$R=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$,$A \Rightarrow B = \begin{bmatrix}1 & 0\\ 1 & 1\end{bmatrix}$

STRONG IMPLICATION

A=[1/1,0.2/2],B=[1/1,0/2]

$R=\begin{bmatrix}1 & 0\\ 0.2 & 0.8\end{bmatrix}$,$A \Rightarrow B = \begin{bmatrix}1 & 0\\ 0.8 & 0.8\end{bmatrix}$

WEAK IMPLICATION

A=[1/1,0.5/2],B=[1/1,0/2]

$R=\begin{bmatrix}1 & 0\\ 0.5 & 0.5\end{bmatrix}$,$A \Rightarrow B = \begin{bmatrix}1 & 0\\ 0 & 0.5\end{bmatrix}$

VERY WEAK IMPLICATION

A=[1/1,0.9/2],B=[1/1,0/2]

$R=\begin{bmatrix}1 & 0\\ 0.9 & 0.1\end{bmatrix}$,$A \Rightarrow B = \begin{bmatrix}1 & 0\\ 0.9 & 0.1\end{bmatrix}$

3. MEASURE OF CLOSENESS TO STRICT IMPLICATION

3.1 Definition of Measure of Closeness

We now give the definition of a measure of closeness of weak implication through fuzzy material implication.

The measure $d(A \Rightarrow B)$ of closeness of weak implication to strict implication is defined by

$$d(A \Rightarrow B)=\max(d_1(A \Rightarrow B), d_2(A \Rightarrow B)) \quad (1)$$

where

$$d_1(A \Rightarrow B)=|\mu_R(A,B)-\mu_R(\bar{A},B)|$$
$$d_2(A \Rightarrow B)=|\mu_R(A,\bar{B})-\mu_R(\bar{A},\bar{B})| \quad (2)$$

are derived from the fuzzy material implication

$$A \Rightarrow B = \begin{bmatrix}\mu_R(A,B), & \mu_R(A,\bar{B})\\ \mu_R(\bar{A},B), & \mu_R(\bar{A},\bar{B})\end{bmatrix} \quad (3)$$

3.2 Examples of Measure of Closeness

The values of $d(A \Rightarrow B)$ are given for examples cited above in Table 3. Further we obtain values of d(A^B) for several examples in sociology given by Boudon in [I];d(A>B)=0.5 for the conservation of religious tradition,d(A=> B)=0.31 for the marriage system in ancient societies and the names called of mothers and mother's sisters,d(A=* B)= 0.20 for the effect of TV performance

Table 3. Values of $d(A \Rightarrow B)$

strict	strong	weak	very weak
1	0.8	0.5	0.1

of political candidate to audiences. The values of d in Boudon's counter example to Zetterberg's implication can be written as $d(A \Rightarrow B)=0.2$, $d(B \Rightarrow C)=0.3$, and $d(A \Rightarrow C)=0.1$ for fuzzy implication

$A \Rightarrow B = \begin{bmatrix} 0.6 & 0.4 \\ 0.6 & 0.6 \end{bmatrix}$, $B \Rightarrow C = \begin{bmatrix} 0.7 & 0.3 \\ 0.6 & 0.6 \end{bmatrix}$

and $A \Rightarrow C = \begin{bmatrix} 0.5 & 0.5 \\ 0.6 & 0.4 \end{bmatrix}$. However we have

$d((A \Rightarrow B) \circ (B \Rightarrow C)) = 0.2 \neq d(A \Rightarrow C) = 0.1$

for fuzzy compositional implication

$$(A \Rightarrow B) \circ (B \Rightarrow C) = \begin{bmatrix} 0.6 & 0.4 \\ 0.6 & 0.4 \end{bmatrix} \neq (A \Rightarrow C)$$

4. BOUDON'S INDEX AND CLSOSENESS MEASURE

4.1 Relation between Index f and Measure d(A⇒ B)

Boudon's index of closeness to strict implication is defined by

$f=n_{11}/n_{1.}-n_{21}/n_{2.}$ or $f=n_{11}/n_{.1}-n_{12}/n_{.2}$

with the notation in Table 1, from which we obtain the following fuzzy subsets A and B when the maximum of components of relation matrix is $n_{11}/n_{1.}$;

$A=[(n_{11}/n_{1.})/1, (n_{21}/n_{2.})/2]$,

$B=[(n_{11}/n_{1.})/1, (n_{12}/n_{1.})/2]$ and

$\mu_R(A, B)=(n_{11}/n_{1.}) \vee (n_{12}/n_{1.})$

$\mu_R(A, \bar{B})=(n_{11}/n_{1.} \wedge n_{12}/n_{1.}) \vee (n_{12}/n_{1.})$

$\mu_R(\bar{A}, B)=(n_{21}/n_{2.} \wedge n_{11}/n_{1.}) \vee (n_{22}/n_{2.})$

$\mu_R(\bar{A}, \bar{B})=(n_{21}/n_{2.} \wedge n_{12}/n_{1.}) \vee (n_{22}/n_{2.})$

Noticing that $|(n_{11}/n_{1.})-(n_{22}/n_{2.})| = |(n_{12}/n_{1.})-(n_{21}/n_{2.})|$,

$d(A \Rightarrow B)=\max(d_1(A \Rightarrow B), d_2(A \Rightarrow B))$

$=\max(|f|, |(n_{12}/n_{1.})-(n_{21}/n_{2.})|$

$=|f|$

if $(1/2) > (n_{21}/n_{2.}) > (n_{22}/n_{2.})$ for $f>0$

$(n_{21}/n_{2.}) > (1/2) > (n_{22}/n_{2.})$ for $f<0$

$d(A \Rightarrow B)=\max(|(n_{11}/n_{1.})-(n_{22}/n_{2.})|, |f|)$

$=|f|$.

if $(n_{21}/n_{2.}) < (1/2) < (n_{22}/n_{2.})$ for $f>0$

$(1/2) < (n_{21}/n_{2.}) < (n_{22}/n_{2.})$ for $f<0$

It is, however, plausible to assume under meaningful weak implication that

$(n_{21}/n_{2.}) < (1/2) < (n_{22}/n_{2.})$

although another ill-conditioned case $(n_{21}/n_{2.}) > (1/2) > (n_{22}/n_{2.})$ occurs for a very weak condition. In fact, $d(A \Rightarrow B)$ have the same values as $|f|$ values for previous examples. Therefore we conclude that in the fuzzy relation matrix deduced by the 2x2 contigency table, the absolute value of Boudon's index $|f|$ is equal to our $d(A \Rightarrow B)$ under those conditions.

Similar procedure can be done for the pxq contigency table adding zero element to get square matrix. The grade of fuzzy subsets should be chosen to contain the maximum element of the matrix. The distances may be defined as follows;

$$d_j(A \Rightarrow B_j) = \max_{i,k} |\mu_R(A_i, B_j) - \mu_R(A_k, B_j)|$$

for a fixed j, thus we have

$$d(A \Rightarrow B) = \max_j d_j(A \Rightarrow B_j)$$

5. CONCLUSION

In the previous section we assumed that the 2x2 contigency table expresses a fuzzy relation after the normalization in rows. We must ask what kind of justification there are on this procedure, which gives actually frequency probabilities of A and B in Table 1. The question comes to the problem of the determination of the grade of fuzzy subset by empirical data. Some attempt to solve this problem has been done by S.Watanabe in [8] already. For generalized fuzzy set, a possible extension of the present idea could use his grade of implication 8 instead of our d. (A-> B).

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SEGMENTATION OF IMAGES BY EXPANSION AND CONTRACTION

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A new method for segmenting Images using edge points to separate regions of smoothly varying intensity is discussed. Region segmentation using edge points has not been very successful in the past because small gaps would allow merging of dissimilar regions. The present method uses an expansion-contraction technique in which the edge regions are expanded to close gaps and then contracted after the separate uniform regions have been identified. In order to perserve small uniform regions, the process is performed iteratively with increasing expansions, but no expansion for edge regions that already separate different regions. The final result is a set of uniform intensity regions (usually less than 100) and a set of edge boundary regions. The program has successfully segmented scenes with industrial parts, landscapes, and IC chips.

1. INTRODUCTION

It is generally agreed that It is necessary to organize the Image data as the first step in image understanding. In organizing the image data two courses of action are generally employed: (1) Locating discontinuities in Intensity (edge points) and connecting them [1,2], and (2) Trying to find regions of fairly uniform intensity by growing regions [3,4] or thresholding at a calculated level [5].

The goal of the latter approach is to segment the picture into a set of uniform intensity regions to increase the degree of organization. The early methods involved merging regions sharing the weakest boundary in an iterative process [3,4] until the weakest boundary was stronger than some threshold. To continue merging regions in complex pictures, it was necessary to use semantic information [4], limiting the general usefulness of the method. A thresholding technique developed by Ohlander [5] was found to be very effective on complex color pictures.

Because of the shortcomings of the region-growing method (without semantic information) and failure of the simple histogram thresholding approach to work on monochromatic pictures in general, we developed an entirely different method. It uses an expansion-contraction technique in which edge regions are expanded to close gaps and then contracted after the separate regions have been labeled. Expansion-contraction techniques have been very useful for the analysis of binary pictures [6], but their use on edge data has been limited [7,8].

2. SEGMENTATION METHOD

In transforming the gray-level picture into regions of uniform intensity, processes 2.1-2.8 are performed serially with processes 2.3-2.7 performed in three cycles of 0, 1, and 2 pixel expansion. The segmentation techniques will be illustrated using Fig. Ia. The resolution is 240 by 256 with 32 gray levels, and its intensity histogram is shown in Fig. Ib. Note that this picture is not thresholdable by Ohlander's criteria [5] of ratio of peak maximum to peak minimum > 2.

2.1 Edge-Finding

Figure Ic was obtained by applying the Sobel edge operator [9] at every pixel of the gray-level picture (Fig. Ia).

2.2 Thinning

Eberlein's relaxation algorithm [10] was used to thin the edges. A threshold was calculated from the curvature of the thinned edge distribution [11]. Figure Id shows the results of thinning and thresholding the edge picture.

2.3 Expanding Edge Points

Expansion of edge points is necessary to fill small gaps in the edge boundaries. The present method involves no expansion of pixels which touch two different regions [11]. The expansion was done in three stages: (1) no expansion (see Fig. Id), (2) expansion of edge pixels to fill a 3 by 3 pixel square (see Fig. 2a), and (3) expansion of edge pixels to fill a 5 by 5 square (see Fig. 2b).

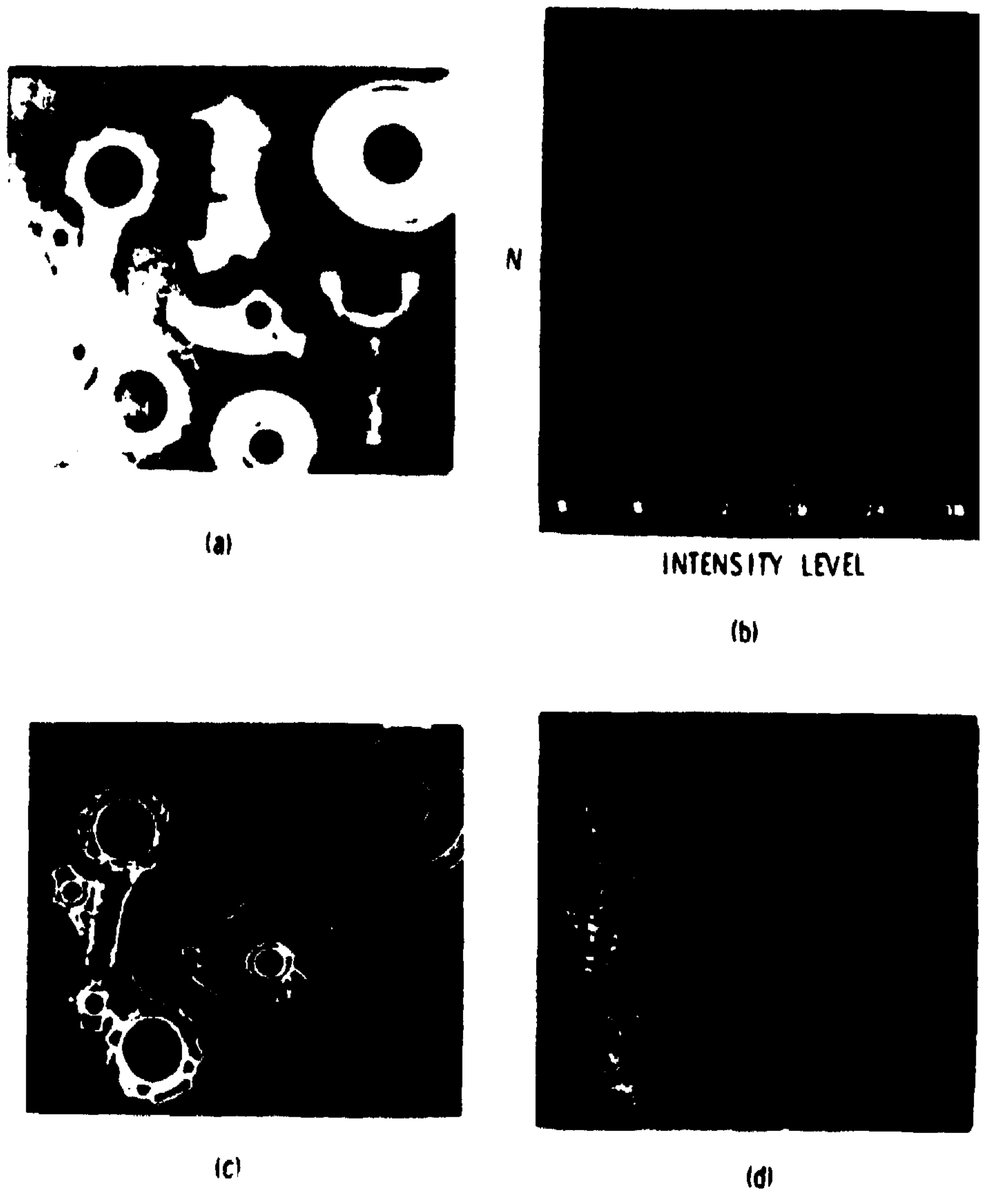

Fig. 1. (a) Digitized picture of some industrial parts. (b) Intensity histogram. (c) Edge magnitude. (d) Thresholded thinned edge array.

2.4 Labeling Uniform Intensity Regions with Connectivity Algorithm

Using the expended edge boundary between uniform intensity regions, pixels in each uniform intensity region are connected by giving each pixel the same label with a four-connected algorithm [12]. Uniform intensity regions are taken to be four-connected and edge regions eight-connected [13].

2.5 Eliminating Small Uniform Intensity Regions

For simplicity, small uniform regions (less than 10 pixels) are eliminated by merging them into their surrounding edge region.

2.6 Shrinking Edge Regions

Edge regions are contracted by replacing "expansion" edge pixels with uniform intensity region numbers [11].

2.7 Placing Edge Boundaries Between Uniform Intensity Regions

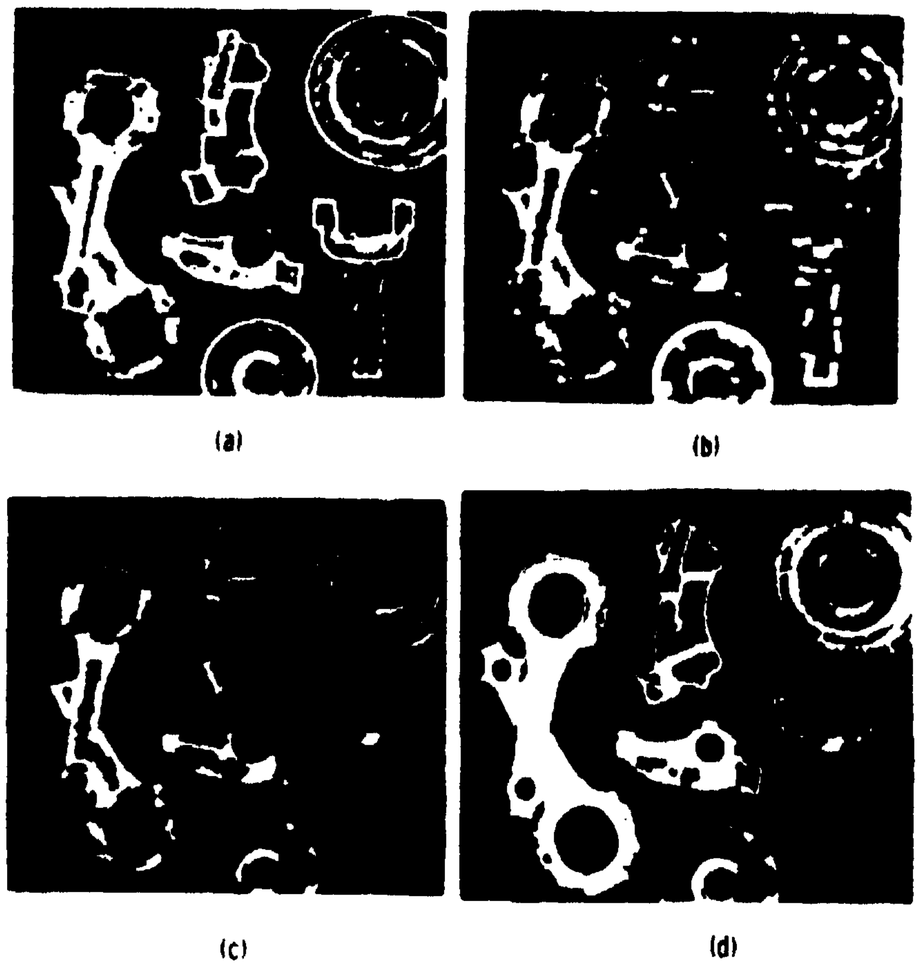

Fig. 2. (a) Expansion of edges to fill 3 by 3 square. (b) Expansion of edges to fill 5 by 5 square. (c) Edge regions after final contraction and elimination of small regions. (d) Reconstructed gray-level picture with bright edge regions. Total CPU time = 31 sec. on IBM 370/3033.

After removing artificial edges (process 2.6), some region pixels are replaced by edge pixels to separate different regions.

2.8 Eliminating Small Edge Regions

For simplicity, small isolated edge regions are eliminated after the segmentation into uniform intensity regions is finished. Figure 2c shows the final edge regions after shrinking and eliminating small regions. The thick edge regions are indicative of textured areas [11].

The gray-level picture of Fig. 2d was generated using the average-intensity region data. Edge regions are shown at the maximum brightness. A comparison of Fig. 2d and Fig. Ia shows that the initial data has been greatly simplified by the organizational process with a slight loss in detail. The final result is 72 uniform intensity regions and 10 edge regions.

3. RESULTS

This segmentation technique was tested on many scenes. Figure 3a (206 by 255 with 8 bit resolution) shows a landscape scene that was analyzed previously by a region growing

technique (see Fig. C of [4]). The final result (Fig, 3d) has 38 uniform intensity regions and 5 edge regions which embody more of the meaningful information than the results of the non-semantic region grower (Fig. C2 of [A]).

When does this segmentation method fail? It fails if the gaps between the edge points are so large that the expansion cannot close them as illustrated in Figs. 1 and 2 for the universal yoke in the lower right-hand corner. Some possible methods of eliminating this type of failure (such as using boundary coincidence of edge points and intensity threshold [14]) are discussed in [11].

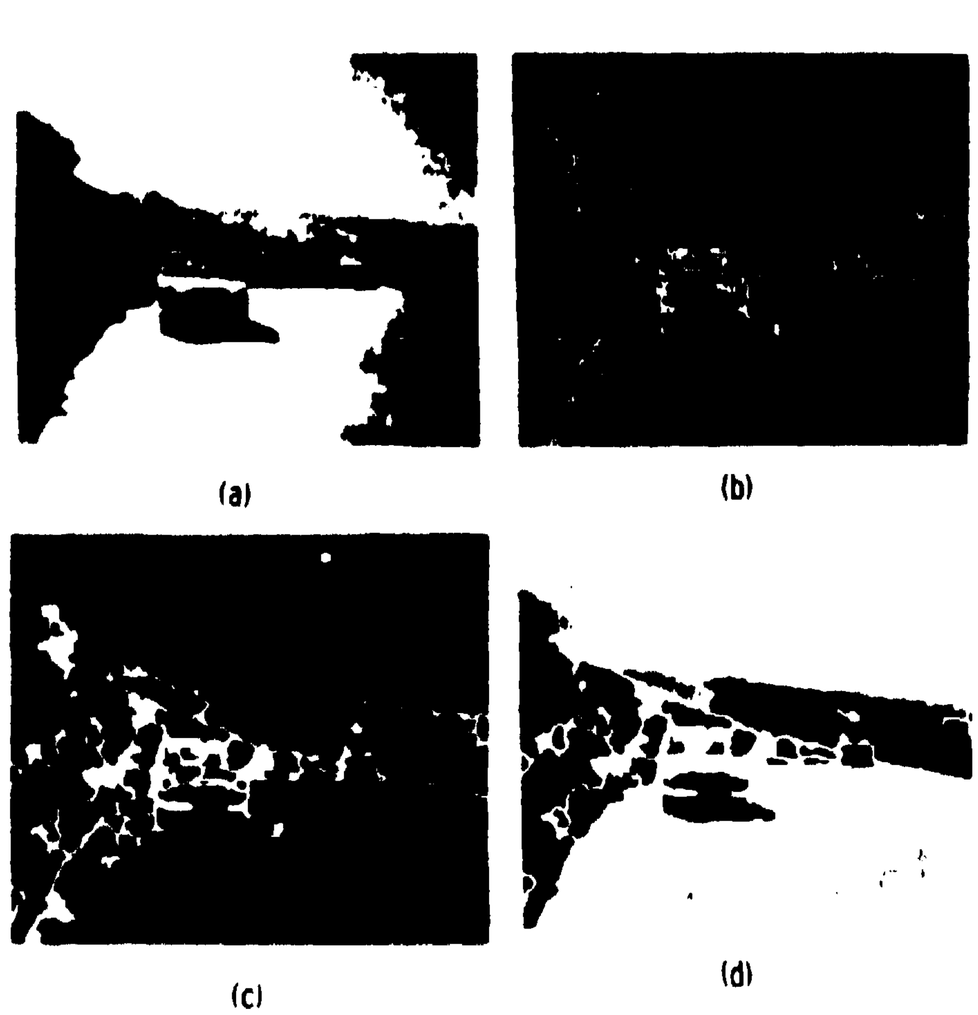

Fig. 3. (a) Digitized picture of landscape scene. (b) Thresholded thinned edge array. (c) Final edge regions. (d) Reconstructed gray-level picture with bright edge regions. Total CPU time = 27 sec. on IBM 370/3033.

4. CONCLUSIONS

The area segmentation method described here has some advantages over the region-growing and histogram-thresholding techniques. Without semantic information, it can segment an image better than the region growing technique. For many scenes (particularly monochromatic images) the intensity histograms do not have clearly separated peaks (see for example Fig. Ib) and often there is no optimum threshold, although clear edge boundaries exist [14].

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MOTION AND STRUCTURE FROM OPTICAL FLOW

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We show that a moving observer can (in principle) compute the relative depth map of the environment given only the instantaneous positional velocity field on his "retina". The depth map (and surface normals) are computed by recovering the egomotion parameters which in turn determine the ratio of depth associated with any two neighbouring "retinal" points. The surface normal map may be computed to a degree of accuracy determined by the resolution of the "retina", and by the accuracy of approximation obtainable in the solution of three non-linear equations of the third degree in three unknowns.

1. THE PROBLEM

The problem addressed here is computing the surface layout of the environment, and the parameters of observer's motion (egomotion) from the information on the image plane. The problem is similar (though not equivalent) to the one tackled by the workers in computer stereo vision [1].

Consider a monocular observer with his "eye" and "head" fixed, with planar "retina", and moving along a smooth curvilinear path in a stationary 3D environment. Each discriminable optical element on his "retina" will possess a velocity; the whole comprising a positional velocity field. Such an observer can be viewed, instantaneously, as simultaneously rotating and translating for (again instantaneously) any 3D motion can be viewed as a rotation about some centre on some osculating plane. The instantaneous positional velocity field (IPVF) is then expressable as being due to the vector sum of two angular velocities due to the translational and the rotationalcomponents of the movement [2].[3]..

Given a IPVF our task is to recover the egomotion parameters (i.e., the translational and rotational components of the egomotion). We do this with respect to an external, static reference frame instantaneously coincident with our egocentric reference frame (centered at 0 in Fig. 1).

The actual velocity of any point Q on the image plane is given by

$$\underline{V}' = (Vl/S\ (\bar{Vl} \times \bar{Q}) + A \times \underline{Q} \qquad (1)$$

Here, Vl is the magnitude of the translational component (the speed of egomotion). $\underline{Vl}$ is its direction vector. And S is the distance to the centre of polar projection of the environmental point P of which Q is the projection on the "retina" (see Fig. 1). $\underline{Q}$ is the position vector of the point Q in the egocentric reference frame centered at O. $\bar{Q}$ is the unit vector in this direction. $\underline{A}$ is the rotational angular velocity vector the components of which are to be recovered in the first place (for more detail see [4]).

Refer to Fig. 1. As can be seen, the "retinal" velocity vector of point Q, $\underline{V}''$ must necessarily lie in the plane spanned by $\bar{Q}$ and $\underline{V}'$. Given the IPVF, $\underline{V}'$ may be derived for each point Q, since

$$\underline{V}' = \underline{V}'' - (\bar{Q}.\underline{V}')\bar{Q} \qquad (2)$$

(This follows from the equivalence of angular velocities generated by $\underline{V}'$ and $\underline{V}''$.

Given that we know $\underline{V}'$, we can rewrite (1) to obtain

$$-(Vl/S)Q\ ((\bar{Vl} \times \bar{Q}) \times \bar{Q}) = \underline{A} \times \underline{Q} - \underline{V}' \qquad (3)$$

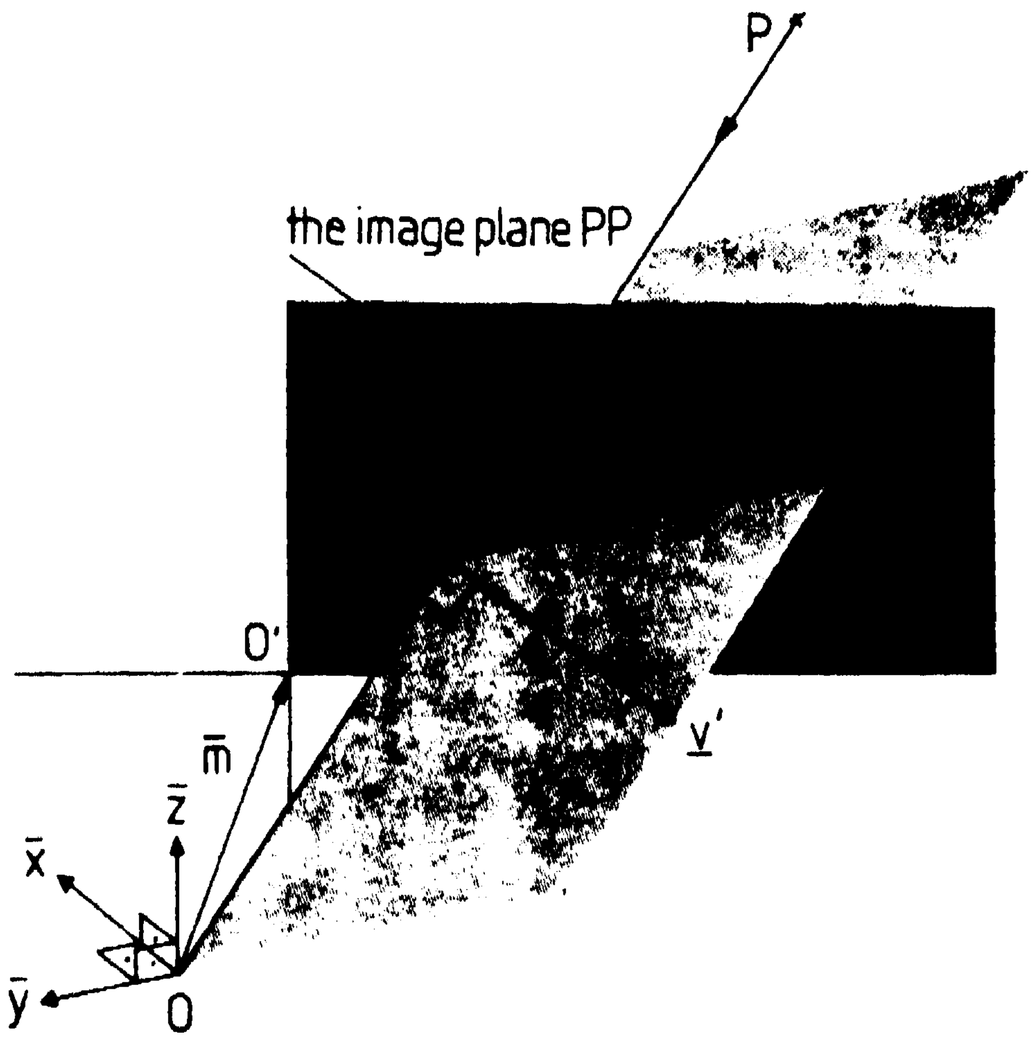

Fig. 1

An egocentric reference frame centered at the centre of polar projection, 0, is defined, together with a planar projection surface PP. A "retinal" 2D rectangular coordinate frame centered at 0 is defined on PP.

V' and V" lie on the same plane, the unit normal of which is (V' x Q).

Refer to Fig. 2. The vector (VI x Q) x Q lies in the plane of VI. Given the fact that VI must lie in all such planes corresponding to dTffer-ent points Q, its direction will be determined as the intersection of these planes. The direc-tion of the line of intersection of two planes specified by their normals NI, NJ is (NI x NJ), Referring back to (3) we see" that "" ""

$$NI = (A \times Q1 - VI') \times QI \qquad (4)$$

lies in the direction of the vector normal to the plane PV1 (see Fig, 2). From this, using simple vector algebra, we see that for any three distinct "retinal" points QI, QJ, and QK the relation

$$[NI, NJ, NK] = 0 \qquad (5)$$

must hold. Here, the square brackets denote a scalar triple product of the three vectors. Equation (5), written out, is an equation of the third degree in 3 unknowns (the components of *A*).

A set of 3 such equations (a minimum of 5 distinct "retinal" points is needed to define such a set) does not have an analytical solu-tion: in general the solution can be obtained only using an iterative technique (a very fast and simple method reported in [5] is used in our computer implementation).

2. COMPUTER IMPLEMENTATION

The solution to a set of equations (5) can be computed locally, given some non-empty neighbour-hood of a "retinal" point Q. In a 'real world* application one should not, however, use locally clustered points. To obtain accuracy in the presence of noise one should use points spread as widely as possible. Also, considering more points in the process of solving for A (perhaps by minimizing some suitable function of differences between the values of A computed at different regions locally) improves" the accuracy with which A can be obtained.

A computer program incorporating the method has been written and experimented with using simu-lated input data (no distortions or noise). The program consists essentially of a local operator which computes A, VI, and the surface normal corresponding to" a"~given image plane point. All three values are computed locally from a neigh-bourhood of a given "retinal" point. The size of the neighbourhood is presently (due to some computational limitations) about 1 degree of arc. The surface normal produced by the opera-tor is essentially that of the best fit planar scale at a given point. The application of the operator to the whole image results in a sur-face-normal map.

The results are encouraging. Using the single precision arithmetic the accuracy of the surface normal map lies within the error of (approxi-mately) 1 degree of arc.

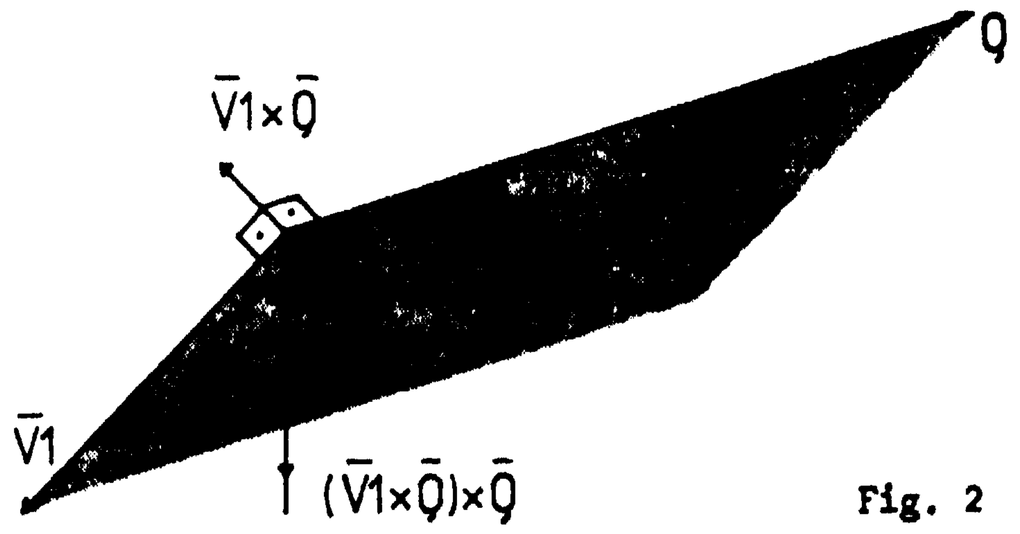

Fig. 2

$(\bar{V}1 \times \bar{Q}) \times \bar{Q}$ and $\bar{V}1$ lie in the same plane, P_{V1}.

3. DISCUSSION

Using the proceeding analysis, it seems plausible that a relatively simple process may be used to recover the instantaneous egomotion parameters and surface normal map in a stationaxy WORLD, The only assumptions made were the smoothness of the movement trajectory, rigidity of the objects, and the existence of the IPVF. This latter is taken for granted and constitutes the greatest weakness of this kind of approach. There is very little known about the behaviour of the correspondence computation-like methods suggested by Ullman (V) using real images, and these or similar mechanisms are, at present, theOnlyway to generate the IPVF.

On the other hand, the above approach applies equally well to the case of a rigid 3D world of moving objects. To see this note the reciprocity between the motion of an object and the motion of the observer; for any objection motion there is an observer motion which, assuming the object to be stationary, generates the same IPVF in the region of the object. (This is the main reason that smoothness of path was the ONLY restriction put on the observer's motion.) Using a simple technique suggested by Nakayama and Loomis [3], we may compute the depth contours to perform a figure-ground separation. Applying the analysis above to each separated image region leads then directly to the surface normal map corresponding to the region. It is not possible, however, to recover the object motion since absolute distances (of which the optical flow is a function) are not recoverable from IPVF*s.

4. CONCLUSION

A method is outlined which is capable (at least in principle) of delivering a surface normal map from an instantaneous positional velocity field (IPVF) generated by a curvilinearly moving observer. While the method is not as elegant and simple as the one developed in Clocksin [7] for the case of a rectilinearly moving observer, it is considerably more general.

It is possible that the analysis outlined above for the case of moving objects may offer some insights into the phenomena of position constancy ("How is it possible that when we move, and thus every optical element on the retina moves, we still perceive a stationary world?**). In that case, after applying the method locally, an "egomotion map** may be constructed which maps each point on the "retina" to this "egomotion space** (spanned *by* the orthogonal components of A And VI). Some evaluation mechanism may be operating in this space, choosing, for example the point into which the 'majority' of image plane points maps as the stationary reference frame. All point mapping into this point (or perhaps some small neighbourhood of it) would then be regarded as projections of the stationary environment.

ACKNOWLEDGEMENTS

I'm in debt to Drs M. Brady and P. *Hays* for many helpful suggestions, and to my wife Dasha who did the layout.

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A KNOWLEDGE-BASED SYSTEM FOR LOCATING MISSING HIGH CARDS IN BRIDGE

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A knowledge-driven system for locating missing Bridge honours In closed hands Is described. The program Is Intended to follow the development given In an expert-level book. Although It Is Incomplete, being as yet confined largely to reasoning from the bidding and opening leads, Its performance to date Is promising! In roughly the first half of the book, It Is able to replicate the conclusions about card location In more than eighty percent of the cases studied. The paper describes the three principal sections of the current program which deal with the analysis of the bidding, understanding the opening lead, and the 'Inference engine' respectively.

1. INTRODUCTION

Recent years have seen the emergence of more and more high-performance systems whose power derives not so much from the merits of an underlying general algorithm, but rather from the richness of the knowledge structures they employ. So for Instance, Instead of having a system to do X that consists of a sophisticated quasl-declsion process (such as a resolution theorem prover) together with a small number of axioms that are sufficient for X in the logical sense, a system of this new breed might be a simple generate-and-test type of data base Interpreter together with a large collection of rules, advice, methodologies and distilled wisdom extracted in some more or less painful way from a human X-pert. A goodly sample of them appears In [8] while the much-cited survey [1] gives an excellent overview.

This *paper* describes the *present* status of such a knowledge-based system whose application area is one small corner of the game of Bridge. After the opening lead each player can see two hands—his own and that of the dummy—leaving two 'closed' hands. Any high card (ace, king, queen or Jack) that does not appear in the open hands must be In one or the other of the closed hands, and often the ability to determine In which hand It lies holds the key to the development of s correct line of play. Expert players can usually do much better than guessing which closed hand holds a particular high card. Clues from the bidding and partial play of the hand may be sufficient to place any given high card with certainty or at worst with high probability. Several expert-level books, notably [2] and [3], are devoted to techniques for achieving this. Since Lawrence's book Is particularly helpful, the goal of this system Is to perform high-card location to the level of that found In [2] and using the techniques outlined therein.

There were two motivations for tackling this particular task. Unlike most games, Bridge Is played with Incomplete Information; this characteristic has *perhaps* been responsible for the relative dearth of AI programs in this area (see [6,7]).

The work reported here was performed while the author was visiting the Computer Science Department, Stanford University, and using facilities made available there by the Heuristic Programming Project and the Artificial Intelligence Laboratory.

Thus knowledge about card holdings can be unspeclflc *(East has either the ace or the king)* and uncertain *(he probably has the king).* Moreover Information can come from different sources; what a player did or did not bid, what he led or did not lead, and so on. In short this problem Is a microcosmio environment In which reasoning processes typical of 'real' problems can be brought Into play. Secondly, It was used to investigate the utility and generality of some current rule-based models, their accessibility to a neophyte knowledge engineer, and their adequacy for this non-trlvlal problem.

As It stands, the system Is only part-way towards Its goal. The following sections give an Illustration of the level of performance that It Is currently able to achieve, and a comparison of results to date with the model (I.e. the book).

2. AN EXAMPLE

Imagine if you will that you are sitting in the South seat for the hand shown in figure 1. Your analysis as you attempt to locate the missing honours might run something like this:

> West led the ¥4. He would not underload an ace, so he does not hold the ace in the suit lesd. Neither the dummy nor I have it, so East must have the ¥A.
>
> West's lead is weak, suggesting that he was unable to make a stronger lead such as from the ace-klng or king-queen of an unbid suit or from any sequence of honours in his own suit. In particular, then, he does not hold both the VQ and VJ.
>
> It Is unlikely that East would have played from the middle of a sequence. Since East holds both the VA and vK, he cannot also hold the VQ (otherwise he would not have played the king). Therefore West hss It
>
> Since West does not have both the VQ and VJ, but does have the VQ, then East must have the V J.
>
> There are 40 high-card points in all. Dummy and I together have 10, so East and West together hold 21.1 already know that East has the VA, VK and VJ for a total of 8 high-card points; If he held so much as another queen then West would have opened the bidding with at most 11 high-card points, which is unlikely. Therefore the ♦A and 4Q and the 4A are with West.

Reasoning along these lines, South is able to pinpoint each missing honour except the 4J. In his analysis he has made

North
♠ K Q 5
♥ 6 2
♦ K 10 8 3
♣ Q 10 3 2

South
♠ A J 10 9 4
♥ 9 7
♦ J 7 5
♣ K 9 4

West	North	East	South
1♥	pass	2♥	2♠
pass	3♠	pass	pass
pass			

Opening lead: ♥4
First trick taken by East with ♥K

Figure 1: A sample hand for analysis.

use of several sources of Information. Besides facts about this particular hand there are rules or guidelines that South believes his opponents will adhere to, such as

An opening bid indicates at teast 12 high-card points.
Opening ieaders avoid underfeeding an ace.
Third hand does not play from the middle of a sequence.

The guidelines are used in conjunction with facts to obtain new facts by •everyday' reasoning processes. Knowing that West would not underload an ace *(guideline)* and that he led the ¥4 *(fact)* give *us* that he does not have the VA *(fact).* Having determined that he does not hold both the VQ and VJ *(fact)* but that he has the VQ *(fact)* implies that he does not have the VJ *(fact).* The guidelines are also used negatively—patterns such as 'If he held x he would have done *y*\ since he didn't, he does not hold x are common In bridge books.

3. SUMMARY OP RESULTS

The first substantial chapter of the book basically restricts itself to analysis of who has what using Information from the bidding and first trick. It contains fourteen case studies, in all of which the unknown hands belong to the defenders. For each study we *are* given the open hands, the bidding and opening lead, and sometimes further history of the play of the hand.

In Its current state the system can handle these studies fairly comfortably. Its conclusions are identical to those of the book In twelve of the fourteen cases; the example of the previous section Is one of them. Of the other two cases, one is almost correct—a single queen Is misiocated. The remaining case Is unusual In that the analysis In the book, which follows play down to the fifth trick, is concerned only with the more likely location of a single card, using both a rule for understanding play and a technique called *counting* that have yet to be incorporated in the program. On this example the system understandably flounders.

In the next chapter the focus Is on the opening lead, with a battery of quizzes and eight more case studies. The system performs well on six of the eight, Is slightly deficient in one case (missing out on one queen), and has substantial difficulty with the remaining case, which uses Information from the first three tricks and once again requires counting.

These chapters constitute about 40% of the material In the book. Of the twenty-two case studies they contain, the system locates the missing high cards with the same precision In eighteen cases, slightly lower precision In two cases, and with shortcomings attributable to the absence of crucial mechanisms In two cases.

As a further test, the program was run on some hands that had not been used In its development: those from the next chapter of [2] and from the bidding analysis chapter of [3]. For each of these 18 hands the program was given only the bidding, known hands snd opening lead. It managed to locate a total of 14 honours with certainty (all correct), and made an additional 13 less specific asserlons of the form 'x holds either y or z[1] (one error). It accurately established the high-card points of esch closed hand (usually to within a range of two or three points) In all but one case when It was one point out.

4. DESCRIPTION OF THE PROGRAM

Like Gaul, the system Is divided roughly Into three parts concerned with bidding, opening leads and commonsense reasoning respectively. (There is In addition an embryonic play section which merely ssys that play from a sequence Is either from the top or the bottom.) The system Is written In INTERLISP [6] and takes a few seconds of DEC KA-10 time to complete the analysis of a hand.

4.1 Bidding

Bridge bidding Is notoriously complex. The bidder must choose what Incomplete Information he wishes to convey about his hand and the most economical message for doing so unambiguously. However, our program does not have to *make* bids but Instead *understand* them; It does not have the problems of choice of Information or bid, but only the problem of decoding the message once the bid is made. The Information extracted from a single bid Is primarily the range of high-card points and suit holdings that It indicates, but more general distributional Information for the opening lead module Ia also extracted from the bidding as a whole.

The method of determining the nature of a bid is simply to find a rule which it matches in context, so this part of the program is similar to a pure production system. The 2¥ bid In figure 1 matches a rule that may be stated aa

if partner has Just opened or overcalled in a suit, and
the intervening bidder has passed, and
this bid is a minimum raise of partner's suit
then this Is a weak reply Indicating 5-9 high-card points and three or more cards in the suit bid

To date only the more common bids have been Included—the program understands passes; openings of one In a suit or strong no-trump; overcalls; second round openings; tskeout doubles; free, weak and strong replies; and reblda. Thla entire body of bidding knowledge consists of 18 rules.

4.2 Opening Lead

The second principal source of facts is the opening lead. All twenty-two case studies reach a suit contract, so the program was restricted to analysis of opening leads against sub-slam suit contracts; sections for leads against no-trump and slam contracts should be quite similar.

Analysis of the lead requires mechanisms that are awkward to express In any conventional rule format. The underlying Idea is that leads are ranked by their strength, and that a neutral or weak lead Indicates an inability to make a stronger one. This ranking Is most fluently represented as a strongly ordered sequence of rules of the form *If—then*—e/se, where no rule can fire unless all previous ones have failed to do so. For Instance the first such rule developed tests for the lead of an ace In an unbld suit, while the second Is

If the lead Is a king of an unbid suit

then the leader also holds either the ace or queen of that suit, but not both

e/se the leader does not hold the ace-king or king-queen of any unbid suit

where the e/se clause uses the ordering of rules to establish that the lead was neither the ace nor king of any unbid suit.

The lead-understanding module in fact contains three components; a supplementary unordered set of productions, a procedural section to classify suits (e.g. as *unbld),* and 12 of these unorthodox *If—then—else* rules. Despite its simplicity It turns out to be surprisingly accurate, accounting exactly for all but three of the 80-odd such opening leads In the book. One error was the result of a strong lead of trumps, the other two were caused by perverse distributions. The procedural section attempts to Identify suits In which the leader Is likely to hold either a singleton or a doubleton, using Information from the open hands and distributional clues from the defenders' bidding. If the real distribution of the suit led is *Very* different from the predicted one then the lead can be misinterpreted. However the figures indicate that such situations are rare.

4.3 Commonsense Reasoning

The bidding and opening lead are sources of facts. The third component of the system Is the embodiment of reasoning processes that inter-relate guidelines and facts to obtain new facts. This component was developed using AGE [4], a package that guides the novice in the design and testing of rule-based systems. The prototype AGE was limited to a 'blackboard' model In which rules are partitioned Into 'experts' Invoked by 'events', but this seemed quite appropriate for the reasoning task. The package did suffer from a real if temporary limitation, however, in that an event could Invoke only a single expert. Rather than program around this and other very minor Irritants, the structures developed were translated to INTERLISP pending a more advanced version of AGE.

The most Interesting facts are naturally those ascribing particular high cards to particular hands, it is not always possible to discover facts of this form directly; instead, they must be derived from Intermediate, less Interesting facts. However the variety of facts that have bearing on the location of missing high cards is limited. A hand can be asserted to hold a particular card, one or more of a set of cards, or not all of a set of cards. It can also be described by the possible range of high-card points and suit holdings it contains. An event is taken as the discovery of any such fact, and can trigger one or more of eight experts containing a total of fifteen rules. Each expert encapsulates all knowledge of some facet of the reasoning task? for Instance, one knows about the consequences of high-card point ceilings, another about the implications of locating a particular card. A sense of purpose is maintained by giving priority to experts capable of generating facts of the first (and most interesting) form.

6. CONCLUSION

The performance of the program to date Is encouraging, especially In the light of the small number of rules with which it has been equipped. The next steps In Its development are clear: the addition of a section for counting, the Installation of a more powerful play-understanding component, and the fiiiing in of the gaps in the system's knowledge of bidding and leading. None of these present any conceptual problem.

The program has one glaring weakness. While It can accomodate vagueness it cannot resolve conflict such as might arise if the opening lead Indicates that one player does not have a particular ace, while arguments from high-card points indicate that he does. There is a need to be able to associate a degree of certainty with a fact or a guideline. Fortunately one of the most advanced features of AGE Is Its provision of mechanisms for specifying, propogating and updating such certainty factors. When the program is recoded in AGE this weakness should disappear.

The program in Its present form represents about two man-months of effort and 13 pages of code. With the exception of the *If—then—else* rules, the concepts and techniques It uses are standard. This suggests that current ideas for rule-based systems, especially when Incorporated In systems with a tutorial capability, have put knowledge engineering within reach of the masses.

ACKNOWLEDGEMENTS

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USE OF THEMATIC INFORMATION TO SPEED SEARCH OF SEMANTIC NETS

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ABSTRACT

A model is proposed for the representation of thematically integratable information in semantic memory and a process for searching through this memory. We assume that releted fects about an individual are not directly attached to the individual node, but rather, are indirectly attached via a thematic sub-node. Thematic sub-nodes allow much faster search of memory under certain conditions, but not others. We tested these predictions with human subjects a*nd* found support for these notions.

There is little doubt that the time to searcn a computer data base depends in part on the number of facts stored *in* it. Similarly, the time for humans to retrieve a specific feet from memory has been shown to depend on the number of other, related facts. A large number of reaction time studies (e.g., Anderson, 1974; Anderson & Bower, 1973; Hayes-Roth, 1977) have found that subjects are slower to recognize a fact the greater the number of facts learned to the same concept. For example, subjects are slower to recognize the fact "The psychologist wanted to go to Japan" if they have also studied "The psychologist thought the research was good" and "Everyone loves Japan" than if no other experimental fects share concepts, with the probe. This particular result has been named the *fan effect* because latencies are found to be a function of the number of propositions *fanning* out of a given concept node in a propositions! network representation (see Anderson, 1976). (Subjects are also slower to reject unstudied probes as a function of the fan of their concepts.)

There is a paradoxical aspect to the result that the more facts a person knows about a concept the slower he or she is to verify any one of them. It seems intuitive that experts (a) know lots of facts about certain topics, and (b) can answer more questions on those topics and answer them faster than anyone else. However, certain situations can be pointed out where experts seem to experience a type of interference that results from too much similar information. Learning a new text editor in many ways is much easier if one has used a similar editor before. However, the more editors a person uses, the harder it is to keep the commands straight.

Even though experts may sometimes suffer more interference than non-experts, it also seems that if their information can be *Integrated* into various themes, then somehow the information should be less interfering. Consider the following knowledge representation for facts about an individual and process model for searching this knowledge: all facts studied about the individual are attached to that individual's concept node. However, propositions that can be considered to be thematically related are not attached directly to the person node; rather, they are attached to a theme node that is attached to the person node. Figura 1 gives a representation for the following four sentences: *Melvin crossed his skis. Melt/in shussed down the slope. Melvin washed his* car. *Melvin* got *on the chair lift.* Facts that can be considered as having to do with Melvin-skiing form a sub-node attached to Melvin. Facts that are not so related are attached to Melvin directly. The *fan* out of the Melvin concept, then, is two rather than four.

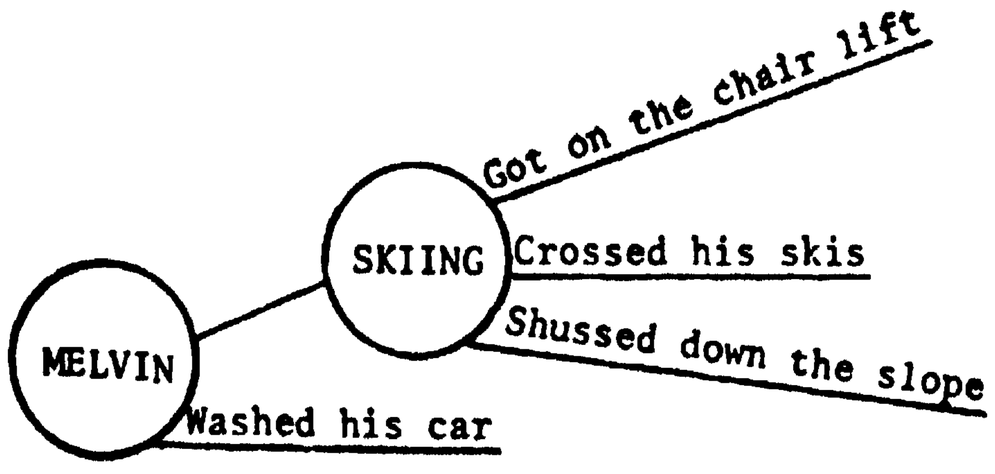

Figure 1: Portion of the Semantic Network encoding facts about Melvin.

s researcn was supported in part by NSF grants BNS76-00959 and BNS78-17463 to John R. Anderson and by a*n* NIMH post-doctoral fellowship to Lynne M. Reder. We would like to thank T. Iwasawa for assistance in programming and in running subjects.

The search mechanism works as follows: The probe sentence is parsed Each concept of the probe is activated in memory and activation spreads out along each arc attached to the concept. *Starch energy* is assumed to be a constant for each activated concept. How much activation or search energy a particular arc receives Is a function of the total number of arcs emanating from the concept (the amount of fan).

In earlier experiments on the fan effect, the facts associated to a person were unrelated. In those situations, the search mechanism predits a simple effect of number of facts on time to recognize a probe. However, our predictions are more complex for the representation in Figure 1. We would predict that the time to verify *Melvin washed his oar* would be the same us if we had learned only two unrelated facts about Melvin. Our predictions about *Melvin crossed his skis* are somewhat more complex.

The fan out of the Melvin concept is two. The fan out of the Melvin-skiing sub-node is three. Whether there is an effect of sub-node fan when attempting to recognize one of several thematically related facts depends on the nature of the *foils* or false probes. If, for example, the probe to be rejected is *Melvin baked a* cafes, search need not continue past the Melvin-skiing sub-node: it is clear to the subject that cake-baking is not part of the skiing theme. If, on the other hand, the probe to be rejected is *Melvin perfected his stem-christies,* search must proceed beyond the sub-node to inspect each proposition attached to it until the correct one is found or all stored propositions a*re* exhausted.

EXPERIMENT

To verity this model* we conducted an experiment where subjects learned facts about various characters. These facts belonged to various themes, e.g., buying a car, jogging, going to a circus. A particular character could have one or two themes associated with him or her and one or three facts associated with a given theme. For example a character with six associated facts would have three facts about each of two themes. A character with four facts would have one fact from one theme and three facts from the other. Each condition in the experiment can be described by tv/o digits, representing the number of facts in each ineme associated with a given character. The conditions *are* (1,0),(1,1),(3,0),(3,1),(3,3). The O's denote conditions where there was only one theme.

Subjects studied these character-predicate pairings until they knew the facts perfectly (could recall all the facts about each character several times in succession). After this phase was completed, subjects went into the critical phase in which reaction times were collected to answer questions about the material studied. One sentence was. displayed on the screen at a time. The subject was told to press the yes or no response key depending upon whether the subject thought it had been studied during the acquisition phase. Test probes were presented in random order. The foils (sentences subjects had not studied) were of two types and were separated into different test blocks. One type was the *thematically related foil* (e.g., *MeU/in enjoyed deep powder),* and the other type was the *unrelated foil* (e.g., *Melvin baked a* cake). Both types of foils have the *property* that their predicates (verb-phrase) were studied with another

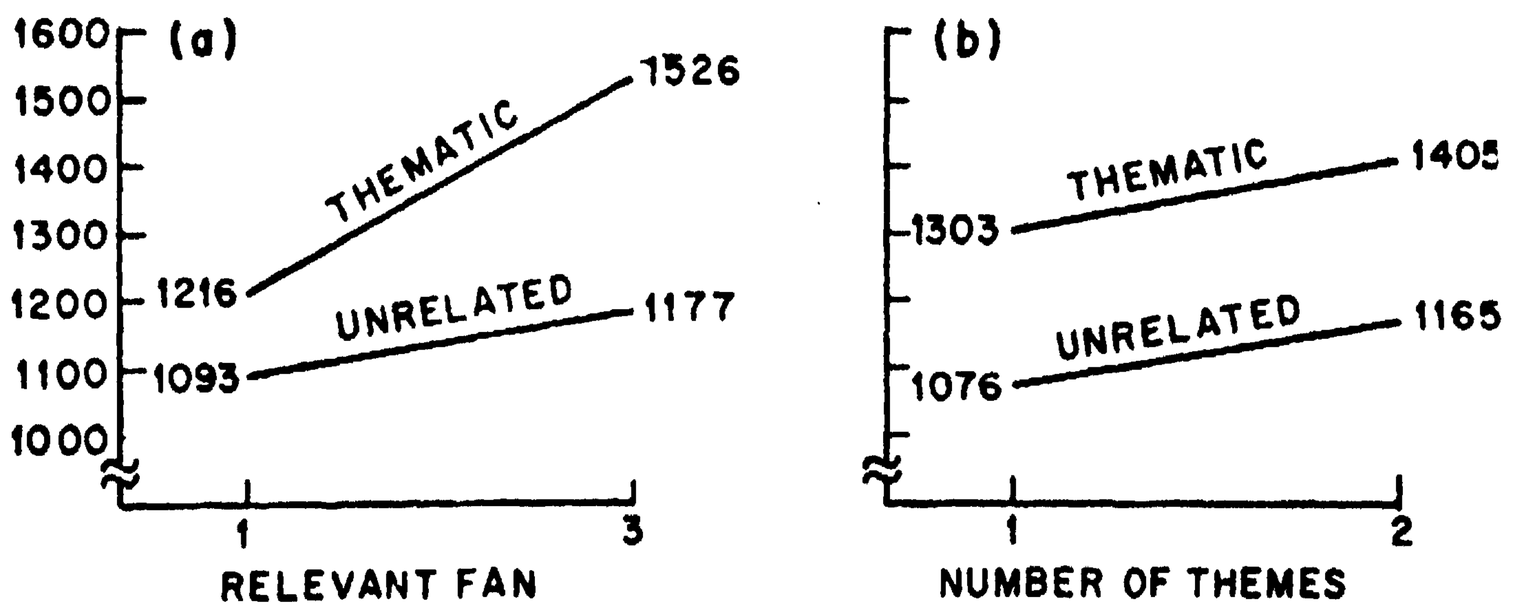

Figure 2: Mean reaction time to judge that a probe had beon studied as a function of number of thematically related facts (graph a) and as a function of number of themes (graph b).

*We actually tested two alternative models in this experiment, but space constraints require this simplification.

character during the experiment. This ensured that subjects could not reject a probe simply on the basis of lexical familiarity.

We had two principal predictions for this experiment. First, when the foils are unrelated, there should be a much smaller effect of number of facts studied. This is because subjects should be able to make their judgments just by inspecting the theme subnodes.** They would not have to search the facts attached to these nodes. Our second prediction was that there should be an effect of themes (more themes means more arcs out of the person node), but that it should be small since subjects can quickly reject the wrong theme sub-node, and not be affected by type of foils since the extra sub-node is rejected in the same fashion regardless of foil-type.

RESULTS

Figure 2 displays the data (latencies in milliseconds to decide whether the probe had been studied or not) partitioned two ways: on the left, the data are analyzed as a function of the amount of fan relevant to the probe that is attached to the character in question. For example, the relevant fan for a Melvin skiing probe would be three because the subject studied three Melvin skiing facts. If the probe had concerned Melvin and his car, the relevant fan would have been one. On the right, the data *ere* displayed as a function the number of themes associated with the character in the test probe, which can be one or two. Melvin has two themes, skiing and car washing. (There is no sub-node for car-washing because only one such fact was studied.)

Each graph plots two functions, one labelled unrelated and one labelled thematic. As explained above, the unrelated-thematic factor reflects the type of foils from which the subject had to discriminate the studied probes. The left panel plots the data as a function of the number of facts involving the same theme as the test probe. Subjects take longer to verify that a fact was studied the more other related facts were also studied. However, this fan effect is severely attenuated when the foils are not thematically related. Moreover, as predicted, subjects respond much faster in general when the foils are unrelated. We take this to mean that subjects have a less stringent criterion of saying "yes, this sentence is old" in these blocks. Subjects only search as far as the sub-node before responding when foils are not related to the sub-node. Smith, Adams, and Schnorr (1978) have also found that the fan effect is reduced with unrelated foils. (However, they did not have the other conditions of this experiment viz., testing with thematic foils, and manipulating the number of themes associated with a character.)

If there it only on* them fact, wo assume subjects do not bother to form a subnode Inspecting nno proposition is probably equivalent to inspecting o theme sub-node.

The data on the right shows the effect of number of themes. *Here* too there is an effect of fan for themes, however this effect is smaller and is not affected by the related/unrelated foil block distinction. The lack of interaction of theme-fan with foil-block type was predicted. Regardless of type of foil, the subject must at least find the relevant sub-node before responding "old". If there is only one theme associated with a character, the fan off the character node will be less. Therefore, search should be faster than with two sub-nodes or a fan of two off the character node.

CONCLUSION

The data support the view put forth in the introduction that facts are not necessarily attached directly to the concepts in their propositions, but rather can be organized into thematically consistent subnodes. It seems to us that, in general, sub-nodes in memory serve several functions. First, sub-nodes make plausibility judgments easy. Typically people are not asked to discriminate thematic foils from related statements; normally one would accept as plausible other related skiing facts about Melvin (see Reder, 1979, for a fuller discussion) Second, by having many sub-nodes in memory, the number of propositions that must be inspected is smaller. If a subject is searching for a fact about Melvin baking a cake, she or he *need* not search all of the skiing facts to find it--search stops on a wrong path as soon as the sub-node is reached.

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THE STRUCTURE AND PERFORMANCE OF THE INTERIM.2 GO PROGRAM.

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We describe interim variants of a Go program based on skilled human models. The program maintains a permanent, selectively-updated, multilevel network analogous to the skilled player's perceptual and cognitive representation of the game situation. Moves are chosen by a hierarchy of experts and critics operating on this network. Lookahead is a selective, goal-related process, one among many components of Go skill. After an overview of system organization, we illustrate the program's performance with three segments from actual games.

1. PROGRAM DESIGN CONSIDERATIONS

Berliner [1] suggests that though whole-board exhaustive search programs may one day play championship-level chess, "such an approach cannot possibly work for Go, and this game may have to replace chess as the task par excellence for AI." Go certainly has many features that recommend it for this purpose. Its primitive elements, black and white stones played on the 361 points of a 19 x 19 grid, generate complex patterns and problems that tax the highest levels of professional skill.

Go games typically run 200 moves or more, and each turn offers on average close to 250 legal plays. Brown and Dowsey [2] estimate the number of possible games of Go at about 10 700, compared with 10 120 for chess, and they point out that exhaustive Go search only three moves deep would entail generating and evaluating about 8,000,000 whole-board positions. Yet videotaped game records [3] show that advanced amateur players can look 30 moves ahead, and the Go literature contains still deeper lookahead sequences. This means that lookahead in human Go play is a highly focussed, selective, goal-related process. The size of the possibility space appears to rule out a Go program organization analogous to the exhaustive whole-board lookahead and evaluation schemes used in most current chess programs.

The game also has a very strong visual or perceptual element. Local stone patterns and large-scale spatial relations among groups and territories both are crucial. Most of these patterns and relations continue unchanged from any one move to the next. This argues for a permanent, selectively-updated, multilevel network of data structures to represent the elements, patterns, and properties, as well as the interrelations within and across levels.

Finally, both positive and negative interactions are extremely significant at all levels. To play Go well, it is necessary not only to determine the most important objective at any given time, but also to advance it in ways that simultaneously achieve as many secondary benefits as possible. This motivates the use of hierarchies of experts and critics, each responsible for a class of options, properties, or functions associated with elements of a given type and level.

2. DATA STRUCTURES AND CONTROL FLOW

With these considerations in mind, turn now to Fig. 1 , which shows the flow of control in the INTERIM.2 program. At the top level, this consists of a two-part cycle. First, immediately following a play by either side,

Fig. 1 is a simplified representation. Many function names have been changed for mnemonic reasons. Many other functions at the control levels depicted in the figure have been omitted altogether. To take an extreme example, DEVELOP.GROUP actually consists of about 20 distinct option specialists. Finally, PROBE is called at many points other than those shown, and is bracketed to indicate this.

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```
MOVE
  UPDATE.POINT.TYPES
  UPDATE.STRINGS
  UPDATE.LENSES
  UPDATE.LINKS
  UPDATE.GROUPS
  UPDATE.WEBS
  UPDATE.SECTOR.LINES
  UPDATE.TERRITORIES
  UPDATE.TACTICAL.ANALYSES
    [PROBE]
  UPDATE.GROUP.STABILITY.ESTIMATES
REFLEX
  LOCAL.URGENT
    PLAY.JOSEKI
    STRING.ATTACK.AND.DEFEND
    LINK.ATTACK.AND.DEFEND
    RE.EDGE.LINK
      [PROBE]
    VITAL.SHAPE.POINT
    CONTACT.FIGHT
DEVELOP.GROUP
  KILL.CUTTING.STRING
  EXTEND.AND.SQUEEZE
  COUNTERATTACK
  CROSS.SECTOR.LINE
  STABILIZE.POTENTIAL.TERRITORY
  RUN.TO
ATTACK.GROUP
  WIPE.OUT
  SHAPE.POINTS
    [PROBE]
  SQUEEZE
  ENCLOSE
RUN.TOWARD.DEAD.GROUP
EXTEND.SECURE.INVADE
DEVELOP.POTENTIAL.TERRITORY
ENDGAME
```

Figure 1. Program Organization.

MOVE updates all those elements of GAMEMAP, the program's multilevel representation of the situation, that have been affected by the latest move. Next, if it is the program's turn to play, REFLEX chooses a move.

GAMEMAP is indexed through a set of interrelated GAMEBOARDS. Each board is an array that points to all data structures of a particular type. At the lowest level, the TYPEBOARD gives quick access to bit pattern information about specific points (empty, occupied by black, part of a white territory, etc.). Some boards, e.g., STRINGBOARD and LINKBOARD, index the basic game elements at the various levels (strings, linkages, groups, territories, and potential territories). Thus

In Fig. 2, for example, looking up the board point B6 in the LINKBOARD array enables any program function to access the data structure

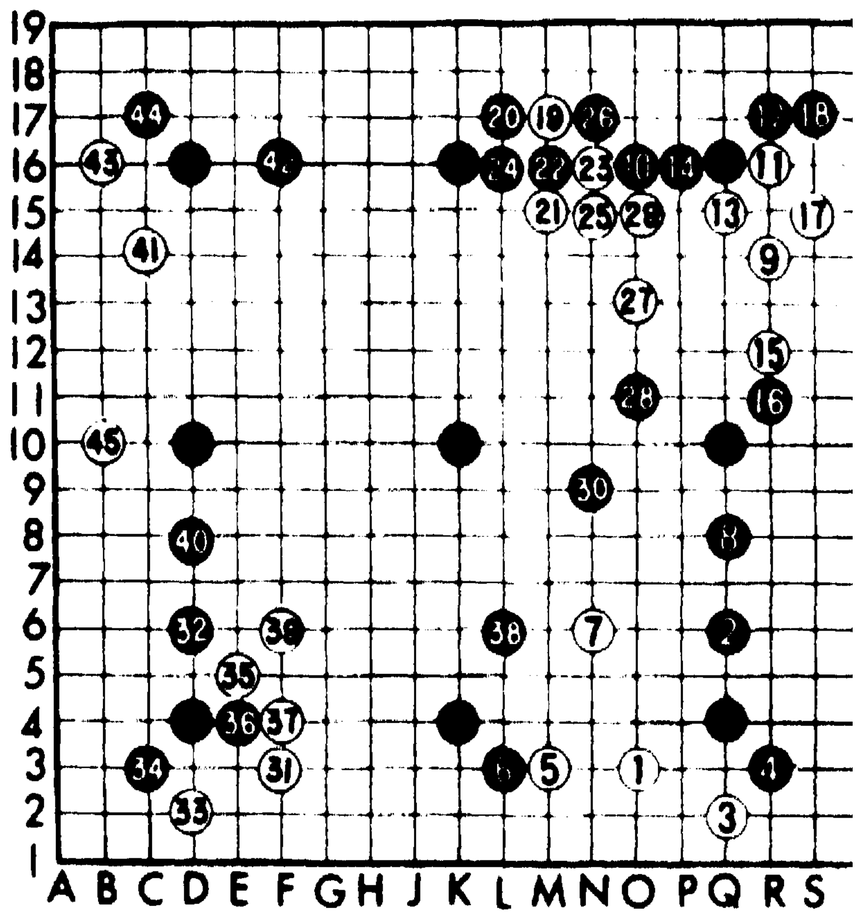

Figure 2. The First 45 Moves.

representing the linkage from the DB string to the left edge of the board. Other boards, e.g., LENSBOARD, WEBBOARD, SECTORBOARD, and TACTICSBOARD, index elements analogous to those in a skilled Go player's perceptual and cognitive representation of the current situation. Lenses represent and monitor local stone patterns. Web data structures are surrogates for certain kinds of visual scanning. Webs follow the external configuration of groups, radiating out and indexing the surrounding board points. Thus they are useful in analyzing and detecting changes occurring around individual groups. Referring again to Fig. 2, looking up B8 in the WEBBOARD, for example, gives access to the webs around white B10 and around the black group on the lower left. Sector lines, e.g., the one between B10 and C1M, correspond to those looser relations among stones that dynamically divide the board into tenuously defined regions. These sector barriers help define potential territories and strategic threats to groups. Finally, the TACTICSBOARD indexes tactical data structures associated with individual strings, linkages, and significant board points. These data structures record the results of analyses produced by calls to PROBE, the entry point to

the subsystem responsible for all INTERIM.2 lookahead. This is selective, best-first lookahead. Each such analysis answers some specific tactical question about the associated element. The resulting tactical data structure is maintained as part of GAMEMAP unless invalidated by subsequent moves that affect strings or board points involved in the analysis, at which point PROBE is called to reanalyze the situation.

2.1 Updating the Representation after a Move

To fix ideas, consider the situation shown in Fig. 2. Ignore the order of play for the moment. As soon as white plays move 45 at B10, MOVE is called to update GAMEMAP. This updating is selective. Only structures directly or indirectly impacted by the move are affected. UPDATE.POINT.TYPES alters the TYPEBOARD entry for BIO from UNOCCUPIED to WHITE-OCCUPIED, and UPDATE.STRINGS sets up a string data structure representing B10. Now UPDATE.LENSES creates a lens that will monitor any future board changes around the pattern formed by white B10 and black D10. In addition, it sets up a shape lens which it associates with B10. This lens, when queried, will suggest locally good developmental plays for white, e.g., at BB and B12. The existing shape lens associated with D10 is modified, since white B10 alters the shape development possibilities for D10. Finally, the existing lens monitoring the D6-D10 linkage also is altered, since white BIO changes the 'possibilities available for attacking and defending that linkage.

White *45 disrupts the linkage between black D10 and the edge of the board. Therefore, when UPDATE.LINKS is called, it deletes from GAMEMAP the data structure representing this linkage. Such changes in higher-order data structures may induce further changes in lower-order ones. This change, for example, results in UPDATE.-POINT.TYPES deleting from the TYPEBOARD the information that A10, B10, and C10 are involved in a black linkage to the edge of the board.

Some plays, e.g. white 43 and black 44 at the top left of Fig. 2, add stones to existing groups. Others, such as white 45 at B10, create new groups. UPDATE.GROUPS is responsible both for modifying existing group data structures and, as in the present case, creating new ones. GAMEMAP represents white B10 at both the string and group levels because the analyses and decisions at the two levels entail quite different kinds of considerations. Next, UPDATE.WEBS creates a web data structure indexing the board points surrounding B10. The web reaches out to the white group at B16 and C14, the open area around E12 and E13, and the black group beginning at D10 and running down toward the bottom of the board. Finally, as the B10 stone impinges on the existing webs radiating out from the white group on the upper left and the black group running down the left side, UPDATE.WEBS also modifies those webs, to reflect the presence of this white stone in their vicinities. These web data structures may be used by any REFLEX functions considering attacks on adjacent enemy groups, or defensive plays running a group toward friendly groups or out into unoccupied areas.

UPDATE.SECTOR.LINES now creates a data structure representing an imaginary line running from B10 to C14. This sector line is used by UPDATE.TERRITORIES when it creates a potential territory data structure corresponding to the area bounded by the two white groups on the left of the board. UPDATE.TERRITORIES also modifies the territory data structure running between the lower left edge of the board and the black group running down from D10. Before white 45, that territory was bounded at the top by the linkage from D10 to the left edge. Since UPDATE.LINKS has deleted that linkage, the territory must be redefined. This is done by designating the next nearest intact linkage, from DB to the edge, as the new upper bound. This higher-level modification also induces changes in the TYPEBOARD, since points such as B9 and C9, which formerly were black territory points, now no longer are.

Now UPDATE.TACTICAL.ANALYSES calls PROBE to assess the tactical status of strings and linkages created or potentially affected by the most recent play. No actual lookahead is required for the B10 string, which is found to be tactically secure on the basis of context information from GAMEMAP. When contextual information is insufficient for a decision, PROBE may generate lookahead sequences running from a few hypothetical board positions to 50 or more. It is worth reemphasizing two points here. (1) All PROBE lookahead is intended to answer a specific question, e.g., about the tactical security of a string or linkage, posed by the function invoking PROBE. (2) PROBE records its results for each such element in a tactical data structure which is maintained as part of GAMEMAP until the analysis is called into question by some subsequent move. This tactical data structure can be accessed both from the data structure representing the string or linkage, and also through the TACTICSBOARD (see Section 5 for an example).

Finally, UPDATE.GROUP.STABILITY.ESTIMATES provides a stability rating for the B10 group. It also alters the stability rating for the black group running from D10 to C3. This is because white 45 has undercut the side territory associated with the group. This information will now be available to DEVELOP.GROUP when next it is invoked from REFLEX.

To summarize, MOVE and its subfunctions serve at least three vital purposes. They carry out, at progressively higher levels, the aggregation and analysis of the patterns and structures representing the game situation. Thus they provide the basic elements the REFLEX functions deal with. They maintain the data base that allows the REFLEX functions to deal with each element in context. This enables the program to locate interactions and find moves that do several jobs at once. Finally, MOVE updating corrects the representation after each play, deriving its immediate implications at every level it affects. This is how the program finds out the consequences of its own moves, and those of its opponent.

2.2 Choosing the Program's Next Move

Returning now to Fig.1, REFLEX is a temporary control structure that steps through an ordered list of functions and accepts the first move returned from them. LOCAL.URGENT and its subfunctions are responsible for dealing with any urgent problems that may have arisen as a consequence of the immediately preceding black-white move pair. Each subfunction uses information generated by MOVE, and each has a limited ability to assess the local significance of the class of problems it deals with. If STRING.ATTACK.AND.DEFEND finds that a significant friendly string is threatened with capture, it will attempt to generate a move to save it. If the threatened string serves no important function, however, control passes to the next subfunction. The situations dealt with by the LOCAL.URGENT subfunctions are illustrated in the examples that follow.

If there are no significant locally urgent situations resulting from the immediately preceding moves, control passes to DEVELOP•GROUP. This function, working both with the group stability data computed under MOVE, and with assessments of the values of each of the program's groups, selects the friendly group it considers to be most worth developing. It then invokes its subfunctions in the order shown in the figure. Each has information about a class of developmental options, the conditions under which these options are appropriate, and the means available for realizing them. KILL.CUTTING.-STRING, for example, determines whether there are any enemy strings separating the group to be developed from an adjacent friendly group. If so, it will try to kill one of them. Several other DEVELOP.GROUP subfunctions, e.g., CROSS.SECTOR.LINE and STABILIZE.POTENTIAL.-TERRITORY, also are described in the examples that follow.

If there are no valuable friendly groups in need of development, control passes to ATTACK.GROUP. This function considers the various enemy groups, again ordered by value and stability, and attempts through its subfunctions to generate suitable attacking moves against its target. Section 4 presents a detailed illustration of attacks generated by the SHAPE.POINTS subfunction.

If there are no attackable enemy groups, control passes to the remaining midgame and endgame functions, in the order indicated. Thus RUN.TOWARD.DEAD.GROUP is a midgame function that attempts to reduce the scale of capture of a friendly group. This function may be called for any of its groups the program considers to be strategically dead, i.e., incapable of development to the point of absolute stability.

To summarize, the move choice process proceeds from general problems and options to more specific ones. The system relies on the experts at each level to know a good deal about the options available there. This has two consequences. First, usually only the best few possibilities at any level are considered. Second, if higher level experts have chosen properly, then lower levels also need only consider the best more specific options. Thus, referring ahead to Section 4, if REFLEX is correct in concluding that at that point in the game its best option is to attack, and ATTACK.GROUP is correct in its choice of an appropriate target and a specific means of attack, then SHAPE.POINTS need only come up with the plays that best carry out this hierarchy of objectives in this situation. There may be other considerations at a lower level that might improve the final choice there, but that is the responsibility of the critics at that level. Since the functions at each level generally provide an ordered set of choices, the critics have alternatives to work with. And if the situation changes, so that the specific low-level objective no longer has priority, both the situational change and its

immediate implications will be picked up on the next pass through the MOVE-REFLEX cycle.

2.3 implementation

The INTERIM.2 programs are written in LISP/MTS and run on the AMDAHL/470. They compile into about 330k words, use about six cpu seconds per black-white pair of moves, and create about 86 hypothetical board positions per move pair. Real response time usually is a good bit faster than that of the program's human opponents. For additional information about lenses, webs, PROBE, and all aspects of the program code, see [4], [5], [6], and [7], respectively.

3. OPENING GAME PLAY

We begin our examples with Fig. 2, which showns the first 45 moves from a nine-stone handicap game against a 10 kyu opponent. White's first two moves, and the program's responses, form a standard, mutually equitable, sequential pattern (joseki). The program plays out such sequences from information stored in a Joseki lens. This is accessed under the control of the PLAY.JOSEKI subfunction of LOCAL.URGENT. We include in the program's knowledge base only a handful of the thousands of such patterns, because we are mainly concerned with developing the program's ability to analyze situations and generate appropriate responses on its own.

With black 6 at L3, the program leaves the joseki. Black 6 is generated by LOCAL.URGENT, because white 5 undercuts a black potential territory to the left of K4. Black 8 is motivated by white's jump at 7 to N6. Prior to white 7, the black group in the lower right is considered stable, in part because it is adjacent to an unthreatened potential territory (the area along the right side between Q6 and Q10). Edge potential territory is considered secure if neither of its side boundaries is (1) undercut, or (2) defined by a single stone flanked by an enemy stone (in which case an enemy invasion of the potential territory would, simultaneously, threaten the boundary stone), and if (3) there is no nearby enemy stone with access to the outer boundary. This third condition is assessed by determining whether there are any enemy webs that cross into the potential territory. After white 7 at N6, MOVE finds this third condition violated. The potential territory is therefore declared unstable, and this then causes UPDATE.GROUP.-STABILITY.ESTIMATES to declare the adjacent black group unstable.

When control passes from MOVE to REFLEX, since there are no significant LOCAL.URGENT situations, DEVELOP.GROUP is called to restabilize the lower right black group. Finding no good attack on an adjacent enemy group, DEVELOP.GROUP calls STABILIZE.POTEN-TIAL.TERRITORY in an attempt to restabilize the adjacent potential territory. This produces the play at Q8, which restabilizes the potential territory, unites the Q4 and Q10 groups, and lays claim to what is now a real territory along the side. After white 9 at R14 and black's joseki lens response at 016, white 11 at R16 branches off into a Joseki not in the program's repertoire. Once MOVE has updated GAMEMAP, REFLEX calls LOCAL.URGENT, which finds three alerts. White 11 threatens black's claim to corner territory. It initiates a contact fight, because white's stone has been played in contact with one of black's [8]. And it creates a vital shape point at Q15. Reestablishing the territorial claim takes priority because the territory is large and contributes to the stability of the Q16 group. Therefore, RE.EDGE.LINK is called. Using lens pattern data for such a local configuration, RE.EDGE.LINK comes up with two move candidates, R17 and Q17. Of these, R17 is preferred because it gives white less room to maneuver. R17, however, would set up a linkage to Q16 that might, in some board configurations, be subject to a successful white cut. Thus RE.EDGE.LINK now invokes PROBE, to see whether the cut can be sustained in this context. PROBE finds it can not be, so REFLEX returns R17 for black 12.

White 13 at Q15 also triggers several LOCAL.-URGENT alerts. The first priority is to protect R17. Any move proposed is checked by PROBE lookahead to see if it also secures the threatened Q16-R17 linkage. The proposed move is further checked against two other sets of criteria, those applying to contact fights and those for plays around territorial boundaries. In this case, the move finally chosen satisfies both the priority objective and these others as well.

White 15 again threatens to undercut a territory, and so provokes black 16 at R11. This is appropriate since the opponent is stronger than the program, the territory is large, and protecting the territory helps keep the black side group stable. White 17 at S15 triggers a LOCAL.URGENT shape alert, since it threatens the followup at S17. The program

Go ranking is explained in Section 6.

therefore plays 18 at S17, to deny white that point. The idea is to preempt and defuse such situations whenever it is locally advantageous for the program to do so.

With 19, white invades the program's top potential territory before it gets too large and secure. The program's response at L17, its first bad move, results from a bug. White 21 also is an error, however. And now through black 26 the program takes advantage of white's error to repair its own. MOVE updating discloses the threatened black linkage between L17 and 016, and this triggers a priority LOCAL.URGENT alert. When white 23 threatens to reconnect his stones and capture black M16, the program connects at L16. It does this under LOCAL.URGENT control, because the PROBE lookahead indicates that this starts a sequence that saves this stone, protects the L17-016 linkage, and captures white M17. M17 is a cutting string, and capturing it unites the two black groups. Thus, when white 25 connects at N15, the program concludes the capture sequence with black 26 at N17. Note that the program plays 24, even though its shape critic complains about the inefficient shape it produces, because no other move achieves its priority objective.

White 27 and 29 put no LOCAL.URGENT pressure on black, so for the first time since black 8, control falls through to DEVELOP.GROUP. Now is black's chance to take the initiative. The program, however, believes that the whole black group on the lower right is unstable, so CROSS.SECTOR.LINE is called, and wastes 28 and 30 trying to restabilize it. Why does the program worry about this group? Because white Q2 undercuts the supporting territory. A human player can see the intervening corner, which mitigates this effect, but the program lacked the appropriate check. As this example suggests, making effective use of the information provided by the system's analogues for perception is a recurring problem.

Moves 31-34 in the lower left are joseki again. When MOVE updates after white 35, however, PROBE finds that although white E5 does not threaten any black strings or linkages, it does create a white linkage between F3 and E5 that can be cut. The program classifies this as an easy cut. The first move creates no new string and thus does not lead to complications. A LOCAL.URGENT alert is triggered, the program plays black 36 at E4, and white responds at F4. The idea here is to introduce defects in the opponent's position. These defects may or may not be utilized subsequently, depending upon the opponent's response and the surrounding conditions. In this case, after white 37 the program does not cut at F5 because such a play would not be supported by any existing black group. Here we see a real limitation of the INTERIM.2 program, the lack of strategic analysis. A strong Go player would have made a strategic analysis before playing 36, found he could make no immediate use of the cut at F5, and deferred the preparatory move at E4 until he could see some strategic purpose to the sequence.

White 37 does not produce any LOCAL.URGENT alerts, but since white 35 created a sector line between E5 and N6, DEVELOP.GROUP calls CROSS.SECTOR.LINE, which proposes black 38 at L6. This takes the unstable black bottom center group out across the line. White 39, played to protect the cut point at F5, destabilizes the lower left black potential territory and group, and induces black 40 at D8. The motivations and operations are the same as those described for white 7, black 8 on the right side. The next four moves are joseki again, followed by a white slide to B10, at which point the opening terminates and the game moves into a protracted midgame fight.

Summarizing the results of the play to this point, although the program has made several errors, mostly owing to minor bugs, it nonetheless has secured all of its groups, and it has center influence, 60-70 points of reasonably secure territory, and prospects for more. White still has insecure groups, only about 15 points of secure territory, and no immediate prospects of gaining much more. This is a high handicap game, so we should expect black still to be ahead. But white can hardly be satisfied with his progress.

4. MIDGAME SHAPE ATTACKS

The second sequence we consider starts from the situation shown in Fig. 3. The sequence itself is presented in Fig. 4. (Move 111 is shown in the figure as 11, etc.). White 111 at M4 triggers no LOCAL.URGENT or DEVELOP.GROUP alerts, so control falls through to ATTACK.GROUP. There is only one attackable candidate, the white group at the upper right. The program has been making preparatory moves against this white group for some time, and now at move 112 the program tries for the kill. The white group has one internal Liberty (eye) at P15, but to live it needs either to get one more, or else to connect to some other secure white group. With white already bounded and enclosed, the attempt to kill is largely a

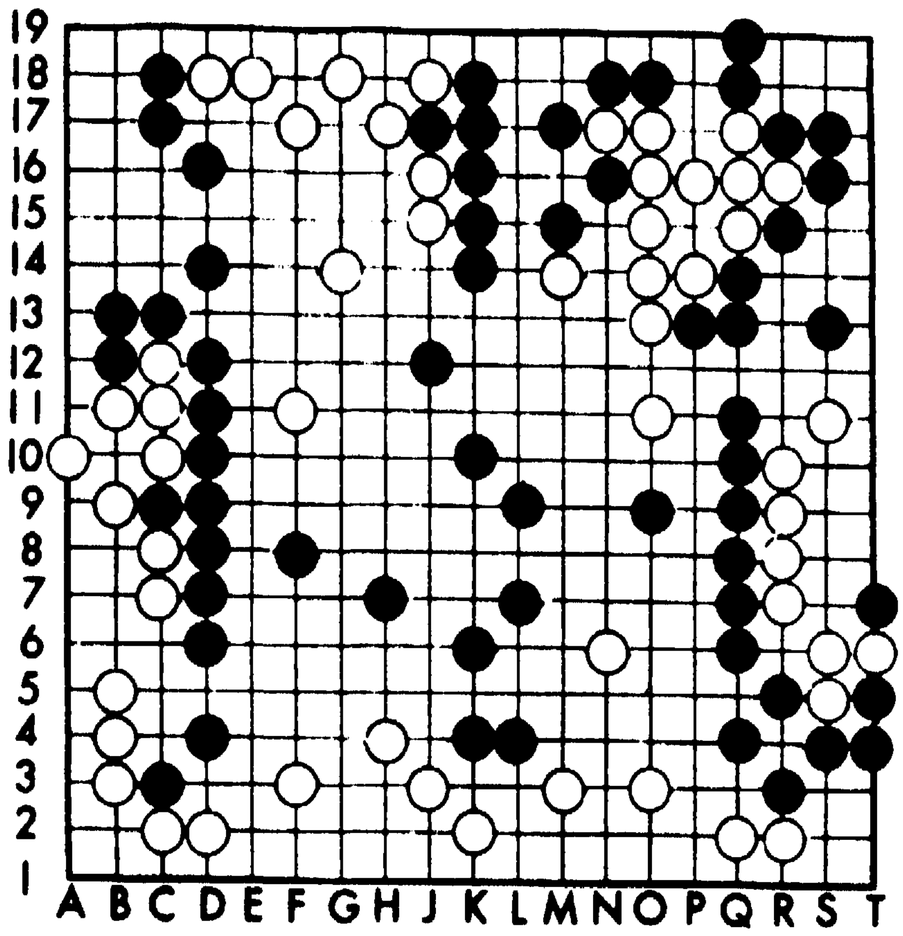

Figure 3. Board Prior To Attack.

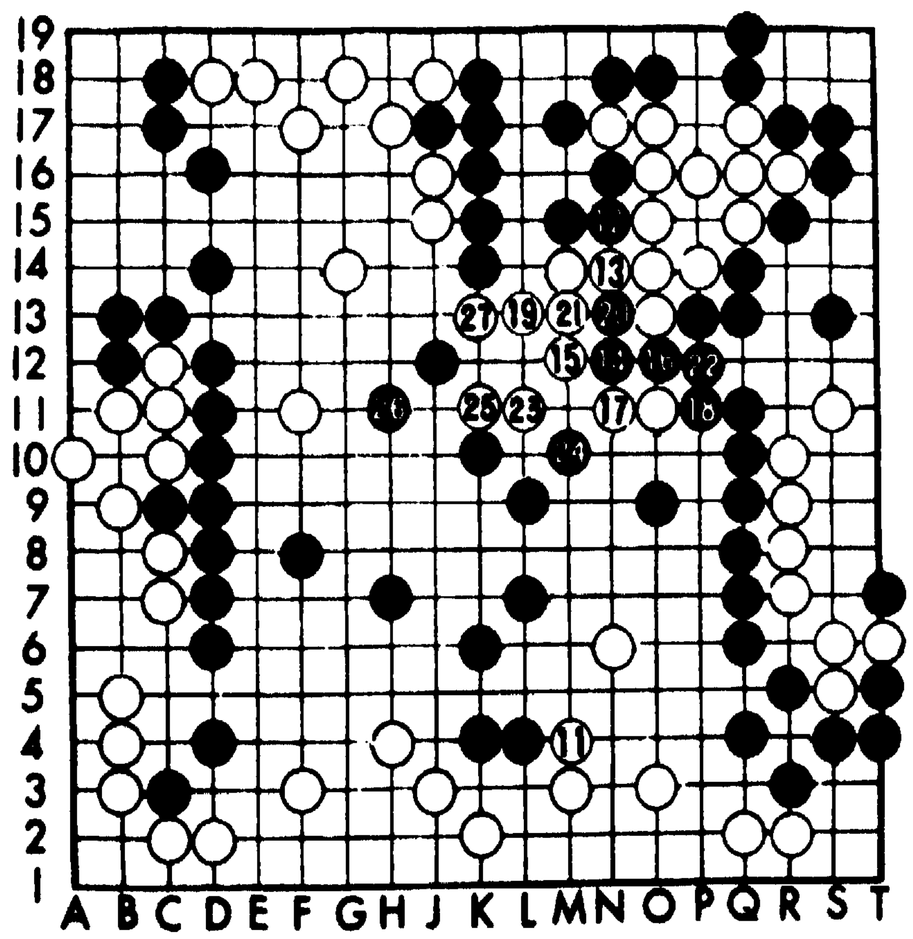

Figure 4. The Shape Attack Sequence.

matter of shape attacks to keep white from forming eyes.

The attack is under the immediate control of

SHAPE.POINTS. To understand how shape attacks are made, recall from Section 2.1 that whenever any stone is played, a shape lens is set up to monitor its shape-development possibilities. The prototype fields for the lens will check for significant proximal stones. Take the white stone at M14 in Fig. 3. When this stone was added at move 99 to the existing white group, one of the prototype shape fields checked for a two-stone pattern at a one-point jump from the focal M14 stone, and found white 014 and 013. A field covering this base shape of three stones (M14, 014, and 013) was then instantiated as part of the lens monitoring the local area around M14. Every completed lens includes fields monitoring each of the recognized base shapes involving the focal stone. Each field is maintained until its occupancy preconditions are violated by a subsequent move. Every completed lens also lists good moves for developing, and spoiling, the eye potential of the board area monitored by the lens. Thus in our example SHAPE.POINTS can now read off white's shape development moves, e.g., M12 and M13, as well as the local black shape attack points. In general, the more stones in the base shape of a field, the faster the empty points in the field can be used to create a good eye, using the eye potential of all the base stones working together. The final shape attack move is chosen on the same principle, i.e., it is the move that deprives the largest possible subset of enemy stones of their eye-forming potential. There presently is one severe restriction on permissible shape attack moves. The play finally chosen must form a connection with an existing friendly group. This is a temporary restriction, to reduce the possibilities for complications, and does not apply to eye-destroying moves, e.g., throw-ins, played inside real territory.

After black N15 and white N14, the dominant white lens field is the one defined by the triple of M14, N14, and 013. This suggests attacking moves at M12 and N12. Both form connections with black groups, but the lens information designates N12 the more severe. It destroys white's shape in this area completely. In addition, N12 also threatens the white 011-013 linkage. Black 114 induces 115 at M12. This is the only reasonable move for white. Black 116 is played from a LOCAL.URGENT alert, to save N12. N11 would have been better, to further reduce white's shape possibilities, but the early INTERIM.2 versions cannot exploit interactions across the top level REFLEX functions, in this case across LOCAL.URGENT and ATTACK.GROUP. After white 117 at N11,

LOCAL.URGENT proposes P11, to save the black string. P12 would have been better, but this again would require multiplexing across top-level functions. White 119 at L13 both continues trying to make shape, and also threatens one of the enclosing black linkages. Black 120 directly blocks an eye, but L11, aiming at falsifying the eye and also denying white some additional shape possibilities, would have been better. Finding this move takes lookahead, however, and the shape attack system presently uses PROBE only for determining safety and connection. After the M13, P12 exchange, white continues to try to make shape with 123 at L11. At this point, black has two possibilities, at M10 and K12. The program, again not able to call PROBE, plays 124 at M10, the wrong choice. White 125 at K11 contributes both to his shape and his breakout possibilities. Not being capable of strategic analysis, the program is compelled to abort the shape attack at this point in order to reenclose white with 126 at H11. As white 127 at K13 threatens both to break out and also to form an eye, the white group is now secure, and the program abandons the attack.

5. PROBE LOOKAHEAD PRODUCES A KILL

We conclude with an example of the INTERIM.2 system at its best. Fig. - 5 shows a midgame situation from a game against a 3 kyu opponent.

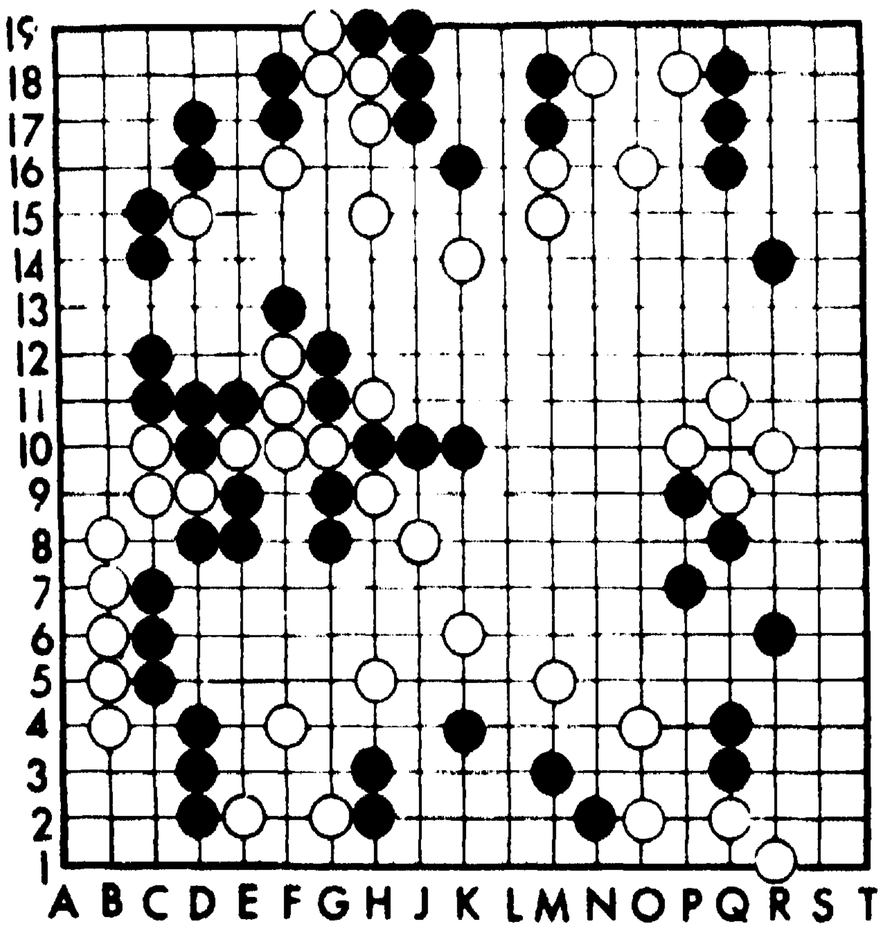

Figure 5. Board Prior To PROBE Reanalysis.

Although white has lost a small group around F10, he is otherwise in fine shape. In particular, white has enclosed the program's top and bottom groups tightly enough that both black and white are treating them as strategically dead, incapable of achieving absolute stability. Per Fig. 6 (move 101 shown as 1, etc.), the program plays its next move, black 86, at H13- White evidently

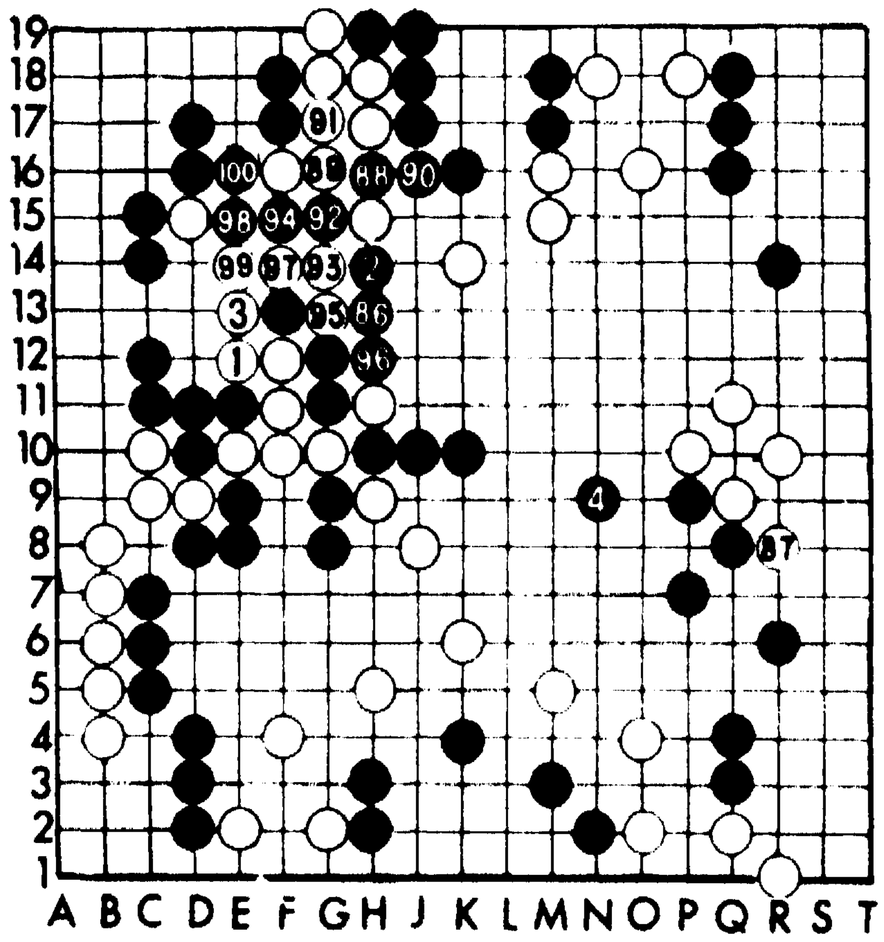

Figure 6. PROBE Lookahead Produces A Kill.

regards this move as locally insignificant, and he plays 87 on the right side. The program then plays black 88 at H16, and in the 16 moves that follow, not only kills the white G19-G18-H18-H17 string, but thereby also saves his entire top group.

How did this come about? Ever since white's efforts to save his F10 stones led to black and white plays around G12, the program has been reanalyzing the tactical status of the white H17 string after every move in the G12 area. This is because PROBE previously had determined that any change in the status of the empty points around G12 might invalidate its conclusions about the tactical security of the H17 string. Therefore it put those points in the relevant points list of the tactical data structure associated with the H17 string, and also stored a pointer to this tactical data structure with each cell in the TACTICSBOARD corresponding to one of these relevant points. Thus, once black has played 86 at H13, on the

next entry to the MOVE-REFLEX cycle, MOVE updating accesses this tactical data structure through the TACTICSBOARD cell for H13 and passes it to UPDATE.TACTICAL.ANALYSES. This time, when PROBE reanalyzes the tactical status of the white H17 string, it comes up with a killing sequence. When REFLEX takes control, LOCAL.URGENT discovers that an important enemy string has just been flagged as killable, and it returns H16, the initial move proposed by PROBE, as the program's next play. The program's performance here is at the intermediate amateur level or better, both in detecting the opportunity, and in following through.

6. OVERALL PROGRAM PERFORMANCE LEVEl

Human Go players are ranked on a scale consisting of about 44 unit-interval steps, labelled as follows. A total novice is ranked 35 kyu. As a player's skill improves, the numerical value of his kyu ranking decreases. Thus intermediate amateurs conventionally rank from about 5 kyu to 1 kyu. The next rank after 1 kyu is 1 dan. Advanced amateur ranks run from 1 dan to an upper limit approaching 9 dan. Professional players roughly overlap the region from 6 to 9 dan on the amateur scale.

The groundbreaking programs of Ryder [9] and Zobrist [10] rank close to the total novice level. The one game Ryder reports was played against such a novice. The program's play was quite interesting at many points, but it eventually lost by a substantial margin. The stronger of Zobrist's two versions achieved a rank of about 31 kyu. The first of our programs, INTERIM. 1 [4], ranked about 27 kyu. The initial INTERIM.2 versions, from which the examples presented above were taken, rank about 20 kyu. For an evaluation of an entire INTERIM.2.0 game, see Mann [11]. Introduction of the PROBE system is responsible for most of the difference in playing strength between the INTERIM.1 and INTERIM.2 systems. Our current version, INTERIM.2.3, which allows multiplexing at top REFLEX levels, ranks around 15 kyu.

We have described the operations that create, update, and use the INTERIM.2 program's multilevel representation to play Go. We also have illustrated the system's performance with three examples from actual play. As these indicate, the interim versions of the projected system produce sustained play, serving reasonable goals, at approximately the level of a knowledgeable beginner. The system has a good way to go, however, before it can claim to be an adequate solution to Berliner's AI task par excellence.

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Building and Exploiting User Models

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This paper describes the issues involved in building and exploiting individual user models in order to guide the performance of an interactive system. A system called Grundy, that recommends novels to people, is described and analyzed as a forum in which to explore those issues. One of the major techniques exploited in Grundy is the use of stereotypes as a mechanism for quickly producing an initial approximation to a model of the user. Experiments with the system show that despite the fact that stereotypes are inherently imperfect, their use does contibute significantly to the system's ability to build useful models of its users.

1 Introduction

As computers come to be used by a larger number of people to help perform a great variety of tasks, it is becomming more and more important for them to be easy for people to use. There are many factors that can contribute to the case of ir.e of a computer system, ranging from the good design of terminals; to the speed of the system's response, the appropriateness of its response, and the naturalness of its input and output languages. Yet another factor that can significantly affect the ease with which people can use a system is the ability of the system to tailor its behavior to the specific needs of a*n* individual user. It is this aspect of the habitability problem than will be discussed in this paper.

In order for a system to be able to respond to the individual needs of its users, it must have access to some kind of model of each user. Because the term "user model" can be used to mean several different things, it is important to specify what we mean by it. The three major dimensions along which user models can be classified arc:

- Are they models of a canonical user or are they models of individual users?

- Are they constructed explicitly by the user himself or are they abstracted by the system on the basis of the user's behavior?

- Do they contain short-term, highly specific information or longer-term, more general information?

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The work described here has concentrated on user models in one corner of this space. Models of individual users were built because of the facility for personalization they provide that is lacking in a canonical user model. Implicitly constructed models were used because of the inherent inaccuracy and the annoyance of requiring users to construct their own models of themselves. The choice of position along the third dimension was much less clear cut. Doth short-term knowledge (such as the topic currently being discussed or the goal now being pursued) and long-term knowledge (such as the level of the user's knowledge about the problem domain or goals that are likely to be pursued) can be important to the performance of an interactive system Hut it appeared likely that different techniques would be appropriate for dealing with the two types of knowledge. Models of long-term user characteristics were chosen because very little work has been done with them, while short term user models were already being explored, particularly in the context of natural language understanding. So the rest of this work will deal explicitly with the issues involved in individual user, implicit, long-term user modeling.

2. Some Requirements for an Individual-User, Implicit, Long-Term User Modeling System

The model must be built dynamically, as the system is interacting with the user and performing its task. Because the model is to be built implicitly and because users do not want to be forced to answer a long list of questions before they can begin to use the system, it is necessary that the system be able to exploit a partially constructed user model a*nd* that it be able to tell, as it is performing its major task, when it is appropriate to update the user model and how to do so.

The system should be able to infer as much knowledge about the user from a . little information as possible. This is important if the user is noi to be required to answer a large number of questions about himself. The major technique that can be exploited to do this is the use of stereotypes. A stereotype can be activated on the basis of a single action and can suggest a large

array of likely characteristics of the user. Stereotypes serve a function *very* similar to that of scripts [2]; they group together frequently co-occurring events to provide useful prediction', than can guide the system.

The User modeling system must be able to cope with the uncertainty that will arise from the fact that most of what It beleives about the user is really just a good guess, Because most of the Knowledge about the user will be based only on likely inferences drawn from his behavior, the system must associate with those inferences some measure of how confident it is of them. It must also remember the basis for each inference so that when conflicts arise (as they *are* sure to do), it will be able to resolve them in some reasonable way. Of course, to do this, it must also possess some conflict resolution rules. In this respect, user modeling systems are similar to other probabilistic reasoning systems, such as MYCIN [3],

It rnust be possible to modify the data base of stereotypes so that they will eventually characterize the system's users as. accurately as possible. Since it will almost *never* be possible to construct stereotypes that are completely accurate and since the stereotypes *are* so important to the function of the system, it is important that the system monitor their accuracy and change both them and their triggers as warrented by the actions of the users.

3. A Brief Description of Grundy

In order to have a forum in which to explore these issues and to be able to make a convincing case that some solutions had been found, it was deemed necessary to tackle the issues in the context of a specific task domain a*nd* actually to build a system into which the solutions to the issues could be incorporated. The task that was chosen for this experiment is to suggest to users novels that they might like to read. This is *an* appropriate domain since a wide variety of people read novels, hut they do not all like the same ones; and there is enough flexibility in the task that knowledge about the individual user can be exploited.

The novel recommending program, called Grundy, first asks one or two questions, on the basis of which it begins to build its model of the user, usually by evoking one or more stereotypes Then it begins the process of recommending novels. Farh time it selects a book, it asks the user whether or not he has read it. If he has, he is then asked whether he liked it. If he did, Grundy can update its model of him on the basis of the known characteristics of the book. If he did not like the book, Grundy attempts to find out why not and then to update its model of the user appropriately. If, on the other hand, the user has nol mad the book, then he is given a description of it and then asked whether he thinks he would like it. If he thinks he would, Grundy need do nothing — it appears to be on the right track. But if he thinks he would not like it, Grundy must try to discover why not and then to update its model of him. Thus, as Grundy interacts with the user, its model of him will evolve and begin to contain specific knowledge about him, infereed on the basis of his responses, in addition to its early beliefs, which were principally based on the predictions of stereotypes.

4, The Performance of Grundy

In order to collect evidence that Grundy is succussfully exploiting user models, twenty-three people were observed using the system. Several aspects of Grundy's performance were investigated.

4.1. Grundy's Success at Recommending Novels

Although building the ideal novel recommending program was not the primary goal of this research, it is important to establish that Grundy exhibits some form of intelligent action in order to show that the user modeling techniques are effective. In order to measure the system's success, a small experiment was conducted at the *end* of each conversation Grundy had with a user. Some books were selected randomly from the data base and then suggested to the user. It was then possible to compare Grundy's rate of success at recommending books that looked good to the users both when it was exploiting the user model and when it was not. Figure 1 shows the results of the comparison. It shows the number of good suggestions (i.e. the user said he might like) *and* the number of bad ones (i.e. the user said he would not like) in both the controlled and random modes. The data clearly demonstrate that the user models do contribute significantly to Grundy's performance as a novel recommender.

	CONTROLLED	RANDOM
GOOD	102	54
BAD	39	60

Figure 1: GRUNDY's Success Rate

4.2. Grundy's Success at Building Models of Its Users

Several attempts were made to test more directly Grundy's success at building models of its users, by comparing the models built by Grundy to self-descriptions provided by the users. This is not a perfect measure of Grundy's success, however, because people's descriptions of themselves do not tend to be *very* accurate (or even consistent). Despite this, the data indicate that Grundy is doing quite a good job at building models of its users. This conclusion is not, of course, surprising in light of the data on Grundy's success at recommending books.

4.3. Learning in Grundy

As has already been discussed, it is important that the stereotypes and triggers that form the bulk of the database of a user modeling system be able to change to reflect the actual body of users of the overall system. On the other hand, it is important that no single user be allowed to have a momentous effect on a

system's global view of the class of all users. So in running Grundy with about twenty users, only the most commonly invoked stereotypes could be expected to change significantly. The most frequently activated stereotype was the MAN stereotype, and it did show interesting and significant change over the period Grundy was run. For example, the stereotype initially predicted that men would like books that are very fast-moving and full of suspense. The values of both of those characteristics decreased considerably on the basis of Grundy's experience with its users. Both of these changes can easily he explained by the difference between the group the stereotype was originally intended to characteri7e (all adult male Americans) and the group it was actually applied to in practice (some adult male intellectuals). The people who used the system, although they were *men* and did seem to like fast-moving, exciting books, also tended to like philosophical novels an I literary classics, which tend to be much calmer. Thus. by the end of the experiment, Grundy had a more accurate picture of the men it was encountering than it had had at the outset. This suggests that the learning mechanisms are capable of causing at least some sorts of improvement in the stereotype data base of a user modeling system.

4.4. The Effectiveness of Storootypes

In looking at the results of GRUNDY's attempts to use stereotypes to build useful models of people, one is reminded of one important characteristic of stereotypes and thus of systems that use them. Although a stereotype may often provide highly appropriate and useful information about a person, it is, at best, an expression of a tendency and not an absolute truth. One example will serve to illustrate this point clearly.

Several stereotypes in GRUNDY predict that people who fit them will be interested in the conflict ''art-vs-scicncc''. Those predictions caused GRUNDY to believe, correctly, that several users were interested in that conflict and thus. to recommend books involving it. But one person, who fit three stereotypes that predict an interest in that conflict said, on the second questionnaire, that he was definitely not interested in it. Figure 2 shows all the situations in which GRUNDY believed the user was interested in art-vs-science.

User	Stereotypes Predicting Interest	Interested?
4	Intellectual, Contemplative, Scientist	yes
6	Intellectual	yes
7	Intellectual, Contemplative	yes
8	Intellectual	yes
9	Contemplative	yes
10	Intellectual, Artist	yes
11	Intellectual	yes
13	Intellectual	yes
20	Intellectual	yes
22	Scientist, Artist, Contemplative	NO

Figure 2: An Illustration of the Fallibility of Stereotypes

5. Conclusion

If one were to distill this thesis into its most essential points, there would, I think, be three.

The first is the awareness of the potential usefulness of user models of this sort. This awareness is just now becoming more important as the use of computers spreads further and further into the daily lives of more and more people. If this thesis does nothing except make people think about building these computer systems so that they can better serve their users, this effort will not have been wasted.

But realizing a need a*nd* satisfying it *are* not the same thing. The second significant point of this thesis is that, for at least one such system, in at least one domain, *an* individual user model was made to work and to guide a performance system successfully.

And yet the third contribution, after arguing for necessity, and demonstrating legibility, is suggesting technique. Not only are user models ireful a*nd* doable, specific techniques for building them have been developed. Although no claim is being made that these techniques are the perfect one'., they have been shown to be workable in one domain and extensible to others.

These three points, the usefulness, the feasibility, and the techniques of user modeling, constitute the major contribution of this thesis.

A more detailed discussion of all of the issues that were mentioned in this papers, as well as several that were not, including a description of the actual mechanisms employed, and a discussion of how to extend the ideas to other domains, can be found in [1].

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WORD EXPERT PARSING*

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An approach to natural language meaning-based parsing in which the unit of linguistic knowledge is the word rather than the rewrite rule is described. In the Word Expert Parser, knowledge about language is distributed across a population of procedural experts, each representing a word of the language, and each an expert at diagnosing that word's intended usage in context. The parser is structured around a coroutine control environment in which the generator-like word experts ask questions and exchange information in coming to collective agreement on sentence meaning. The Word Expert theory is advanced as a better cognitive model of human language expertise than the traditional rule-based approach. The technical discussion is organized around examples taken from the prototype LISP system which implements parts of the theory.

1. Background

In building a natural language understanding system, one of the first major decisions to be made is that of how to express and organize linguistic and conceptual knowledge for the parser. Depending upon the level of analysis desired (e.g., from simple keyword and key phrase recognition to "full" conceptual understanding in context), different methods suggest themselves. For the most part, models of parsing to this point have made the assumption that systems of rewrite rules are good media for expressing knowledge about sentence-level parsing. Examples of relatively successful systems and theories based on this assumption can be taken from every nearly every level of analysis, from the simple keyword analysis of PARRY [1], the syntactic analysis of LUNAR, up to more semantic and conceptual parsers such as those by Riesbeck [2], [3], and Wilks [4], [5]. Although the implementation styles of these models differ markedly, they share the view that rules of language understanding are best captured by rules which span relatively large sentence constituents (e.g., a phrase, a "picture producing" clause, a verb case framework). This assumption preordains a certain view of language comprehension by imposing structure at the sentence level and treating the words of the language as tokens which simply participate in comprehension by virture of their inclusion in sentence and concept level rules.

While it is highly likely that any knowledge whatsoever about language can be expressed in the form of a system of rewrite rules, this form of representation defines a particular point of view in which individual words of the language mean nothing outside the system of rules which make reference to them. This seems peculiar, since we intuitively know that each word of our language is an object with an often very rich knowledge structure attached to it. We know many contextual uses of each word (sense), we know its morphology, perhaps its history in some usage, perhaps when we first learned it, its idiosyncratic uses, perhaps even idiosyncratic uses of it with respect to some particular speaker we know. Intuitively, there is a considerable amount of knowledge associated with each word.

One can easily argue that all such knowledge can be captured in a system of rules which make reference to the word; indeed, each rule we add to the system will incrementally extend our knowledge about the words to which it makes reference. To extend the system, one adds new rules and revises or deletes old ones. If asked what it knows about any given word, the system can report all patterns in which the word participates. During comprehension, if the patterns of the system have been written to include enough sentential and conceptual context, exactly the right rules will filter to the forefront to drive the parser in its extraction of meaning and/or syntax. Such a system is clearly theoretically adequate.

We believe, however, that the underlying assumptions of this traditional approach are not correct. Out of curiosity a while back, we posed the following question: What would the knowledge in a language comprehension model look like if organized around words rather than systems of rewrite rules? Superficially, this seems like an engineering matter; one symbol's forward pointer is another symbol's backward pointer! But, as we have found, a remarkably different set of issues arises, and a considerably different approach to parsing suggests itself when the model defines the unit of knowledge to be the word rather than the rewrite rule.

This paper describes our "word expert" view of natural language comprehension. In the following sections, we describe why the theory seems more attractive than rule-based system, and we describe the architecture and operation of the Word Expert Parser, a LISP implementation of the ideas.

2. Word Experts

Our thinking on these matters was first stimulated by a simple observation about existing models. This observation was that no model (except for Wilks' model of preference semantics) seems ever to have made more than a token attempt at handling multiple senses of any given word in its vocabulary. Riesbeck's impressive parser, for example, while pioneering in many of its ideas about control via conceptual dependency schemata, was designed in a way that made it awkward to deal with highly ambiguous words; although the system did (and does) clever rule and expectancy switching on a limited set of examples of conceptual ambiguity, the system does not deal with the problem in generality. Wilks' system, on the other hand, is designed to deal with exactly this problem of word ambiguity, but at a more semantic (e.g., "things which are human eat things which are food"), rather than fully conceptual level where arbitrary world knowledge might be required for understanding. It is a mixture of Riesbeck's and Wilks' goals that most closely defines our goals, since we feel that word sense disambiguation in the context of open-ended world knowledge is of ultimate importance in a natural language system.

We therefore took the point of view that mechanisms for dealing with word ambiguity should be deeply built in to the model, perhaps even the most central mechanisms of the comprehension process. To gain some empathy for this point of view, consider almost any common English noun, verb or adjective. With twenty minute's thought, and perhaps a few reminders from Webster's, it is usually possible to identify dozens of different usages of that word. (We have looked at words like "take", "make" and "give" in some detail; each has dozens of distinct usages.)

How do we approach the problem of representing all the contextual usages of such highly ambiguous words? The traditional approach would be to write one rule for each usage. Each such rule would contain enough contextual probes so that it would fire at exactly the appropriate moments. But there are several negative features of this approach. First, each rule must be self-contained, and have enough information to fire only when the appropriate sentential and conceptual context pertained. This quickly leads to large, often highly redundant context descriptions in each rule. Second, some uniform interpreter capable of rule arbitration must exist to select the "most appropriate" competitor from among the several rules which will typically fire as potential interpretations. Third, being separate from all the other competitors, each rule must be able to place an absolute judgement on its relevance to the context at hand; there is no convenient way to have a rule decide on its relative appropriateness, with respect to its competitors.

These observations pointed away from rule systems, and toward the idea of writing more unified word experts. This led us to the notion of word (sense) experts. In our present model, each word expert is a procedural entity cognizant of all the possible contextual interpretations of the word it represents. When placed in a run-time context (i.e., informed of its position in the sentence, and given access to the neighboring experts and to a database of world knowledge context at that point in the comprehension of the larger fragment of which the sentence is a part), a word expert should be capable of issuing an orderly progression of inquiries about its context, and making a set of decisions based on the responses (or lack thereof) to its queries which lead to a selection of the best relative interpretation of its word in that context. Each word expert is, in effect, a unified compilation of what otherwise would be

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a collection of rules describing the contextual veriants of the word. By unifying them, ve create a central knowledge structure which can poae sore concise questions to differentiate contextual usages, and which superimposes a unifying framework on all possible interpretations of s word.

In further pondering the nature of word experts, it occurred to us that what we are really talking about is not so such words, but rather lexical units that are capable of contributing meaning or structure to s sentence. From this Idea, it becomes clear that we want experts not only for words, but also for common morphemes ("-ing", ''-ed", etc.), and possibly even for punctuation. The sentence (and a host of others like it, studied heavily in linguistics circles) "The man eating spaghetti growled." Illustrates very clearly the desirability of an -ing" expert. Looking to its left and right experts (or the concepts they may already have constructed^ -ing should be able to decide how the concepts referenced by men" and "eat' in this sentence best fit together. Because of observations like this one, we have come to take a broad view of aense experts that will allow meaning-contributing units other than words.

Parser Overview. Naturally, adopting the word and morpheme rather than the rule as the base unit expressing knowledge leads to differences in the organisation and control of the parser. Rather than a uniform rule interpreter/appller, the Word Expert Paraer is more a model of coroutine control and intercommunication. As we are about to describe, in the Word Expert Parser, the parse of each sentence Involves the pacing in of all required experts, the Initialisation of community and private workspaces, then the control of the numerous experts as they execute, suspend themselves, ask questions of one-another, and contribute fragments of meaning to the final interpretation of the sentence. Because of its organisation, the Word Expert Parser must define not only the structure and contents of each expert, but also a cognltlvely plausible control paradigm for coordinating the experts.

The body of the paper Is a description of our present model of word experts and their control. Briefly, each word expert Is s Senerator-llke coroutine whose decision logic is organised as a iscrimination net. Terminals of the net are the distinct usages of the word (its senses), while non-terminals are multiple-choice questions which probe the run-time environment. Also at each non-terminal node is control information describing what to do In case the question is not yet answerable (e.g., make an assumption, forward a suggestion to another expert, suspend temporarily). Meaning representation of the Final interpretations (i.e.. the meaning patterns stored at the terminal nodes of the experts) nas not been an issue in the development of the parser to this point. We presently use predicates that are descriptive of each of the different senses of the word, and have not made attempts to develop a consistent representation. Although the nature of the parser may well be affected by eventual commitments to one particular representation, we have so far been able to develop the ideas about word expert structure and content, and about parser control without regard for the form of the final representation.

We hope to convey our Intuitive feeling that word level organisation of knowledge about language Is both natural and powerful. In addition to dictating an Interesting style of parser control, solving some Important problems about word sense ambiguity, and addressing the Issue of relative (rather than absolute) selection of the most appropriate Interpretation of each word, the word expert organisation leads to some other Interesting ideas about language, particularly about language learning. We discuss several of these ideas in the final ■action. Additional discussion of the Word Expert topic can be found in (61. 17]. [8]. and [91.

3. The Word Expert Parser

The Word Expert Parser is a model of the human interface between an external language of inter-human communication, and an internal representation language of concepts and ideas. As a human reader processes a sentence, various conceptual conglomerates are created that provide the key to his understanding [10]. The process of creating these structures is as important as the structures themselves -- not only do stages in the processing of a sentence often depend on aspects of earlier processing, but sometimes the meaning of a sentence is explicitly influenced by how it is processed [11]. This should be quite clear for spoken language, but is so for written text as well if any degree of ungrammaticality or fragmentation is to be tolerated. The Word Expert Parser is a model of conceptual language analysis that strives for theoretical perspicuity of process.

3.1. Model Overview — A Simple Example

We will first describe the execution of the Word Expert Parser on the phrase "the heavy rain" to illustrate the model's procedural framework on a simple example. Initialization of the parser commences with the creation of a sentence level workspace for this particular input. This workspace consists of a collection of word bins and their associated word sense discrimination experts (word experts or sense experts). A word bin is a repository for information about a single word (or sub-lexical morpheme) of the input, and its corresponding word expert contains the word-specific (and procedural) linguistic knowledge that directs this particular execution of the parser. Each word expert is capable of disambiguating its word in any context, and interactions among word experts deterministically disambiguate the meaning of the sentence.

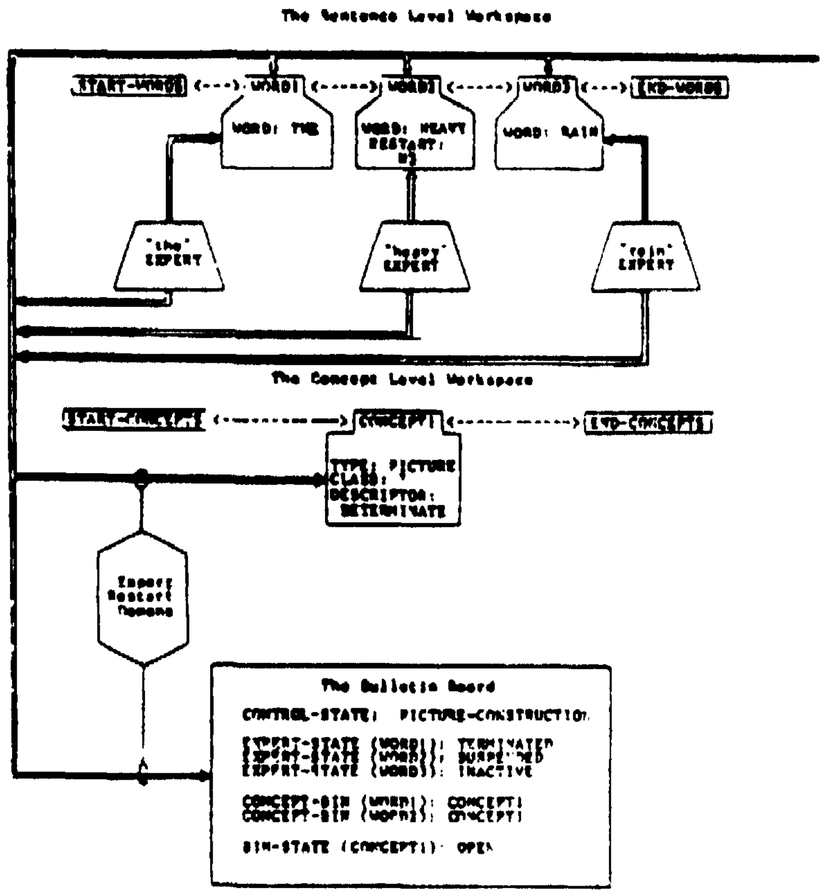

Figure 1: Parser Workspace

The "the" expert runs. The parser begins execution with the word expert for "the", which is the first on the RUN-ME queue (initialized to the input sentence). The flow of control now becomes unpredictable (in theory), as the word experts themselves completely determine control state changes and conceptual actions of the model. The "the" expert tries to determine its role in the sentence, knowing only that it is the first expert to run. Since the role of "the" is usually obvious (as it is here), its expert immediately changes the control state description of the parser from "new sentence" to "picture construction". This state involves the creation of a new conceptual object (called a concept bin) and associating with it a (partial) description. The the expert proceeds to create this concept, mark it "determinate", and terminate.

The "heavy" expert runs. The RUN-ME queue now consists of heavy" and "than. and the expert for "heavy" is removed and started executing, since s concept bin Is currently active, heavy knows to contribute Its conceptual descriptions to that bin. If no appropriate concept bin Is active when an expert runs, it createa one (es "the almost always doee). If the word describes the same concept as the one preceding it In the sentence, on the other hand. Its expert performs as the "heavy expert does here. This first step completed, the word expert must now discriminate among the many senses of "heavy and resolve on s single contextually accurate word sense. Since it has not yet seen the word to Its right (as we have!), it cannot discriminate among the senees meaning "having large mass , being in large quantity", or "being serious or emotional".

This ambiguity causes the expert to suspend its execution temporarily until It has seen the word to its right. For an expert to suspend, it must specify the conditions upon which It is to be reawakened and the location in the RUN-ME queue at which it should be placed. The heavy" expert specifies resumption when the word expert to Its right terminates, the end of the sentence reached, or a new concept created* Before suspending, however, this expert also posts s memo to the experts on its right, telling them to expect one of the conceptual object types that heavy" could describe (e.g.. abstract object). Expectations In the model are treated differently from constraints — they provide guidance but are not binding. The heavy" expert is now suspended, and the execution state of the model corresponds to Figure 1.

The resumption of suspended word expert proceeses is through spontaneous mechanisms which respond to both conceptual information and changes in the control states of model processes. The restart conditions may be quite complex in general, snd hsve been modeled after the spontaneous

computations of Riager [12]. When a reetert condition involves process control states, It is called a control state demon. For control state demons to be practicable,—1—central" tableau of information about the control structures of the model must be maintained. In the Word Expert Parser, the bulletin board is the center of this control knowledge:——Control—fftste descriptions of word experts, the pareer itself, and the concept bins are delineated on the bulletin board. In addition, the model's expectations, such as those contributed by the "heevv" expert above, are posted on this board. By making this knowledge of process available to the word experts, control states and expectations of various model components can affect the execution of the others.

The "rain" expert runs. Processing now continues with the expert For rain which has become the first on RUN-ME. This expert process contributes its conceptual information to the existing concept bin. and as a consequence of "heavy"'s expectations and rain 's simple usage, immediately determines its sense and terminates. Termination of "rain' causes the spontaneous resumption of the "heavy" expert, which continues processing where it left off. Since two of "heavy"'s three senses become meaningless in describing rain, the "heavy" expert resolves upon being in large quantity and terminates. This causes the model's single concept bin to close, completing the parse.

The control possibilities are clearly quite complex, and the processing is not. ,always going to give as clear and successful parse as It did on the heavy rain . However, the Word Expert Parser is a model of cognitive processing, and as such, the state of the parser after incomplete processing must be of psychological appeal. The parser's actions on ambiguous input (extremely rare when conaldered contextually) demonstrates its cogency — the end result would be a collection of partially completed suspended processes, coupled with a set of reawakening conditions specifying the reasons for the ambiguity (actually, the requirements for its resolution).

3.2. Workspace Representation

The sentence level and concept level workspaces of the model are represented as partitions of a PLANNER-like associative database. The data In a bin of either workspace is therefore accessible by any of Its contents, and in fact, declarative representations can be retrieved associatively from any bin. Descriptors of a particular conceptual object can be accessed by the Internal name of the concept (its bin), and more significantly, the objects in the concept-level are retrievable by their descriptions. In this way, a word expert determines the nature of any concepts in the workspace that could influence Its actions.

The Sentence Level Workspace. In the initial state of the parser:—The word bins contain two" pieces of information — the literal word corresponding to the name given it by the parser (e.g., "the" for WORD1) and the left and right neighbors of the word in the input sentence. These word bins acquire a more subtle and interesting role, however, es the word expert processes are initialised. At this point, each word bin contains the restart information (stack frame [13]) for the procees, including Its local variables and bindings, and Instruction pointer. By representing this information in the word bins, a word expert can easily constrain another by simply altering Its local variables or the place that It starts (or resumes; execution.*

The Concept Level Workspace. Each concept in the Paraer has a Type which determining kind of information found in its concept bin. The parser counts three such conceptual object types, pictures, settings, and events. A picture concept [14] involves physical and abstract and objects and their descriptions. A setting Is a time, location, situation. The creation of a setting is frequently Introduced by a preposition In the sentence. For example, "in the morning' in the house , and "In trouble" are examples of time, location, and situation examples (respectively) of setting concepts. Event concepts consist of conceptual case schemata.

The Bulletin Board. Posted on the bulletin board is a collection of control state information about the processing by the model.
The process state of each word expert in the model, the statue of each conceptual object, and •description of the state of the entire parser are found on this board. Any spontaneous computation triggered by tome indication of control state is attached to a memo posting function (or server [15]) on the data channel to the bulletin board.

are based on lower-level descriptions of OPEN or CLOSED concept states. A concept can be UNOPEN, OPEN, or CLOSED, depending on its state of completion. Word experts processes and are therefore described by the states inactive, SUSPENDED, and TERMINATED. As work on the descriptions will continues (16). refinements of these state descriptions will emerge, clarifying the strength of our work as s process model of human cognitive behavior.

*The modularity of the experts requaries that manipulation of restert pointers be carefully explicity states word expert contains a descriptive header that explicitly states

3.3. Word Sense Discrimination Experts

The principal knowledge structure in the Word Expert Perser is the word sense discrimination expert. A word expert is a representation of the linguistic knowledge (procedurel) needed to disambiguate the meaning of a single word In any context. A word's context Includes both sentential and conceptual information — not only are the Immediate lexical neighbors of s word Important, but conceptual knowledge of the entire text and even the physical world are frequently crucial in underatandIng it. A word expert performs its discrimination processing by asking context-related questions of the various components or the pareer or the story comprehension model In which it is embedded (see [7] and [8] about the GRIND etory underatandIng model).

The Important aspects of s word expert are the questions that it asks (and of whom it asks them) and the actions that it performs upon receiving the answers. Sometimes an action is taken because no answers were forthcoming, namely, suspending execution until the information is available or until control states are reached at which point the availability is likely (or non-availability is significant). Other word expert actions Include creating and building up concepts, constraining other experts, posting expectations on the bulletin board, and charging the control state of the pareer.

3.3.1. Word Expert Structure

Each word expert exists In two forms in the model — a declarative representation which is a directed acyclic graph and called e word senee discrimination network (or sense net), and a procedural representations like—a conniver generator (or stack group [17]) which is called a word expert process. Both repreeentatIons are briefly discussed here, ana than raisons d'etre explained.

Network Representation. A word sense discrimination network is a graphic representations of the contextual disambiguation of a single word. This structure was motivated by the central theoretical notion of the sense net theory of language, that each word of English carries with It the information necaaaaary to determine its contextual meaning. Each node in a aenee net represents an ordered set of decisions that converge on e single appropriate sense of a word.

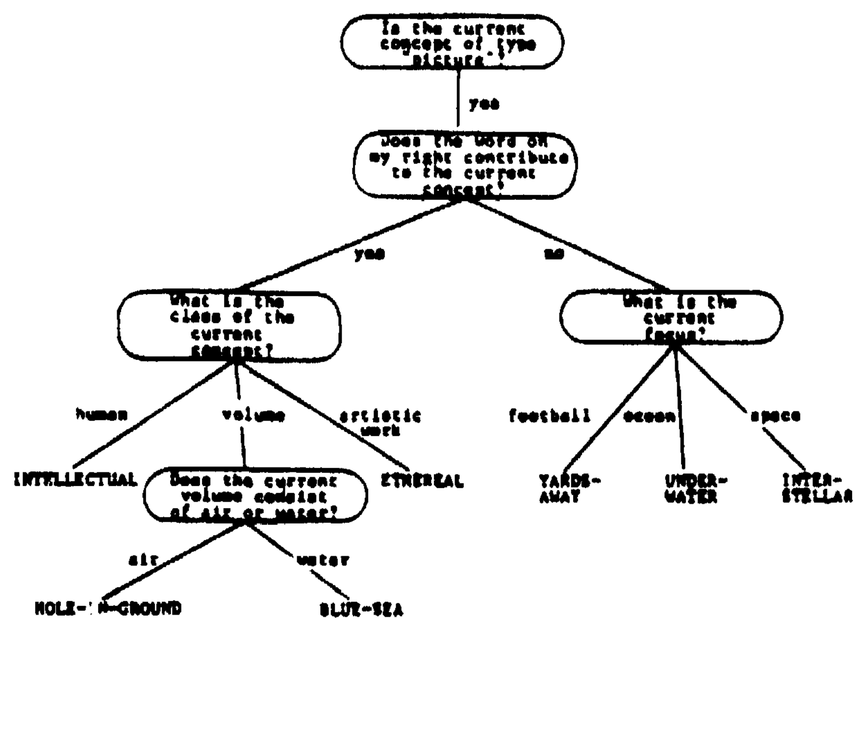

Figure 2: Sense network for "deep"

An example network for "deep" is shown In Figure 2, and ehows several of its senses. The first two questions of the network src aimed et determining If "deep" denotes an object (the deep") or e description (e.g., "the deep thought). Aa a question Ir answered, one branch of the graph is favored over others, end the number of possible senses of a word Is reduced. Finally, a terminal node is reached, end e single word sense chosen.

The possibility arises that a question cannot be answered because it depends on information from other networks that is not yet available, in euch e case, a sense net must remember its location in the graph and wait for the information it needs to continue. Another eepect of inter-network activity is when e sense net determines constraints on another — a network waiting for certain data is told to reetert at Ita root node, or told to resume at a different node than it expects. The Influence of one senee net on another reflects the crucial contextual nature

of their word sense disanbiguation tasks.

Process Representation. The Word Expert Paraer compiles each sense—discriminations network into an executable process when it Is first called to perform Its task. Although every word expert has a representations as a sense network, this graphic repreaentation lacks important aspects of a true executable expert process. In particular, whereas the details of an expert's suspension and resumption, or interactions with other experts, may seem irrelevant at certain levels of explanation, they are in reality quite significant to the view of the parser as a process model of human language analysis. The network representation also falls to capture the important side-effect actions performed by an expert. The structure and execution of word experta therefore will be outlined through the process representstlon. Use of an expert's implicit graph structure as a metaphor, however, will certainly be uaeful.

The compilation of a word expert is significant in that certain nodes of a sense network may be pruned away before It becomes an expert process. In this way, contextual Information about the plot of a story, its characters, the current focua (aee US]), and so forth, can be used to eliminate a word's irrelevant senses. In reading "the ship cruised' in a nineteenth century story, for example, a aenae of "ship" denoting something which travels between planets can be pruned away immediately. Certain constraints cannot be made a priori, however, and In such cases, an already compiled proceas must be manipulated.

Word expert processes are implemented in the model in a manner resembling CONNIVER generators. They can be suspended in the middle of execution and resumed spontaneously according to a variety of trigger patterns. These include not only the standard patterns of conceptual data, but data about the control states of other processes as well. Processes can commmunicate by affecting the local variables of another, Including thoae which tell the process where to start (or resume) execution. This effectively prunes the implicit graph structure of the expert. Word expert processes also provide Information to other experts by posting control data and expectations on the central bulletin board.

3.3.2. What Word Experts Can Do

The role and significance of word experts in the model are most easily understood through an examination of both their internal actions like the queatlona they ask, and their side effects, actions that affect the rest of the model. A word expert can ask questions about the other words of the sentence, concepts Introduced, expectations, the control state of the parser, or the control states of other experts. An expert can affect the data found In word bins, concept bins, the bulletin board, and the process reatart queue of spontaneous computations.

Internal Proceas Actions. The fundamental internal actions of a word expert " are questions-asking and branching. One of the Important contributions expected In development of the Word Expert Parser Is the taxonomy of context-probing questions aaked by experts. The nature of some of these questions Is emerging and is of several varieties — lexical, conceptual, global, and control. This last category consists of questions about the state of the cognitive processing task thus far, representationally encompassing the states of word experts, the paraer state, and the atates of the bine.

The existances of a particular word to the immediate left or right of e given word can often discriminate among its senses. A word expert asks about the nature of the words arbitrarily far to its left and right in the aentence. Furthermore, It can ask about a word's senses (in totality or only those still remaining) through the word s conceptual categories, aubclaaaes of these categories, or the explicit names given to its senses. When a word expert is constrained, the pruning may be done along any of these same dimensions.

Conceptual Information Is usually very Important in discriminating among word senses, as are the posted expectation about this information. The concept bin to which the executing procesa contributes also contains conceptual data from other experta which la often crucial to understanding the current word. A simple example was given in the model overview, when the "heavy" expert needed Information from its own concept bin (i.e., data regarding "rain'*) before It could determine the correct sense. The concepts to the left and right of the active concept are useful in the same way. It la likely, however, that in the initial left to right acan of the aentence, concept blna to the right *of* a given one may not yet exist. This fact indicates that a strict ordered scan of a aentence la sufficient to parse It only If no expert needs information from concepts to Its right. The organisation of the Word Expert Parser therefore supports our common sense institution about conceptual parsing by humans.

The Word Expert Parser Is embedded within the GRIND story comprehension model, and as such, haa access to the global world of a , children's story. Relevant aspects include the personalltlea of the characters, interactions among characters, the plot line, anaphoric references, and current foci of interest. The plot of a medieval story, for example, might tell the reader that "knights", *lords "maide'', and workers" take certain strict interpretations In local contexta. Or the focua of understanding In a story might be the Algonquin Round Table, In which caae the deep ought to be interpreted as referring to thoae intelligent persona who regularly ate lunch together at that hotel. Global context significantly influences the underatandIng of certain sentences of texte.

Control State Descriptions. A new and important aspect of the word—Expert parser is that control information is accessible to (and often used bv) the discrimination processes. The fact that the expert to the immediate left of the executing expert is suspended, or that the expert to its right has not yet executed, is often the central datum enabling its successful termination. The state of a concept bin is also uaeful information, particularly in deciding where one concept ends and the next Pegins. A concept bin is cloaed only when the conceptual notion it represents is complete; that is, when a change in its date requires the kind of severe becktracking that humans perform extremely rarely (on so-called "garden paths'). In the exemple parae of "the heavy rain", the control state of the paraer elded the executions of the "heavv" and "rain" experts. Control state knowledge is fundamental to the successful conceptual analysis of most sentences. In both the internal nature or the expert processes and their relationship to the entire model (suspension and resumption), the self-examining knowledge of control flow and processing states is fundamental.

Process Side Effects. Conceptual analysis is an inherent part of natural language understandIng but not the whole part. As auch, word sense discimination by the Word Expert Parser must provide the information it acquires to other components of s large understanding model to complete the task. Assimilation of new data into a picture of the world (see [19] for a discussion of modeling belief systems) by making the necessary inferences, disambiguating references, and so forth (see [8]), constitute the other facets of understanding a text. The side effects of the processing by a word expert provide the information required for further stages in the conceptual analysis phase of understanding, as well as conceptual data for the subsequent phases.

Conceptual knowledge is augmented by creating new concepts and storing new facts about old concepts, A word experts first task is to determine the conceptual notion to which it contributes. If a concept bin Is active at the time, the expert could choose to contribute to it. This would mean that the word it is trying to disambiguate participates in the same concept as the word to its left In the sentence. If no concept bin is active, or if the expert determines that its word starts a new concept anyway, the word expert would open an new one. It is possible (in certain circumstances likely) that an expert would not know which bin to contribute to — in this case it would suspend its execution until the expert to Its right has executed (this is usually enough).

When a word expert has determined its concept, it may store facts there. If it opens the bin itself, It must provide a type (picture, setting, or event) to the bin. Otherwise, it ma> provide the concept's class, or augment its descriptor. An expert that completes a concept may close its concept bin, Indicating that its word is the last (rightmost) one contributing to that concept. If all experts participating in the concept have not yet terminated when one of them attempts to close it, however, the model will plant a demon to close the bin when the last of the relevant experts terminates.

A word expert also affects certain internal data structures, uaeful solely by the paraer. These are extremely important and include suspending itself and constraining other experta. The example execution of "the deep pit" (aee below) demonstrates this constraining action — since neither "deep" nor "pit" can determine its correct sense on the first try, "deep finally tells "pit" to be one of the things that "deep can deacribe, namely, a hole in the ground or a person. It does this by changing the place in "pit" network where it begins execution, thus staking It believe that it had successfully discriminated farther than it really had. After constraining it In this way, the parse cen complete. If "pit" had not yet been compiled, the sense net itself could have been pruned before compilation.

An expert suspends Its execution if the model's lack of certain information keeps it from proceeding. When this occurs, the expert stops execution end plsnts a demon to wake It up when the fact it needs becomes available. Theae facta can be of any variety, Including data regarding the statea of other processes. A typical suspenaion consists of an expert process needing something from a not-yet-executed process to its right, and waiting until it haa executed (SUSPENDED or TERMINATED) to resume. Another example In "in the morning" Involves e setting, where the in" network waits until a picture bin Is closed before it resumes. At that time, it can complete its own setting concept, knowing the class and deecription of the picture to Its right. As a reault of theae suspensions and Bpontaneous resumptions. the range of control flows in the conceptual analysis model is wide and complex — our confidence in the model's cogency is only strengthened by this varlety.

3.4. Example: "the deep pit"

The Word Expert Parser is Illustrated below through the example phrase the deep pit . An actual trace of the parser's execution is presented, accompanied in the righthond column by some explanatory annotations. The example phrase causes the creation of a single concept of type "picture". The word sense ambiguity of the component words causes a number of expert suspensions and resumptions, demonstrating the strength of the system.*

Execution of "the deep pit" is an interesting example of the complexity. , of control flow in the Word Expert Parser. Since both "deep and "pit" have more than a single sense, they must exchange pieces of Information about themselves before either can succeed at determining Its sense.

```
EVAL: (%PARSE: THE DEEP PIT)
CONTROL-STATE: NEW-SENTENCE
VALUE:      T
```

The ZPARSE function initializes the parser workspace by retrieving (from a disk file) the word experts for the input phrase, and creating for each one an associated data repository called a "word bin". Each word expert Is placed on the RUN-ME queue, and then executed in turn, with the experts themselves eventually determining the flow of control in the model.

```
EXECUTING 'THE' EXPERT: WORD 1
*****TRANSLATING   SENSE EXPERT FOR W0RD1
**EXPERT COMPILE TIME: 56
**OPTIMIZATION TIME: 1237
*****EXPERT    FOR W0RD1 TRANSLATED
— - > AT NODE: NI
NEW CONCEPT: CONCEPT 1    TYPE: PICTURE
CONTROL STATE: PICTURE-CONSTRUCTION
EXPERT TERMINATED: W0RD1
```

The word expert for the" is translated from a network representation into a coroutine, which is then executed. It creates a new contracts concept of type PICTURE, changes the paraer state to PICTURE-CONSTRUCTION, and terminates.

```
EXECUTING 'DEEP' EXPERT: W0RD2
*****TRANSLATING   SENSE EXPERT FOR W0RD2
♦♦EXPERT COMPILE TIME: 281
**OPTIMIZATION TIME: 5808
♦••••EXPERT FOR W0RD2 TRANSLATED
–>     AT NODE: NO
——> AT NODE: NI
EXPERT SUSPENDED: WORD2
```

The deep expert *it* translated and started executing. After a short time, however, it needs Information from the word expert to its right. Since the pit expert has not yet run at all, deep temporarily suspends execution until "pit's word expert has SUSPENDED or TERMINATED. Although permitted to do to, deep" posts no expectations and makes no constraints, thereby insuring that the expert for "pit" has full freedom.

```
EXECUTING 'PIT' EXPERT: WORD3
*****TRANSLATING   SENSE EXPERT FOR W0RD3
**EXPERT COMPILE TIME: 307
••OPTIMIZATION TIME: 5852
•••••EXPERT FOR W0RD3 TRANSLATED
-—-> AT NODE: NO
——> AT NODE: NI
—> AT NODE: N2
    **RESTART DEMON FOR W0RD2 TRIGGERED:
    •     (*EXPERT-STATE* W0RD3 SUSPENDED)
    ••EXPERT FOR WORD2 QUEUED FIRST
EXPERT SUSPENDED: WORD3
```

"Pit" now runs, but cannot discriminate between its two noun senses of "fruit pit" and "hole in the ground". It suspends its execution until something happens to help resolve its word sense deadlock. Since "pit" has now executed, "deep" is spontaneously reawakened.

```
EXECUTING 'DEEP' EXPERT: WORD2
- —> AT NODE: NI
— - > AT NODE: N4
    ••RESTART DEMON FOR W0RD3 TRIGGERED:
    *     (•EXPERT-STATE* WORD2 SUSPENDED)
    ••EXPERT FOR WORD3 QUEUED LAST
EXPERT SUSPENDED: WORD2
```

Resumed by the suspension of the "pit" expert, the "deep" expert now says: "I gave the word to my right a chance to be what it wanted and It had no Idea. Now I'll constrain it to be something that I can describe — a hole in the ground or a person." At his point, therefore, "deep" constrains "pit" and suspends itself until "pit" terminates. Since "pit" was waiting for exactly this sort of activity, one of its restart demons fires, and the word expert for "pit" ia queued up*

```
EXECUTING 'PIT' EXPERT: WORD3
–>     AT NODE: N2
——> AT NODE: N3
CONTROL STATE: UNKNOWN
    **RESTART DEMON FOR WORD2 TRIGGERED:
    •     (*EXPERT-STATE* W0RD3 TERMINATED)
    ♦♦EXPERT FOR W0RD2 QUEUED FIRST
EXPERT TERMINATED: WORD3
```

Pit now runs for the last time, its constraints focusing the discrimination. Since "pit" terminates, the restart demon for deep is triggered, and deep" is queued.

```
EXECUTING 'DEEP' EXPERT: WORD2
 —> AT NODE: NI
 —-> AT NODE: N3
——> AT NODE: N2
EXPERT TERMINATED: W0RD2
CONCEPT CLOSED: CONCEPT !

VALUE:      T
```

Finally, deep runs for the last time, terminating with the sense of large volume". Although "pit" tried to close its concept bin, "deep" still had not terminated, and so a demon was planted to close the concept when "deep" finished. Thus, the picture concept is now closed and the parse complete.

```
EVAL: (ZSCAN •CONCEPT 1)

 *DESCRIP* (SIZE-DIMENSION DEPTH) W0RD2)
 *DESCRIP* (SIZE URGE) WORD2)
 *DESCRIP* (VOLUME-TYPE HOLE-IN-GROUND) W0RD3)
 *DESCRIP* (CLASS VOLUME) W0RD3)
 *DESCRIP* DETERMINATE WORD1)
 *CONCEPT-CLASS* VOLUME)
 *CONCEPT-TYPE* PICTURE)

VALUE:      CONCEPT 1
```

As the Word Expert Parser analyzed the input phrase, it created and augmented a data repository of conceptual Information. This "concept bin" contains description of the meaning content of the phrase as well as various pieces of control state data. The concept bin for "the deep pit' is called CONCEPT1 and contains several deacriptors which together describe a large volume of air in the ground.

*Execution traces of the Word Expert Parser are available from the authors. All examples re expert in this paper as well later examples of full sentence parses
pe
request.

4• Summary and Conclusions

We have mapped out a theory of organization and control for a meaning-based language understanding system. In this theory words, rather than rules, are the units of knowledge, and assuae the form of procedural entitles which execute as generator-like coroutines. Parsing a sentence In context demands a control environment In which these experts can ask questions of each other, forward hints and suggestions to each other, and suspend. Our theory Is a cognitive theory of both language representation and parser control. It has stemmed from feelings about the fundamental Inadequacies of rule-based theories.

In addition to the advantages already discussed, the word expert approach enjoys a number of other pragastlc and theoretical advantages. By way of conclusion, we enumerate what we feel are the important theoretical and practical characteristics of the theory.

1. It allows for the modular growth of language knowledge in the implemented model. Unlike a rule-based system (where obscure interactions and dependencies among seemingly unrelated rules can occur), each word expert Is a relatively perspicuous, central aggregate of knowledge about one easily Identified unit of language knowledge, I.e., the word. One can look at that structure and more easily say whether or not it takes any given usage Into account. If It does not, It is clearer where knowledge about that new usage should be grafted in.
2. It encourages a healthy type of redundancy in the codification of language knowledge. When writing a word expert, one's goal Is to create a stand-alone agent able to function in a wide variety of run-time contexts. We have noticed that this nearly always leads to bi-directional handshaking when two experts interact; they come to some mutual agreement because they find common ground. This type of redundancy is healthy, since It is then less likely that the shortcomings of one expert will block the comprehension of the sentence or concept in which that expert occurs.
3. It suggests some approaches to language acquisition. Since each word expert reflects the state of knowledge about a given word, when new usages of the word are perceived, rather than writing absolute rules to describe the new context, it is possible to grow a new branch within the word expert. This brancn need only capture one relative difference between the existing visages and the new usage, an intuitively simpler and safer operation than generating an entirely new rule. Since the scope of the change is intuitively smaller, it is less likely to interfere with other experts In the system.
4. It encourages the codification of idiosyncratic uses of language by providing uniform data structures as focal points for that diverse knowledge. If, for example, there is an esoteric sense of the word take , one need only sprout a branch of the "take" expert's decision logic to Include it. Because of the branching logic organization of the experts, little overhead Is Incurred by adding special cases. We have felt all along that an organization which encourages knowledge about Individual words to grow to large proportions without degrading the efficiency of the system at large is highly desirable.
5. It adapts well to largeness. Even if there are 100,000 word experts, each of which on the average requires 1000 words of computer memory, actual memory space required to parse any given sentence will be small. This is because the parser requires only the experts Involved in the sentence at hand to be in core. This is a modest requirement when compared to large rule systems where all the rules must be kept In core at once (for efficiency), or where potentially complex paging systems must be devised to Interact with a rule system on mass storage. While this is strictly an engineering issue, it nas immediate consequences on today's computers'
6. It forces the parallel development of cognltively plausible theories of sequential, coroutine-like process models of humans. If the assumption about word (rather than rule) primacy in humans is correct, we stand a chance of making reasonable conjectures about flow of control in a human language understander. That is. some fairly crisp pictures of word expert control follow directly from the structure of the word experts themselves. As we discover how to control the experts in a LISP model, we may also be discovering how humans think when comprehending language.

Although much remains to be worked out, we find ourselves Increasingly convinced of the appropriateness of the word expert approach. In the near future, we hope to be able to demonstrate the system at work on complete sentences, and hope to provide convincing evidence that large experts with many word usage alternatives are practical to develop and coordinate.

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COREFERENCE IN A FRAME DATABASE*

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This paper analyzes coreference within a frame-based semantic system. We discuss mechanisms for determining whether a new piece of knowledge (expressed as a frame) is actually a previously known referent. We propose frame database heuristics that allow new knowledge to be uniquely disambiguated for coreference so that concepts initially represented in many forms can be assimilated to those parts of the database that express the same knowledge, though perhaps in a different form. We hypothesize that these coreference mechanisms can be used by a text processing module whose control structure makes use of the organization of the text to reduce the combinatorial explosion of coreference searches in a database.

1. Introduction

We will present in this paper a computational model of coreference. We hypothesize that reference in text makes use of an underlying, modality-independent coreference module. When we understand a piece of text, we translate the individual sentences into some formal linguistic representation such as an annotated surface structure [2] with associated case information. This linguistic representation can in turn be translated into a "deep structure" consisting of (a set of) partially instantiated frames. These candidate frames will be the formal input to our reference mechanisms, whose output will consist of target frames lpcated in the database, which are coreferential with the candidate frame. Thus frames represent the formal semantic objects on which our reference mechanisms operate. An example of transforming text into an internal frame representation is the PAL system [6,8]. PAL takes English input from the domain of office scheduling and maps this first into an annotated surface structure and from this into FRL FRL will be briefly described in Section 2. It serves as our formalism for representing meaning as frames.

The translation from English language text into a formal semantic structure is independent of the coreference module, which operates on the frames and not on the the text input By viewing text processing in this light, we transform the problem of intersentence reference into the more tractable problem of how, given (a) some semantic representation, which we will formally specify in FRL, and (b) some new piece of knowledge, which can also be represented in FRL, we can determine if any frames in (a) are coreferential with those in (b). Thus reference in text processing is a special case of the general problem of determining coreference in memory. FRL in fact provides a general formalism for representing knowledge gained from several sources, not just linguistic. Each mode of input may be structured so as to support reference mechanisms that are peculiar to the mode. Language, for example, contains a number of special reference mechanisms that make use of such particularly linguistic evidence as pronominal reference. However, since information once translated into FRL is modality independent, we propose that a modality independent coreference module supports these more specific reference mechanisms.

A coreference module is necessary in large databases where knowledge is constantly being accessed, added and removed. There is a danger that new knowledge will actually be identical to, or closely related to, what is already known, but that this relation will not be perceived. In fact, the size of the database is less critical than the range of allowable descriptions *of* the data. If Fahlman [3] is right, then implementing search mechanisms in a hierarchically organized database will be efficient regardless of its size. But even in a database containing only a few facts, one would like to be able to refer to them in a variety of ways.

2, Knowledge Representation

Roberts and Goldstein [7] have developed a working frame system that forms the basis for our knowledge representation. Their Frame Representation Language has been used successfully to represent knowledge from a variety of domains: office scheduling [4], the wheat commodities market [9], places and travel [5]. FRL extends the traditional characterization of properties as attribute/value pairs to allow comments (meta-knowledge), abstractions, defaults, constraints and attached procedures. A frame is a named collection of slots and forms the semantic definition of a concept. A slot has an arbitrary number of user- and system-defined facets. In addition to the Value facet, useful system defined facets are: Default, which specifies a default value;

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Require, which specifies procedural constraints on the values for that slot; If-Needed, which specifies procedures that compute a value for the slot; and If-Added and If-Removed, which specify actions to be taken when a value is modified.

FRL allows concepts (represented as frames) to be arranged in an inheritance hierarchy. The value of the AKO slot (meaning "is a kind of) is a generic frame of which the current frame is a specialized INSTANCE. Thus the frame system forms a tree structure. Generic knowledge is stored higher up in the hierarchy and shared by frames lower down; specialized frames specify new distinguishing characteristics. Generic knowledge, including all attached procedures, is inherited automatically. For instance, in Fig. I, the frame Appointment-72 is AKO Appointment This means that the requirement on the Participants slot of the Appointment frame applies to the Appointment-72 frame, although it is not specified explicitly in the description of that frame. The requirement states that Appointment can have (by definition) only two Participants. It is a procedure that evaluates whether or not the restriction is satisfied. Appointment-72 also has values for the various slots that form the definition of an appointment

```
MUTING
   AKO                -VALUE-  MEETING
   CLASSIFICATION     -VALUE-  GENERIC
   INSTANCE           -VALUE-  APPOINTMENT, PARTY. CLASS
   PARTICIPANTS        REQUIRE- (77 (AKO -VALUE- PERSON))
   PLACE              -REQUIRE- (7? (AKO -VALUE- PLACE))
   TIME               -REQUIRE- (77 (AKO -VALUE- TIME))
   SELF               -MATCH-  (MATCNSL0TS PARTICIPANTS PLACE TIME)

APPOINTMENT
   AKO                -VALUE-  MEETING
   CLASSIFICATION     •VALUE-  GENERIC
   INSTANCE           -VALUE-  APPOINTMENT-66, APPOINTMENT-72
   PARTICIPANTS       •REQUIRE- (• (NUMSER (PARTICIPANTS) 2)

APPOINTMENT-66
   AKO                 VALUE-  APPOINTMENT
   CLASSIFICATION      VALUE-  INDIVIDUAL
   PARTICIPANTS        VALUE-  MARY, JOHN
   PLACE               VALUE-  OFFICE-75        :John's office
   TIME                VALUE-  11:45AM

APPOINTMENT-72
   AKO                -VALUE-  APPOINTMENT
   CLASSIFICATION     -VALUE-  INDIVIDUAL
   PARTICIPANTS       -VALUE-  DILL, JOHN
   PLACE              -VALUE-  OFFICE-75        ;John's offlco
   TIME               -VALUE-  1:30PM
```

Fig. 1 - Examples from the Frame Database.

3. An example of reference

The following scenario depicts a hypothetical dialogue between a person and a scheduling program. *Italia* indicate the person's requests, the normal font indicates the scheduler's response.

(SI) *What is the schedule for this after noon?*
(SI) There is a meeting at 3 in Fred's office.
(S3) *Who will be there?*
(S4) You, Bill, and the Marketing people.

(S5) *When is my first meeting today?*
(S6) An appointment at 11:45, with Mary.

(S7) *Change the place of that tales meeting to be my office.*
(S8) OK.

(S9) *What will be discussed?*
(S10) The report on the recent advertising error.

(S11) *What was the report i conclusion ?*
(S12) The incident was not considered harmful.

We will ignore the sophisticated language processing this scenario implies, and focus on the forms of reference visible in this passage.

3.1 Name Reference

A concept can be directly referenced through its names. Some names used in this scenario were: Fred, Bill, office, and Marketing people. Names in text reference the frame if it already exists in the active data base, or else cause retrieval of the generic frame and the addition of an instance of it to the database for the scenario. Suppose, after reading a sentence with "Bill" as its topic, we then are given a sentence containing "Marketing V.P.. Presumably this also is another name for the same frame (if this is Bill's job title). There are other names that can be used as unique designants of the frame, whose use results in a reference to the "Bill" frame if a previous use of a name has added it to the database. Each frame must have an associated list of allowable names which directly access it.

Names often serve as a shorthand for other forms of reference. They summarize the results of more complex reference processes, eliminating needless duplication of effort when the same reference reoccurs. Many of these names are widely used in general discourse ("O.P.E.C.*, for example). Other names, however, are unique only within a specified context The name therefore must be contextually bound. For instance, there are other vice presidents of marketing. Ambiguities among global names can only be resolved by recourse to contextual information. Names sometimes contain descriptors that can be used to distinguish among several possible frames (e.g„ "this month's report" distinguishes a particular Report frame). These modifiers often require linguistic solutions (e.g., "this" versus "that").

3.2 Contextual Reference

Contextual reference is the use of a descriptive term in a context where it functions as a reference. In the scenario, the use of the phrase The incident" in (S12) is an unambiguous reference to the "advertising error" of (S10). In the context of the discourse, only the "advertising error" is an incident Other contexts might result in the phrase having a different referent Contextual reference involves the use of a general term in a context where its referent

can be uniquely disambiguated. Repeated use of a particular contextual referent in a text causes it to become a local name. After its initial introduction, "incident" would refer to the "advertising error" throughout the scenario. If "incident* itself had names, these would also function as local referents to "advertising error".

Contextual reference is reference by description, where the description is contextually bound. Consequently, in determining these referents we will need two things: a search space that defines the local context, and a description. We shall see that using a hierarchical semantic system allows us to generate both of these from the referent. In contextual reference, the search space can grow very large, since such referents may not lie in the direct heritage branch of their referents. In a descriptively rich system it is possible to describe a complicated concept, object, or event in many ways. For instance, fighting in the Middle East could be described as "an international incident", "a border clash", "a skirmish", and so on. Or, consider a "forecast". Almost anything can be a forecast, since all that is required is that it not yet have occurred. However, we do not wish to make everything inherit from the Forecast frame. There may be no unique semantic arrangement in terms of a tree hierarchy, such that all terms are exactly superior to just those terms they dominate. Achieving this would require a tangled hierarchy, one in which a frame could be AKO several other frames.

3.3 Generic Reference

Generic reference is the use of names that have a direct relation to the referent in the heritage structure. Two frames may be coreferential if the heritage path of one entirely contains the heritage path of the other. If one frame matches another frame's heritage path, but descends deeper into the frame tree, we have a possible generic reference. There exists along the AKO link a direct path in the frame tree between these two terms. A reference to a frame is also a potential reference to any frames which inherit from it. The reverse is equally true. A daughter frame can be a reference to superior frames in its heritage path. This follows from the fact that on the one hand, the more generic concept subsumes the more specific one, while on the other hand, the more specific concept contains all the semantic properties of the more generic concept. In (S6) of the scenario, appointment functions as a generic reference to the meeting of (S5). Fig. 2 shows the hierarchical organization of meetings, appointments and other activities in our scenario. Generic links can be found by determining if the heritage path for a new frame contains any other new instances, and then matching the reference to the candidate frame*.

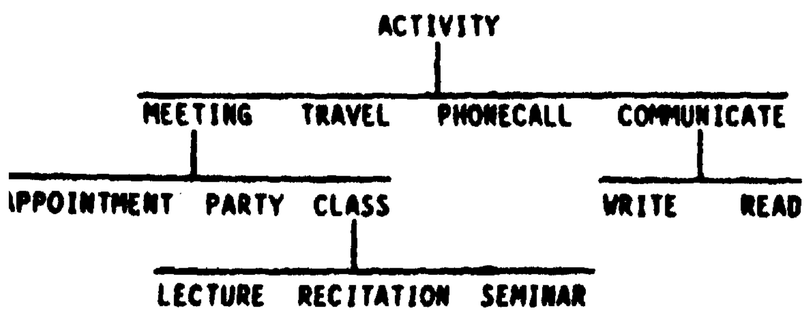

Fig. 2 -- A Hierarchy of Activities.

3.4 Frame Refereace

Frame reference is a function of the empty slots of a frame. The sentences (S2) and (S3) can be linked through the realization that the meeting in (S2) has an unspecified slot for participants, (S3) specifies this slot in its request for information, eliciting the value of this slot in the reply (S4). Frame reference inherently involves forward expectations. Any new item in the database might potentially be a part of any empty slot in an existing frame. In a database of any site, checking all these empty slots for each new item is prohibitively expensive. Instead we think of empty slots generating expectations which search for an instantiation among new items. Thus frame reference involves the issue of control, as well as a matching problem. Later on in Section 5 we will discuss one mechanism, Sentinels, for controlling matching in FRL Sentinals require a description of the referent, and this will involve the same matching processes as the other reference processes. They differ only in when the match is carried out

4. Reference mechanisms In FRL

We will now refine our discussion of reference by developing a formalism within which we can extract the common elements and underlying mechanisms involved in these reference processes. Consider a general model for matching two frames. Matching a reference (candidate frame) to a referent (target frame) requires three things: (a) a search space, (b) a matcher that is capable of using (c) a candidate frame description that can be matched against frames in the search space to produce a a set of target frames.

4.1 Specifying a search apace

Consider first how two frames can be related within FRL. Any two frames will share a common heritage path in the frame tree descending from the topmost frame, the THING frame, which will branch at some daughter frame. For instance, in Fig. 2, both Appointment and Party inherit from Meeting. This branching node, together with the semantic features inherited from its father frames (such as Activity), defines the minimum semantic concept which includes both frames. It contains the intersection of semantic features common to any frame in one branch with any frame in the other branch of the heritage tree. Frames in the branching portions define semantic characteristics of the heritage path which are not common to both frames through additional slots on the frames themselves.

A search space for reference in FRL consists of a piece of the he. itage tree which contains both referent and reference. We can specify this space by giving a node in this heritage tree which we know dominates both the referent and the reference Call it a Location. Only frames below this node need be considered by the matcher.

The minimum search space is defined by the lowest node on the frame tree from which both frames inherit If the reference and referent are on different branches, then the frame at which these

two branches diverge defines the minimum search space. Any frame lower down in the tree will exclude one or the other frame, while frames higher up will include more irrelevent frames. If the reference and referent are on the same branch, the superior frame defines the minimum search space. As we go up the heritage tree from the minimum search space, each new superior node will dominate more branches, until we arrive at the topmost node, the Thing *frame.* This defines the maximum search space; namely, the entire frame system.

We continue now with the overview of our model. Each reference is turned into a pattern to be used by the matcher. The pattern contains two kinds of information: a Location, specified as a frame name, that the matcher uses to define a search space; and a Description, specified as a pattern frame, that the matcher compares to frames in the search space.

4.2 Constructing the description

A matching process comprises two parts: search and compare. The search space is defined by the Location, and searching is restricted to the branches descending from this node. A pattern is a frame like description that can be compared against frames in the search space. It is a prototype of what the target frame looks like, containing information to delimit the search space as well as information about how to compare the frame with possible candidates. The pattern construction process differs slightly from one type of reference to another, but the pattern itself, once complete, is a unifying thread. It makes possible the use of a single general purpose matcher. The following two operations, common to all forms of reference, must be done to construct an initial partial pattern.

4.2.1 Collect requirements

Each of the slots in the reference frame has a counterpart in the partial pattern. Defining characteristics for each slot of the pattern are gathered by inheriting the information in the slot's REQUIRE facet from each frame along the AKO branch of the reference frame. In addition, since FRL allows slot description frames that describe the role played by a particular slot in a frame, further requirements for individual slots of the pattern may be discovered by inspecting any slot description frame for that slot Global requirements, applicable to the frame as a whole, reside on a special SELF slot of the pattern and are gathered from the reference frame just like the requirement on any other slot.

Requirements are either procedures to be applied to the value in the target frame or, in the case that the value itself is another frame, sub-patterns to be matched against the slots of the value. A typical requirement might check that the value is one of a set of permissible types, for example. Not all requirements are relevant to a particular match. Furthermore it is possible for specialized matching constraints to coexist in the same frame with requirements used for other purposes. Appropriate requirements are selected using identifying comments attached to each one.

4.2.2 Assign slot and frame matching procedures

A corresponding process of collection and selection assigns a matching procedure to the frame pattern and its slots. These procedures occupy the MATCH facet of the reference frame, and will bear the local responsibility for determining whether the pattern matches a target frame. Again, the SELF slot supplies global knowledge: in this case, the procedure that controls the actual comparison between the pattern and a target frame. Explicit matching procedures for the frame provide the flexibility to vary the "weight" given to various slots and conditionally alter the course of the match. Matching knowledge is thus distributed throughout the frame hierarchy like other forms of procedural attachment in FRL.

Local matching procedures allow a pattern to specify for a particular match the actual criteria under which the match will succeed. Not all slots are relevant in effecting a match. Some non-essential slots may be safely ignored. The slot description frames already mentioned can supply other information useful to the matching process, since they include knowledge about the relation represented by the slot; for example, that it is transitive, or that it has an inverse? The kinds of matches that occur in practice will be discussed in a later section.

The details of the pattern construction process differ with the type of reference.

Generic Reference: Either a GENERIC or a INDIVIDUAL frame is specified, and this frame becomes the pattern with the addition of matching information to specify the direction of the match, from value to requirement (INDIVIDUAL), or from requirement to value (GENERIC).

Frame Reference: The matching procedures specify that the local and global requirements from only the unfilled slots are compared against the pattern.

Contextual Reference: The input is a prototype from the database. It has all the characteristics of a regular frame except that it is not a part of the AKO hierarchy.

Name Reference: The pattern is trivial -- a frame with the name used, or one looked up in the paraphrase list.

Since all referents are turned into a pattern, only one matcher is needed to handle all forms of reference. The different behavioral types of reference, which can be specified in FRL, can now be seen to really be underlying variations on a pattern containing two parts: a Location, specified in terms of a node on the frame tree; and a Description, specified as a frame pattern.

4.3 Matching frames

Two frames may share all semantic features in common, expressed by identical slots, but contain different values for those slots. They are then different instances of a generic frame. We shall call this potential difference between two instances of a generic frame a pragmatic difference. Since procedural attachments are defined on the generic frame's slots, these will be held in common also. For example, the Appointment-72 and Appointment-66

frames are both instances of the generic Appointment frame. Both the Appointment-66 and Appointment-72 frames have a slot for participants, and inherit the same REQUIRE facet of this slot. However the value for this semantic feature will differ in the two instances; the two participants in the Appointment-66 frame are Mary and John, while the participants in the Appointment-72 frame are Bill and John. This pragmatic difference allows two instances to not be coreferential.

Matches between a reference and target frames in the search space will always have a semantic and pragmatic component. The semantic constraints can conflict. The two frames might not have identical semantic features (i.e. slots). It is not necessary for a successful match for both frames to have identical slots. In Generic Reference one set of slots subsumes the other. The inherent semantic relationship between generic referents means that we need only compare the common slots. We can assume the extra slots on one frame do not cause any semantic conflicts.

Contextual reference involves two frames that share some slots, but can each contain slots not on the other frame. It is possible that these differences exclude coreference. For instance, a Tree and a Dog each have unique slots when compared to each other, and are not coreferential. If a Dog has a slot for ambulation, whereas a Tree is explicitly marked as stationary, these two slots are mutually exclusive. (We exclude the case of conflicting slot values, as in a breathing slot marked "yes" for Dog, but "photosynthesis" for Tree.) By comparing the non-equivalent slob on different branches for mutual exclusion, the matcher can determine if frames on one branch are able in principle to function as contextual referents. However, it is also true that two frames whose slots form a partial set intersection can be coreferential. Take the case *of* a Father frame, which is AKO Person, and a Marketing V.P. frame which also is AKO Person. Clearly Fathers and Marketing V.P.S can each have properties that the other doesn't. Yet Fathers and Marketing V.P.S can be coreferential. Even a partial match requires that we are able to determine none of the slots on the Marketing V.P. frame conflict with those on the Father frame. In this case, the reference provides a best match, though not necessarily a complete match,

If there is no semantic conflict, the two frames are potentially coreferential. A match of the pragmatic features will determine this. (Note that by using the notion of a search space, very few inappropriate semantic matches need be entertained. We should seldom get in the position of considering whether dogs are references to trees, for example, since they do not bear a close relation in the frame tree.) This pragmatic match will compare values for the slots which are held in common. These values may be identical; they may differ, but be in slots which take a set of values; or they may conflict. If the slot accepts a set of values, and the values don't match, but meet the requirements of the slot, we may still be willing to consider it a match. Similarly, if the values conflict, but are ephemeral, like hair color, we may not require them to be identical unless there are multiple candidates to be discriminated among. One frame might have a slot value, while the other has none, but does have requirements; one value may be a subset of the other value. If a slot on one frame has a value, but doesn't on the other, this value must be consistent with those that the value-less slot can take. New values for uninstantiated slots may trigger associated procedures that evaluate the potential new value.

The matcher makes use of procedural knowledge associated with frames since it does not itself contain the knowledge. Thus, (a) the matcher must know how to use this knowledge, which is not explicitly put in for matching (it is there for semantic definition), and (b) the matcher must make use of the fact that knowledge is distributed in the frame hierarchy and can be collected appropriately in the pattern. Not every slot needs its matching requirements explicitly stated if it can be inherited efficiently. The equirements for the particular slots will determine the outcome, and will also contain knowledge about how they can be relaxed, as in the case of values which change over time. Consequently there will be a degree of matching determined by the assigned value matching procedures. This allows us to formalize the notion of a good match as being a continuum.

5. Controlling the Matcher

The system we have been proposing is an "ideal" system in that it ignores the time dimension. Both reference and referent exist at the same time. However, information, as in the scenario, is understood over time. Reference may be forward or backward. A reference may be added at some future time, as well as already existing in the database. Indeed, there is no guarantee that the reference wilt ever occur? If for each new item in the database we always check to see if it is a reference, we will be making many useless searches. Therefore deciding when to compute reference is an important process. There is one class of reference where this choice can be reasonably determined. Frames will often have empty slots, and many of these slots are filled in by subsequent information.

To implement Frame Reference, we have chosen an approach that treats the empty slots of a frame as expectations. In practice, the decision to use forward expectations must take into account the extra computational burden this would place on the system. Maintaining forward expectations is useful to the extent that new information can be uniquely recognized by a set of special demons [I] called Sentinels created for the purpose. Sentinels were developed with James Stansfleld by one of the authors (Steve Rosenberg). If all new frames are matched against all empty slots, a goal driven strategy of using expectations is equivalent to a data driven one of matching each new input against empty slots. However, by using the information available in the frame tree, we can reduce the number of matches each expectation requires, combining the best aspects of a goal driven and data driven approach in the notion of Sentinels.

Many demons in a database can slow processing, since the traditional notion of demons does not make use of the semantic organization inherent in frame based hierarchical system. Thus we introduce the concept of instance-driven demons. Consider •

demon attached to the instance slot of a particular frame; e.g., the Instance slot of Meeting. Whenever a new instance occurs that inherits from Meeting, the demon matches its pattern against that new frame. Thus, if the following sentence occurs:

(S13) *There is another meeting.*

another instance of Meeting is created, triggering this demon. Other new frames that do not inherit from Meeting (e.g., a new instance of Travel) do not trigger the demon. Such a demon will match against only a selected subset of new input. By choosing the appropriate frame to attach such demons to we insure that they match against only likely candidates with precise semantic relations to the frame.

Sentinels are initially goal-driven, in that they are created as active expectations. However, they draw on the information available about frames that car satisfy the expectation to place data driven triggers, called sensors, in appropriate places in the frame tree. These sensors are activated by only a small subset of the input, that subset with the highest likelihood of fulfilling the expectation. Whenever a sentinel is triggered, through the addition of a new instance that meets the sensor's requirements, it evaluates this triggering value, and determines if in fits the expectation. If so it adds the new instance as the value of the appropriate slot and frame. Once this is done the sentinel will erase itself and its sensors. Thus the system will not be cluttered with unneeded procedures that fire inappropriately. Sentinels are a way to create and manage demons in an organized semantic system. Two of their features are a limited life span, and the ability to move sensors around in response to a condition that is computationally determined as it develops. A sentinel can have several sensors which report to it. The sentinel is satisfied when some arbitrary logical or temporal conjunction of its sensors succeed. A sentinel has the capacity to evaluate conditional relations among its sensors, and even to remove current sensors and place new ones as a response to these conditional constraints.

In order for sentinels to efficiently encode expectations, they must be given a Location. New instance values inherit procedural attachments from up the tree. Thus a sensor on the Instance slot of the Thing frame would be triggered by any new instance added to the system. This is equivalent to testing every new instance against every expectation, exactly the case we wished to avoid by making use of the organization of the semantic network! On the other hand, if we do not know the precise form of the expectation, we would like to place the sensor at a location in the hierarchy where it is sure to be triggered by the right value, although there may be some false alarms. Thus the use of the frame hierarchy lets us place sensors where they will be triggered by semantic classes of items that are sure to contain the target items. If the description of the expectation is vague, we will need to accept more false alarms, but in any case we can use the organized hierarchy to make use of descriptions so that the expectations are optimally placed. In sparse databases such sentinels act as more efficient demon implementations. In rich databases, with much inferencing, they allow us to suspend processing at many places, since such processing will only be reactivated in highly appropriate circumstances.

Frame Reference uses the slot name and requirements to generate a pattern which defines a lowest possible node in the frame tree from which an instantiating value must inherit. For example, the Participants slot of a Sales-Meeting frame might inherit a requirement, in the form of a sub-pattern specification, from Meeting that says "AKO employee"; the slot itself has the additional requirement "includes Marketing-people". The sentinel on the instance slot of this indicated frame will examine each new token inheriting from this employee frame, and finally fulfill the expectation when at least two proper instances of employees have occured, one of which also has a job slot value which is AKO Marketing-people.

6. Conclusions

We propose a model of coreference for frame databases. We discuss coreference from the behavioral standpoint in terms of the FRL formalism, and present a single elegant mechanism for handling all the coreference forms discussed. This mechanism consists of a pattern and a search space, both generated from the reference. The pattern is matched to items in the search space to generate target references. We briefly explore the issues involved in controlling such a reference module, principally through the use of Sentinels.

Once input has been translated into a frame representation, the coreference problem becomes independent of the medium in which the information was originally expressed. An intimate connection does exist between the form of the memory and the operation of the reference mechanism. We view text or discourse structure as providing a control mechanism which drives the underlying processes of memory. Thus the use of themes and topics, as well as more specifically linguistic clues, restricts the context for reference so that it works efficiently.

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REASONING IN INCOMPLETE DOMAINS

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Most real world domains differ- from the micro-worlds traditionally used in A.I. in that they have an incomplete factual database which changes over time. A traditional rule interpreter such as Planner can be extended to construct plausible inferences in these domains by (A) allowing assumptions to be made in applying rules, resulting in simplifications *of* rules which can be used in an incomplete database; (B) monitoring the antecedents and consequents of a rule so that inferences can be maintained over a changing database.

I. 1NCOMPLETE DOMAINS

A traditional reasoning program, such as Planner [(>), has difficulty dealing with incomplete information. Consider how such a program might make inferences about the price *of'* wheat. We, formulate the problems as follows:

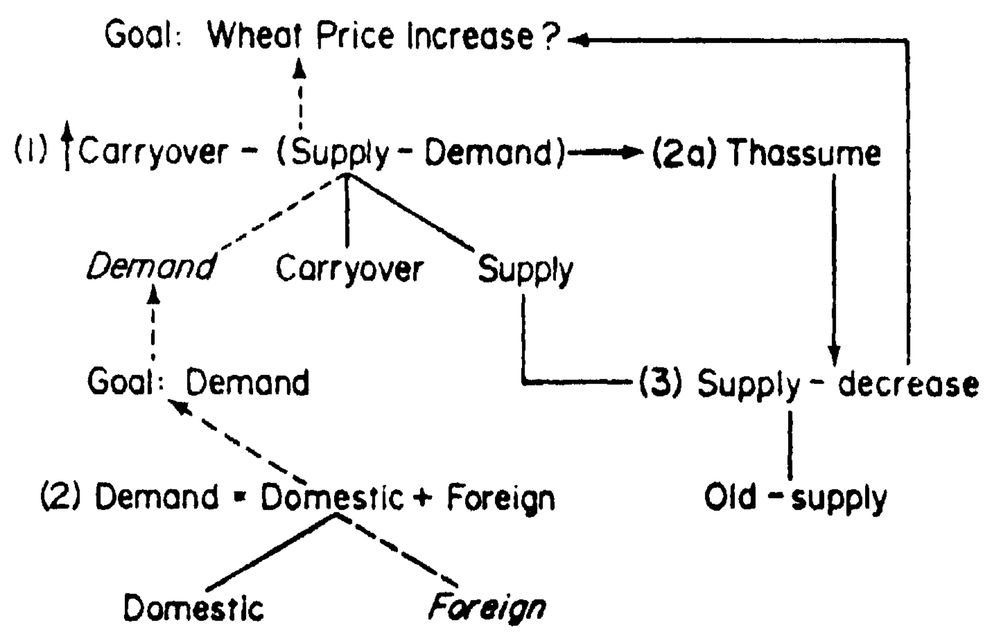
Many real world databases are:

a ' Incomplete because not all the information needed for an inference is available at a particular time.

b. (Instable, since the particular subset of information available can change fairly rapidly !n the real world .

for .example, a farmer, in deciding how large a wheat crop to plant, has incomplete information about ultimate wheat price and demand, based on rapidly changing information, such as daily weather reports, weekly crop surveys, and so *on,*

(Thgoal (price-increase wheat))



(In the diagrams, italics and a dashed line indicate antecedents which are missing; a solid line indicates an existing antecedent; a solid line and arrow indicate deduced links between rules and assertions; a dashed line and arrow indicate inferences which have failed.)

Thml states that to show a price increase for wheat, show that the difference between supply and demand is less this year than last. Suppose that no assertions for wheat demand exist in the database. In this case, Thml would fail, since one of its antecedents is missing. For such cases, Planner provides a strategy. If an assertion is not in the database, Planner will try and prove it. Thm2 states that to deduce demand for a commodity, find the foreign and domestic demand for this commodity, and add these together. We will assume no assertion for

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foreign demand exists. Thus Thm2 will fail. If there are no other methods for proving the missing assertion, the inference process will fail.

The inference attempt failed not necessarily because it was wrong, but because not enough information exists to make correct inferences. By making assumptions about missing information in such cases we can often succeed by using a simpler rule. For example, a farmer might reason that as long as the supply of wheat is decreasing, it will be worthwhile to plant more regardless of demand. Thus, if the full set of assertions concerning supply, demand and carry-over are unavailable, we might try to prove that supply has decreased. By substituting goals that require only a subset of the assertions that the original theorem required, we develop a notion *of* rule simplification.

The knowledge of which other rules can be used as simplifications, and under what circumstances, must be represented. A rule interpreter can make use of this metaknowledge [1] to substitute simpler theorems for a rule which fails. The appropriate place to specify this metaknowledge •s in a separate class of theorems. e.g.

```
(Thassume Thm2A (X) (Supply-G-demand ?X)
     (Thgoal (supply-decrease ?X))
     (Theaveat (Default)))
```

This new class of theorems, such as Thm2A, contains information concerning simplifications and assumptions. A Thassumption will specify A) a goal; theorems satisfying this goal can function as a simplification; B) the assumptions involved in using that simplification. These are expressed as a caveat. If the assumption being made is that the missing antecedents can be ignored, the caveat will contain a Default.

Using a simplification always reduces the plausibility of the reasoning. By ignoring the demand for wheat, a farmer is willing to assume that if demand changes, it will not change in a direction or quantity which would invalidate his reasoning. By making explicit this notion of assumptions, we can extend the list of options available. For example, we can encode constraints on our use of assumptions through the caveats.

Returning to our example, after Thm2 fails, simplifications will be considered, and Thm2A (proving a decrease in wheat supply) found. Thm2A first tries to satisfy the goal (Thgoal (Supply-decrease ?X)). Thm3 can be used to prove this. Thm3 states that to show a decrease in supply, show that last year's supply is greater than current supply. If current supply and old-supply are known, Thm3 will succeed, and support the hypothesis of higher wheat prices.

2. UNSTABLE DOMAINS

As the database changes, our goals may remain relatively stable. Support for an hypothesis is conditional on the assertions available at the time it was first considered (i.e., the inferences which were possible at that time). However in many deductive systems, once deductions are made from a set of assertions, no effort is made to insure that while the results of those deductions are used, the assertions still hold true. Generally, the user does not expect the database to change so as to invalidate prior inferences.

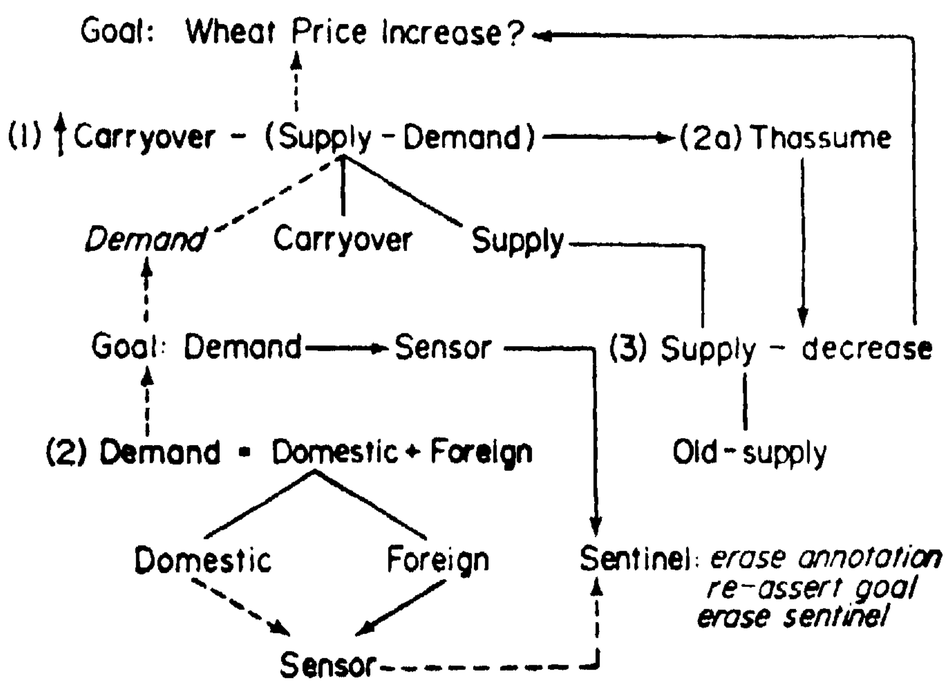
We can extend our concept of rule interpretation bv making the maintenance of rule instances a function of their interpretation. We implement this by giving each active rule the autonomy to respond to changes in its environment. As each rule is applied, an associated Sentinel Is created. The Sentinel knows how to respond to changes in that rule's antecedents or consequents. The result is the maintenance of hypotheses through a method of local autonomy. A rule instance must be continuously enabled while it is used in support, of some hypothesis.

A Sentinel associated with a rule instance will place sensors in the database. A sensor is a demon which responds to changes in the pattern that triggers it, and evaluates whether these changes violate some criterion. If so, the sensor reports to the Sentinel. The Sentinel is satisfied when some arbitrary logical conjunction of its sensors succeed. The Sentinel can then take a variety of actions. The standard ones arc to A) erase itself; B) erase the rule instance; C) reinvoke the goal.

Individual rules will succeed or fail as a function of their antecedents. When a successful rule's antccedents change, its sentine1 will be triggered. When this happens the sentinel causes the goal the rule was supporting to be re-evaluated. At this point the sentinel can erase itself. (Note: A sentinel causes a goal to be re-evaluated. There is no constraint that the same rule be used again. Another rule may now be the best choice. However, in this example it is assumed that there have been no other changes in the state of the system that would cause another rule to be selected first.)

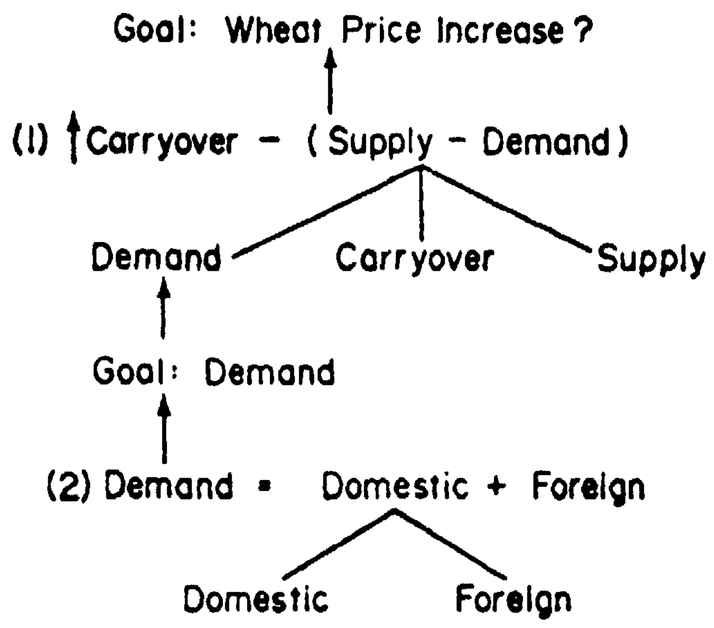
If a rule's goal is removed, its sentinel will also be triggered. In this case we do not wish to re-evaluate the goal. The sentinel will remove itself and erase the associated rule instance.

Consider how this local association of rule instances with sentinels can give rise to the right global behavior. Suppose that a failed rule now is capable of succeeding, through its missing antecedent being asserted. lor instance, the missing foreign demand for wheat can be asserted.



This will trigger the associated sentinel to erase the annotation for this rule instance, reassert the goal as something to be proved, and then to erase itself. This time Thm- succeeds, resulting in a proof of the missing demand for wheat. This will in turn trigger the sentinel associated with the rule instance of Thml for which the missing demand is an antecedent.

This sentinel repeats the actions of the prior sentinel. However, in erasing the annotation, it erases the record of the assumption made. This will trigger the sentinel on Thm3, the simplification. Since the use of a simplifica tion is conditional on another rule failing, the sentinels associated with theorems used as simplifications monitor the annotation recording that failure, so that they will Know when the simplification is no longer required. They will then respond to the erasure of this annotation by erasing the annotation for the simplification. Since the formerly missing antecedent for demand has now been inferred, ThmJ succeeds, as does our inference attempt.



Thus, unneeded rule instances will know when to remove themselves. Through local propagation, the representation responds to changes in the available database. Changes in the database can reinvoke the goal of infercncing, which can then proceed. Doyle [2] has developed a scheme for recording deductive dependencies so that when facts turn out to be incorrect, the entire "context" of dependent facts can be removed from the database. The current approach does not allow explicit manipulation of deductive dependencies, since the changes it is designed to respond to are those imposed on the domain by "outside" changes in the data, and not ones due to deduced inconsistencies. McDonald [3| has contrasted this approach to other methods.

The rule interpretation features of sentinels and simplifications were programmed in FRL (Frame Representation Language) [4].

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A SEMANTIC NETWORK OF PRODUCTION RULES

IN A SYSTEM FOR DESCRIBING COMPUTER STRUCTURES

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A novel Implementation of the basic mechanisms of a semantic network is presented. This constitutes • merging, in terms of the underlying language architecture, of a powerful problem-solving mechanism, production-rule systems, with a proven representation formalism. Details are presented on the most basic aspects of the network, namely on representing nodes and on mechanisms for their access. Commands for definition, modification, and search-based displays of network information are discussed. The relations of the network are divided into six groups: taxonomic, structural, functional, descriptive, means-ends, and spatial. The importance of uniformly representing methods and network, and the importance of distinguishing temporary from permanent states are discussed. There is sketched a production system position on a number of relevant issues for advanced capabilities. The domain of application is the symbolic description and manipulation of computer structures at the PMS (processor-memory-switch) level. The system will ultimately be used for computer-aided design activities.

1. SYMBOLIC DESCRIPTION AND MANIPULATION AS A TASK FOR AI

1.1..Motivation and research context

One aspect of computer-aided design is the manipulation of symbolic descriptions of physical systems. Problems in this area have been discussed by Eastman [3] and by Sussman [12]. Other AI research has discussed mechanisms that may be applicable to design systems while maintaining a general viewpoint and vocabulary, eg, Rieger's Commonsense Algorithms [9] and Moore's MERLIN [8]. The present research* aims to deal with the following problem areas:

1. Describing the basic system components.

2. Organizing those components into structures.

3. Establishing hierarchies of components and structures ranging from abstract ones to various concrete realizations.

4. Comparing structures and putting them into correspondence with each other (mapping).

5. Analyzing structures and determining effects of changes.

6. Synthesizing structures from elementary components, trying to fulfill functional specifications.

7. Coordinating multiple viewpoints of the same system.

8. Searching the design space.

9. Simulating system behavior symbolically, to ascertain dynamic properties.

An approach to these problem areas would be applicable to a wide range of systems: buildings, software systems, chemical processes, cities, etc. In addition, it could provide a central mechanism for diagnostic, tutorial, explanatory, and theory explication systems.

Computer structures at the processor-memory-switch (PMS) level are the domain of the IPMSL (Instructable PMS Language) system. The basis is that of Bell and Newell [2] In particular, the following abstract components are considered:

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C	Computer	L	Link
p	Processor	D	Data-operation
M	Memory	N	Network
S	Switch	X	External (non-digital)
K	Controller	T	Transducer
H	Port		

Knudsen's [7] work in the PMS area is a direct predecessor to the present effort, with strong influences from Barbacci and Siewiorek *[l]*

2. THE IPMSL SYSTEM: BASIC SEMANTIC NET REPRESENTATIONS

IPMSL (Instructable PMS Language) is a set of production rules for building semantic net structures in response to user commands.* IPMSL starts out as a set of "procedural" productions that perform the basic net-building operations. The net itself is composed of "declarative** productions whose contents are the net's facts. There are a few "procedural" productions devoted to constructing the "declarative" ones, on command and also as a result of other processing. Both kinds of productions are interpreted according to the same basic recognize-act cycle. The user sees the information he enters being structured into a semantic network, while underneath, that information is stored as, and manipulated by, rules.

2.1. Underlying problem-solving architecture

The implementation language for IPMSL is the 0PS2 [4, 10] architecture, extended for this task by changing its external appearance. The extension is named 0PS3RX. The primary capability afforded by 0PS3RX is the ability to represent data elements as sets of attribute-value pairs. OPS3RX makes things look much more like "schemas" or "frames", and development of the language will continue in this direction. (In fact, production rules seem to be an ideal way of expressing procedures in a frame-based system.) There are usually about 100 attribute-value sets in Working Memory (WM), each containing about five attribute-value pairs.

Rules are used tc implement both the interpreter of the network and the network itself. WM serves both to hold onto various processing goals and to accumulate temporary network structures. A network rule stores the facts of only one node in the network plus pointers to other nodes. When some goal requires the expansion of the net *in* WM alonp some direction (eg, in order to search for some piece of information), a subgoal appropriate to going in that direction is formed, resulting in a rule being executed. This causes appropriate structures to be hooked into existing WM structures, both by creating new WM nodes and by using pattern matching to detect appropriate linking locations.

*An expanded versions of this papers is available from the author, under the same title..

2.2. Basic network design

IPMSL divides its knowledge about computer structures, and about itself, into six subnets, each containing a particular sort of knowledge:

- Structural. Parts, Partof, and Coparts relations. A component of a computer can be considered as a black box, or as an assemblage of known parts. Components are related to each other at the same structural-hierarchy level with the Coparts relation.

- Taxonomic. FSs and FSof relations. "FS" stands for "further specification", as used in the Merlin system [8] An object is an FS of another if it can be viewed as the other with some additional characteristics (cf "ISA"). More precisely, the set of attributes in the description of the FS is a superset of those that describe the parent, *and* the values of those attributes may be modifications of the corresponding ones in the *parent*

- Descriptive. This category includes various attributes that don't fit elsewhere, eg, cycle time, memory size, and bandwidth. Further classification may occur later.

- Physical. This includes: cabinet size, power supply requirements, cooling requirements, and noise, to name a few.

- Functional. *Here are* collected properties having to do with how a component functions or behaves within *an* assembly of other components. Specifications of inputs and outputs are examples (see [6]).

-' Means-ends. Relations in this subnet directly correspond to the language for expressing methods (discussed below).

Figure 1 depicts a fragment of a network including three of the subnets (the structural subnet is represented graphically; this picture is manually generated).

The figure suppresses some details about the actual node and link structure; it is intended primarily to be an example 0f the kinds of information dealt with, and how the six subnets partition them. Note that the division into subnets essentially assigns one set of nodes and interconnects them using six different sets of relations. As will become evident from details below, the implementation actually attaches six subnet nodes to each main node, one for each subnet, and then attaches relations emanating from that node to the appropriate subnet nodes. Relations coming into a node from others in the net all point at the one main node, however (ie, they use only (he name of the node).

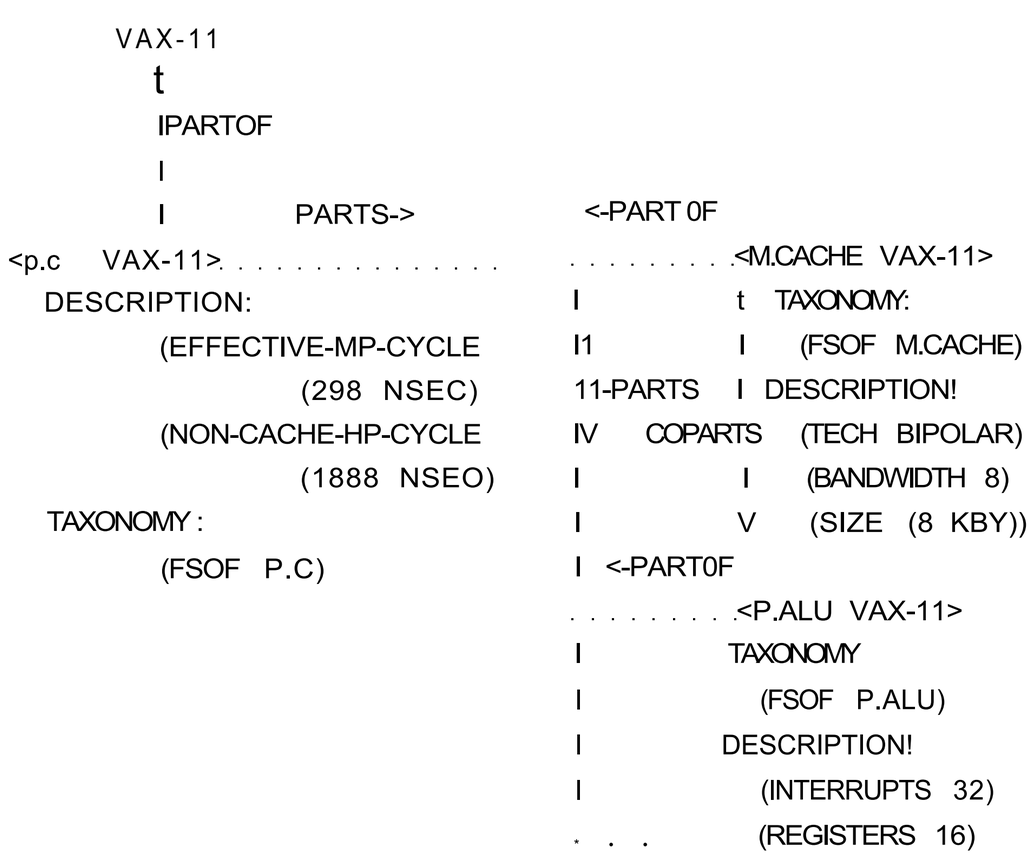

Figure 1: A fragment of a PMS network

Nodes in WM are temporary and consist of temporary symbols with attribute-value pairs attached. There is a main node for each object in the network, and a subnet node for each subnet that is defined and evoked. Figure 2 shows the WM elements for a typical component, with Lisp internal formats translated to a more readable graphic arrangement.

S8123
KNOWLEDGE-ABOUT P.C
ROLE MAIN
STRUCTURE S8136
TAXONOMY S8138

S8136
KNOWLEDGE-ABOUT P.C
NET S8123
SUBNET STRUCTURE
PARTS (D.ALU M.REG)
PARTOF C
STRUCTURE PI89

S8138
KNOWLEDGE-ABOUT P.C
NET S8123
SUBNET TAXONOMY
FSOF P
FSS (<P.C LSI-II> <P.C VAX-II>>
TAXONOMY P282

Figure 2: WM elements for a typical component

Figure 2 includes a main node and two subnet nodes for the P.c (central processor) component: SO 123 is the temporary name for the main node, SO 136, for the structure subnet node, *and* SO 138, for the taxonomy subnet node. Each node is identified by the "knowledge-abouf attribute - this serves to tie together the three nodes, in such a way that pattern- matching in rules can easily collect together the separate nodes. The main node has two pointers to its subnet nodes, and each subnet node has a pointer back to the main node. The two subnet nodes include, as values of "structure" and "taxonomy" attributes, the names of the productions that built them, so that modifications can be done. (The main node is built by a general production, so it doesn't need such a pointer.)

The production that builds the subnet node for the structure of P.c is the following:

P198: IF THE GOAL IS KNOWLEDGE-ABOUT THE STRUCTURE SUBNET OF P.C
AND THERE IS KNOWLEDGE-ABOUT THE NODE OF P.C WITH THE MAIN ROLE,
THEN BUILD A KNOWLEDGE-ABOUT P.C NOOE WITH SUBNET STRUCTURE, WITH NET THE NOOE OF P.C WITH THE MAIN ROLE, WITH PARTS (D.ALU M.REG), AND WITH PARTOF C,
AND MARK THE GOAL SATISFIED
AND ADD TO THE NOOE OF P.C WITH THE MAIN ROLE THAT ITS STRUCTURE IS THE NEW NODE.

The syntax used here is a hand translation from the list-structure version, for readability. Some clumsiness remains, due to the effort to retain as much of the attribute-value flavor of the representation as possible. "Of and "with" denote a relation between a pair and the object name to which the attributes apply.

All such network-information rules have a similar structure: a simple "if" part that detects the goal to access the knowledge and gets from WM existing information about the main node for the component desired; and a "then" part that constructs the appropriate dynamic node for the particular subnet, along with updating pointers back and forth.

Two general productions are involved in accessing network knowledge, one to build the "main role" node when it is absent from WM, and the other to notice that the knowledge desired is already in WM, and thus to mark the "knowledge-about" goal to be satisfied. These are P98 and P99, respectively, and are displayed below:

P98» IF THE GOAL IS KNOWLEDGE -ABOUT SOME SUBNET OF SOME OBJECT
AND THERE IS NO KNOWLEDGE-ABOUT THE NODE OF THAT OBJECT WITH THE MAIN ROLE,
THEN BUILD A KNOWLEDGE-ABOUT NOOE FOR THAT OBJECT WITH ROLE MAIN.

P99: IF THE COAL IS KNOWLEDGE-ABOUT SOME SUBNET OF SOME OBJECT
AND THERE IS KNOWLEDGE-ABOUT THE NODE OF THAT OBJECT WITH THE MAIN ROLE WITH THAT SUBNET BEING SOME NOOE
AND THERE IS KNOWLEDGE -ABOUT THAT NOOE,
THEN MARK THE GOAL SATISFIED.

Note that -some" and "that" refer to unrestricted pattern variables in the actual productions; the word following them is not a semantic restriction on values assumed by the variables, but enhances human readability only. The way that these three types of knowledge-access productions work together is dependent on the conflict resolution strategy of 0PS2, particularly the special-case criterion, by which the rule that matches more data is preferred. P98 is the least special-case of the three, and its condition is explicit enough that it will be true only when the others cannot be, so special-case is not so critical for it. But neither PI90 (and all others of its type) nor P99 has any negative conditions, so PI90 can be true at the same time as P99, and here the special-case criterion makes the difference.

One other form of access is used: access to a particular attribute of an object, where the particular subnet is not known, *an* example of which is PI45:

P145: IF THE GOAL IS KNOWLEDGE-ABOUT THE PARTS ATTRIBUTE OF SOME OBJECT,
THEN A00 TO THE COAL THAT THE SUBNET IS STRUCTURE.

There is a production like PI45 for each attribute that is known to the system. Note that PI45 remains true even after it fires, but that conflict resolution prevents it from repeating in a couple of ways (one is sufficient, of course): the refraction principle inhibits such repetition explicitly; the lexicographic recency will give preference to other rules whose conditions include the subnet information that PI45 adds - the productions displayed above are all good candidates so that those others will fire next.

The kind of action done by PI45 is typical of the production system style used here: a goal is a symbol structure to which a variety of rules can contribute small pieces, until enough is accumulated to make the goal satisfied.

2.3. Basic IPMSL methods

The above has sketched the mechanisms of basic access of information in IPMSL. Now we turn to three central IPMSL commands, which build on the basic access to form actions with wider effects

A user causes the construction of new network nodes with the *DEFINE* command. The method for doing this involves taking the information from the user and embedding it in the fixed structure common to all knowledge-access productions, of which PI90 above is an example.

Modification of existing net structures is done with the *LET* command, which includes the attribute and the new value of the symbol to be modified. WM structures are modified directly. PM (Production Memory) structures are accessed via the appropriate pointers in WM (ie, rule names that are kept with each node) and then their actions are edited so that future executions will result in the modified structures being built in WM Usually the Let command has the proper subnet filled in by rules that know which attributes are part of which subnets, eg, PI45 above. This subnet inferral Is done In the process of accessing the knowledge, as part of Let. The purpose of this access is to check that the Let command is actually specifying a change to existing information.

The user can evoke a region of the network and have it displayed in a tree format by using the *SHOW* command. This command sets up goals to search from a starting node through all nodes related to if in specified ways. At each node visited, information is collected into a tree structure, and after the search is completed, this tree is printed. The Show command has a number of options, which specify what kind of additional information is to be collected at each node.

To summarize, the basic IPMSL commands provide access (query), definition, modification, and search-and-display capabilities. Generality has been maintained: there is very little in IPMSL that is specific to the division into six types of subnets, or to the PMS domain. Also, the methods, expressed as rules, have proved to be easily modifiable. Two other design issues can be mentioned:

- The net is divided into six subnets for several reasons: to make rules a reasonable size, to avoid extra information being added to WM, to impose some structure on knowledge as it corner, into the system from the user, and to modularize the methods that work with the net.

- Efficiency is a concern, since IPMSL is intended to be worked with interactively. Response times for network definition commands *are* in the range of one to two minutes on our time-shared DEC KL-10. This is usually significantly exceeded the time it takes a user to decide how to formulate the next piece of network to be added, and is therefore a tolerable response delay.

3. THE IPMSL APPROACH TO INSTRUCTION AND AUGMENTATION

IPMSL started out as a small set of productions (less than 50) called *Kem\2 (Kernel* version 2). Kernl2 allows simple kinds of interaction to take place, including interaction that leads to adding new rules. The first interactions with Kernl2 involved adding to and improving Kernl2*s capabilities, while later ones were more and more devoted to adding the basic IPMSL commands. Kernl2's essence is a set of methods for interpreting and executing user inputs that *are* expressions in a simple method language. This method language allows the user to designate elementary components of a method. After a number of such designations, the user gives a command essentially saying that the method is ready to be formed into productions, and Kernl2 does the rest of the work: keeping track of what is designated and finally putting it

together into rules. Kernl2 also includes rules that describe itself in a declarative way. Thus, a user can both construct methods of his own for new goals and access the Kernl2 network to understand and augment Kernl2 itself. Both of these operations have in fact taken place as IPMSL has grown.

The Kernl2 approach to growing a system, ie to instruction, builds on two previous independent approaches: that of the Instructable Production System project [11] and that of Waterman's Exemplary Programming [13].* The idea behind having Kernl2 be a part of what is basically a semantic network system has three aspects. First, the method language of Kernl2 allows a user to easily build up new system behavior, ie, it is a means to making the system fully extensible. Second, method construction takes place within a dynamic WM context that is similar to that in which the method will work after it is finished. Third, all of the above-mentioned method language facilities are available both to the user and to internal methods built from rules.

The basic IPMSL system is composed of 316 rules, of which about a third a*re* network rules, another third *are* Kernl2 rules, and the remainder a*re* IPMSL methods.

Some auxiliary software has been added to aid the direct coding of rules, bypassing the method language approach to growing the system whenever this seems expedient. This includes a facility for abstracting and displaying all or a select part of the rules in a particular method in a relatively small screen space; more flexible rule entry and editing, including the ability to copy information from one rule into another (thus one can make a new rule "like" another, and then edit in the discriminating elements); and the ability to make listings of the rules organized according to method. With these aids, it is possible to grow and debug the system at a rate of about two to five rules per on-line hour.

4. ADVANTAGES AND DISADVANTAGES OF USING RULES FOR A NETWORK

My evaluation of production rules as a basis for a semantic network system consists so far of a set of subjective impressions and design characteristics. The existing implementation of a net is an unusual mix of procedural and declarative components. The net is active in a real sense, though controlled by particular activation goals. Control in general for the net can be distributed around, as rules, but since WM is global and inspectable at all cycles by all rules, there can be global (centralized) control to a large extent. As yet, there has been no problem of searches in the net getting out of control, and in particular, unexpected rule firings have not interfered with processing.

The following lists a number of specific advantages that production-rule systems seem to have for network systems.

- WM serves as a large dynamic context. It records uniformly both the state of methods that are being executed and the state of the network as it is searched.

- The single shared dynamic state allows flexible control of searches. That is, ordinary searches can be monitored by global, general rules, by specific search heuristics, and by control knowledge that is distributed throughout the net - all expressed as rules.

- WM is useful for growing large, hybrid, temporary structures and mappings - things that one would not necessarily want to become a permanent part of the net.

- Rules can bring together (by recognition) complex patterns of diverse knowledge, thus making it possible to integrate information in new ways.

- The rules are readily organized into an instructable structure.

- Searching methods and others can themselves be described using the same network conventions as the subject domain.

- Goals are interrelated in ways that can be much more open (heterarchical) than conventional recursive (hierarchical) forms: the goals are global structures in WM that can be processed in varied orders, can be satisfied in accidental ways, and can be examined and re-ordered flexibly.

- Existing efficiency techniques for production-rule systems can be immediately carried over to network searches. In fact, the rules in 0PS2 are compiled by converting their patterns into a very efficient network structure, developed by Forgy *[5]*

- The recognition part of the execution cycle is amenable to simple parallel implementation.

- The net need not be uniformly encoded: one could do various arbitrary things to evoke information (or to respond to it) in special cases.

The above positive features can be balanced with the following disadvantages.

- Space usage seems high: a few attribute-value pairs require a good bit of surrounding rule structure. But any such network requires some space overhead.

- Search is serial: nodes are developed one at a time. But as mentioned above, given a parallel processing architecture, production systems are favorable for exploiting it.

*The interested reactor should consult those rafarancat and tha datailad version of this papor, available from (ho author

5. CONCLUSIONS

In concluding, a few major points can be re-emphasized. Implementing the network as production rules has allowed the fruitful merging of two hitherto separate technologies: a problem solving procedure formalism and a semantic net representation formalism. The network organizes both domain information and information about the methods of the system itself. Using production rules allows the system to take advantage of recent progress in techniques for growing such systems.

The production system architecture provides a number of useful features. Methods, and network share the same working space (WM), so that rules are readily applicable both to control the evocation of network information and to provide useful information for methods to use.

Advantages of using a semantic net implemented as production rules appear to outweigh the disadvantages, and examination of problems that can be expected when more demands are made of the system supports the continuation of this line of work. IPMSL has so far proven effective for defining, updating, and displaying a network for the DEC VAX-11 computer. Research is currently proceeding on using the basic ingredients presented here to provide IPMSL with higher-level capabilities, approaching operations that will prove useful to its intended domain of computer-aided design. The work so far has advanced knowledge on at least two fronts: In formulating knowledge precisely so that a system such as IPMSL can encode it, one inevitably improves the basic knowledge of the domain, in organization, precision of detail, and explicitness of assumptions. In addition, we continue to improve our knowledge about the requirements that demanding intellectual tasks place on the production system architecture and on the whole body of AI concepts and techniques.

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ADDENDUM

As of the time of final revision of this paper, IPMSL has grown to a size of 610 rules with no degradation in its overall manageability, and with very little decrease in efficiency of interpretation. The total system size relative to the PDP-10 is becoming much more of a problem. Of the new rules, about 237 are network, as compared with 307. in the system detailed above, with the remainder being new melhods for display of information, better handling of descriptive attributes of computers, and better network access and editing capabilities.

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BIOLOGICAL SOFTWARE

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Abstract and introduction: The robot in the common science fiction nmnrel appesrs as a tram an the surface, but is built mechanically from wheels and levers inside. In A.I., we usually visualize an A.I. system as having a similar structure: it communicates in man's language (English), or performs other tasks which make it appear man-like, but it is in fact a large program, written in a programming language, and executed under a common time-sharing system.

The present paper argues on the contrary that A.I. *systems should not* need to appear man-like, *and* that it is necessary, both from the A.I. point of view and from the software engineering point of view, that the next level down in the A.I. system has quasi-biological properties, such as the ability to reproduce

Remark: dm to spaa limitations, this paper has been written in a condensed style.

1. *Reproduction Is a mechanism for a species to adapt.* It is natural to make analogies between the biological system that forms the substrate of natural intelligence, and the computer hardware/software system that forms the substrate of A.I. Among characteristic properties of organisms we find homeostasis and the ability to reproduce. Do they have counterparts in software?

The common game of writing programs that create many identical copies of themselves, misses an important reason for biological reproduction: it is *a mechanism for adaptation,* from the point of view of the species. Human reproduction involves not only copulation and child-birth, but also two decades of work for training the new individual (sometimes called "social reproduction" by sociologists). In the training process, the new person inherits some knowledge, but also selects, reviews and reorganizes his or her intellectual heritage. Imagine how much progress there would be if humans lived forever and never reproduced!

2. *Software also needs to adapt, in response to changing user needs.* Conventional software does not *adapt autonomously to any significant extent: it is adapted* by a programmer who changes the program *("maintenance")* or throws it away and writes a new one.

Future software systems with a more complex behavior will have much bigger needs to adapt, and will be harder to change from the outside. They should therefore be enabled to change without programmer intervention, in response to requests from the end user. They can do so either by modifying their internal state, or by creating a modified copy of themselves. *Both of these methods are viable if the programming technique of* conceptual programming *is used.*

Remember that adaptation was a topic of interest in earlier A.I. work, but it has gone out of fashion because it seemed one could only do trivial things with it, such as adjusting numerical parameters. What one would really like to do was to adapt programs, but that seemed too hard, and had to wait for automatic programming to happen first.

But there is a trend in several areas of software to use specialized application languages (implemented either as interpreters i.e. general, highly parametrized programs, or as program generators) to develop applications. Examples of this trend are:

- commercial program generators for reports, screen layouts, data base queries, etc.
- the system for information-flow applications, developed in our group (ref. 1).
- special-purpose languages in A.I. research e.g. grammar languages.

These are signs of an emerging software technology where computer applications are implemented by selecting a small number of general-purpose i tools, combining them in appropriate ways, and providing them with a description of the application in (several) specialized application languages. This style of programming has been called *conceptual programming* in ref. 2,3,4.

Self-modification in a system should clearly be relatively easy if it can be performed by modification of parameters or application-language expressions, as compared to direct self-modification of a conventional program. This is both because easier, "maintenance" is one of the reasons for specialized languages, and because end-user requests for modification are naturally expressed in application-language terms.

3. *Should an A.I. system 'live' forever?* In other words, is internal self-modification sufficient as an adaptation mechanism, and is reproduction unnecessary? The answer is that perhaps it is not practical for software to adapt forever. For adaptation, new knowledge has to be added to a system, which means that other knowledge has to give way, otherwise the system will grow indefinitely. But whenever knowledge is removed, one encounters a well-known but yet un-named problem which I propose to call *the delete problem,* for example in the following simple form; suppose A has been asserted in a data base, and B has also been asserted by forward inference using "A implies B^H, and later A is to be deleted. Should B be deleted as well? There might be other, independent support for B, so that it should not be deleted. The problem is well-known on many software levels, from conventional garbage collectors to semantic networks.

The conclusion is that for a system to be indefinitely adaptible, it must contain a considerable overhead of information about the details of its own inside*, such as back pointers from B to all its independent supports, in the example. Reproduction offers an alternative, with copying garbage collection as an example on the low software level, and training of off-spring as examples among animals and (I conjecture) for A.I. systems.

4. *Reproduction takes many forms; ours is a biological exception.* Reproduction in mammals has a simple structure: two individuals together generate an offspring which grows up continously. But butterflies, ants, fish, jellyfish, frogs, and funghi offer a rich reportoire of more complicated schemes, where the organism exists in more than one physical form during the reproductive cycle.

In several projects in our research group, I have seen needs for similar, non-trivial schemes for reproduction in software.

- *Background: some of the group's work assumes that the programming techniques that have been developed in A.I. research, are a significant spinoff result of that research, and should be used for other purposes as well.*

Two specific cases are of interest:

A) Use of the Interlisp system for development of pilot versions of application programs, (A pilot version is one which can easily be changed until the end users are happy). Development of the initial program went smoothly, but the subsequent user-initiated modifications were clumsy to make. Analysis: when conventional languages are used, one does debugging in the production environment (i.e. using the regular compiler). The Interlisp system provides a "dry-dock" environment for program development, which implies that a non-trivial effort is required to take the program into and out of the "dry dock". This is worthwhile if a lot of work has to be done there, and in particular if the program never really leaves the development environment, as is often the case in A.I. research. But the same programmer support did not seem worthwhile as the programmer's effort for transfer from development environment to production environment was much bigger than the effort of the update itself.

The problem was solved by allowing each application to exist in two forms: a development system and a production system. The development system was the one that really 'adapted', and it had the ability to create corresponding production versions.

This solution embodies the following basic attitude: a programming system should not be like a street-front clinic, where a program walks in to be operated on (for example, for being compiled, or debugged during

a debugging session), and then leaves again. It should instead be a permanent dwelling for the program. The programming system plus the program it accomodates, should be viewed as an organism, which contains a fair amount of knowledge about itself, and in particular has the ability to generate systems which are similar to itself although tuned for production use - like a queen bee does.

B) Modelling information-flow systems. Many data processing applications can be characterized as information-flow systems-, there are specialized work-stations for different people or roles in the organization; information packets ("transactions") are generated in such stations, sent in channels from one station to the next, accumulated in files that are local to each station, and the task of the person at a station is to review the information that flows by, take actions, add more information to the transactions, and pass them on.

Recent work in our group has resulted in a prototype software tool which allows the various aspects of the information-flow application to be described in specialized languages, and which allows one to do pilot execution of the system work on a generator of production systems is in progress. The system is designed with the programming techniques that are usual in A.I. programing, such as strongly parametrized programs, handles, and data-driven procedure calls.

In the terms of the previous sections, this system is "organism-like" in that it can create modified copies of itself, namely copies for each of the work-stations. These specialized production-phase copies have been obtained by selecting subsets of the parameter structure, and by specializing programs through "smart" compiler macros.

These and other applications in our group are using a general-purpose tool for accomplishing system reproduction, called ACTEMAN (ref. 5).

5. *Knowledge acquisition.* The reproduction in these two examples as presently implemented, does not involve any selective acquisition of knowledge by the off-spring. (There is however a rea^{T} need already to have that). The major reason for the examples is to illustrate that multiple 'life-forms' and unusual (for us) reproduction structures may be useful for software systems.

With a system which is organized along the lines of conceptual programming, as mentioned above, knowledge acquisition by the young off-spring could be organized as follows:

- let the ancestor generate a basic system (for example a fresh instance of the Lisp system), and load the appropriate general programs into it. Also let the ancestor transfer the appropriate parameters and datadriven procedures to the descendant, but usually only a subset of what the ancestor "knows"
- let the descendant engage in work, usually by serving a human user, where in doing so one identifies missing parts in its structure and obtains the information by communication with senior computer systems, (in particular, systems similar to the "deveopment phase" system described above, which contain extra knowledge and which specialize in training new systems), and only in hard cases, communication with a human programmer.

In such an architecture, it is possible but not natural to let the computer systems communicate between themselves in human natural language It is much more natural to exploit the properties of the computer medium, and let them communicate in terms of program segments, data structures, and so forth. (This does not preclude that some of the characteristics of naturallanguage communication will still ?e needed)

6. We can now proceed to the other issue mentioned in the introduction to this paper: *The emphasis in current A.I. research on systems with humanoid behavior.* Its main historical reasons are:
A) The training issue: it has been argued that intelligence presumes knowledge, and that the computer can only gain knowledge by talking to people and/or being among people, as a robot.
B) The usefulness issue: it has been argued that an intelligent computer system can only be useful to us people, if it can talk to us in our language (which is assumed to be natural language).

The training argument addresses the wrong bottleneck. It is true that a lot of work will have to be spent by people for transferring knowledge to computer systems, and it is conceivable that it will be facilitated if natural language may be used. But already scores of programmers have as their profession to transfer knowledge and ability to computers. The significant problem is instead that computer systems can not transfer knowledge to each other. If one computer system could train others, then it would not matter if the initial knowledge transfer to one computer system had to be done in a formal language

The reproduction chain can start when we have built systems which have the necessary properties for being useful, and for generating useful offspring, recursively. In order to start it, we ourselves will have to understand the reproduction process fairly much in detail. It then seems more convenient to create the

first generation by performing manually the operations that will later be done by the ancestor, rather than create a natural-language understanding capability only for the purpose of the first system generation.

The usefulness argument (B) is valid if we consider current research results as given, and search for possible applications But suppose instead that we would focus on *current* data processing (DP.) applications, and ask what role programmed intelligence could play in them. The role might not be dominant: the resulting thought product is not necessarily a computer intelligence incarnated into an application. A car with a micro computer in it is well described as a car and not well described as a computer, and intelligence might be very useful in a similar, subordinate role in the D.P. system

7. *There is a significant area of common interest for A.I. and software engineering.* In A.I., conventional programming has traditionally been considered

- as an intelligence-requiring activity that is observed to occur in real life, and which therefore *is* a candidate A.I. application, and
- as a part of the support work for an A.I. lab and a temptation for the graduate student to waste his time on

It is then assumed that software engineering and A.I. are disjoint areas The arguments of the present paper imply on the contrary that

- systems which adapt, internally and by reproduction, are necessary both for AX and for future software engineering
- conceptual programming techniques may facilitate design of large and complex systems (which is a topic of common interest for A.L and S E.) as well as adaptation and reproduction.
- such systems, performing conventional D.P. tasks, are a likely early application area for A.I. research. But intelligence can not then be obtained as an add-on: the system has to be built from the start using some of the programming techniques which are common in A.I.

8. *How does this fit in with other work in A.I* Hewitt's actor concept is clearly related in the abstract sense that he also talks of structures formed by individuals with a local autonomy and initiative. However, he has mostly worked with actors of very simple structure, in particular as an elementary object in a theory of computation. We emphasiie systems which are complex enough to contain intelligence; systems which are pseudo-individuals. Marr's work in computer vision has already started a trend to take the biological foundations of intelligent systems seriously again

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AN OVERVIEW OF
AN AUTOMATICALLY COMPILABLE HIERARCHICAL DEFINITION MATCHER

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The problem addressed in this paper is that of determining whether the conditions expressed in the definition of a concept are satisfied by a set of assertions (a task of attempting to match the assertions to the definition). The approach presented here is to precede the matching activity proper with a one-time preprocessing phase, during which the definition is automatically transformed from a rather complex form in which it is originally expressed into a simpler form which appears to be more suitable to the matching task at hand. Use of this transformation process permits the functions of recognition and interpretation to be separated, thereby improving the efficiency of the matching process. This separation is performed by distinguishing those components of the definition which must be found to be true from those whose truth may subsequently be inferred and those whose truth is irrelevant to the matching process. The transformation is performed by means of a process of symbolic instantiation of the definition — the translation of the definition from a set of criteria for satisfying the definition into an exemplary instance of the concept itself. The algorithm for the transformation and the subsequent matching process are outlined and illustrated in the text.

1. FORMULATION OF THE TASK

This paper describes an approach to a problem that has arisen within the TAXMAN II project on Legal Reasoning [4], [5], [6], [7], [9] — the design and implementation of a MATCHER that will correctly identify exactly those subcases within a case description (i.e., that will identify those subsets of the facts of a legal case) that satisfy the conditions expressed in the definition of some legal concept. As the purpose of the TAXMAN II project is to investigate the structure of legal concepts, and of decisions based on those concepts, through the representation of those concepts and decisions in AIMDS, it is evident that a MATCHER will be required to play a central role in the envisioned system. The MATCHER described in this paper was designed to meet that need.

Work in the first few months of the TAXMAN II project has centered on a single concept in the domain of corporate tax law — a kind of corporate reorganization called a BREORGANIZATION. A BREORGANIZATION is a complex concept, involving the exchange between two corporations (related in certain ways) of property bearing a particular, rather intricate, relationship to those two corporations. The initial task posed for the MATCHER (the task with which we shall be concerned in this paper) was, therefore, to take a case description consisting of a possibly very large set of possibly very intricately related facts, and to identify every subcase (i.e., every subset of those facts) that indicated the existence of some instance of a BREORGANIZATION.

A later version of the MATCHER is expected to be able to take a set of legal concepts

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(AREORGANIZATION, BREORGANIZATION, CREORGANIZATION, and so forth), and, in a single pass, identify for each concept all those subcases satisfying its definitional conditions. Another extension to the MATCHER that we contemplate is of a different kind: the current MATCHER identifies a subcase S as a match to the definition if and only if S exactly meets the definitional conditions; a future version of the MATCHER will permit, in the absence of an exact match, a sequence of gradual deformations until a match to S has been found.

Let us return to the version of the MATCHER currently under development. Careful examination of the definition given for BREORGANIZATION and of representative case descriptions disclosed

1) that some of the assertions comprising the definition were irrelevant to the determination of whether the definitional conditions had been met — that is, they did not need to be true; these clauses seemed somewhat better suited to a description than to a definition;

2) that some other assertions comprising the definition, while they did have to be true, could be inferred to be true on the basis of certain other knowledge; the issue of mutual inferrability was not directly addressed, as mutually inferrable sets of assertions in this domain appeared to be expressible in terms of a canonical set of clauses whose truth had to be observed — that is, clauses of neither type 1 nor type 2.

For example, consider that the following is part of a definition of a ZOPPLE

Every creature with a beak and feathers is a ZOPPLE.

Every ZOPPLE has wings.

A ZOPPLE may have orange feathers.

If we encounter a creature with a beak and feathers, then we know it is a ZOPPLE without concerning ourselves further. The color of the feathers (type 1 above) is irrelevant to our classification of the creature; the presence of wings may be inferred (type 2), once the creature has been identified.

From the characterization of the problem given above, we may readily admit the desirability of

SPEC1) reducing combinatoric problems wherever possible,

SPEC2) identifying as a valid BREORGANIZATION every subcase for which all of the conditions included within the definition — aside from assertions of the types described in 1 and 2 above — were true, and subsequently devising some means of filling in whatever additional information could then be filled in.

In terms of the example presented earlier, we might identify as a ZOPPLE any creature with a be;.* and feathers, subsequently inferring the presence of wings, and adding the fact the feathers are orange, wherever this is true of the ZOPPLE in question.

In view of our plans for later phases of the work, we should also like our design to permit the easy representation of the process of partial matching.

SPEC2 permits us to characterize our task in terms of the paradigms of recognition and interpretation. Recognition is the process of determining whether or not a particular object satisfies any of a set of conditions — i.e., given an object and a set of sets C of conditions, it returns a ves or a nfi. for each C. Interpretation associates with an object not only a classification — or a set of classifications (recognition), but (for at least one of the classes) additional material as well, such as a structural description. For example, a structural matcher, by distinguishing between the presence and absence of an isomorphism between two networks, performs recognition; a parser, by distinguishing between the grammatically valid and invalid strings presented to it (recognition), and associating at least one parse tree with every grammatically valid string, performs interpretation. Note that a parser may be viewed as performing recognition by means of interpretation.

As we can see, our task may be decomposed into two modules — one in which the recognition of valid BREORGANIZATIONs is performed, and one in which an interpretation is produced for every valid BREORGANIZATION. Note that, by this method, the classification of a case as a valid or invalid instance of a BREORGANIZATION would be completed by the recognition module, and that, unlike the parsing analogue, our interpretation module would be required only for the creation of the appropriate structural descriptions.

This design strategy

1) would successfully avoid certain combinatoric problems often encountered by parsers

a) by eliminating the requirement that the conditions for recognition failure (i.e., the conditions requiring a no. to be produced by the recognition module) must be identified through the failure of interpretation (i.e., through the inability of the interpretation module to create an interpretation), and

b) by removing the necessity of generating interpretations for matching subcases when only recognition was desired,

2) would successfully avoid a problem encountered by many structural matchers, by eliminating the possibility of recognition failure caused solely by the absence in the case description of non-essential information which was present in the original definition, and

3) would permit the computation of missing but inferrable information to be performed by the interpretation module.

Before we proceed to a discussion of the means selected to meet the two specifications given above, let us look more closely at the way in which the definitions and the case descriptions are represented. The representation is in AIMDS, a frame-based language [8]. AIMDS allows the representation of a set of types$_f$ a set of Instances of the types, a set of typed relations that may be asserted to hold between pairs of instances of the appropriate types, and a set of pattern-directed inference rules called consistency conditions (£Ca) which specify the allowable combinations of assertions about relations between instances.

One of the attractions of representing sets of assertions in AIMDS is that those representations have an analogue in network form. Several powerful methods have been devised for manipulating structures which permit a network representation. Two such methods involve the use of recognition networks and structural matchers for networks.

A recognition nqfrwyrk performs much like a parser for pieces of subnet, performing recognition by assigning a full semantic net to the input subnets (interpretation). An automatically compilable recognition network (ACORN), developed by F. Hayes-Roth and D. J. Mostow [3], has been used in the understanding of connected speech. A structural matcher, on the other hand, performs recognition by determining whether every component of a criterial network has a unique counterpart in the network whose recognition is being attempted. A program with the capability of structural matching, called DMATCH, was developed by D. Touretzky [12] for use with AIMDS.

In order to see to what extent either or both of these methods might be applicable to our own task, let us look more closely at the degree to which the representations in AIMDS of definitions and case descriptions have analogues as networks.

A case description is a set of assertions about relations between instances. For example, an assertion in a legal case description represented in AIMDS might say that the instance TRANS-1 of the type TRANS has in AGENT relation the instance ACTOR-1 of the type ACTOR. A case description may be represented as a network in which the nodes correspond to the instances, and the links correspond to the relations between them.

A definition, which specifies all structures meeting a set of conditions, consists of 1) a set of propositions specifying the allowable relations between instances, and 2) a set of consistency conditions (CCs) expressing constraints on how the propositions in the first set may be instantiated. For example, in the domain of corporate tax law, propositions of the first set might state that an instance of the type TRANS (a transfer of property) may have an instance of ACTOR in AGENT relation, and may have an instance of ACTOR in OLDOWNER relation. A CC in this domain might state that an instance of TRANS may have an instance of ACTOR in AGENT relation if and only if that instance of ACTOR is also in OLDOWNER relation to that instance of TRANS. The propositions of the first set may be represented as a network in which the links correspond to relations, and the nodes stand, not for instances, but for the types of instances. No obvious analogous way of also representing CCs in network form presents itself. (Possible graphical representations of CCs, such as those based on Petri nets, would not appear to have useful analogues in case descriptions.)

These observation have failed to show us how we might formulate an analogue to a definition in solely network form (as we have said that an analogue to a case description may be

formulated). They do permit us, however, to see more clearly how a solution to our problem might be devised, or, at least, what problems stand in the way of our working out a solution. Let us summarize the crucial observations.

1) We have seen that only a subset of the assertions in the definition need be found to be true in a subcase S for S to match the definition.

2) We have seen that, given two networks (N1 and N2), it is possible to use a structural matcher to recognize that every component of N1 has a unique counterpart in N2.

3) We have seen that methods have been devised for generating a full semantic net (an interpretation) from a set of subnets.

If we can identify that subset of the assertions in the definition that have to be found to be true, and represent them, together with the CCs, in network form, then, by performing a structural match, with this network as N1 and a case description as N2, we can determine whether or not N2 satisfies the definitional conditions (recognition). If it does so, then we may try to utilize methods analogous to those used in the original ACORN to fill in whatever missing assertions we can (interpretation).

Such a strategy, if it could be implemented, would have clear advantages. By permitting the representation of the definitional conditions in a single mode, it would be conducive to easy understanding and, most probably, economy of storage. By permitting recognition to take place through a single kind of process, it would be likely to further enhance comprehensibility and storage economy, as well as efficiency of operation. For example, elimination of the need during recognition for pattern-directed inference processes (which very likely would have been used if interpretation were also being done at this time) would permit recognition to be performed in LISP directly on the data structures without the overhead required for running AIMDS (which is written in the language FUZZY, which is itself written in LISP). Furthermore, since the single representational mode (that of a network) and the single recognition process (that of structural matching) have been the objects of both theoretical and empirical study by many researchers, the strategy outlined above would most probably enable us to draw on the results of others in improving our own design and implementation.

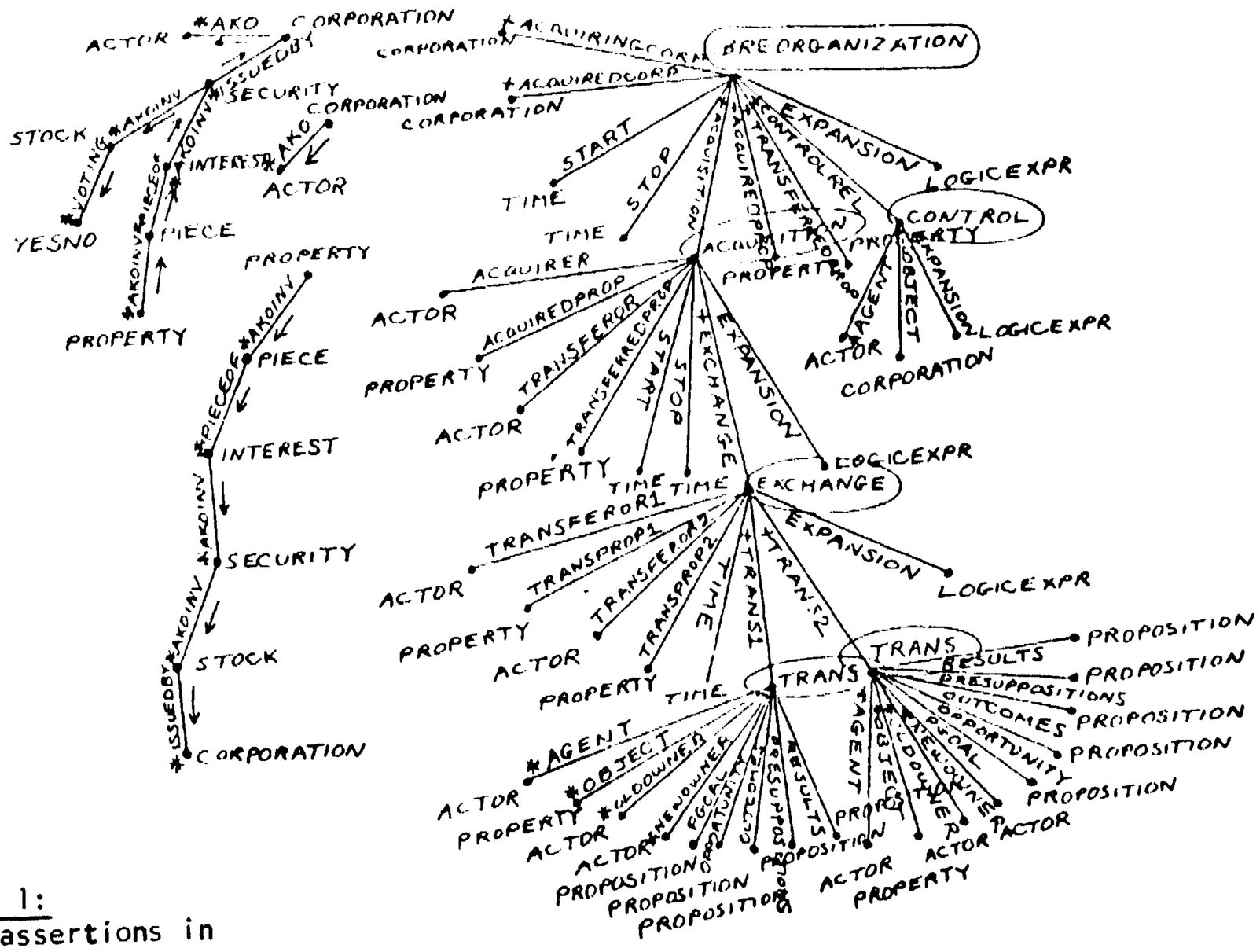

Figure 1:
The assertions in the definition.

If we decide to attempt such a strategy, the following two questions arise:

Given a definition of a legal concept expressed in AIMDS,

QUESTION!) can we generate the network to serve as N1 in our structural matcher, and if so, how?

QUESTI0N2) can we generate an ACORN module to fill in all the information that is missing in the case description but can be inferred from other knowledge, and if so, how?

2. SKETCH OF *A* SOLUTION

An answer to the questions posed above was devised, and is outlined below.

to take all the assertions (in the form of relations between typed variables) present in the definition, and, for all the variables contained in the assertions, to perform, using the consistency conditions (ccs), a process of symbolic instantiation of the variables, in such a manner that two variables are bound to the same instance if and only if they are required to have the same binding in all case descriptions satisfying the definition. (The use of a single symbolically instantiated form is sufficient for the syntactic class of definitions under discussion here. These definitions contain conjunction, but neither disjunction nor negation, either of which would require a more complex symbolically instantiated structure. For further discussion, see [6] and [7].) The assertions in the definition for a BREORGANIZATION (before symbolic instantiation) are illustrated in Fig. 1.

We can then divide the assertions (now in the form of relations between instances) into four sets:

A) those whose truth must be observed in the case description — these will provide us with all the bindings we are required to identify in S (The assertions of set A for a BREORGANIZATION are illustrated in Fig. 2.);

B) those which can be used to pass these bindings on as the structural description is built up during interpretation;

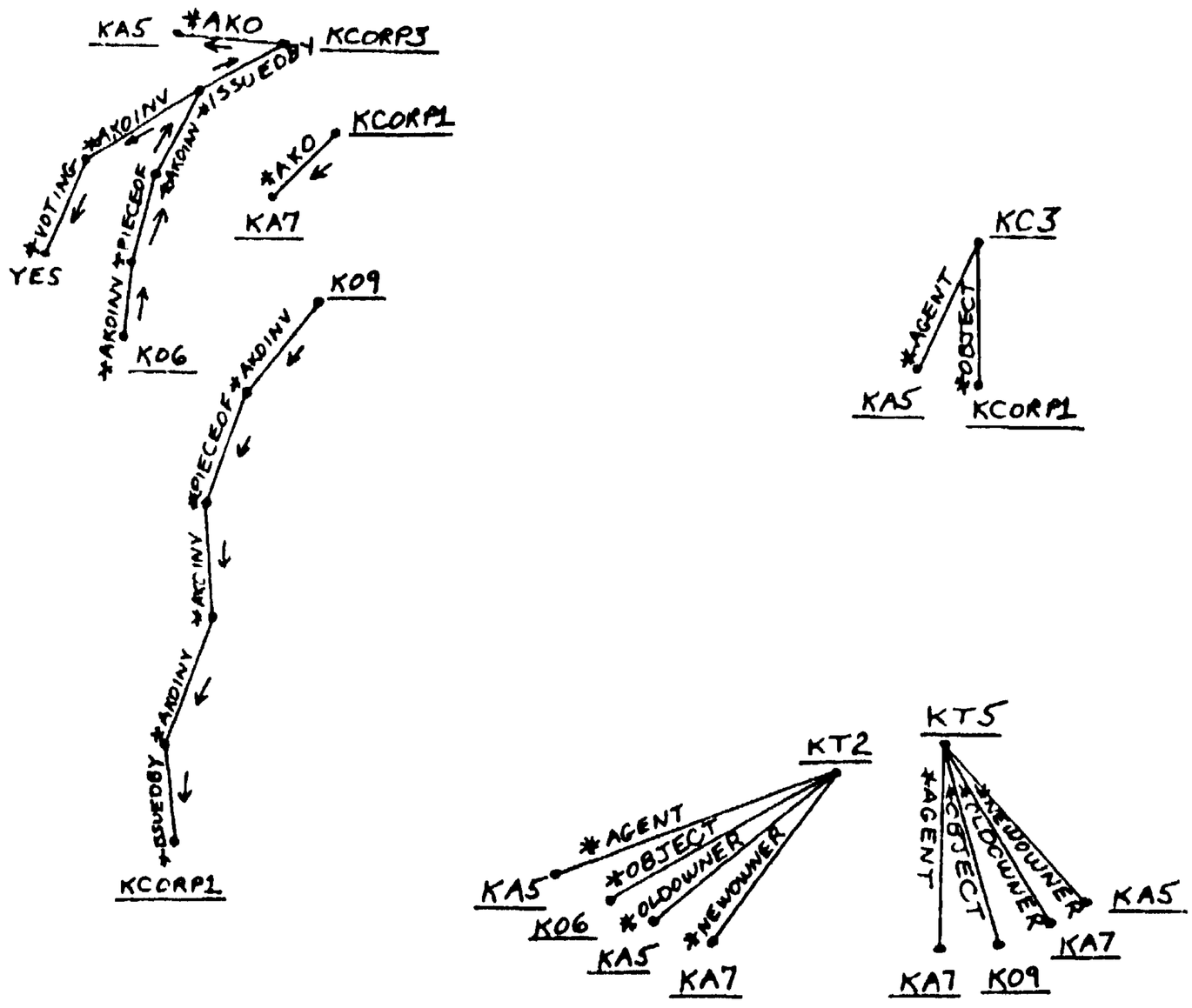

Figure 2:
The assertions of set A.

C) those whose truth can be inferred, on the basis of the CCs, from that of the assertions in sets A and B;

D) those whose truth is not relevant to a determination of whether the definition has been satisfied.

Sets A, B, and D, each of which now consists of sets of instantiated assertions, can then be used to produce the recognition and Interpretation modules characterized above. Set A is used to create the network to which a structural match of a subcase can be attempted by the recognition module (N1 in the preceding section). We call this the KERNEL structure for the definition (or, more simply, the KERNEL structure). The assertions of set B are transformed into a set of commands to make additional assertions — that is, to add new assertions to those already present — this plays part of the role of the ACORN module mentioned in the preceding section, and creates the first part of the desired interpretation. We call this set of commands the INNER ACORN generator. The assertions of set C are discarded. After the first part of the interpretation of a recognized subcase S has been completed, those assertions of set D that are true for S are used to add (with additional commands) to the structural description of S, thereby completing the role of the ACORN module, and concluding the interpretation process. This additional set of commands, which we call the AUGMENTED ACORN generator, augments the interpretation of the recognized subcase with clauses of a descriptive, rather than a definitional, character. We call the combination of the INNER ACORN generator and the AUGMENTED ACORN generator simply the Acorn generator.

The compilation process sketched above thus results in a KERNEL structure and an ACORN generator, which can then be used for recognition and interpretation whenever a case description is presented for comparison with the definition. The compilation and execution processes are illustrated in Figures 3, 4, and 5.

The way in which the compilation algorithm has been formulated makes it possible to construct an informal proof that the algorithm correctly transforms any well-formed definition with the purely conjunctive structure sketched above. The algorithm and the proof are presented in detail in [6]. Details on representational issues involved in our method for manipulating definitions may be found in [7],

3. EXECUTION

In the preceding section, we saw how the compilation of the KERNEL and ACORN for a definition with a conjunctive structure

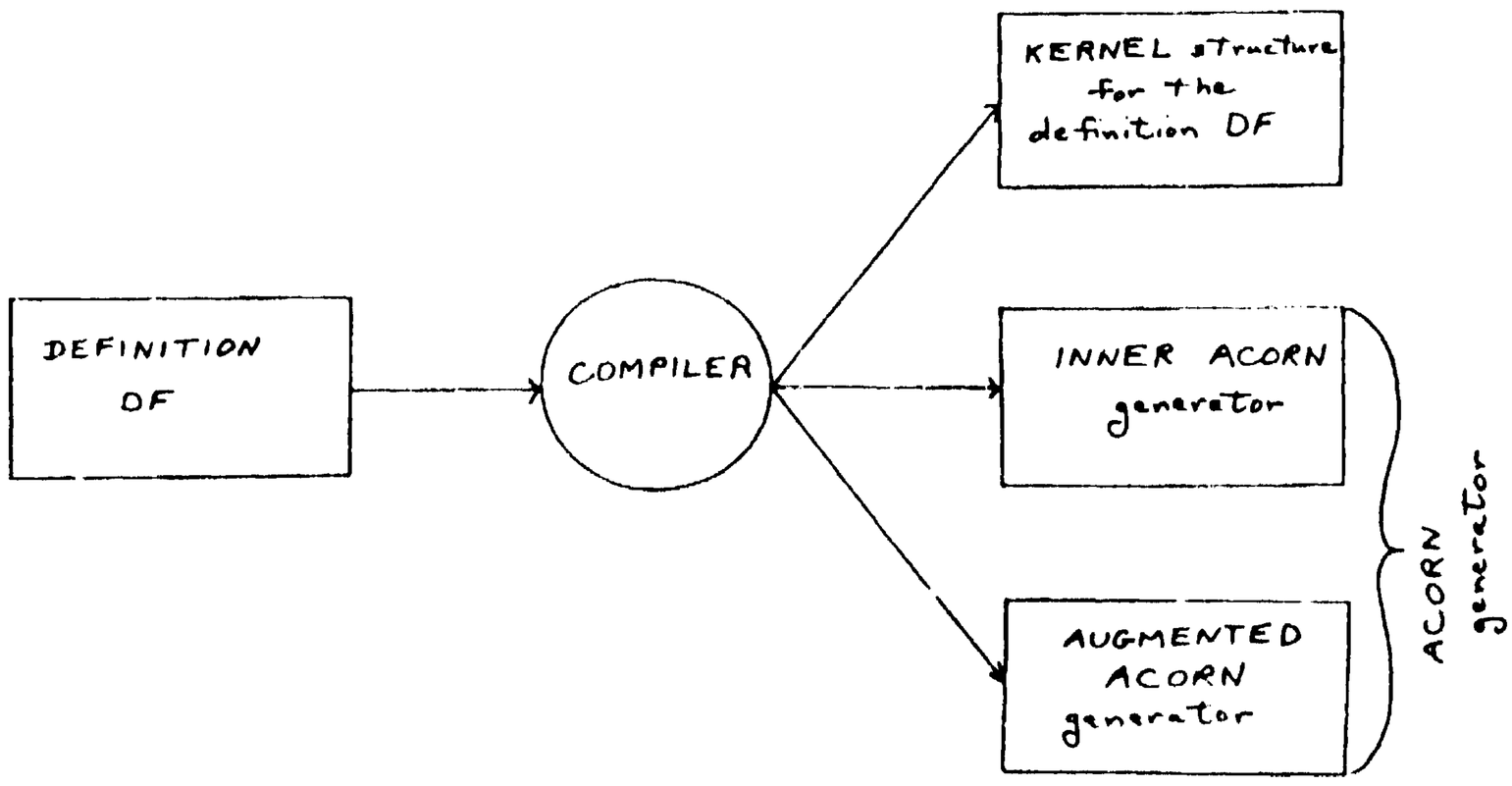

Figure 3:
Compilation of KERNEL structure and ACORN generator.

proceeds. Once this compilation has been completed, it need never be repeated (unless the definition itself should change), and the compiled KERNEL structure and ACORN generator may be used directly for comparison with the definition whenever a case description is presented.

The matching of subcases against the KERNEL structure takes place first; at the option of the user, this process may terminate with the identification either of a single matching subcase, or of a larger set of matches (including the set of all matching subcases). When the desired number of matching subcases have been recognized (or when all cases in the case description have been examined), control returns to the user's program. At this point, any procedures of the user's choice may be executed, including (whenever desired) execution of the ACORN generator to produce interpretations for any or all of the matching subcases identified by the recognition routine.

In order to control possible combinatoric difficulties, the KERNEL is decomposed into a set of small networks, against each of which all substructures of the same type in the case description are tested for an exact DMATCH (STAGED. (We hope to be able to select "small networks" from the KERNEL in such a way that matching to any single small network will involve a minimal degree of combinatoric complexity.) The substructures that survive STAGE1 (and no others) are then combined in all possible valid ways into larger networks of some degree of increase in complexity. A DMATCH of each of these structures with the corresponding substructure of the KERNEL is then attempted, and bindings constraints between formerly separate components of the new network are thereby tested. This process is repeated with surviving substructures until the DMATCH is conducted against the KERNEL structure itself. This final stage of DMATCHing will be terminated as soon as the desired number of matching subcases have been recognized. If this stage is permitted to run to completion, the survivors represent all and only the subcases in the case description that meet the conditions expressed in the definition.

The execution of the recognition component is illustrated in Fig. 6. For this example, 5 instances of TRANS (T1, T2, T3, TH, T5), 2 instances of CONTROL (C1, C2), and 2 instances of OBJECT (06, 09) were used. The value of MAKEFULLLIST shows the survivors of STAGE 1. The value of BGO shows the single valid instance of a BREORGANIZATION that can be created from these components.

If interpretations of any of the identified matches are desired, the ACORN generator may then be used to produce them.

4. IMPLEMENTATION

Implementation activity on the matcher has taken two directions. First we constructed and ran an automated demonstration of the execution of a hand-compiled KERNEL and ACORN. Having demonstrated the feasibility of the design for our application, we began work on the compiler for the KERNEL and ACORN, concurrently refining the algorithm outlined in this paper, and presented in detail in [6]. This effort has so far yielded encouraging results.

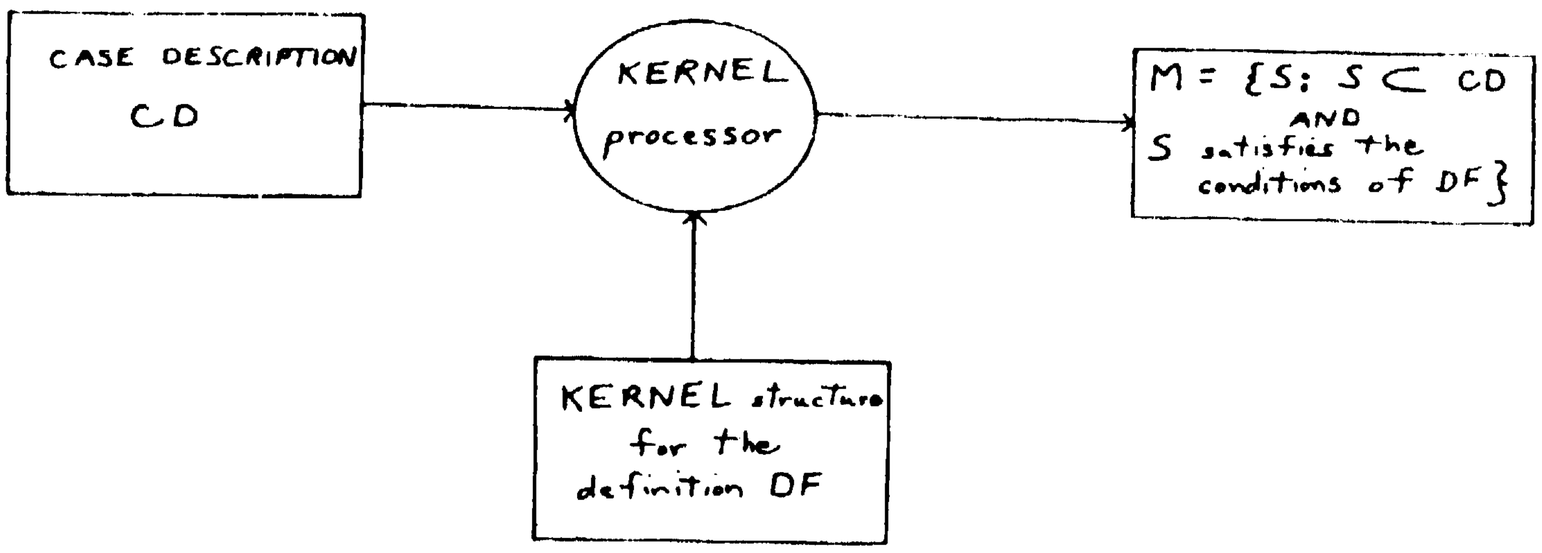

Figure 4:
Execution of recognition component,
using the compiled KERNEL structure.

5. IMPLICATIONS

The primary attractions of the definition matcher appear to stem from the separation of recognition and interpretation, and from the reduction of the recognition process to the structural matching of networks. This design strategy significantly enhances matching efficiency by eliminating the requirement that the absence of a match must be recognized through the failure of interpretation, by removing the necessity of generating interpretations for matching subcases when only recognition is desired, and by permitting the recognition process to be performed without the overhead associated with the use of pattern-directed inference rules. In addition, this strategy eliminates the possibility of match failure caused solely by the absence of non-essential information, and permits the computation of missing but inferrable information to take place during the interpretation phase.

In addition to its immediate practical advantages, the use of the KERNEL+ACORN paradigm seems not only to induce a more accurate representation of definitions, but also to provide a sound basis for the expected development within the Legal Reasoning Project of a deformation-oriented definition matcher.

ACKNOWLEDGEMENTS

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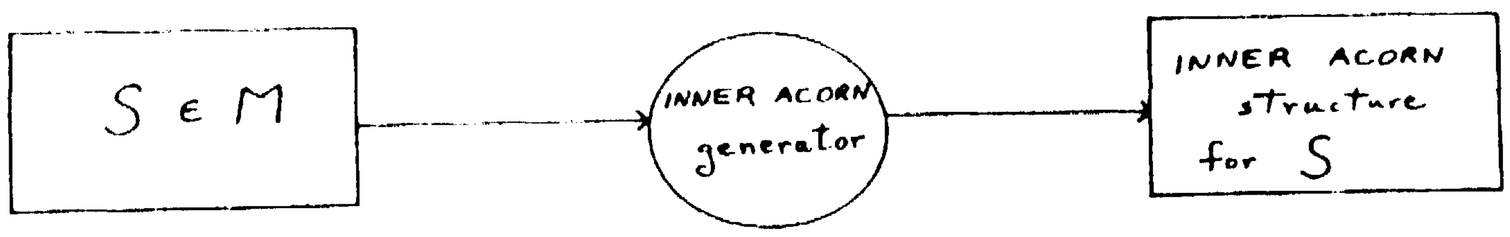

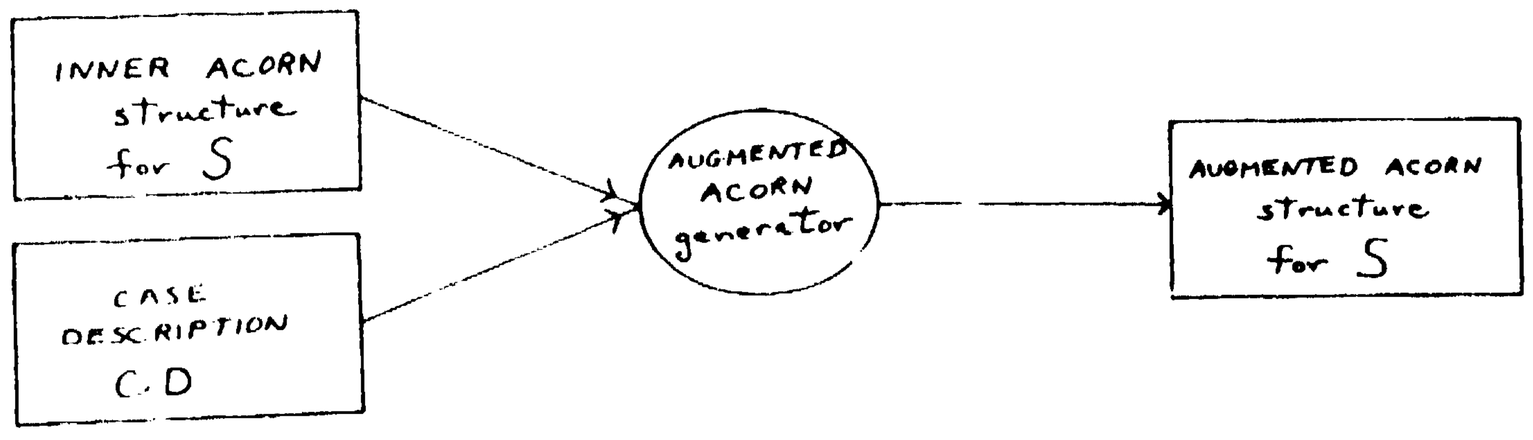

Figure 5:
Execution of the interpretation component, using the compiled INNER ACORN generator and AUGMENTED ACORN generator.

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SECOND-CONTEXT »          (DCO)

Enter MAKEFULLLIST:
? PROTS » (PROTOTRANSI PROTOTRAr   PROTOCONTROLI PR0T009 PR0T006)
MAKEFULLLIST « ((06) (06 09) (CI C2) (T2 T4 T5) (T2 T4 T5))



<(T2 T5 C2 09 06) NIL)
```

Figure 6:
Sample execution of the recognition component

TOWARDS A MATHEMATICAL THEORY OF PROGRAM SYNTHESIS

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This paper attempts to set a theoretical foundation for Program Synthesis. A programming language Prog is introduced together with its interpretation in the semantic domain D. A formal system QFT, which is an extension of the Heyting arithmetic, is then introduced in order to express specifications formally. Roughly stated, the main result is: Given a QFT-proof of the specification ∀x∃zA[x,z], it is possible to construct a program p such that A[x,p[x]] is true in D for any input x. Moreover, a formal proof of ∀xA[x,p[x]] can also be obtained. Since any program p in Prog always terminates, the above result establishes the total correctness of the synthesized program at the same time. Finally, it is shown that any program p in Prog can be faithfully simulated by means of LISP.

0. INTRODUCTION

Before we start talking about *program synthesis,* we wish to clarify our standpoint as to what we mean by the terms such as *program, specification* and *verification** A *program* is a well-formed expression in some formal language (i.e., a *programming language).* We write a program in order to solve a certain problem. We need a theory to specify the problem precisely. (See [Burstall and Goguen 1977]. They give an example of matrix inversion. I.e., we need a theory of matrices to state the problem of matrix inversion.) As far as program synthesis is concerned, we must further have a formal language (i.e., a *specification language)* in which the above theory can be formalized. Then, in the specification language, we can *specify* the problem formally by a formula A[x,z] which describes an input-output relation between the input variable x and the output variable z. We say that a program P *realizes* the specification A[x,z] if, under a certain interpretation, A[x,P[x]] is true for any input x, where P[x] denotes the result of executing P for the input x. Here we remark that we are implicitly assuming that our specification language essentially contains the programming language in which the program P is written. If we furthermore wish to formally *verify* that P realizes the specification A[x,z], we need a formal theory such that the formula VxA[x,P[x]] is provable in it. Thus this theory must contain the theory which we required for the specification of the problem. We call the former theory *verification theory* and the latter theory *specification theory.* Now we can formulate the problem of program synthesis as follows.

* This work was supported in part by the Sakkokai Foundation.

Program Synthesis Problem (PSP): *Find a procedure which produces, from a given specification* A[x,z], *a program* P *which realizes the specification.*

Even though at a rather meta-level, we need a theory to specify PSP. As the specification theory of PSP, we adopt the theory QFT which is a quantificational extension of the theory FT of primitive recursive functionals of finite type. (Theory of primitive recursive functionals of finite type was initiated by [Godel 1958], as a device to prove the consistency of the Peano arithmetic. Our systems QFT and FT are very similar to the corresponding systems due to [Schiitte 1977].) The reasons of our adoption of QFT and FT are as follows.

(1) Every provably recursive function (in the sense of [Takeuti 1975] p.123) is expressible in FT, so that a large class of interesting algorithms can be dealt with.

(2) QFT contains the Heyting arithmetic HA as a subsystem, so that we can discuss the synthesis of programs which compute number theoretic functions.

(3) Every functional of type o-n in FT may be regarded as a program which computes a functional of type T from a given functional of type o. Thus we can discuss the synthesis of a program which yields another program from a given program, in case both o and T are not of type 0.

(A) Important proof-theoretic results concerning FT and QFT can be used as theoretical foundations for program synthesis.

(5) The computation in FT can be easily simulated by LISP.

We will solve PSP under the following framework:

(a) A program is a (closed) term in FT.

(b) The specification theory is QFT.

(c) The verification theory is QFT.

Suppose that the specification A[x,z] of a problem is given. Then either by a theorem prover

or by a man-machine interactive proof checker, we try to construct a QFT-proof π of the formula $\forall x \exists z A[x,z]$. (This is the most challenging part of our procedure, since no decision procedure exists for the provability of a QFT-formula. Other parts of our procedure are completely mechanical.) If we succeed in constructing such a π, then from π we can construct, primitive recursively, a program P such that A[x,P[x]] is provable in QFT (Theorem 9). Furthermore we can formally verify that P realizes the specification, since $\forall x A[x,P[x]]$ is provable in QFT. We note that, according to Theorem 1, the program P always terminates for any input x. Hence, the total correctness of the program will be established at the same time.

We think that it is fundamental for any program synthesis approach, which may be called mathematically well-founded, to satisfy the following conditions.

1. The semantics of the programming language is precisely specified.
2. The specification theory is precisely specified.
3. The verification theory is precisely specified.

However, it seems to us that many of the existing approaches to program synthesis are too naive to satisfy any one of the above criteria. In contrast, our approach to be described below satisfy all of the above criteria, and hence is mathematically well-founded.

1. FUNCTIONALS OF FINITE TYPE

1.1 Types

Definition of *types*:

1. The symbol 0 is a type.
2. If σ and τ are types then $[\sigma\to\tau]$ is a type.

For brevity we write $\sigma_1\to\sigma_2\to\ldots\to\sigma_n\to\tau$ instead of $[\sigma_1\to[\sigma_2\to\ldots\to[\sigma_n\to\tau]\ldots]]$. The set of all the types will be denoted by Type.

1.2 Terms and programs

The terms of FT will be constructed from the following language LFT:

1. Denumerably infinite set FV^σ of *free variables* for each type σ: $FV^\sigma=\{a1^\sigma,a2^\sigma,a3^\sigma,\ldots\}$. We put $FV=\cup\{FV^\sigma|\sigma\in Type\}$.
2. Denumerably infinite set BV^σ of *bound variables* for each type σ: $BV^\sigma=\{x1^\sigma,x2^\sigma,x3^\sigma,\ldots\}$. We put $BV=\cup\{BV^\sigma|\sigma\in Type\}$.
3. Constants: 0(zero), S(successor) and J_σ(iterator) for each type σ.
4. Lambda abstraction symbol: λ.
5. Parentheses: (and).

As auxiliary symbols, we have denumerably infinitely many *nominal symbols*: *1,*2,*3,... . By an *n-place* (LFT) *nominal form* we mean a finite string of symbols which contains, in addition to the symbols of LFT, at most the nominal symbols *1,*2, ...,*$\bar{n}$, where $\bar{n}$ is the decimal numeral which represents the natural number n. If A is an n-place nominal form and $r_1,\ldots,r_n$ are strings of symbols, then $A[r_1,\ldots,r_n]$ denotes the result of replacing every occurrence of *$\bar{i}$ in A by r_i $(1\le i\le n)$. We will use *italic* letters to denote nominal forms.

Definition of the set Tm of *terms*, type: Tm$\to$Type and bvar: Tm$\to 2^{BV}$:

1. $a\in FV \Rightarrow a\in Tm$, $type[a]=\sigma$, $bvar[a]=\emptyset$.
2. $0\in Tm$, $type[0]=0$, $bvar[0]=\emptyset$.
3. $S\in Tm$, $type[S]=0\to 0$, $bvar[S]=\emptyset$.
4. $J_\sigma\in Tm$, $type[J_\sigma]=0\to[\sigma\to\sigma]\to\sigma\to\sigma$, $bvar[J_\sigma]=\emptyset$.
5. $r^\sigma, s\in Tm$, $type[r]=\sigma\to\tau$, $type[s]=\sigma$, $bvar[r]\cap bvar[s]=\emptyset \Rightarrow (r\ s)\in Tm$, $type[(r\ s)]=\tau$, $bvar[(r\ s)]=bvar[r]\cup bvar[s]$.
6. $r[a]\in Tm$, $type[r[a]]=\tau$, $a\in FV^\sigma$, $x\in BV^\sigma-bvar[r[a]] \Rightarrow \lambda x r[x]\in Tm$, $type[\lambda x r[x]]=\sigma\to\tau$, $bvar[\lambda x r[x]]=bvar[r[a]]\cup\{x\}$.

Tm is the least set which satisfies the above conditions. We put $Tm^\sigma=\{t\in Tm|type[t]=\sigma\}$. An element in Tm^σ is called a *term of type* σ. Two terms r and s are *congruent* if they are constructed exactly in the same manner, except that possibly different bound variables are selected in the applications of 6 above. We will henceforth identify congruent terms. This identification has the effect of making bound variables really dummy. A *program* is a term containing no free variables. We write Prog for the set of programs, and we put $Prog^\sigma=\{t\in Prog|type[t]=\sigma\}$. We use r, s, t etc. as syntactic symbols denoting terms or programs. For brevity we write $r_1r_2r_3\ldots r_n$ instead of $((\ldots(r_1\ r_2)\ r_3)\ldots)\ r_n)$.

Definition of a binary relation red on Prog:

1. $(\lambda x r[x]\ s)$ red $r[s]$.
2. $J_\sigma 0st$ red t.
3. $J_\sigma(Sr)st$ red $s(J_\sigma rst)$.
4. r^σ red $r' \Rightarrow (r\ s)^\sigma$ red $(r'\ s)$.
5. s red $s' \Rightarrow (r\ s)$ red $(r\ s')$.

We let red* be the reflexive and transitive closure of red. A program p is *normal* if p red q for no q.

Definition of the *numerals* N_n (n: a natural number):

1. $N_0=0$.
2. $N_{n+1}=(S\ N_n)$.

The following three lemmas can be proved by a standard technique. (See, e.g., [Schütte 1977], [Troelstra 1973], [Howard 1970].)

Lemma 1. *A program* p *of type* 0 *is normal if and only if* $p=N_n$ *for some natural number* n.

Lemma 2. *If* p red* q, p red* q', *and both* q *and* q' *are normal, then* q=p'.

Lemma 3. *For any program* p *there exists an normal program* q *such that* p red* q.

Putting Lemma 2 and Lemma 3 together, we have:

Theorem 1. *For any program* p *there uniquely exists an normal program* q *such that* p red* q.

The program q in the above theorem is called the *normal form* of p, and is denoted by [p]. We write D for the set of programs in normal form,

and we put $D^\sigma=\{p\in D \mid type[p]=\sigma\}$.

1.3 Interpretation of terms

We can use the function $[\ ]$: Prog→D which sends a program p to its normal form $[p]$, as a semantic function. For instance, a program p of type $\sigma\to\tau$ may be considered as denoting a functional $\hat{p}$: $D^\sigma\to D^\tau$ such that $\hat{p}[s]=[(p\ s)]$ for any $s\in D^\sigma$. Furthermore, we remark that, by Lemma 1, D^0 is isomorphic with the set $\mathbb{N}$ of natural numbers.

With this interpretation in mind, we define the formal system FT of primitive recursive functionals of finite type as follows.

2. THE FORMAL SYSTEM FT

2.1 Definition of the system FT

Definition of the set Form of FT-*formulas*:

1. $s, t\in Tm^\sigma \Rightarrow s=t\in Form$.
2. $A, B\in Form \Rightarrow (A\supset B), (A\wedge B), (A\vee B)\in Form$.

We use Γ, Δ etc. to denote finite (possibly empty) sequences of formulas. If Γ is the sequence $'A_1,\ldots,A_n'$ then $\Gamma\supset B$ is the abbreviation of $A_1\supset\ldots\supset A_n\supset B$ which, in turn, is the abbreviation of $(A_1\supset(\ldots\supset(A_n\supset B)\ldots))$. If $\Gamma='A_1,\ldots,A_n'$ and $\Delta='B_1,\ldots,B_m'$ then $\Gamma\subseteq\Delta$ means that the set $\{A_1,\ldots,A_n\}$ is included in the set $\{B_1,\ldots,B_m\}$. We define the connective $\neg$ by: $\neg A=A\supset S0=0$. A formula containing no free variable is called a *closed* formula. A formula which only contains equations between terms of type 0 is said to be a *basic formula*.

Definition of the provability relation $\vdash$ in FT:

Axioms:

(λ) $\vdash (\lambda x r[x]\ s)=r[s]$.

(J_0) $\vdash J_0 st=t$.

($J_\sigma S$) $\vdash J_\sigma(Sr)st=s(J_\sigma rst)$.

($=$) $\vdash s=t\supset F[s]\supset F[t]$.

Inference rules:

(Str) $\vdash\Gamma\supset B,\ \Gamma\subseteq\Delta \Rightarrow \vdash\Delta\supset B$.

(Cut) $\vdash\Gamma\supset A,\ \vdash A\supset B \Rightarrow \vdash\Gamma\supset B$.

(CI) $\vdash F[0],\ \vdash F[a]\supset F[Sa],\ a\in FV^0,\ a\not\in F,\ t\in Tm^0 \Rightarrow \vdash F[t]$.

($\wedge$1) $\vdash A\supset B\supset C \Rightarrow \vdash (A\wedge B)\supset C$.

($\wedge$r) $\vdash\Gamma\supset A,\ \vdash\Gamma\supset B \Rightarrow \vdash\Gamma\supset(A\wedge B)$.

($\vee$1) $\vdash A\supset C,\ \vdash B\supset C \Rightarrow \vdash (A\vee B)\supset C$.

($\vee$r) $\vdash\Gamma\supset A_i \Rightarrow \vdash\Gamma\supset(A_1\vee A_2)$ $(i=1,2)$.

In the above definition, $a\not\in F$ means that the free variable a does not occur in the nominal form F.

A formula A is said to be *provable* (in FT) if $\vdash A$.

2.2 Consistency and weak completeness

Definition of *truth* and *falsity* for a closed formura:

1. A closed formula s=t is *true* iff $[s]=[t]$.
2. A closed formula $A\supset B$ is *true* iff A is *false* or B is *true*.
3. A closed formula $A\wedge B$ is *true* iff A is *true* and B is *true*.
4. A closed formula $A\vee B$ is *true* iff A is *true* or B is *true*.
5. A closed formula A is *false* iff A is not *true*

We write $\vdash A$ if A is true. We then have the following consistency theorem. (See [Schütte 1977], Theorem 17.2.)

Theorem 2. $\vdash A$, A: *closed* $\Rightarrow \vdash A$.

Although not all true closed formulas are provable in FT (example: $\neg J_0(S0)S=S$), we have the following weak completeness theorem.

Theorem 3. $\vdash A$, A: *basic* $\Rightarrow \vdash A$.

Putting Theorem 2 and Theorem 3 together, we have

Theorem 4. *A closed basic formula is provable in* FT *if and only if it is true.*

3. THE FORMAL SYSTEM QFT

3.1 Definition of QFT

Definition of the set Form of QFT-*formulas* and $bvar: Form\to 2_0^{BV}$:

1. $s, t\in Tm^0 \Rightarrow s=t\in Form$, $bvar[s=t]=bvar[s]\cup bvar[t]$.
2. $A, B\in Form \Rightarrow (A\supset B), (A\wedge B), (A\wedge B)\in Form$, $bvar[(A\supset B)]=bvar[(A\wedge B)]=bvar[(A\vee B)]=bvar[A]\cup bvar[B]$.
3. $A[a]\in Form$, $a\in FV^\sigma$, $x\in BV^\sigma-bvar[A[a]] \Rightarrow \forall xA[x], \exists xA[x]\in Form$, $bvar[\forall xA[x]]=bvar[\exists xA[x]]=bvar[A[a]]\cup\{x\}$.

Two formulas are *congruent* if they are constructed exactly in the same manner, except that possibly different bound variables are selected in th applications of 3 above. We will henceforth identify congruent formulas. A formula is *quantifier free* if it contains no occurrence of $\forall$ or $\exists$. A quantifier free QFT-formula is just a basic FT-formula. We define the negation $\neg A$ of a formula A by $\neg A=A\supset S0=0$.

Notational conventions: Let $s='s_1,\ldots,s_n'$ be a sequence of terms $s_1,\ldots s_n$ and let $t='t_1,\ldots,t_m'$ be a sequence of terms $t_1,\ldots,t_m$, where $m,n\geq 0$. Suppose that $type[s_i]=\sigma_1^i\to\ldots\to\sigma_m^i\to\tau_i$ $(1\leq i\leq n)$ and $type[t_j]=\tau_j$ $(1\leq j\leq m)$. Then we let $(s\ t)$ denote the sequence $'s_1t_1\ldots t_m,\ldots,s_nt_1\ldots t_m'$. We use r, s, t etc. to denote sequence of terms. Similarly, we use a, b, c etc. to denote sequences of free variables, and x, y, z etc. to denote sequences o bound variables. If $x='x_1,\ldots,x_n'$, $t='t_1,\ldots,t_n'$ and A is an n-place nominal form, then $\forall\vec{x}A[x]$, $\exists xA[x]$ and $A[t]$ are the abbreviations of $\forall x_1\ldots\forall x_nA[x_1,\ldots,x_n]$, $\exists x_1\ldots\exists x_nA[x_1,\ldots,x_n]$ and $A[t_1,\ldots,t_n]$, respectively.

Definition of the provability relation $\vdash$ in QFT:

Axioms:

(FT) $\vdash$ A (in FT), A: basic $\Rightarrow$ - A.

($\forall$1) $\vdash \forall xA[x]\supset A[t]$.

($\exists$r) $\vdash A[t]\supset\exists xA[x]$.

(IP'_0) A:quantifier free $\Rightarrow \vdash(\forall xA[x]\supset\exists yB[y])\supset\exists y(\forall xA[x]\supset B[y])$.

(M') A:quantifier free $\Rightarrow \vdash\neg\neg\exists xA[x]\supset\exists xA[x]$.

(AC) $\vdash\forall x\exists yA[x,y]\supset\exists z\forall xA[x,zx]$.

Inference rules

(Str), (Cut), (CI), ($\wedge$1), ($\wedge$r), ($\vee$1) ($\vee$r): same

as in FT for QFT-formulas.
($\forall$r) $\vdash \Gamma \supset A[a], a \notin A \Rightarrow \vdash \Gamma \supset \forall x A[x]$.
($\exists$1) $\vdash A[a] \supset B, a \notin A \Rightarrow \vdash \exists x A[x] \supset B$.
In the above definition, $a \notin A$ means that none of the free variables in the sequence a occurrs in the nominal form A. Also in the above definition, IP, M and AC stand for 'independence of premiss', 'Markov's principle' and 'axiom of choice', respectively. Two formulas A and B are *equivalent* in QFT if both $A \supset B$ and $B \supset A$ are provable in QFT.

3.2 Interpreting formulas

A QFT-formula F is an *interpreting formula* if it is of the form $\exists x \forall y F_0[x,y]$, and F_0 is quantifier free. (We use the subscript *0* to denote a quantifier-free nominal form.)
Definition of Gödel translation: With each QFT-formula F, we associate an interpreting formula F* (*Gödel translation* of F) as follows.
1. F: quantifier free $\Rightarrow$ F*=F.
Let $A^* = \exists x_1 \forall y_1 A_0[x_1,y_1]$ and $B^* = \exists x_2 \forall y_2 B_0[x_2,y_2]$.
2. $F = A \supset B \Rightarrow F^* = \exists \tilde{x}_2 \exists \tilde{y}_1 \forall x_1 \forall y_2 (A_0[x_1, \tilde{y}_1 x_1, y_2] \supset B_0[\tilde{x}_2 x_1, y_2])$.
3. $F = A \wedge B \Rightarrow F^* = \exists x_1 \exists x_2 \forall y_1 \forall y_2 (A_0[x_1,y_1] \wedge B_0[x_2,y_2])$.
4. $F = A \vee B \Rightarrow F^* = \exists z \exists x_1 \exists x_2 \forall y_1 \forall y_2 (z=0 \supset A_0[x_1,y_1] \wedge \neg z=0 \supset B_0[x_2,y_2])$.
Let $(A[a])^* = \exists x_1 \forall y_1 A_0[x_1,y_1,a]$
5. $F = \forall x A[x] \Rightarrow F^* = \exists \tilde{x}_1 \forall x \forall y_1 A_0[\tilde{x}_1 x, y_1 x]$.
6. $F = \exists x A[x] \Rightarrow F^* = \exists x_1 \forall y_1 A_0[x_1,y_1,x]$.
The following theorem can be verified without difficulty. (AC) plays a role in the proof.
Theorem 5. *For any* QFT-*formula* F, F and F* *are equivalent in* QFT.

3.3 Reduction of QFT to FT

Let $F = \exists x \forall y F_0[x,y]$ be an interpreting formula. A quantifier free formula $F_0[t,a]$ is called a *reduction* of F, if a is a sequence of free variables such that $a \notin F_0$, and if t is a sequence of terms whose free variables, if any, always occur in F_0. Note that $F_0[t,a]$ is a basic FT-formula. Also, note that t is closed if F_0 contains no free variable. We then have the following important theorem due originally to [Gödel 1958].
(Gödel gives the reduction of the Heyting arithmetic HA to FT. Reduction of a system which admits quantifications over functionals of any type to FT was first carried out by [Yasugi 1963].
For a correction to [Yasugi 1963], see [Troelstra 1972].
Theorem 6. *If a* QFT-*proof of an interpreting formula* $F = \exists x \forall y F_0[x,y]$ *is given, then we can construct, primitive recursively, a reduction* $F_G = F_0[t,a]$ *of* F *and its proof in* FT.
We call above F_G the *Gödel reduction* of F. By Theorem 2 and Theorem 6, we have the following consistency theorem for QFT.
Theorem 7. *The system* QFT *is syntactically consistent, i.e., there exists a* QFT-*formula* A *which is not provable in* QFT.

3.4 Truth definition for QFT-formulas

Definition of *truth* and *falsity* for a closed QFT-formula:
1. $A = s=t \Rightarrow$ A is *true* iff $[s]=[t]$.
2. $A = B \supset C \Rightarrow$ A is *true* iff B is *false* or C is *true*.
3. $A = B \wedge C \Rightarrow$ A is *true* iff B is *true* and C is *true*.
4. $A = B \vee C \Rightarrow$ A is *true* iff B is *true* or C is *true*.
5. $A = \forall x B[x], x \in BV^\sigma \Rightarrow$ A is *true* iff $B[t]$ is *true* for all $t \in D^\sigma$.
6. $A = \exists x B[x], x \in BV^\sigma \Rightarrow$ A is *true* iff $B[t]$ is *true* for some $t \in D^\sigma$.
7. A is *false* iff A is *true*.
In contrast to the constructive definition of truth for FT-formulas, the above truth definition is nonconstructive because of 5 and 6 above. A true QFT-formulas will be referred to as *classically true* when we wish to emphasize this nonconstructive character of truth definition. Anyway, we remark that the above definition gives a (at least classically) natural interpretation of QFT-formulas in the domain D.
We now extend the truth definition to any QFT-formulas as follows. An *assignment* is a type preserving function ϕ: FV$\to$D. Let ϕ be an assignment, and A be any QFT-formula. Let $a = 'a_1, \ldots, a_n'$ be the stock of all free variables occurring in A (a is empty if A is closed). Then A is of the form $A[a_1,\ldots,a_n]$. Now, A is *true under* ϕ (notation: $\phi \Vdash A$) if the closed formula $A[\phi[a_1], \ldots, \phi[a_n]]$ is true. A is *valid* ($\Vdash A$) if $\phi \Vdash A$ for any assignment ϕ. A closed formula is valid iff it is true.
A tricky point about the system QFT is that the axiom schema (AC) is not always valid. For by Problem 9-(b) in Chapter 8 of [Shoenfield 1967], there is a recursive function $f: D^0 \to D^0$ such that (i): $f \neq \hat{f}$ for all $r \in D^{0\to 0}$, (See §1.3 for the definition of $\hat{f}$. $f \neq \hat{f}$ means that two functions are extensionally distinct, i.e., there exists some $s \in D^0$ such that $f[s] \neq \hat{f}[s]$.) and (ii): there is a QFT-formula $A[a,b]$ such that $\phi \Vdash A[a,b]$ iff $\phi[b] = f[\phi[a]]$. Hence the following instance of (AC) is not valid: $\forall x \exists y A[x,y] \supset \exists z \forall x A[x,zx]$. (See also II-§5-2.5.3-(iv) of [Troelstra 1973].) Then, by Theorem 8 below, we see that the Gödel translation F$\to$F* does not always preserve the classical truth value.
The above observation suggests us to define the following variants of QFT: We define the system QFT_0 as the system which results from QFT by deleting the axiom(AC). We obtain the classical system $CQFT_0$ by adding the following axiom ($\neg\neg$) to QFT_0:
($\neg\neg$) $\neg\neg A \supset A$.
We have the following semantical consistency theorem.
Theorem 8. 1) $QFT_0 \vdash A \Rightarrow CQFT_0 \vdash A \Rightarrow \Vdash A$.
2) $QFT \vdash A \Rightarrow \Vdash A^*$.

4. PROGRAM SYNTHESIS

4.1. The problem of program synthesis

Definition of a specification: A *specification* is a triple $\Sigma=\langle A; 'b_1,\ldots,b_n'; 'a_1,\ldots,a_m'\rangle$ where A is an $m+n$-place nominal form such that $A[b,a]=A[b_1,\ldots,b_n,a_1,\ldots,a_m]$ is a formula containing at most $b_1,\ldots,b_n$ and $a_1,\ldots,a_m$ free. We put

$D_I(\Sigma)=D_{\sigma_1}\times\ldots\times D_{\sigma_m}$, where $\sigma_i=\mathrm{type}[a_i]$,

$D_O(\Sigma)=D_{\tau_1}\times\ldots\times D_{\tau_n}$, where $\tau_j=\mathrm{type}[b_j]$ and

$R(\Sigma)=\{(s,t)\in D_I(\Sigma)\times D_O(\Sigma)\mid\vdash A[t,s]\}$.

We call $D_I(\Sigma)$ the *input domain* of Σ, $D_O(\Sigma)$ the *output domain* of Σ and $R(\Sigma)$ the *input-output relation* of Σ. An element s in $D_I(\Sigma)$ is called an *input*. We identify $s=(s_1,\ldots,s_m)\in D_I(\Sigma)$ with the sequence $'s_1,\ldots,s_m'$. Two specifications Σ and Σ' are *equivalent* if $R(\Sigma)=R(\Sigma')$. A sequence of programs will simply be called a program.

Definition of realization: A program p *realizes* the specification Σ if $A[ps,s]$ is *true* for any input $s\in D_I(\Sigma)$.

A specification Σ then determines the following.

Program synthesis Problem PSP(Σ): *"Construct a program* p *which realizes the specification* Σ."

In order that PSP(Σ) may have a solution, it is necessary that the formula $B=\exists y\forall x A[yx,x]$ is true. (Because if a program p realizes Σ, then $\vdash B$.) We note that B is true iff there exists a program $p='p_1,\ldots,p_n'$ such that $\{(s,\beta[s])\in D_I\times D_O\mid s\in D_I\}\subseteq R(\Sigma)$, where $\beta[s]=(\beta_1[s],\ldots,\beta_n[s])$ and $\beta_i[s]=\lceil(p_i\ s)\rceil$. Roughly speaking, B is true iff $R(\Sigma)$ contains the graph of a program. We also remark that the formula B semantically entails the formula $C=\forall x\exists z A[z,x]$. The formulas B and C are equivalent in QFT, but, as we have seen in §3.4, they are not necessarily semantically equivalent.

By a *prenex formula* we mean a formula of the form $Q_1x_1\ldots Q_nx_nA_0[x_1,\ldots,x_n]$, where Q_ix_i is either $\forall x_i$ or $\exists x_i$. Since $CQFT_0$ is a classical system, any formula A can be transformed into a prenex formula B, which we call the *prenex normal form* of A, such that A and B are equivalent in $CQFT_0$.

We have the following easily verifiable lemma.

Lemma 4. *If* A *is a prenex formula, then* $QFT_0\vdash A^*\supset A$.

We are now in a position to prove the following Main Theorem:

Theorem 9. *Let* $\Sigma=\langle A;b;a\rangle$ *be a specification, and let* $B[b,a]$ *be the prenex normal form of* $A[b,a]$. *Then if a* QFT*-proof of the formula* $\forall x\exists yB[y,x]$ *is given, we can construct, primitive recursively, a program* p *which realizes the specification* Σ. *Moreover, we can formally verify that* p *realizes* Σ, *i.e., the formula* $\forall xA[px,x]$ *is provable in* $CQFT_0$.

Proof. Define a nominal form B^* by $B^*[b,a]=(B[b,a])^*$. Then $B^*[b,a]$ is of the form $\exists u\forall vB_0[b,a,u,v]$. Let $C=\forall x\exists yB[y,x]$. Then $C^*=(\forall x\exists yB^*[y,x])^*=\exists z\exists w\forall x\forall vB_0[zx,x,wx,v]$. Then by Theorem 6, we have $FT\vdash(C^*)_G$, where $(C^*)_G$ is of the form $B_0[pa,a,qa,c]$ (p and q are sequences of closed terms, i.e., programs, since C* is closed, and a,c are sequences of free variables). Then we have:

$FT\vdash B_0[pa,a,qa,c]$
$\Rightarrow$ $QFT_0\vdash\exists w\forall x\forall vB_0[px,x,wx,v]$ (by $(\forall r),(\exists r),(MP)$)
$\Rightarrow$ $QFT_0\vdash\forall x\exists u\forall vB_0[px,x,u,v]$ (by Lemma 4)
$\Rightarrow$ $QFT_0\vdash\exists u\forall vB_0[pa,a,u,v]$ (by $(\forall 1),(MP)$)
$\Rightarrow$ $QFT_0\vdash B[pa,a]$ (by Lemma 4)
$\Rightarrow$ $CQFT_0\vdash A[pa,a]$ (by assumption)
$\Rightarrow$ $CQFT_0\vdash\forall xA[px,x]$ (by $(\forall r)$).

We have thus established the second part of the theorem. That p realizes Σ now follows by Theorem 8-(1).

Remark. 1. If *A* is quantifier free, then *B* is identical with *A*. We note that this category already contains many working examples such as quotient-remainder, GCD etc. For more examples see [Takahashi 1977].

2. Note that we have solved the problem by changing the given specification Σ to its equivalent variant $\Sigma'=\langle B;b;a\rangle$, providing the problem does not fall in the category mentioned above. (*A* and *B* are equivalent in $CQFT_0$!) That this modification is necessary can be seen as follows. Let $Ac=\forall x\exists yF[x,y]\supset\exists z\forall xF[x,zx]$ be a *false* instance of (AC). (See §3.4.) Let Σ be the specification $\langle A;'b';'a'\rangle$ where $A=Ac\wedge{}^*1=0$ and $\mathrm{type}[a]=\mathrm{type}[b]=0$ so that $A[b,a]=Ac\wedge b=0$. Then $\Sigma'=\langle B;'b';'a'\rangle$, where $B[b,a]$ is the prenex normal form of $A[b,a]$. Now, if we feed the formula $\forall x\exists yA[y,x]$ to a QFT-theorem-prover, then since it is provable in QFT, we will have a program $p=\lambda x0$ whose graph is $D_0\times\{0\}$. But $R(\Sigma)$ is empty since $Ac\wedge b=0$ is *false* under any assignment ϕ. Thus our program p does not realize the specification Σ. (Caution: That a false formula is provable in QFT does not imply its inconsistency. See Theorem 8-(2).) We have avoided such awkwardness by shifting from Σ to its equivalent variant Σ'. In this case the formula $\forall x\exists yB[y,x]$ is simply unprovable in QFT.

3. There are several interesting relations between the inference rules employed in the proof of $B[b,a]$ and the structure of the synthesized programs, of which we cannot go into details because of the limitation of space. Roughly speaking, (MP), $[(\vee\rightarrow),(\rightarrow\wedge),(\mathrm{Str})]$ and (CI) correspond to composition of programs, conditional (*if_then_else*) and primitive recursion, respectively. In particular, a *structured proof* yields a *structured program*.

4.2 Simulation by LISP

We have seen that the semantic function $[\ ]:\mathrm{Prog}\rightarrow D$ is recursive (Theorem 1). In order to simulate this function by a LISP S-function, we proceed as follows. Let Sexp denote the set of LISP S-expressions.

Definition of $\psi:\mathrm{Prog}\rightarrow\mathrm{Sexp}$:

$\psi[0]=0$, $\psi[S]=S$, $\psi[J_\sigma]=J$, $\psi[x\bar{i}^\sigma]=X\bar{i}$

$\psi[(r\ s)]=(\psi[r]\ \psi[s])$, $\psi[\lambda x r[x]]=(L\ \psi[x]\ \psi[r[x]])$.

Definition of the S-function reduce:

```
reduce[x]=
[normal[x]→x;
 atom[caar[x]]→[eq[caar[x];L]→reduce[lconv[x];
                T→subreduce[x] ];
 atom[caaar[x]]→
  [eq[caaar[x];J]→[atom[cadaar[x]→reduce[cadr[x]];
                  atom[caadaaar[x]]→[eq[caadaar[x];S]→
reduce[list[cadar[x];list[list[list[J;cadadaar[x]];cadar[x]];
                          cadr[x] ]]];
                                    T→subreduce[x] ];
                  T→subreduce[x] ];
   T→subreduce[x] ];
 T→subreduce[x] ]

subreduce[x]=reduce[list[reduce[car[x]];reduce[cadr[x]]]]

normal[x]=
[atom[x]→T;
 atom[car[x]]→subnormal[x];
 atom[caar[x]]→[eq[caar[x];L]→NIL;T→subnormal[x]];
 atom[caaar[x]]→[eq[caaar[x]];J]→
  [atom[cadaar[x]]→[eq[cadaar[x];0]→NIL;
                    T→subnormal[x] ];
   atom[caadaar[x]]→[eq[caadaar[x];S]→NIL;
                     T→subnormal[x] ];
   T→subnormal[x] ];
 T→subnormal[x] ]

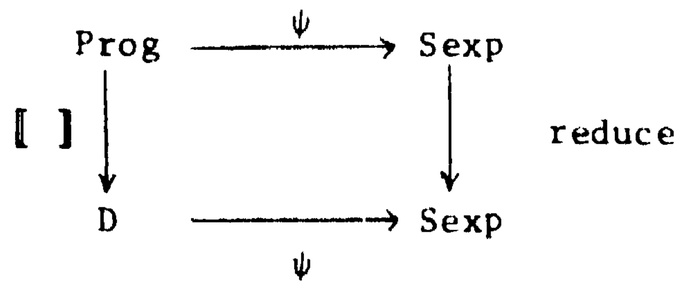
subnormal[x]=[normal[car[x]]→normal[cadr[x]];T→NIL]

lconv[x]=lconv1[caddar[x];cadar[x];cadr[x]]]

lconv1[x;v;y]=lcnv[x;NIL;v;y]

lcnv[x;bv;v;y]=
[atom[x]→[eq[x;v]→[memq[v;bv]→x;T→y];T→x];
 atom[car[x]]→[eq[car[x];L]→list[L;cadr[x];lcnv[caddr[x];
append[cons[cadr[x];NIL];bv];v;y ]];
                T→list[lcnv[car[x];bv;v;y];
                       lcnv[cadr[x];bv;v;y] ] ];
 T→list[lcnv[car[x];bv;v;y];lcnv[cadr[x];bv;v;y]] ]
```

Theorem 10. *The diagram below commutes:*



Thus we have seen that the function reduce simulates the semantic function [ ]. If ψ were a one-to-one function, then we could compute [ ] by the equation $[p]=(\psi^{-1}\cdot reduce\cdot\psi)[p]$. But ψ is not one-to-one since $\psi[J_\sigma]=J$ for any σ Type. However, we note that $\psi\times type$?Prog→Sexp×Type such that $(\psi\times type)[p]=(\psi[p], type[p])$ is one-to-one. Hence we can compute [ ] by the scheme $[p]=(\psi\times type)^{-1}[reduce[\psi[p]], type[p]]$. (Note that [ ] preserves type.)

4.3 Concluding Remarks

We believe that we have successfully set a theoretical foundation for program synthesis. It is not difficult to implement our procedure, and we wish to encourage the interested readers to actually implement it. In fact, at a suggestion of the author, [Goto 1978] has implemented a system of program synthesis. However, hie system differs at an essential point from the one described above, and, at present, no proof exists which guarantees the correctness of the program synthesized by Goto's system. The possibility of using Godel interpretation as a tool for program synthesis has also been suggested by [Kreisel 1977]. [Takasu 1978] also studies the application of Godel interpretation to program synthesis using the formalism of Gentzen's sequential calculus.

Since the basic data type of Prog is natural number, it may appear that such data types as list, stack etc. cannot be dealt with in our formalism. However it is not the case, and we can treat these data types as well by treating them as abstract data types. We wish to discuss this point further in a paper to be published later.

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Automotive Stereo Vision using Deconvolution Technique

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A new stereo vision system using deconvolution technique is proposed. This system is composed of the upper and the lower cameras. By deconvoluting the upper image with the lower one, the system constructs a horizontal section image. After the automobiles are separated from the other things in this horizontal section image, the distances and relative velocity are measured. This segmentation is realized by the thresholding procedure which utilizes the relation between the distance and the breadth of the automobile. The experimental results are presented. It is also shown that the deconvolution technique is able to construct a finer and higher resolutional horizontal section image compared with a correlation technique. Although the SN ratio of the horizontal section image is inconsistent with range resolution, the possibility of the adjustment between the SN ratio and the resolution is presented.

1. Introduction

In order to avoid the motorcar accidents, it would be the effective method that the driver is warned with the warnings by a computer system for safety. This system needs the sensors which detect traffic conditions. Measuring the distances and relative velocity between the driver and the automobiles around him is the most basic function of these sensors. Because of the difficulties to identify the automobiles from other things, this problem has not completely solved yet. The most important key to solve this problem is a fast processing of the horizontal section images around the driver. This horizontal section image can be obtained by a stereo vision (triangulation system) via measuring the value of the shift between two images. In order to measure the value of this shift, many techniques have been utilized (i.e. the correlation technique [1], the technique which utilizes the phase shift of the narrow bandwidth of the target Fourier spectrum [2], etc.). This paper describes an alternative technique using deconvolution.

2. Stereo Vision using Deconvolution Technique

2-1 Obtaining the Horizontal Section Image

With the stereo vision system shown by Fig.1 , it is possible to approximate the upper image $f_2(x)$ is the shifted image of the lower one $f_1(x)$.

$$f_2(x) \fallingdotseq f_1(x-\tau) \quad [= \int f_1(x') * (x' - (x-\tau))dx' \,] \qquad (1)$$

In other word, it can be said that $f_2(x)$ is a convoluted image of $f_1(x)$ and $\delta(x-\tau)$. By measuring the value of the shift τ ,we can obtain the distance between the target ahead and the system. Therefore, one line of the horizontal section image can be obtained by plotting with light and shade the correlation curve, which is obtained by calculating the degree of matching between two images when the upper image is shifted relative to the lower one. Seince the lower camera of this system always gives the front view of the targets on the road as a reference image, this camera arrangement is suited for detecting the traffic obstacles.

The algorithm to obtain horizontal section image is as follows. [see Fig.2]

[1] Two windowed images are obtained by the upper and the lower cameras. [Fig.4(b)and(c)]

[2] The Fourier transformations of the obtained images are carried out by FFT.

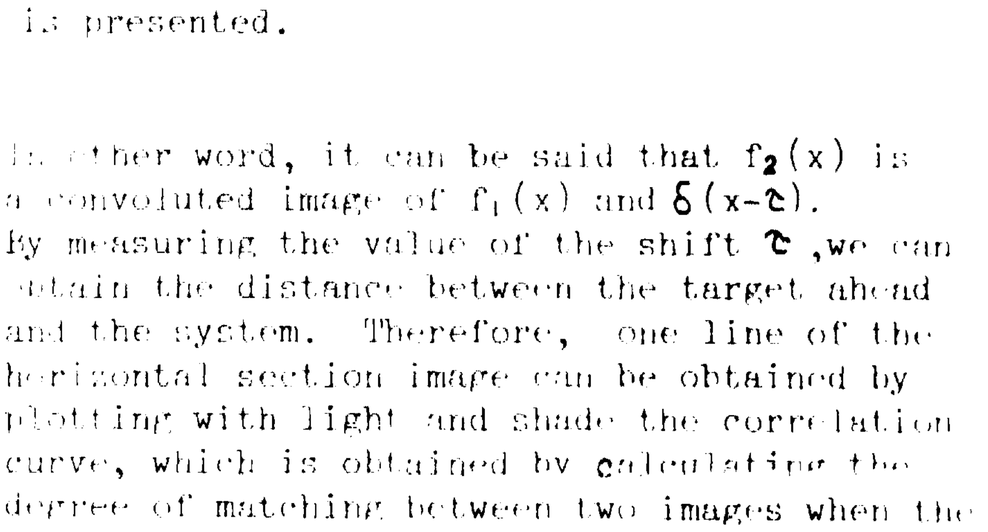


Fig.1 The principle of stereo vision

$$Fi(\omega)=\int_{-\frac{X}{2}}^{\frac{X}{2}} fi(x)*e^{-j\omega x}dx \quad (i=1,2) \qquad (2)$$

where X refers to the length of the image.

[3] By deconvoluting the upper image with the lower one, we calculate the correlation curve in the frequency domain ; $G(\omega)$.

$$G(\omega)=F_2(\omega)*D(\omega)$$

$$D(\omega)=\begin{cases} 1/F_1(\omega) & ; \ F_1(\omega)\geqq F_1\max(\omega)/a \\ 0 & ; \ \text{otherwise} \end{cases} \qquad (3)$$

where "a" [=30 for the following examples] is a constant.

[4] By the inverse Fourier transformation of $G(\omega)$, the correlation curve $g_d(z)$ is obtained. [Fig.3(a)]

$$g_d(z)=\int_{\omega_1}^{\omega_2} G(\omega)*e^{j\omega z}df \qquad (4)$$

where $\omega_1(\omega_2)$ is the lowest (highest) angular-frequency of the target Fourier spectrum.

Repeating these procedures ([1]~[4]) along the horizontal right/left direction, the horizontal section image is obtained. [Fig.4(d)]

2-2 Automobiles Identification and Velocity Measurement

Once the horizontal section image is constructed , the automobiles are separated from the other things by thresholding procedure which utilizes the relation between the distance and the breadth of the automobile. The result of this segmentation is presented by Fig.4(f). Finally, relative velocity is measured by processing two sequential horizontal section images.

3. Deconvolution and Correlation Technique

The horizontal section image can also be constructed using correlation technique. Assuming that the brightness distribution of the vehicle image has a square shape as shown on Fig.1, the comparizon of these methods are derived.

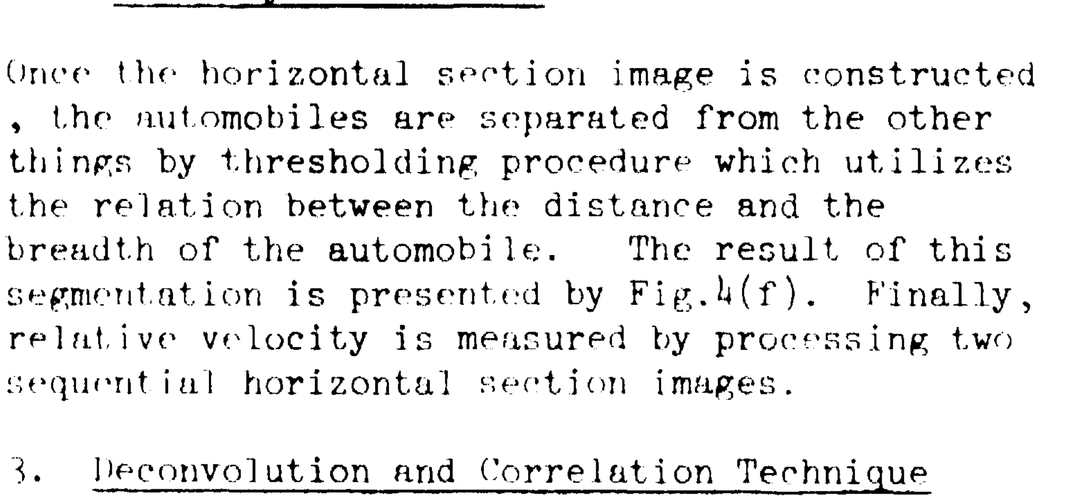


Fig.2 The algorithm of calculating the correlation curve.

3-1 Quality of Horizontal Section Image

(a) Deconvolution Technique : Substituting Eqs.(1),(2) into Eq.(4) , the correlation curve $g_d(z)$ is given by Eq.(5).

$$g_d(z)=\int_{\omega_1}^{\omega_2}\frac{e^{-j\omega\tau}F_1(\omega)}{F_1(\omega)}e^{j\omega z}df=\int_{\omega_1}^{\omega_2}e^{j\omega(z-\tau)}df$$
$$=\frac{\Omega}{2}e^{j\Omega m(z-\tau)}*SINC[\frac{\Omega}{2}(z-\tau)] \qquad (5)$$

where $\Omega=\omega_2-\omega_1$, $\Omega m=(\omega_1+\omega_2)/2$.

The range resolution δ_d [$=2\pi/\Omega=h/2a$; Fig.3(a)] is generally small and adjustable by varying the value of "a".

(b) Correlation Technique : The correlation curve $g_c(z)$ is derived as follows.

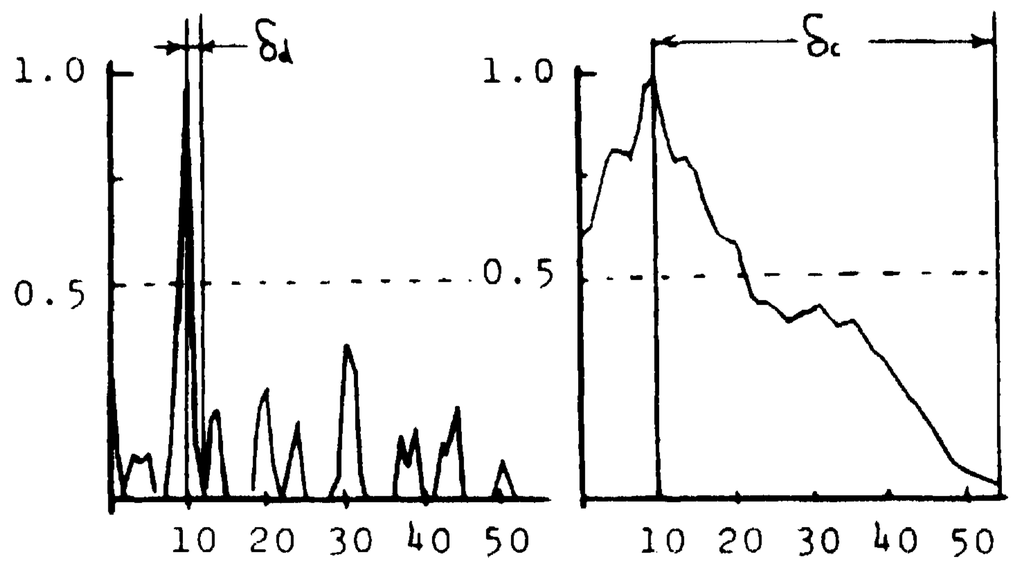
$$g_c(z)=\int_{\omega_1}^{\omega_2}F_1(\omega)*F_1^*(\omega)e^{j\omega(z-\tau)}df \qquad (6)$$

The range resolution δ_c [$=h$; Fig.3 and Fig.4(d),(e)] is generally large.

Comparing these techniques, the correlation curve using deconvolution has a constant shape of SINC function, and its shape depends only upon the target Fourier spectrum. On the other hand the correlation curve using correlation depends upon the target Fourier spectrum itself. Therefore, a finer (easy to process) horizontal section image is obtainable using deconvolution technique.

3-2 Effects of White Noise

When the white noise (its power spectrum is N_0) is added to the square shaped image, the SN ratio [the ratio of peak (matching point) power to the mean noise power] of the horizontal section image is analized as follows [3].



(a) Deconvolution (b) Correlation

The ordinate represents the degree of matching. The abscissa represents the length of shift between two images. The two images are matched when the length of shift is equal to 10.

Fig.3 The shape of correlation curves.

(a) Deconvolution Technique: $SN_d = 3h/\pi N_0 a$ (7)
(b) Correlation Technique: $SN_c = 2h/N_0$ (8)
Considering δ_d and Eq.(7), the deconvolution technique enable us to adjust the range resolution and the SN ratio by varying "a". It is also possible to prove that the additive white noise causes no peak position error of correlation curve by any these two techniques. In the analysis stated above, the input data is assumed to be continuous. Scince real data is not continuous, the discrete calculation (FFT) brings the data a cyclic property. However, this effect can be reduced by windowing and filling zeroes around the input data.

4. Conclusions

1] A stereo vision using deconvolution technique is proposed.
2] This vision system is able to construct a finer and higher resolutional horizontal section image compared with a system using correlation technique.
3] It is also shown that the adjustment between range resolution and the SN ratio of the horizontal section image is easily realized by this technique.
4] The identification of the automobiles from the other things and the measurement of the distances and relative velocity between the driver and the automobiles ahead of him are presented by processing these horizontal section image sequentially.

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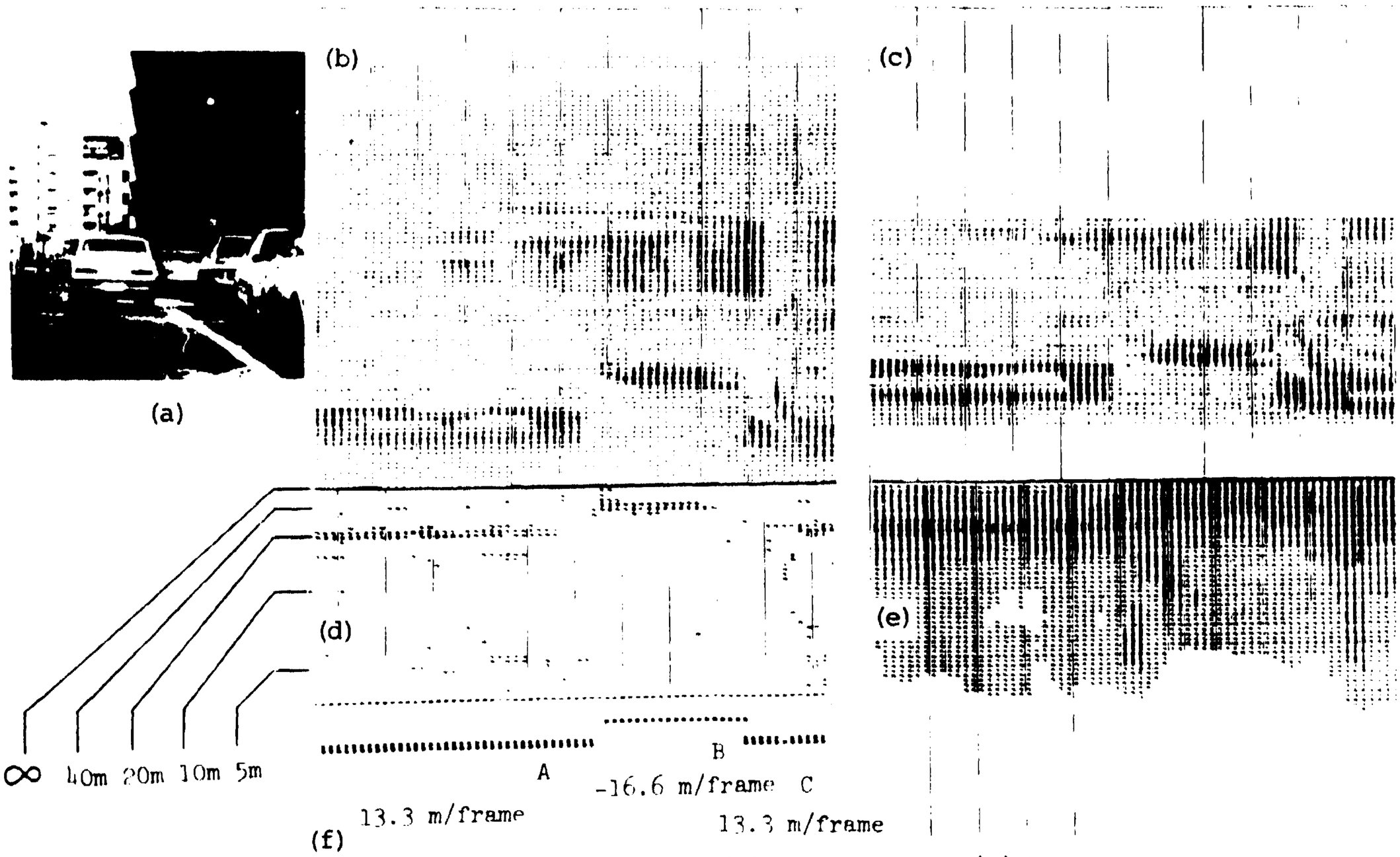

(a) The photograph used for experiments. (b) Upper image. (c) Lower image
(d) The horizontal section image via deconvolution technique.
(e) The horizontal section image via correlation technique.
(f) The result of the segmentation of the automobiles and measurement of velocity.

Fig.4 The experimental results

RETRIEVING INFORMATION FROM AN EPISODIC MEMORY OR WHY COMPUTERS' MEMORIES SHOULD BE MORE LIKE PEOPLE'S •

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A computer memory organization modeled after human memory is proposed, along with strategies for accessing that memory. CYRUS, a program which implements the theory, is described.

Do A.I. programs understand what they read? Much debate has taken place on this issue (e.g., [6]) with little agreement. One thing seems clear, however. No computer program can seriously be said to have understood anything unless it can pass a simple test of remembering what it has supposedly understood. This problem seems obvious and easily solved. We can point to programs that paraphrase or summarize. Clearly, they remember. Or do they?

Memory, after all, also involves the integration of new knowledge with old knowledge and the ability to use newly obtained information for future and as yet unspecified tasks. In our own laboratory, we have developed a number of story understanding programs that summarize or answer questions about the stories they have understood (e.g. SAM, PAM, FRUMP). But none of those programs can apply information gained in reading one story to understand a later story. None have a long-term memory.

What would a long-term memory look like? Psychologists have proposed a number of theories, none of which are completely adequate for describing the structure of memory (e.g. [3], [7], [1]). One way to discover what human memory looks like, and what computer memory should look like, is to look at the memory tasks humans perform that we would want a computer to do.

Some of the memory tasks that people do in the course of normal conversation and understanding are listed below (see [5] for more detail):

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1. Reminding
2. Relating events by time.
3. Recognizing when statements or questions are non-sensical.
4. Recognizing when something has not happened.
5. Making inferences.
6. Using time and place specifications
7. Using maps and other aids.
8. Extensive memory search.

If we want to build an understanding machine that understands in the same way people do, then we have to take into account the vast number of memory tasks that people do. Reminding, for example, is a prerequisite to the process of creativity. Machines that cannot make new, undirected connections between items in memory will never be able to dream or imagine. Machines that cannot be reminded will not be able to think in any serious sense.

To get a handle on the way humans do these tasks, we examined people's responses to a request to tell us about all the museums they had been to ([5]). The results are summarized below:

1. Find museums by searching for instances of the museum script.
2. Find museum experiences (instances *of* the museum script) by searching for them as events within trip instances.
3. Find museums by searching memory for cities visited.
4. Find museum experiences by searching for experiences in places of residence.
5. Find trips by searching for trips to foreign countries or within country of residence, or by searching for episodes associated with those places.
6. Find places by using a map of the general area.

Rules such as these can be stored in the

computer as features of the scripts and other stereotypes that they refer to. A memory set up this way would have its scripts and other stereotypes pointing to information about where in memory their instances could be found. In this way, each stereotype, would specify a set *OF* strategies for. searching memory *find* its. instances. Each script and stereotype would include information about what other scripts or macro-scripts it could be a part of (e.g.,the museum script can be an event in a trip macro-script); which of its parts are important cues for finding its instances (e.g.,look for places different than home to find trips); and what other memory structures can be used to find its instances (e.g., go through a mental map of an area to find places). Using this organization, the following general rules for searching memory can be used:

7. To find instances of a script, search for other scripts and macro-scripts it can be part of.
8. To find objects, search for stereotypical events (such a scripts) associated with that object.
9. To find an instance of a stereotype in memory, find instances of the parts of it that are specified as important.
10. To find places, use a map.

In order to apply these strategies to a memory search, memory must be well-organized. It should be able to answer "Where did John go to law school?" without having to go through John's experiences in elementary school. it seems that experiences that happen to a person are grouped in terms of the larger contexts in which they were embedded. Knowing when an event might have occured, or what events might have occurred before or after it, can help us know where in memory to look for it.

Thus, one good way of organizing experiences is temporally, but with the time line broken into workable parts, each with some unique characteristic. These pieces are called eraas ([2]). The three years of going to law school, for example, make up a professional school era. Some standard ways of breaking up a personal time line are: places lived, jobs held, schools attended, and family situation. An event in a person's life would be organized on the event list of its corresponding era or eras.

Strategies for searching memory can take advantage of this memory organization. When searching for any particular event, only eras relevant to it must be searched. To find an event having to do with someone's job, only relevant occupational eras will have to be searched. To implement this on a computer, each script and other stereotype needs to have information about which times in someone's life he might be involved in that type of activity, and which types of eras and era sequences it can be found in.

The following additional rules can be used for searching a memory organized as described above:

11. To find an instance of a stereotype in memory, search the types of eras and era sequences it could be found in.
12. To find an instance of a stereotype in memory, search the appropriate eras going on at the time when this event is most likely to have taken place.
13. To find an era, search in the appropriate era sequence at the time specified relative to other eras in that sequence and in other sequences.

The CYRUS system ([2]) is a memory model that organizes biographical information about people and uses knowledge about its organization for retrieval and automatic updating. An important aspect of the CYRUS system is that the organization of its memory represents an attempt to model memory in people, and its retrieval and updating procedures mirror the way we believe people access their memories. CYRUS is an implementation of the ideas about memory organization and retrieval described above. A sample dialogue with CYRUS, showing input and output, follows:

Q1: Who is Cyrus Vance?
A1: United States Secretary of State.
Q2: How did he become Secretary of State?
A2: He was appointed by President Carter.
Q3: Where is he today?
A3: Egypt.
Q4: Why did he go there?
A4: He went to negotiate a compromise agreement to Egypt.
Q5: Has he met with the Israelis recently?
A5: Yes, in Washington right before he left for Egypt.
Q6: Who was at the meeting?
A6: Moshe Dayan and Israeli legal experts.
Q7: Will he meet with them in Israel?
A7: Yes, to discuss the compromise.

Each of the memory structures and strategies mentioned above is implemented in CYRUS. The CYRUS episodic memory contains events in the lives of the people represented. CYRUS' stereotype memory holds all the stereotypes

that can be used for representation along with information relevant to each of them.

Eras in CYRUS are characterized by the major role themes a person is involved in at each point in his life ([4]). In CYRUS, each person represented has an occupational sequence of eras (including school), a family sequence of eras, a social sequence of eras, and a residential sequence of eras (where each era corresponds to a place the person has lives). Eras contain all the events in a person's life occurring during that time span and pertaining to that role theme or place of residence. Thus, Cyrus Vance's current occupational era is characterized by his being Secretary of State; his current family era is characterized by his being a husband and father.

CYRUS makes use of information attached to its scripts and other stereotypes to apply the strategy rules described above (rules 7-13). In answering the question, "When was the last time Vance met with Begin?", CYRUS uses information from the attend-meeting script to guide its memory search. CYRUS searches for the meeting by looking in eras and macro-scripts specified by the meeting script as appropriate to meetings. CYRUS' general knowledge tells it that the place for a meeting is usually the country of residence of one of the participants; and that a person must take a trip to get to a place other than his residence. A trip's type and location in memory are determined by the events which happen during the trip, so CYRUS searches for the trip by searching in an era appropriate to the original event being searched for. Input and output from CYRUS follow:

>When was Vance's last meeting with Sadat?
Searching Vance's occupational eras for meetings with Sadat
Searching Vance's occupational eras for trips to Egypt
Found CON562
Searching CON562 for meetings with Sadat
Found CON547
Searching CON547 for meetings with Sadat
Found one
December 15, in Egypt.

CYRUS uses the strategy of searching for meetings to answer this question. Alternative strategies could have also been used to answer this question. Experiences associated with Sadat could have been searched, and a recent meeting with Sadat might have been found that way. Alternatively, Vance's experiences associated with the Arab-Israeli conflict or the Egyptian-Israeli peace talks could have been searched (after inferring that a meeting between Vance and Sadat probably had to do with one of those issues).

Eras and era sequences in Cyrus can also be used to relate events through time. If asked "When did Vance get married?", CYRUS would answer "Soon after he began to work as a lawyer." If asked, "When was he last in Paris?", it would answer "During the Vietnam peace talks, when he was an advisor to President Johnson."

CYRUS infers things not explicitly in memory by making use of expectations derived from the scripts, macro-scripts, and role themes it knows about. It can use its knowledge about enablement conditions for role themes to answer questions such as "How did Vance become Secretary of State?" It uses its knowledge about trips to answer questions such as "How did Vance get to Russia?" by inferring that he took an airplane, even if that information is not explicitly in memory.

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THE CONCEPTUAL CONTENT OF CONVERSATION

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This paper outlines a strategy for conversational analysis that utilizes multiple levels of information flow in order to characterize the conceptual content of a conversation. The role of predictive knowledge structures and contextual information is illustrated in an analysis of a sample conversation, along with a partial outline of conversational rules specific to particular levels of conversational analysis.

1. Introduction

A large portion of the conversational process takes place beneath the surface of the actual conversation, In trying to spell out the rules that people use in conversation, it is necessary to account for all this "hidden" communication; explanations that are limited to the surface interaction will not provide a .sufficient perspective.

Consider the following conversation:

A1: Why were you out so late last night?
B1: 1 went bowling with the boys.

A2: I thought you hated bowling.
B2: It's ok when I have some company.

A3*. Aren't I company?
B3: It's not the same.

A4: Sure, you can't pick up women at home.
B4: I don't pick up women at the bowling alley.

We can analyze any given conversation in terms of [1] the implicit information that is present underneath the surface of the conversation, or [2] the rules of conversation that are operating at various levels of interaction.

2. Contextual Knowledge

We will now consider the various types of knowledge that must be accessed in order to understand our husband/wife conversation.

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A1 Why were you out so late last night?

Because we know a woman is directing this question to her husband, we understand that she had an expectation about his arrival time which was violated. "So late" can only be interpreted in terms of her expectations. Married people expect to be with each other at night, and any deviation from this normative pattern deserves explanation. The same question would make far less sense in the context of a night clerk at a hotel confronting a registered guest.

Knowledge of goals and plans is needed to understand that

A4: Sure, you can't pick up women at home.

is in fact an accusation. Had she countered with, "Sure, you can't burn envelopes at home," it would be difficult to understand her rejoinder. (Why would anyone want to burn envelopes?) Picking up women on the other hand, is easily understood as a plan designed to satisfy the cyclic satisfaction goal of S-sex [1] But the fact that picking up women makes sense is not sufficient for this to be an accusation. It is an accusation only because we know that the marriage role theme assumes a goal subsumption strategy for S-sex which furthermore precludes all other behavior directed towards the satisfaction of that goal. An admission of such behavior is a rejection of his marital agreement. With such a major role theme at stake, we are not surprised to hear his denial.

3. Levels of Conversation

We have thus far detected twelve distinct levels of conversational interaction:

TWELVE LEVELS OF CONVERSATION

1. Direct Q-A: This is the explicit surface level of communication where "literal" content is processed.

2. Knowledge State: Statements here address the knowledge state of the hearer.

3. Dominance *Games*- At this level a speaker tries to get the upper hand in an adversary type conversation.

4. Emotions of *A'* Many statements can be interpreted as expressions of how the speaker is feeling at the moment.

5. Emotion,a of B: This is the same as the one above it, except that it refers to the emotions of the other speaker.

6. Relationships of A And B: This is the level at which implicit or explicit statements are made about the relationship between the participants.

7. Argument strategy: This level describes strategic exchanges when the conversation seeks to resolve some disagreement.

8. Import: This level of analysis identifies and tracks the most significant or compelling aspect of conversational interactions.

9. Implicit Beleifs- Personal beliefs are most often present as presuppositions.

10. Points: The ultimate goal of a conversation can often be about something other than what it seems to be about.

11. Topic Shifts: Statements such as 'Don't change the topic[1] are surface realizations of this level. Topics themselves are tracked and can be discussed.

12. Truth and. trust: The truth, believability, or trust of the other participant are constantly monitored.

The twelve levels of conversation each carries a set of rules which control responses at that level. We shall now consider what the rules are like for a few of the levels. We will examine our example sentence A1: "Why were you out so late last night?" and we will consider the conceptual content of this question at various levels of conversational analysis. To begin we will look at level 3:

CATEGORY: level 3: Dominance Games
INPUT ANALYSIS: "You are going to be on the defensive now!"
HOW WE KNOW: 'Why questions' are candidates for level 3 analysis. If the reason being asked for addresses a role theme violation (or other potential Inadequacy on the part of the hearer), then the above analysis applies.
WHY WE LOOKED THERE: A sufficient condition for a level 3 analysis is an Inadequacy or failure to conform to expectations.
RESPONSE REQUIREMENTS: Level 3 responses are almost always under the surface. When one is put on the defensive, one has the choice of either returning the fire or accepting the defensive. The decision is based on the emotional relationship and power relationship of the participants. Once the choice has been made it affects the form and content of the response.
HOW WE KNOW WHAT TO SELECT: A consistency check on any presuppositions is needed to determine whether the attack is valid. Thus, we need to check facts that exist in memory.

Our sample conversation can be viewed many ways, one of which is as a kind of battle. In this conversation A is attacking B. B is on the defensive Initially, but B fires back in B2 by saying "It's (bowling) okay when I have company". Now this statement says many things, but on the level of dominance games, It is a covert attack on A's value as company. A responds explicitly to the attack but not to the dominance game. An explicit response to the dominance game might have been, "Don't attack me just when I've got you!".

A retakes the offensive in AM by averring that B is picking up women at the bowling alley, which is presumably an agreed upon bad thing. This puts B back on the defensive again in B4.

Another conversational level is level 4:

CATEGORY: level 4: emotions of A
INPUT ANALYSIS: "You don't love me anymore"
HOW WE KNOW: Violations of themes are always checked. A violation implies that thematic preconditions are no longer valid.
RESPONSE REQUIREMENTS: Assure, sympathize, ignore, etc.
WHERE FROM: What to do is determined by the hearer's emotional responses.
HOW WE KNOW WHAT TO SELECT: The appropriateness of an explicit response on this level is dependent on the current emotional relationship and the desires of the speaker.

In our sample conversation A3 ("Aren't I company?") can be considered to be a statement at level *4 meaning 'You don't love me, do you?' B's response to that, ("It's not the same"), can be understood as explicitly ignoring the issue which in a sense, is a qualified assent. This analysis can be seen as part of the reason for the escalation of matters by A in A4. At this point she goes directly on the attack, stating her suspicions overtly. This is consistent with B's previous refusal to discuss the level 4 aspect of the conversation. That Is, B has rejected A by not reassuring her. To 3ee how level 4 can actually appear on the surface, we need only change response B3 to "I still love you." Such a response would make no sense at any other level of conversational analysis or with any other rules of continuity. Yet Is is nevertheless an appropriate response here because level 4 has been implicitly brought up by A and can therefore be explicitly addressed by B if he so chooses.

At level 9 rules about beliefs drive the interaction. When beliefs are presented by a speaker the hearer either (1) implicitly acknowledges their validity by responding on other levels or (2) contradicts them by an explicit rejection.

CATEGORY: level 9: beliefs
INPUT ANALYSIS: "Husbands are supposed to be home with their wives at night"
"Husbands should tell wives what they do"
HOW WE KNOW: Checking the husband role theme. Statements that implicitly refer to a role theme violation covertly assert one's belief in that role theme.
WHY WE LOOKED THERE: Beliefs about husbands' behavior are relevant when a wife is talking to a husband. The husband role theme thus constitutes a background against which inputs are checked.
RESPONSE REQUIREMENTS: To ignore this level is to accept covert beliefs. A belief must be countered if it is not shared.
WHERE FROM: To do this, one must consult one's own beliefs.
HOW WE KNOW WHAT TO SELECT: Contradictory beliefs are selected to be explicitly output if they exist. Thus if B does not share A's belief he can tell her "Being married shouldn't be a Jail sentence."

4. Conclusions

Our final example is intended to illustrate the complexity of this problem by examining possible responses to an admission by B later on in the conversation.

> All right. I was at Joe's house. We had a few beers and smoked some dope. I didn't want to tell you because I know you can't stand Joe.

This can be responded to on each level as follows:

1. Directt. Q=A: How can you stand Joe?
2. Knowledge State: Why didn't you tell me that in the first place? I really like Joe, I just never told you about ray change of heart about him.
3. Dominance Games.: Well I've got news for vou. I've been seeing Joe when you actually do go bowling.
4. Emotions of: I can't love a person who lies to me like that.
5. Emotions of B: You couldn't love me and be friends with him.
6 Relationship of A and B: I want a divorce.
7 Argument strategy: You mean you created this giant argument out of Just that little thing?
8. Import: That's what you were worried about? I don't care about that.
9. Implicit Beleifs: You were smoking dope? That's immoral. I won't stand for it.
10- Points: That's my point exactly. You are a liar.
11. Topic, Shifts: (The topic has not been shifted so this is also inappropriate.)
12. Truth and trust.: How can I trust you after you lied to me like that?

In addition to what we have listed above, it is also possible to combine many of the levels in one response. (Indeed it is quite difficult to avoid such consolodations.)

To effectively model conversation then, it is necessary to find the levels at which people communicate, the rules people use to relate inputs to these levels, the methods of response generation at each of these levels, and the rules people use to select from alternative responses. When we have understood how to do all this, we will have made a start at analyzing the process of conversation and will then be ready to attempt the construction of an automated conversationalist.

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PARSING DIRECTLY INTO KNOWLEDGE STRUCTURES

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A new type of natural language parser is presented. The idea behind this parser is to map input sentences into the deepest form of the representation of their meaning and make appropriate inferences during the parsing process, using interest to guide the processing.

1. Introduction

Over the course of the last ten years, researchers in our project have designed and programmed a large number of parsers - programs that mapped English sentences into the Conceptual Dependency (CD) representation of their meaning. They have all had one methodological assumption in common: the parsing algorithm that they employed was to be as psychologically correct as possible. This assumption brought with it an operating principle which was (with one exception to be discussed later) always followed, namely that the parsing algorithm was a strict left-to-right, one-pass operation, without backup.

One of the major problems with most of our story understanding programs, including their parsers, was their inability to handle genuinely new texts for which they were unprepared. A new vocabulary item, domain of discourse, or previously unencountered syntactic construction would often throw things into disarray. It seemed to us that we could produce one of the desired end-products of a story understanding system, a summary, with a much more robust and much faster program. This was the reason behind the design of FRUMP [1], FRUMP skims for what it is interested in, looking for precisely the items of information it wishes to include in its summary for any particular domain that it has knowledge about. However, since FRUMP is very top down it cannot respond to things it is unprepared for. Therefore it is not a complete understanding system.

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Ideally what we would like is a program with the robustness of FRUMP but with the ability to understand what it does not expect to see. Perhaps a human understander is top-down when appropriate, but bottom-up at other times. What is needed is an understanding system that can do both and be robust at the same time.

Many other researchers have investigated the problem of parsing natural language input into an internal representation. Virtually all of their methods concentrate on syntactic analysis. One very popular technique has been the Augmented Transition Network (ATN). Parsers of this sort have been discussed by Woods [10], Kaplan [2], and others. ATN's have tended to deal almost exclusively with syntax, perhaps with an occasional check of a few simple semantic properties of words. A more recent parser which views syntax parsing as an isolable sub-part of language understanding is by Marcus [31. All of these programs view syntactic parsing as a process largely isolable from the rest of understanding. Our view, as described by Riesbeck [5] and Riesbeck and Schank [6] has always stressed the integration of semantics and syntax in parsing. A similar view was expressed by Wilks [9]. In this paper we will further contend that parsing should be integrated with the overall understanding process.

2. Processing Limitations

Now let us consider the design of a human-like parser. One important feature in such a parser is the speed with which humans can read text. Considering all the inferences, access of background knowledge, and other problems that an understander must deal with in the course of reading or listening to a sentence, people are very fast at the job. This is especially true

when we recognize that understanding is basically finished as soon as a sentence ends. This implies that high level processes cannot wait until the end, after parsing is finished, and also that human processing is integrated. People must be making Inferences as soon as they begin to process a sentence. From this it follows that people will actively use whatever they discover, using high level conclusions to guide low level processing. Thus, as models of human processing, systems that firot do a complete parse and then begin to make inferences are not sensible. It seems plausible that the processing requirements for complete understanding frequently overwhelm the total available processing capability (see [4]). This means some words must be processed very superficially in order to gain time to extensively process words of semantic, syntactic or inferential importance.

It is likely that people are deciding as they go what words to pay serious attention to and what to glide over. Such decisions can be explained on the basis of many factors. One obvious one is interest. That is, people are liable to pay attention to (that is, devote their processing time to) what interests them. We have discussed the concept of interest and its ramifications for the Inference problem in [7]. The main conclusion there was that inference is controlled by interest. This is also likely to be true at the parsing level since we are now viewing the entire understanding process as an integrated phenomenon.

Taking advantage of interest to reduce the time spent on many words has certain implications on processing. One is that the understanding process may not be strictly left to right. Since the most important words often come at the end of a phrase, the preceding words may be skimmed over until they are known to be important and then 'gathered up.' To do this the understanding process must be top down in order to allow the understander to know what to ignore. Uninteresting words are simply stored in a buffer in short term memory until a word that requires them to be processed is found. When (and if) such a word is found, the words in the buffer are gathered up and analyzed more fully. Under this theory there is little wonder at the fact that understanders frequently cannot remember the actual words that they read. They may never have actually read them at all!

3. A Detailed Example

A front page story in the New York Times began, "An Arabic speaking gunman shot his way into the Iraqi Embassy here [Paris] yesterday morning, held hostages through most of the day before surrendering to French policeman and then was shot by Iraqi security officials as he was led away by the French officers."

We will examine this sentence word by word and consider the kind of processing that would be desirable in an integrated understanding scheme. Our model will use interest to enable it to be psychologically plausible, a requirement forcing it to be completely finished with each sub-part of the sentence as it is processed.

Since language is received as a stream of words, we can assume words become available in chunks, both visually (clauses) and aurally (delineated by pauses). Thus in our processing we can always assume that the next word of a sentence is available, often simplifying the problem of disambiguation.

An Arabic speaking gunman...

AN is a word that can be skipped initially. This means that it is looked up in the dictionary, and what is found there are instructions to go to the next word and place AN in short term memory (STM).

ARABIC is listed in the dictionary as a word that is skippable, so it is skipped and saved in STM. (The information that ARABIC, like many uninteresting adjectives, is skippable has already been compiled and it is simply looked up here. The procedure for determining what can be skipped is obviously one of the interesting problems in the issue of the development of language ability. Schank and Selfridge [8] discuss these issues.)

SPEAKING is also skippable as long as no potential actors have been encountered. A search for actors in STM finds none, so this word is also skipped.

GUNMAN is marked as a HIGH INTEREST ACTOR, demanding immediate processing. It causes us to create top down requests to find certain information, such as the answers to the following questions:

WHO is he? — causes us to gather up saved
adjectives and add them to
the memory token for this GUNMAN
WHAT did he do? —
in GUNMAN's permanent memory we find
he SHOT someone. An inference that
he shot or will shoot is made and
we predict we will hear more about it.
WHO did he shoot? — creates interest in the
verb's syntactic object.
WHY did he shoot? — makes us look for a reason
WHERE did this happen? — makes us look for
a location
WHAT SCRIPTS might this instantiate? —
GUNMAN can Indicate a script may be
instantiated. Candidates are $ROBBERY,
$TERRORISM, $KIDNAP. We try to confirm.

The formulation of the above questions (as requests, see the next section) now guides the process of understanding this story. These requests relate to matters of parsing, inference, script application and goal pursuit - all levels of the understanding process.

****
shot his way into the Iraqi Embassy...
****

SHOT is encountered and found to satisfy an expectation created by GUNMAN so we now build the first conceptual structure, a SHOOT event with the gunman token as actor, and an unfilled slot for the victim. The parser is now interested in finding the victim, which can be done by looking for the next main noun.

HIS is skipped and saved in STM.

WAY does not satisfy the expectation to fill the empty slot. WAY is listed as both skippable and pointing to a direction or location. A request is set up for the location and we attempt to find it.

INTO is skipped.

THE and IRAQI are skipped and saved in STM.

EMBASSY is found and set up as the location of the SHOOT event. Furthermore, EMBASSY is marked as a place of political significance. This piece of information causes us to instantiate the $TERRORISM script that had (among others) been predicted from GUNMAN. Since EMBASSY is interesting, its requests are activated. One of these is for the nationality of the EMBASSY. IRAQI is found in STM as satisfying this request and is picked up.

Setting up $TERRORISM causes us to lose interest in the representation of the isolated sentence and focuses us on setting up that script as the representation for the entire story. Thus, we now expect answers to the following questions:

Were HOSTAGES taken?
Were demands made? (money?) (free prisoners?)
Was any damage done?
Were measures to counteract the terrorist
taken? (return fire; arrest; free hostages)

****
here yesterday morning...
****

HERE, in a news story, means to add the dateline to the location.

YESTERDAY is found to be a time word and is added to the time slot of the event.

MORNING is also handled in this manner.

****
held hostages through most of the day....
****

HELD is skipped and saved since it matches none of the requests. The dictionary entry for HELD says only that it is a verb. No verbs were needed so we skip it. Only had it been inherently interesting would we have done detailed processing. The advantages of this system of parsing are clearly shown here. HELD is a highly ambiguous word that previously might have demanded great effort to disambiguate. An integrated understanding system simply goes on and waits for something interesting.

HOSTAGES satisfies an extant request. The TAKE HOSTAGES scene of $TERRORISM is instantiated. At this point a check is made on the saved verb, HELD, to see if doing this is okay. HELD is found to be precisely the kind of word desired. The important point is that HELD never had to be disambiguated, which is nice because words like HELD really do not have any particular meaning. Its meaning is derived from its connection to HOSTAGES and HOSTAGES is understandable only through $TERRORISM.

THROUGHOUT is found to point to either a time or place so a request is made for a time or place word. However, at this point our understanding system knows that this information is not as interesting as the outstanding expectations, because there are

death-related requests active (see [7]). Thus the rest of this phrase is virtually ignored due to lack of interest.

MOST, OF and THE are skipped and saved in STM.

DAY is saved and ignored. It satisfies the low level request for a time word.

before surrendering to French policemen...

BEFORE is a time ordering word that predicts a new event and marks its time relative to the preceding event.

SURRENDERING is a word that is marked as an important part of a number of scripts, including $TERRORISM. The surrender scene of $TERRORISM is instantiated and requests are fired off looking for reasons for this action, the captors, etc. Predictions are made about certain words that might follow. *To' would mark *off* captors, for instance.

TO tells us that the captors are coming (from the prediction).

FRENCH is skipped and saved in STM.

POLICEMEN is marked as an ACTOR so STM is consulted to gather up any modifiers. POLICEMAN is a possible captor, so it fulfills an expectation.

and then was shot by Iraqi security officials..

AND says a new event is coming.

THEN orders the event.

WAS specifies that the actor stored in STM is the conceptual object of the new event. This sets up requests for the actor, indicated by 'by*, and the action.

SHOT is found to be Interesting and Is treated similarly to the way that GUNMAN was except that we expect only the things that were particular to the SHOOT action. Thus we have:

WHO was shot? — GUNMAN
WHO shot him? — not answered
WHY was there a shooting? — not answered
WHERE did this happen? — already known

WHAT SCRIPTS does this instantiate? —
SHOOT can also instantiate a script. Candidates are $ROBBERY, $TERRORISM, $KIDNAP, ordinarily. But in a context set up by $TERRORISM, none of the above fit easily. We look for plans and goals.
WHAT were the RESULTS of this action?—
A request is set up to find the results. If not satisfied the usual results are inferred - the victim's death.

BY tells us the actor of the SHOOT will follow.

IRAQI and SECURITY are skipped and saved in STM.

OFFICIALS ends the processing of the noun group. It satisfies the requests for WHO aid the shooting and, as we now have an actor we ask about why he would kill a TERRORIST. There is no obvious reason, so we are surprised by this event. We seek to explain it by postulating a REVENGE or SHUT HIM UP type theme, but this is a guess.

as he was led away by French officers.

We are basically done now as no further requests need to be satisfied immediately. We are still interested in the goals of each of the actors, however, so WHY requests are still alive.

AS is known to be a time co-occurrence word. Since we are only interested in anything that occured at the same time if it is itself interesting, we can now skip ahead looking for something interesting.

HE and WAS are skipped.

LED is uninteresting and is both noticed and then skipped.

AWAY, BY, THE, and FRENCH are all skipped.

OFFICERS is skipped because there are no requests asking for it.

The period tells us we are done.

The final representation for this sentence:

$TERRORISM
ACTOR Arab gunman
PLACE Iraqi Embassy
SCENES
 $HOSTAGES some
 $CAPTURE
 ACTOR French policemen
 OBJECT Arab gunman
 PLACE Iraqi Embassy
UNEXPECTED RESULT

 $SH00T
 ACTOR Iraqi officers
 OBJECT - Arab gunman
 RESULT
 STATE dead
 ACTOR Arab Gunman

4. An Partial Parser

We will now look briefly at the integrated partial parser (hereafter IPP) we have written to implement the theories we have been describing here, This program was written to handle a limited class of stories, namely newspaper stories about terrorism and related areas. We have not tried to address all the issues involved in parsing, instead concentrating on the areas crucial to integrated partial processing. The parser, written in LISP on a DEC System 20/50, currently handles over 50 stories taken directly from newspapers. We are in the process of increasing its vocabulary and its domain of interest.

IPP is structured about a classification of words, which determines on how each word type should be processed by an understander, independent of strict syntactic classification. The immediate fate of a word upon being read determines its primary classification. There are three classes. The first consists of words requiring immediate action. These are interesting words which add crucial information to our story representation and generate expectations which guide further processing. The class is subdivided into words which build event structures (Event Builders, or EBs) and words which fill in slots in event structures (Token Makers, TMs).

EBs build the event structures which provide the framework for a final representation. Events structures which are predicted or interesting by themselves are instantiated and their expectations activated, Events which are not predicted, and not interesting are virtually ignored.

The discovery of a TM causes a token to be created. If the token satisfies an expectation, is interesting, or an interesting modifier is in STM, then the modifiers in STM are applied to the token. If the token is interesting the expectations included in the TM's dictionary entry, are activated. These expectations may, for example, look for plausible scripts.

The second class of words do not require immediate attention, but may be needed later. These words are processed by a skip and save strategy, keeping them in one of several short erm memory locations until, and unless, they are needed. This typically occurs when an interesting EB or TM is found. Frequently these words will never be used again, making the total effort needed to process them negligible.

The final class of words are those we skip entirely. The only processing effort is in identifying them. While few words are skippable in all domains, in any particular domain, a surprisingly large number of words can be totally skipped without degrading understanding. Clearly it is advantageous for an understander if this class is as large as possible, since processing time for skippable words is negligible.

Much of IPP's processing knowledge is implemented in the form of requests (5]. A request is a form of production, or test-action pair. If the test of an active request is found to be true, then the corresponding action is performed.

The tests and actions performed by IPP requests perform only a limited set of functions. As actions, requests may build new conceptual structures, fill slots in conceptual structures with other conceptual structures, activate new requests, and de-activate requests no longer appropriate. The tests may check for concepts (tokens or events) of a specified type, specific lexical items, or lexical items satisfying some property.

5. Runs

What follows are computer runs of IPP on stories from the New York Times.

•(IPP S1)

Input:

(AN ARABIC SPEAKING GUNMAN SHOT HIS WAY INTO THE IRAQI EMBASSY HERE THIS MORNING HELD HOSTAGES THROUGHOUT MOST OF THE DAY BEFORE SURRENDERING TO FRENCH POLICEMEN AND THEN WAS SHOT BY IRAQI SECURITY OFFICIALS AS HE WAS LED AWAY BY FRENCH OFFICERS)

Output:

```
** MAIN EVENT **
SCRIPT   $TERRORISM
ACTOR    ARAB GUNMAN      PLACE    IRAQI EMBASSY
CITY     PARIS
SCENES
 SCENE   $HOSTAGES        SCENE    $CAPTURE
 PLACE   IRAQI EMBASSY    PLACE    IRAQI EMBASSY
 ACTOR   ARAB GUNMAN      OBJECT   ARAB GUNMAN
                          ACTOR    POLICEMEN

** UNEXPECTED EVENTS **
ACTION   $SHOOT
ACTOR    IRAQI OFFICIALS  OBJECT   ARAB GUNMAN
AFTER    SCENE $CAPTURE
RESULT
 STATE   DEAD      ACTOR   ARAB GUNMAN
```

673- msec CPU (0. msec GC)

•(IPP S2)

Input:

(A GUNMAN WHO DIVERTED A VERMONT BOUND BUS WITH MORE THAN TWENTYFIVE PASSENGERS FROM THE BRONX TO KENNEDY INTERNATIONAL AIRPORT AND KILLED TWO HOSTAGES SURRENDERED ON A RUNWAY LATE LAST NIGHT ENDING A DAYLONG SIEGE OF TERROR AND GUNFIRE)

Output:

```
•• MAIN EVENT ••
SCRIPT     $HIJACK
ACTOR      GUNMAN     CARRYING  (GREATERTHAN 25)
VEHICLE    BUS                  PASSENGERS
RELATED
 ACTION    DO         RESULT
 ACTOR     GUNMAN      STATE    DEAD
                       ACTOR    TWO HOSTAGES
SCENES
 SCENE     $CAPTURE
 OBJECT    GUNMAN
 ACTOR     POLICE
```

718. msec CPU (0. msec GC)

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PROBLEMS WITH PARTS

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Abstract. Two problems in representing and using relationships among parts of objects are analysed, and partial solutions are proposed. The first is the problem of extracting information from overlapping partitioning hierarchies. Contrary to a common assumption, "part -of" relationships cannot be extracted from arbitrary sets of partitioning assertions by simple label-propagation methods: the problem is in general NP-complete. However, if the lowest-level parts of all entities under consideration are drawn from a common pool of pairwise disjoint "ultimate" parts, then relatively simple, complete inference methods for deriving "part -of" and other relationships can be supplied. The second problem is that of property inheritance, i.e., the transfer of relationships among parts of a generic object to corresponding parts of a successor of that object in the type hierarchy. Earlier solutions are criticized and a new solution based on function tables attached to concepts is proposed.

1. Introduction

Much of our knowledge of enduring relationships (as opposed to events) concerns relationships among parts of physical and abstract objects. Yet part-whole relationships have until recently received scant attention in the AI literature, compared for example to generalization (IS-A) relationships. Interest in parts structure has been confined almost exclusively to its role in relational models for computer vision (e.g., CI-51). However, the ability to reason about parts was an important feature of Raphael's program SIRC61. It was able to chain together both particular and generic subpart relationships, and to combine parts inference with subset inference to answer questions about (sets of) parts of (sets of) individuals. The "slots" of Minsky's frames [7] may facilitate the representation of part-whole relationships, among others, but do not presuppose any particular theory of such relationships. To date, the most elaborate proposals for representing and reasoning about parts structure appear to be those of Philip Hayes C8,9].

The work reported was done while the author was on leave at Universitat Karlsruhe, Institut fur Informatik I, W. Germany

The present paper addresses two problems in the use of parts knowledge which people find trivially easy but which have not been adequately mechanized: the extraction of "part-of" relationships (and disjointness relationships, etc.) from overlapping parts hierarchies, and relation - ship inheritance for parts of objects in a type hierarchy.

Sec. 2 introduces a convenient representation for sets of partitioning assertions, called "parts graphs". Although based on partitionings, parts graphs can represent non-exhaustive and overlapping decompositions of parts structure.

Sec. 3 notes that label-propagation methods for extracting "part-of" (and other) relationships from simple partitioning hierarchies do not generalize to arbitrary parts graphs; the problem is in general NP-complete. A restricted type of parts graph, called "closed", is defined, which reduces all parts of the top-level object to a common set of pairwise disjoint ultimate (lowest-level) parts. For closed parts graphs, efficient complete inference methods can be supplied.

In *Sec.* 4 a relationship inheritance scheme is proposed in which corresponding parts of concepts in a type hierarchy are identifiable by the names of their Skolem functions. This overcomes a difficulty with Hayes' [8,9] property inheritance scheme, without sacrificing any of its advantages.

2. Parts graphs

The following takes for granted a notion of "part-of" which is at least a partial ordering with the extension property (if all parts of x are part of y, then x is part of y), and for which there exists a unique empty part θ, a dyadic "overlap" function $\sqcap$ (the largest entity which is part of both arguments), an n-adic "merge" function $\sqcup$, n=2,3,... (the smallest entity which has all of its arguments as parts), and a dyadic "remainder" function $\setminus$ (the part of the first argument which is not part of the second). These properties are stated formally in [10]. Bunt's [11] axiomatization of "part-of" satisfies these constraints and leads to a logically consistent generalization of Zermelo-Fraenkel set theory. Thus the theories of "part-of" and "subset-of" are closely related, and much of what is said here about the representation and use of parts knowledge also applies to the representation and use of knowledge about set inclusion relationships.

People tend to conceptualize objects in terms of pairwise disjoint, jointly exhaustive parts, i.e., in terms of partitionings. For example, the top level of a human parts hierarchy might reasonably divide the human body x into a head h, neck n, torso t, arms a&a', and legs l&l'. Thus it is natural to base computer representations of parts structure on a partioning relation P,[1] where [x P $x_1 \ldots x_m$] iff

$$\bigwedge_{1 \le i < j \le m} [(\sqcap\, x_i\ x_j) = \theta] \quad \& \quad [(\sqcup\, x_1 \ldots x_m) = x].$$ [2]

Thus (∀x)(∃hntaa'll')[[x human]→
[[x P h n...l']&[h head]&[n neck]&...&[]' leg].

It is important to notice that "part-of" is expressible in terms of P. For example, [b part-of a] can be rewritten as [a P b c], where c is a previously unused constant denoting ($\setminus$ a b), i.e., the (possibly empty) remainder of a with respect to b. In general, arbitrary sets of "part-of" assertions and disjointness assertions can be converted to sets of partitioning assertions. However, the conversion may introduce parts wich are possibly empty, even if all of the original parts are known to be nonempty.

---

[1] cf. the partitionings of Grossman [12] and "complete splits" of Fahlman [13] for concept taxonomies.

[2] In the form of predicate calculus used here sentential formulas are in infix form and delimited by square brackets (so that the second list element is the predicator or operator) and functional expressions are in prefix form and delimited by round brackets; e.g., (∀xy)[[x =(mother-of y)] → [x female]].

Sets of partitioning assertions can be represemted as "parts graphs" as illustrated in Fig.1.

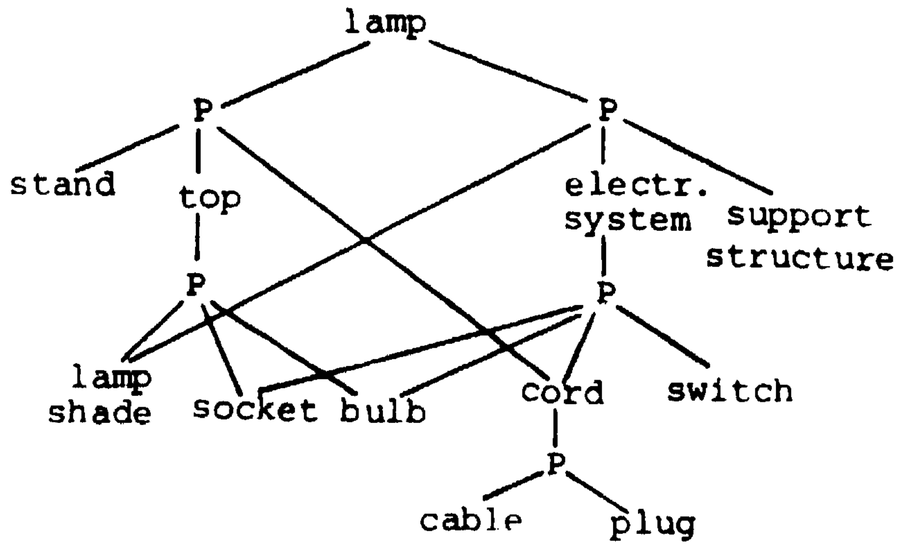

Fig.I. Parts graph for a desk *lamp.* The nodes marked "P" represent partitioning assertions while the named nodes represent parts.

This shows two overlapping parts hierarchies for a particular (as opposed to generic) lamp, with a "structural view" on the left and a "functional view" on the right.

In the graphical representation, partitioning assertions and particular parts are represented as assertion nodes and constant nodes respectively. Assertion nodes are marked "P" and have an incoming edge from the first argument of the assertion and outgoing edges to the remaining arguments. Such parts graphs are readily represented as semantic nets in the network formalism of [143.

Hierarchies are distinguished from unrestricted parts graphs by having exactly one downward edge from each nonleaf parts node and a unique path from the root to each parts node. As Fig.I shows, the available knowledge about an object need not form a single hierarchy."Tangled" hierarchies result when there are multiple views of the same object, known overlap regions such as shoulders, waist, or knees, or parts with unknown mutual overlap.

3. Extracting information from parts graphs

A partitioning hierarchy has the important advantage of allowing efficient inference of part-of and disjointness relationships. In fact, if a rind b are any two nonempty parts appearing in a hierarchy, then b is part of a iff a is an ancestor of b, and a and b are disjoint iff neither is an ancestor of the other.

For parts within a common subhierarchy of a

[3] Incidentally, these conditions can be checked in constant time using a method based on left-to-right numbering of the leaves, whereas the worst case complexity of label-propagation methods is inear in the number of edges.

non-hierarchic parts graph the same methods can be used. For example, in Fig.1 the plug must be part of the electrical system since the latter is an ancestor of the former in the "functional view" of the lamp; the cord is disjoint from the bulb since neither is an ancestor of the other in the "structural view".

However, not all implicit part-of and disjointness relationships can be extracted in this way. In Fig.I, the switch must be part of the stand; in fact, the switch and support structure must partition the stand, because the stand on the one hand and the switch plus support structure on the other are the only nonoverlapping parts of the two lamp hierarchies. Another point worth noting is that even without the assertion Clamp P stand top cord], it follows from the graph that "top" is part of the lamp, because all of its parts are.

One can devise additional inference methods to handle these particular cases, but such stopgap measures are almost surely futile because of the following result.

Theorem 1. The problem of confirming [b part-of a], where a and b are nodes of a parts graph, is NP-complete.

This is proved in [10] by mapping the unsatisfiability problem of the propositional calculus into a "part-of" problem for a parts graph, and vice versa.

This suggests that additional constraints should be imposed on parts graphs so as to permit efficient information extraction, while still allowing for overlap parts and multiple views of the same part. Such constraints are obtained by requiring parts graphs to be closed: G is closed iff any two of its parts nodes are projectible into a common subhierarchy. A node a is projectible into a subhierarchy H if G contains a subhierarchy rooted at a whose leaves lie in H. (Since a single parts node is a subhierarchy, any parts node is trivially projectible into any subhierarchy to which it belongs. Hence any two nodes of a subhierarchy H are projectible into a common subhierarchy, viz.,H).

For example, if the left and right views of the lamp in Fig.I are called HL and HR, then "top" and "bulb" are projectible into HL (because they belong to H), and "top" and "electrical system" are projectible into HR (because the leaves {lamp shade, socket, bulb} of a subhierarchy rooted at "top", as well as "electrical system", belong to HR). However, neither "stand" and "switch", nor "stand" and "support structure" are projectible into any common subhierarchy. Thus the graph is open, but could easily be closed by addition of the assertion [stand P switch support-structure].

The notion of a closed graph becomes clearer if parts graphs are required to be "fully consistent" in the sense that none of the parts they represent are necessarily empty. This rules out graphs, for example, in which two disjoint parts (distinct leaves of a single subhierarchy) have a common descendant, or in which one "view" of a part terminates in a proper subset of the leaves of another "view" of that part.

It is proved in C10] that all leaf nodes of a fully consistent, closed graph belong to a single (not necessarily unique) main hierarchy whose root represents the whole entity. All nodes of the graph are projectible into this main hierarchy. In such a graph, therefore, all leaves are pairwise disjoint and each parts node corresponds to a subset of the leaves. The graph of Fig.1 is now easily seen to be open, since the leaf nodes "stand" and "switch", for example, do not belong to any common subhierarchy.

Fig.2 shows a closed graph with a main hierarchy rooted at a, an overlap part b made up of two parts occurring in the main hierarchy, and two "views" of a part c.

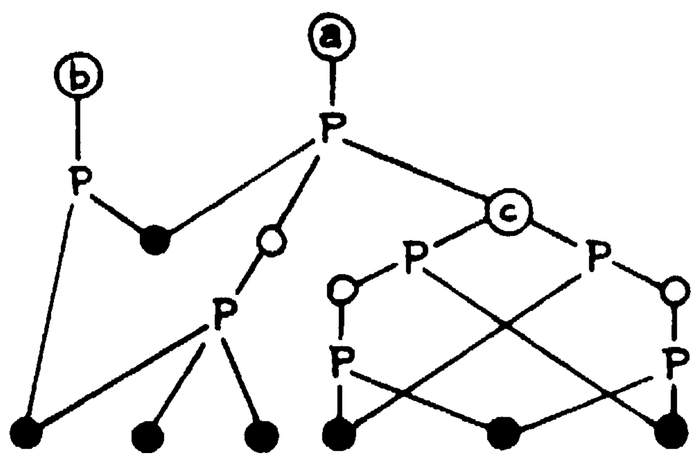

Fig. 2. A closed parts graph with an "overlap part" b and two "views" of a part c. The darkened nodes represent the ultimate parts of a.

Surprisingly, the syntactical restrictions of closed graphs do not lead to any logical restrictions:

Theorem 2. For every parts graph there is a logically equivalent closed graph.

The proof and a procedure for constructing a closed graph from a set of partitioning assertions are given in [10], The sort of idea involved is illustrated in Fig.3. Admittedly, the size of the equivalent closed graph may be exponential in the size of a given open graph. However, this exponential growth is associated with unknown and unrestricted overlap between sets of parts, a situation which rarely, if

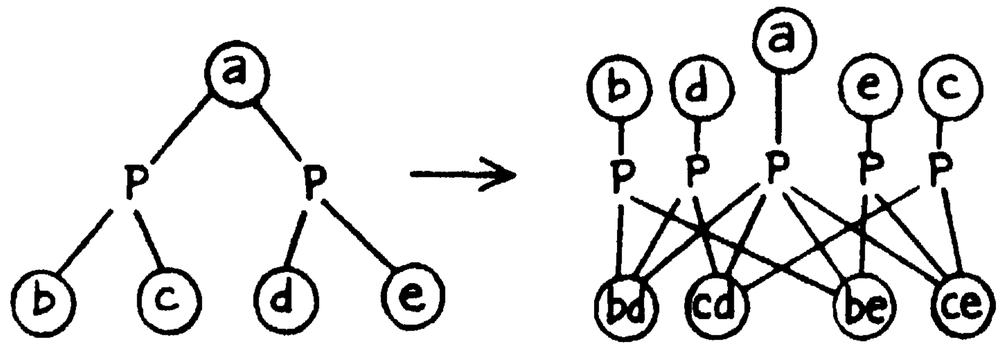

Fig. 3. An open graph and a logically equivalent closed graph.

ever, occurs in our conception of real objects.

The following methods are complete for answering questions of the form ?[b part-of a] and ?[a disjoint-from b] in fully consistent, closed graphs. Projecting a node a into a hierarchy H means determining a set of nodes $A = \{a_1,\ldots,a_m\}$ which lie in H and are the leaves of a subhierarchy with root a (if a already lies in H then $A = \{a\}$).

Preliminary step: Project a and b into a common subhierarchy H, obtaining respective projections $A = \{a_1,\ldots,a_m\}$ and $B = \{b_1,\ldots b_n\}$.

To answer ?[b part-of a]: If every node with an ancestor in B has an ancestor or descendant in A, return "yes"; if some nodes with ancestors in B have no ancestors and no descendants in A, and the merge of these nodes is known to be nonempty, return "no"; else return "unknown" (see Fig.4)

To answer ?[a disjoint-from b]: If no $a_i \in A$ has an ancestor in B and no $b_j \in B$ has an ancestor in A, return "yes"; if some nodes in A have an ancestor in B and/or some nodes in B have an ancestor in A, and the merge of these nodes is known to be nonempty, return "no"; else return "unknown" (see Fig.5).

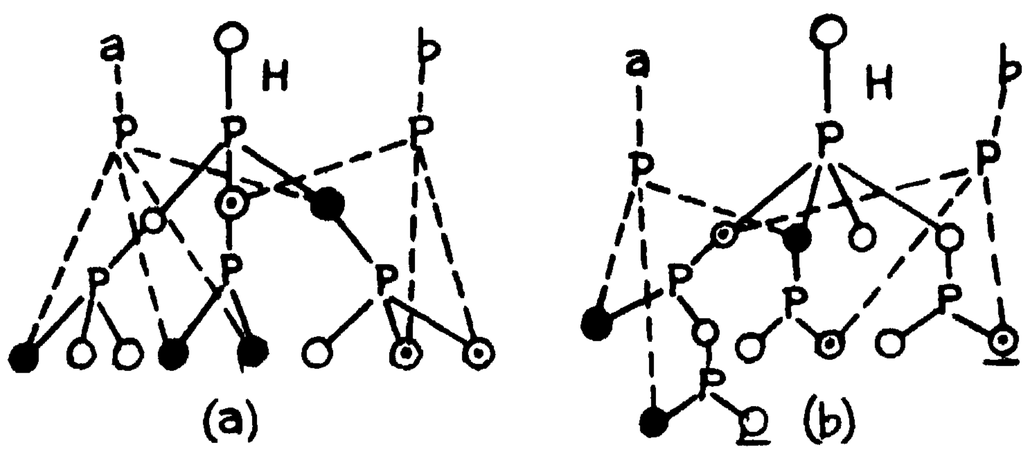

Fig. 4. Answering?[b part-of a] in a closed graph. In (a) the answer is "yes" (Note that one part of b has no ancestor in A, but is partitioned into parts belonging to a). In (b) the answer is "no" if the merge of the underlined nodes is known to be nonempty, and "unknown" otherwise.

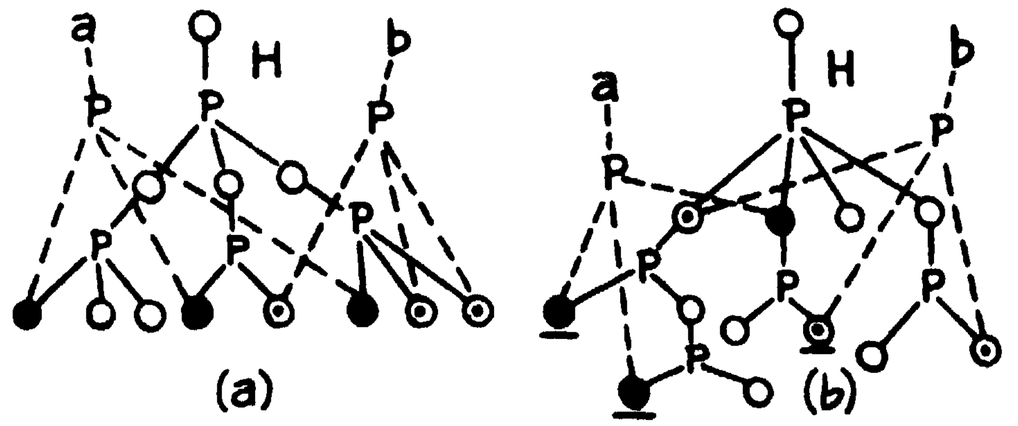

Fig. 5. Answering ?[a disjoint-from b] in a closed graph. In (a) the answer is "yes". In (b) the answer is "no" if the merge of the underlined nodes is known to be nonempty, and "unknown" otherwise.

In [10] the completeness claim is made precise and proved. It is assumed that the merge of a set of nodes $A = \{a1,\ldots,a_m\}$ is known to be nonempty iff[(U a1...am) =] is a logical consequence of the graph, the assumed properties of "part-of", and a set of "nonemptiness assertions" of the form [a = 0] about some of the nodes of the graph. It is shown that the predicate "known to be nonempty" is efficiently decidable when so defined. The given question-answering methods are then shown to be implementable in linear space-time relative to the number of edges of the closed graph. Heuristic methods are discussed which can often give nearly constant question-answering times for closed graphs

Similar methods can be used to compute the "disjoint merge" of two parts, i.e., a set of disjoint parts whose merge equals the merge of the given parts (retain elements of AuB which do not have ancestors in B), the overlap of two parts (retain elements of A with ancestors in B and vice versa), and other functions over tuples of parts. Thus questions involving such functions could also be answered.

Needless to say, reasoning about parts cannot in general go very far on the basis of "part-of" predications or partitionings alone. In the case of physical objects, for example, knowledge about the mode of connection and relative position of parts is indispensable. But the fact remains that people can answer questions such as "Is a toe part of a leg?" or "Is a spark plug part of an automobile engine?" with consummate ease. The proposed methods may help to equip machines with comparable abilities.

One serious limitation of the proposals is that they do not allow for disjunctive parts relationships (even "alternative viewpoints" are logically conjoined). A second is that only the structure of particular objects has been considered, whereas much human parts knowledge is generic. A third

is that no provision has been made for avoiding individual mention of multiple parts of the same type, such as a centipede's legs or a human being's neurons.

In [10] some extensions to generic graphs and graphs containing representations of sets of parts are sketched. The chief problem with generic graphs is that they are dispersed over (possibly overlapping) type hierarchies. For example, only elephant- specific partitioning assertions, such as those subdividing the proboscis, would be associated directly with the concept of an elephant. Most of the remaining partitioning assertions, such as that dividing the body into head, neck, torso, tail, and limbs would be associated with higher-level concepts, such as that of a legged animal. Assuming that the fragments form a closed graph when brought together at corresponding nodes, the question-answering methods of this section can be adapted to generic graphs. The main requirement is the availability of methods for identifying corresponding nodes. This problem is discussed in a more general context in the next section.

The introduction of nodes representing sets of parts into parts graphs complicates both their syntax and use. Additional partitioning relations are needed(e.g., for partitioning an object into a set of parts, and for partitioning the sets themselves), and methods must be provided to deal with more complicated questions-, such as "Is every leg part of some body segment?" Nevertheless, the definition of a closed graph can be modified to allow for sets of parts, and linear or sublinear methods can be provided for answering several types of questions for such graphs.

4. Property inheritance

When one describes a type of object, such as a robin, in some representation system, one would like many of its anatomical characteristics to be "inherited" from the description of a superordinate concept; for example, the position of the beak on the head or of the wings on the body should transfer smoothly from "bird" to "robin".

Hayes [8,9] has discussed two alternative network methods for facilitating property and relationships inheritance from parts of more general to parts of less general kinds of objects. The first method involves connecting corresponding parts with "binders" which then serve as inheritance paths. The second method actually uses the same nodes for corresponding parts of the two kinds of objects; however, the "depictions"[4] for the two kind of objects provide access to different sets of propositions about the parts. The latter proposal was adopted and given a logical interpretation in terms of shared variables in [15]. However, a serious flaw has become apparent in this scheme. The telescoping of nodes, carried all the way down to the level of instances, assigns all instances of a concept to a single node, and similarly for corresponding parts of those instances. As a result, relationships between distinct instances or parts of distinct instances, such as "Polly's beak is larger than Tweety's" cannot be stated. Even above the level of instances, the sharing of nodes prevents expression of relational propositions such as "The African elephant has larger ears than the Indian elephant", "Seagulls recognize each other by the colouration of their eyelids", "Dogs hate cats" (assuming "dog" and "cat" have a common superordinate concept), "No two dollar bills have the same serial number", etc.

The key to a logically respectable alternative which avoids these difficulties lies in the use of functions. For example, suppose that h is the Skolem function determined by the statement "Every higher animal has a head". Suppose further that the head of the universally quantified robin y has been identified with the value (h y) and similarly, that the head of the universally quantified bird x has been identified with the value (h x). If other corresponding parts have been similarly linked via their functional names, it is clear that parts relationships can be trasferred from parts of the bird to parts of the robin as easily as the corresponding universally quantified variables can be matched and the function values dependent on those variables located.

Locating values of functions can be made efficient by attaching a "function table" to each node, in which known values (nodes) of functions applicable to that node are indexed by function name. This scheme resembles Hayes' "binder" scheme, but the correspondence between a part of a subordinate concept and a part of a superordinate concept several levels above it are established in a single, trivial matching operation, instead of a series of binder traversals. Some complications are described in [10], including those arising from the presence of nodes representing sets of parts, and from the application of a function at different levels of a parts hierarchy (e.g., application of a "heart-of" function at the level of the whole animal and at the level of the animal's chest).

Any system for representing parts correspondences explicitly, whether it is based on shared nodes, binders, or functional indexing, presupposes a method of establishing these correspondences in the first place. Hand-coding such correspondences

4 Essentially, a depictions" is a list of assertions which are specific to a particular (kind of) object, accessible via the name of that object.

ces ought to be a temporary expedient, to be replaced eventually by a method of inferring and representing them on the basis of arbitrary sets of parts relationships such as might be obtained from natural language input. To see the problem and an approach to a solution, suppose that a natural language system is told for the first time that "A bird has a tail". The system cannot assume that "tail" is translatable as a logical function; for this would lead to the unwarranted (and false) conclusion that "a bird with two tails" is a contradiction in terms. A plausible translation is

(∀x)(∃y)[[x bird] → [[y tail] & [y part-of x]]].

At the same time, a conjecture that y is normally the only tail should be stored, since the wording would more likely have been "at least one tail", "one or more tails", or something to that effect, had that been the interpretation intended by the informant. Skolemization of y gives

(∀x)[[x bird] → [[(t x) tail] & [(t x) part-of x]]].

If told subsequently that "A magpie has a long tail", how could the system identify "a...tail" with t applied to the universal "magpie" variable instead of creating a new Skolem function? It would at least have to check for a possible referent of "a...tail" among the parts of concepts superordinate to "magpie". After finding such a part at "bird", and verifying that this is probably the only part of a bird satisfying the predicate "tail", it could transfer the name of the Skolem function into the new context, at least tentatively.

In general, a wider search of prior instantiations of "tail" would be required since the first occurrence need not have been at the superconcept level, but might instead have been at the subconcept level, or in connection with a concept which is neither a superconcept nor a subconcept of "magpie" (e.g., "dog"). If an occurrence of "tail" is found for a subconcept of "magpie", then the name of the corresponding Skolem function can be transferred to the "magpie" context, provided that the newly mentioned "tail" is likely to be the magpie's only "tail" (in which case it is also the subconcept's only "tail"). If an occurrence of "tail" is found for a concept such as "dog", then again the Skolem function can be transferred to the "magpie" context provided that both the magpie's tail and the dog's tail are likely to be unique (this policy prevents later naming conflicts at the level of common superconcepts of "magpie" and "dog").

This approach is also workable for compound identifying descriptions. For example, the information that a perch has a spiny fin on its back might be rendered as

(∀x)(∃y)[[x perch] → [[y fin] & [y part-of x] & [y joins (back-of x)] & [y spiny]]].

If a part can be found for the superconcept "fish" which uniquely satisfies "is a fin, is part of the fish, and joins the back of the fish", then its Skolem function name can be used in the Skolemization of the perch's fin y. Much the same as before can be said about occurrences of parts satisfying the description in question but belonging to subconcepts or unrelated concepts.

All this presupposes a method for locating parts satisfying given descriptions, i.e. associative accessing. This topic cannot be covered here; Hayes' associative accessing methods are easily modified for use with semantic nets in which corresponding nodes are linked via their Skolem function names, rather than being telescoped or connected with binders.

5. Concluding discussion

The seemingly trivial problem of extracting parts relationships from sets of partitioning assertions was seen to be quite difficult. The suggested methods for "closed graphs" provide a partial solution.

Effective property inheritance requires effective ways of establishing node correspondences. A method of establishing correspondences through names of Skolem functions was suggested which overcomes a difficulty with Hayes' node-sharing method.

Many problems in generalizing the proposed methods remain to be solved, such as that of providing detailed inference algorithms for extracting "part-of" relationships from fragmented generic parts graphs, or for establishing node correspondences or, the basis of composed functions such as(f (h x))). Moreover, several important problems with parts have not been touched on here, such as the problem of inferring the mode of connection and relative position of parts of physical objects, the problem of determining the number of parts of a given type of a given object (counting the known instances only provides a lower bound on that number), and the problem of accessing parts associatively on the basis of compound descriptions (Hayes considered unitary descriptions only).

In view ot the centrality of parts relationships in human thought, these are important areas for future research.

Acknowledgements

Alan Covington and Randy Rawson contributed to this paper through discussions and their work on a semantic net system. Pat Hayes' careful refereeing provided much useful guidance. The research was supported by an Alexander von Humboldt Fellowship and by Operating Grant No. A8818 of the National Research Council of Canada.

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A LEARNING SYSTEM ABLE TO SYNTHESIZE ARITHMETICAL FUNCTIONS

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This paper describes a system able to synthesize functions and predicates from examples taken in an arithmetical domain. Numbers are represented as characters strings. They are not represented as bags as in Lenat or Knapman's works. The representations of functions and predicates are sets of Horn clauses and the synthesis lies in the construction of new clauses or in the debugging of the existent ones. The paper describes the concepts which are used in the system and the synthesis process.

Keys wards : Learning, Horn clauses, Program synthesis

I. INTRODUCTION

Program synthesis from examples have been studied quite recently. They can be classified according to the following categories :

- Systems which construct function from non-ambiguous and self-contained examples. That means that all the information which is necessary for the synthesis is contained in the example and that there is no ambiguity in the construction of elementaries functions [see [10], [1], [4],[5]

- Systems which are considered as the growing of a knowledge base. The examples do not need to be self-contained or non-ambiguous. That is the case with [17][11], in some sense [8], and more recently [6]

Our system belongs to the second category. It is able to construct some recursive concepts (predicates or functions) as in [8] but uses a more significance and effective representation of numbers than [8] or [6] representation. The representation of numbers which is discovered by the system consists in strings of digits rather than bags as a PEANO representation. The concepts of arithmetical operators (Like successor) are then more effective but they are less obvious to infer.

II. TECHNICAL TOOLS OF THE SYSTEM

II.1 Functions and predicates representation

Functions and predicates are represented as sets of Horn clauses as in First Order Logic. In fact we use an equivalent representation which more accurately represents a procedural form of clauses.

For instance, if Eq is the Equal predicate, the classical clause

$Eq(z,A(x,y)) \subset Eq(F(z),B(H(x),V(y))) \wedge P(H(x),y) \wedge Eq(z,V(y))$

will be represented by

$z \leftarrow A(x,y) \subset a \leftarrow F(z), b \leftarrow H(x), z \leftarrow V(y), a \leftarrow B(b,z), P(b,y)$

II.2 Examples

An expert can interact with the system in two different ways.

- Examples of inputs and of the corresponding output are given to the system as in

2258 ← SUC(2257)
NUMBER (12329)

- An input is given to the system with an interrogation on the output

? ← SUC(159)

The system tries to answer correctly. After having been told by the expert if it has succeded, a positive example is generated. If the system gives a wrong output, a negative example is then generated and the expert gives the correct output. For instance let us suppose that the current answer to the question ? ← SUC(159) is 1510. The expert indicates the correct answer -160- and then both a negative example [x=159,y≠1510] and a positive example [x=159,y=160] are generated.

As [17] and in opposition to [6] , we think that negative examples (which are near-miss in our system) are fundamental for a complete function synthesis and, above all, for predicate synthesis.

II.3 Memory

There are in fact three memories.

- A long term memory which contains every clause of the system. They *are* referred tonames

- An active memory which is a short term memory. This memory will contain the names of functions or predicates which have been recently learnt or used.

- A predicate hierarchy which is a concept hierarchy as in [6]. For each new predicate, we try to find a correct position in the hierarchy and in fact we find more than one possibility. The candidate positions are organized in subhierarchies which are also attached to the name of the predicate.

II.A Evaluator

Our evaluator is a Prolog like evaluator which includes a sophisticated tool used when the prolog evaluator fails. For instance, during the learning of the successor function, when this learning is incomplete, a Prolog evaluator will answer "False" with the input 2750<-SUC(2749) (carry on successor of 9 has not been encountered yet).

A simple answer "False" is not sufficient for us. since we specially want to know the point where the failure is the most relevant. Such a failure point is unique in a Prolog evaluator but it is not so if we change the order of clauses or terms. We need an evaluator which gives the "best" failure point on all these orders (or one point which is reasonably close to the best one). The evaluator we use in the system is described in [12][1].

11.5 Locking

A clause is locked if paths exist from the inputs (here x and y) to the output (here z) which allow to calculate the output, (see [4][1]).
Often during the learning process, the generated clauses are not locked and a significant part of the system deals with locking of clauses.
Locking of predicates is more frequently used to place the predicate in the hierarchy than to actually construct the predicate.

11.6 Learning heuristics

This paragraph describes the main heuristics which are used in the learning process. Some of them are expanding heuristics, some others deal with reduction or simplification.

11.6.1 Cat ehing

When the evaluator fails on an example, it gives a clause which represents the most relevant failure. Catching is then a partial copy of that clause. Predicates or functions which are compatible with the example are copied. Predicates which are false in the example become negative in the catching clause. Multiple values are separated, when a value is out the input domain of a function, a new function is created.
This last action could be considered as an unavoidable combinatorial explosion but subsumption will reduce it.

11.6.2 Remarks

The "remark" heuristic is used with three elements a clause, an example on this clause and the active memory. It is a combinatorial testing of ul 1 concepts which are in the active memory, these concepts being tested on all the values induced by the example.

11.6.3 Unfolding

Our unfolding is the classical one '31. To unfold a function F (or a predicate) which appears on the right part of a clause is to add to this clause the right part of a clause in which F constitutes the left part.
Unfolding is controlled by an example and then the right part of F which is added must be compatible with the example.

11.6.4 Locking by constant

When the three preceding heuristics (catching, remarks, unfolding) have failed to lock the clause. A localization process delivers a set of variables which can be replaced by constants.

11.6.5 Simplification

Near the end of the learning process, many terms become useless, particularly in a recently created clause. The objective of the simplification process is to detect these terms and to get rid of them.

11.6.6 Subsumption [9]

A clause C is said to subsume a clause D if all the positive examples of D are accepted by C. 1) can be cancelled and all its positive examples become positive examples of C.

II.7 Learning process

As the heuristics can be greatly changed, many different learning processes are possible. The objective of the newly designed system is to study experimentally these different kinds of heuristics or learning processes. For this reason we are presently designing a new version of the system which will allow a more flexible change of heuristics or the learning process. The one which is now described here is very close to the first version of the system. !131.

After the expert introduces an example, the system works in this manner :

" for a function

1. EVALUATION
2. If the example is compatible, it is added as a positive example to the clause which accepted it and the process stops
3. If not the CATCHING heuristic is used
4. If the new clause is not LOCKED try REMARKS
3. If the clause if locked now do SUBSUMPTION, if possible, then SIMPLIFICATION and stop.
6. Try UNFOLDING
7. If the clause is not LOCKED try REMARKS again
8. If the clause is still unlocked, LOCK it by CONSTANT function
9. Try SUBSUMPTION, then do SIMPLIFICATION and stop

~ for a predicate

1. EVALUATION
2. If the example is compatible add it to the clause. If there is no subhierarchy, then stop
3. If not, do CATCHING
4. Then do REMARKS
5. If the clause is LOCKED, do an EVALUATION on negative examples. If there is no problem try SUBSUMPTION, SIMPLIFICATION and STOP, else refine the subhierarchy
6. Try UNFOLDING
7. if the clause is not locked, LOCK it by CONSTANT function, try SUBSUMPTION, SIMPLIFICATION and stop
8. Else do an EVALUATION on negative examples, refine the SUBHIEARCHY, try SUBSUMPTION, SIMPLIFICATION and stop

111. Some of the experiments :

The initial knowledge of the system is composed as characer strings and some basic functions or predi cates.
LAST which gives the last character of a string
PREF which gives the whole string except the last character
CONC which gives the concatenation of two strings
NUL which is true is a string is empty
K which is true if the string is a one character string
ST which is always true on strings

Once NB (number) and D (digit) predicates have been learned : the following inputs :
I-SUC(O) , 2<-SUC(I)...9,-SUC(8)
I23<SUC(I24), 36(0SUC(359), 100<-SUC(99)
will give as output :

```
y←SUC(x)⊂x←0,y←1,D(x),D(y)
        ⊂x←8,y 9,D(x),D(y)
        ⊂a←PREF(x,),b←LAST(x),c←SUC(b)
         y←CONC(a,c),x←CONC(a,b),a←PREF(y)
         c←LAST(y),NB(a),D(b),D(c),¬D(x),¬D(y)
         [x= 123, y=124]
        ⊂a←PREF(x),b←LAST(x),c←F(b),d←SUC(a),
         y←CONC(d,c),x←CONC(a,b),d←PREF(y),
         c←LAST(y),NB(a),NB(d),D(b),D(c),¬D(x)
         ¬D(y), [x=99,y=100]  [x=359,y=360]
        ⊂a←PREF(x),d←G(a),c←F(x),y←CONC(d,c)
         d←PREF(y),c←LAST(y),NB(d),D(c),D(x),¬D(y)
         [x=9,y=10]
y←F(x)⊂x←9,y←0,D(x),D(y)        [x=9,y=0]
y←G(x)⊂x←Ø,y←1,NUL(x),D(y)     [x=Ø,y=1]
```

A complete description of the example can be found in [14].

IV. Conclusion

The system which has been described here presents some particularities
- The learning capacity is greatly related to the expert pedagogy. One of our further interests is to study how the modifications or introductions of heuristics can more or less allow a sophisticated pedagogy.
- The concepts which have been synthetized here are relatively complex. In Lenat's work, the concept of addition is simple because addition is a particularisation of union on bags. Our representation of numbers is more realistic. The synthesis of the successor function is constructive and is not a restriction of a previously known concept. However the system is able to infer simple concepts and can be used as a powerfull learning-knowledge-base.

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PUS, A Paradigmatic Language Acquisition Syatem : An Overview

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Thia paper informally describes the capabilities of a teachable analogy-baaed language - independent natural language acquisition System known as PUS. Its language comprehension is intended to resemble that of pre-achool children in certain significant aspects. It can be taught, through examples, to understand and acquire the situational aspects (i.e., phyeical objects, agents, their senaori-motor propertiea and spatial relatione) described in a text. It has no built-in knowledge of English or the domain of discourse. Neither it infers any formal grammar of English.

1. INTRODUCTION

Thia paper informally describes the capabili-ties of a primitive natural language acquisi^-tion system known as PIAS. The version reported here has been implemented using UCI-LISP on the EEC-10 system at the NCSDCT, TIER, Bombay. Its linguistic comprehension is intended to resemble that of a pre-achool child in certain significant aspects. PUS can be taught, through examples, to understand and acquire language utterances representing physical objects, agents, their senseri-motor propertiea (e.g: colour, height, etc.) and spatial relatione (e.g: on the chair, to the left of, etc.). To thia end, PUS has to acquire and use the knowledge to analyse and interpret linguistic utterances, understand proforms, obtain the aubject of a sentence,and identify and associate the sensori-motor pro-perties and relatione with the aubject.

PUS differa significantly from the reported language acquisition systems [3, 4, 5, 6] in one or more of the following aspects: PUS is neither baaed on any built-in knowledge of English nor designed to acquire any formal grammar of English. The language understanding and generation prooedures are analogy-baaed. The primitives of the internal representation of language behaviour and world knowledge are either acquired through natural language inter-action, or built-in and independent of any language, task or domain.

Within it a scope, PUS provides a solation to the issue of assimilation and accommodation raised in [7].

The machinery of PUS has been motivated primarily by our long-term goal to model child language behaviour. Nevertheless,the computational machinery should be useful towards constructing practical expansible natural language interaction systems. Refer to [I, 2] for the paychological aspects of PUS, the explicit substantiation of its features mentioned above and the detailed discussion of its computational machinery.

2. AN EXAMPLE OF INTERACTION

Initially PUS does not possess any knowledge of English or the domain of diaoourae. Using a simulated teaching environment called 'Teach-names[1], the teacher first associates a set of names with the phyeical objects and agents that he proposes to deal with in hie interaction. Note that neither all names of an object/agent nor all objects that a word or a phrase can name need be associated using 'Teach-names[1]. A typical input to 'Teach-names' is:

1. CHAIR 1, CHA1R2; CHAIR; (OBJECT MaEE-OF-WOOD).

Thia means that the language expression 'CHAIR' is a name of the physical objects 'CHAIRI' and 'CHAIR2'; '(OBJECT MADE-0F-W00D)• is called a taglist. It ia intended to Simulate the structured complex of senaori-motor mechanisms which is responsible for the perception/mani-pulation of 'CHAIRI' and 'CHAIR2[1]. However, since articulating thia structure ia itself a challenging open problem, a tagliat ia present-ly assumed to be an unstructured aet of tags where each teg relates to a sensori-motor mechanism. As we shall see in aection 3, the

taglist plays an important role in understanding linguistic utterances. Moreover, it is significant to note that the language expressions used to name tags (e.g: MAEE-OF-WOOD) do not function as language expressions as far as PUS is concerned. let us assume that using 'Teach-names', the teacher has taught PUS the folloving words and phrases:

2. TABIE, THE TABIE; 3. WINDOW; 4. DESK; 5. ROOM, THE ROOM; 6. FOUNTAIN, THE FOUNTAIN; 7. BOX; 8. SHELF*.

Next, the teacher teaches, using another teaching device called 'Teach-aspects*, a set of words and phrases known as aspect tokens as shown below (Aspect tokens are language expressions that denote properties of, and relatione between, objects and/or agents):

9. NAC (BROWN; (COLOUR)).

This means that 'BROWN' is an aspect token of a New Aspect Category (NAC for short). '(COLOUR)' is-the taglist associated with 'BROWN' at the sensori-motor level.

10. (GREEN; (COLOUR)) SAC (BROWN; (COLOUR)).

The aspect tokens 'GREEN and 'BROWN' belong to the Same 4spect Category (SAC).

11. (RED; (COLOUR)) SAC (GREEN; (COLOUR)).
12. (RED IN COLOUR; (COLOUR)) SAS (RED; (COLOUR)).

'RED IN COLOUR' and 'RED' represent the Same Aspect (SAS). let us assume that using 'Teach-aspects', the teacher has taught the following aspect tokens:

13. PLASTIC; 14. WOOD; 15. NEAR THE FOUNTAIN; 16. IN THE MIDDIE OF THE FOUNTAIN; 17. INSIDE THE DESK; IS. ON THE BOX; 19. MADE OF PUSTIC; 20. HEAVT 21. LIGHT.

Next, the teacher uses a teaching device called 'Teach-Proforms' to teach proform tokens as shown below:

22. (THE CHAIR NEAR THE TABIE) ASS (THE ONE NEAR THE TABIE).

This means that 'THE CHAIR NEAR THE TABIE' is an Assignment (ASS for short) of the proform 'THE ONE NEAR THE TABIE'.

23. (THE CHAIR) ASS (IT).

Before we proceed further, it is worthwhile to point out that (i) in principle, 'Teach-names', 'Teach-aspects' and 'Teach-proforms' can be employed in any order and any number of times; (ii) the teaching devices 'Teach-aspects' and 'Teach-proforms' are unrealistic from the viewpoint of modelling the learning environment of pre-school children and can be eliminated, as shown in[l], by incorporating, in PUS, a question-answering environment.

Next, the teacher teaches a text (call Textl) as shown below:

24.. ((A CHAIR) REF 'CHAIRI' AND (A TABIE) REF 'TABIE) REF (C0LLECTION AGG CHAIR1, TABIE) ARE NEAR THE WINDOW.

This means that the tokens ' A CHAIR','A TABIE' and 'A TABIE AND A CHAIR' refer to 'CHAIR1', 'TABIE1' and 'COLLECTIONI' respectively; 'C0LLECTIONI' consists of 'CHAIRI' and'TABIEI'' The sentence taught is 'A CHAIR AND A TABIE ARE NEAR THE WINDOW'. REF and AGO, which stand for 'reference-of' and 'aggregate-of, simulate the extra-linguistic means employed by the language community to associate a language expression with its referent, and to specify the members of an aggregate of objects/agents respectively. Besides interpreting these extra-linguistic markers, PUS has to analyse and interpret •NEAR THE WINDOW' using 15 i.e, step 15; identify 'A CHAIR AND A TABIE' as the subject token; associate the aspect token 'NEAR THE WINDOW' with 'C0LIECTI0N1' and thereby with •CHAIRI' and 'TABIE1'.

25. THE CHAIR IS BROWN IN COLOUR.

Using 1 and 2 i.e., using the knowledge acquired in 1 and 2, PUS interprets 'THE CHAIR' as 'CHAIRI'; acquires 'BROWN IN COLOUR' using 12; identifies the subject token 'THE CHAIR'; associates 'BROWN IN COLOUR' with 'CHAIRI'.

26. THE TABIE IS RED IN COLOUR.

PUS uses 25 to understand this sentence since it is similar to the one in 25.

27. A DESK AND A CHAIR ARE IN THE MIDDIE OF THE ROOM.

•A CHAIR is interpreted as 'CHAIR2' because 'CHAIR'' has been associsted with 'NEAR THE WINDOW' in 24. ' IN THE MIDDIE OF THE ROOM' is understood using 16.

28. THE BROWN CHAIR IS MADE OF WOOD.

PUS interprets 'THE BROWN CHAIR' as 'CHAIRI' and not as 'CHAIR2'. Note that 'CHAIRI' has been associated in 25 with 'BROWN IN COLOUR'. PUS uses *12* to equate 'BROWN IN COLOUR' and •BROWN', and to correctly interpret 'THE BROWN CHAIR' as 'CHAIRI'.

29. THE ONE IN THE MIDDIE OF THE ROOM IS MADE OF PUSTIC.

PUS assigns 'THE CHAIR IN THE MIDDIE OF THE

ROOM[1] to the proform 'THE ONE IN THE MIDDIE OF THE ROOM'. Note that the teacher has taught, in 22, only the assignment 'THE CHAIR NEAR THE TABUS'. Moreover, PLAS has to use 27 to interpret 'THE CHAIR IN THE MIDDLE OF THE ROOM' as 'CHAIR2' and not as 'CHAIR'.

The teacher next tests PUS by asking it to understand a similar new text. For example,

Text 2

THIS IS A CHAIR. THERE IS A BOX ON THE CHAIR. IT IS HEAVY. THE BOX INSIDE THE SHEIF IS LIGHT. THE HEAVY BOX IS GREEN IN COLOUR.

Note that Plas can understand Text2 even though the underlying sentential forme and the described situational aspects vary significantly from those of TextI. Moreover, PLAS should interpret 'IT' in the third sentence as the box referred to in the second sentence even though the teacher has associated only 'THE CHAIR' with 'IT' in 23. Now, *as* requested by the teacher, PIAS generates the following sentences using 'CHAIR' and 'RED[1]':

THE HEAVY CHAIR IS RED IN COLOUR. THE LIGHT CHAIR IS RED IN COLOUR. THE RED CHAIR IS MADE OF WOOD. THE RED CHAIR IS MADE OF PLASTIC. THE CHAIR IS RED IN COLOUR.

Note that none of these sentences appears in TextI or Text2. Moreover, PLAS has not generated any semantically anamolous sentence like 'THE RED CHAIR IS GREEN IN COLOUR'.

3. THE COMPUTATIONAL MACHINERY

Interaction procedures simulate the teaching and tesfing environments discussed in section 2. They invoke sensorimotor procedures and language behaviour procedures to process the sensori-motor level information (i.e,physical objects, taglists, extra-linguistic markers) and the linguistic expressions respectively. In whet follows we shall sketch only the language understanding procedure. To understand a language expression, say 'ON THE TABUS', PLAS first invokes the segmentation procedure to analyse it into a known language schema, say ♦on -' (' - ' stands for a variable) and the filler 'THE TABIE'; 'THE TABIE' itself has to be understood before it is accepted as a filler. The segmented language expression is then validated. For instance, if 'NEAR THE CHAIR' is"an already known valid filler for the second variable of the schema '- IS -', then »PN THE TABIE' is accepted as a valid filler for the same variable provided the taglists associated with the two aspect tokens match (presently two taglists match iff they contain identical tags). The interpretation procedure then interprets the validated" token. For example, using the knowledge that the referent of 'JOHN'S BOOK[1] is ■ay 'B00K10', 'JILL'S TABIE' will be interpreted as, say 'TABIE5'. A successfully segmented, validated and interpreted language expression is said to be understood. If the schema 'On -• is not known already, it will be abstracted out of it by the schematization procedure by replacing understandable or already known language expressions in it. In this case also, before 'ON THE TABLE' is declared understood, it has to be validated and interpreted. Note that what underlies the language understanding procedure is not any language-specific information but are the capabilities to assimilate the unknown in terms of the known, and to accommodate the unknown if assimilation fails. These capabilities are analogy-based. To enable these capabilities is the main function of the data spaces of PLAS.

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NUMERICAL QUANTIFIERS AND THEIR USE IN REASONING WITH NEGATIVE INFORMATION

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Numerical quantifiers provide simple means of formalizing such statements as, "at least three people are in that room", "at most fifteen people are in the elevator", and "everybody has exactly two parents". Although numerical quantifiers generalize the existential quantifier, they have different uses in reasoning. The existential quantifier is most useful for supplying referents for designating phrases with no previously explicitly mentioned referent. Numerical quantifiers are most useful for reasoning by the process of elimination. Numerical quantifiers would, therefore, be a useful addition to the operators of a reasoning program or deductive question-answering system. They have been added to SNePS, the Semantic Network Processing System, to further enhance its inference capabilities.

1. INTRODUCTION

Logic based reasoning programs, that is reasoning programs based on operators (connectives, quantifiers, modals) which have been studied as part of formal logical systems benefit from the fact that the inferential properties of their operators are clear and well known. They need not be restricted, however, to a minimal set of operators. Minimal sets of operators are useful for proving properties of logical systems such as consistency and completeness, but using a logical system for carrying out inferences is simplified (for people) by enlarging the set of basic operators. This is one reason that natural deduction systems like those of [1], [4] and [11], with reasonable sets of connectives and two rules of inference for each one, are easier to use than axiomatic systems with minimal sets of connectives, rules and axioms.

This paper is motivated by an interest in programs that represent knowledge, including the knowledge of rules of reasoning, and that use those rules to perform reasoning. I believe that such programs are enhanced by the availability of a large set of operators that typify and formally model as many of the modes of human reasoning as possible. This paper discusses a set of operators, the numerical quantifiers, which can be implemented in reasoning programs as a single parameterized operator, and which model an important mode of human reasoning.

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Numerical quantifiers, discussed briefly in [10, pp. 63-64], are generalizations of the existential quantifier. They can be used to formalize such statements as:

There are at least two numbers z, such that $z+2<6$.
There are exactly two numbers x, such that $x^2+4=4x$.
There are at most two numbers y, such that $y+5<11-2y$.
(all from [10, pp. 64, 67].)

One numerical quantifier is the more commonly encountered unique existential, expressed as $\exists!xA(x)$ in the notation of [2, p. 199]. We will use the notation $\exists_i^j xA(x)$ for "there exists at least i and at most j x such that A(x)". The usual existential quantifier, $\exists xA(x)$, can then be considered an abbreviation of $\exists_1^\infty xA(x)$ (although later we will make a distinction), and the unique existential becomes $\exists_1^1 xA(x)$. In general, $\exists_n^n xA(x)$ are the "numerically definite quantifiers" mentioned in [3, pp. 165, 6].

We have found the numerical quantifiers particularly useful for the mode of reasoning by the process of elimination: if the maximal number of positive cases are found, the rest must be negative; if the maximal number of negative cases are found, the rest must be positive. Numerical quantifiers thus can introduce explicit negative information into a data base, and can make use of negative information to

derive positive information. To set the stage for this discussion, we will first discuss the role of the simple existential quantifier in deductive question-answering.

2. THE EXISTENTIAL QUANTIFIER

Let us consider statements which:
1) include an existential quantifier;
2) are to be stored in the data base of a deductive question-answering system (QAS);
3) are to be used by the system to answer questions.

We will consider what contribution such statements (we call these, as well as other general statements, deduction rules) can make to the question-answering process.

Existential quantifiers can either be outside or inside the scope of universal quantifiers. If outside the scope of any universal quantifier, for example "There is a man who owns a dog" or $\exists x(Man(x)\&\exists y(Dog(y)\&Owns(x,y)))$, there is no need to retain the quantifier in the data base, one can simply create new individual constants (Skolem constants) and substitute them for the quantified variables, storing, in this example, the three facts Man(m1), Dog(d1), and Owns(m1,d1).

Existential quantifiers within the scope of universal quantifiers can be eliminated by replacing them with Skolem functions. So,
(1) Every person has a mother
can be represented by $\forall x(Person(x)\rightarrow\exists y(Person(y)\&Mother(y,x)))$ or by $\forall x(Person(x)\rightarrow(Person(f(x))\&Mother(f(x),x)))$, where f is a new function. This rule could be used to answer the question, "Does John have a mother?", but the point of the Skolem function is that for each person a new person must be postulated to be his or her mother. So, knowing just (1), and that John is a person, if we asked "Who is John's mother?", the answer would be some individual about whom we know nothing except that she is a person and is John's mother.

It may seem strange that asking a question can cause the creation of a new individual, but consider definite descriptions that refer to individuals which have not been explicitly introduced, as in the statement "John's mother owns a dog". Normally, we would look in the data base for John's mother and assert that she owns a dog, but in this case there is no record of John's mother in the data base. However, rule (1) justifies creating a new individual to be John's mother. "John's mother owns a dog" presupposes that John has a mother. With neither an explicit mother, nor the rule, the sentence has a failed presupposition and should not be accepted.

If the data base contained both rule (1) and "Jane is John's mother", and we input, "John's mother owns a dog," rule (1) is at best useless, and at worst, harmful. If the rule were activated, it would have to produce a new mother, and the phrase "John's mother" would be ambiguous. If rule (1) were not activated, "Jane owns a dog" would be stored. This is technically wrong (consider replacing "mother" with "parent"), but probably what the speaker intended.

In summary, existential quantifiers need be stored in the data base of a QAS only when within the scope of a universal quantifier, and they are most useful for supplying referents for designating phrases with no previously explicitly mentioned referent.

3. MAXIMAL NUMERICAL QUANTIFIERS

Consider the data base containing "Jane is John's mother" and the question, "Is Mary John's mother?" In order to get the correct answer, "No", we need the rule
(2) Every person has at most one mother.
(We will ignore, in this paper, the problem of identity or extensional equivalence. That is, the even more correct answer, "Only if Mary is the same person as Jane". See [7] for a solution to this problem using a combination of path tracing and deduction rules.) Let us call quantifiers of the form $\exists^j xA(x)$, read "there exists at most j x such that A of x", maximal numerical quantifiers. In this notation, (2) becomes
(2') $\forall x(Person(x)\rightarrow\exists^1 y(Person(y)\&Mother(y,x)))$

Unlike the simple existential quantifier, the maximal numerical quantifiers do not justify the introduction of new individuals. However, we can derive negative statements from them once the maximal number of individuals satisfying the quantified statement are known. In our example, rule (2) justifies the answer, "No, Mary is not John's mother".

If a data base consisted of rules (1) and (2) only, and we asked, "Is Jane John's mother?", it might seem that rule (1) would create a new Skolem constant to be John's mother, and then by rule (2) the answer would be "No". However, rule (1) must not be invoked in this case, because it is illegal to instantiate an existentially quantified variable to a constant we already know something about. Since John's mother is not known explicitly, Jane is not ruled out and the correct answer in this case is "I don't know".

The formula $\exists^{j}xA(x)$ is therefore useful when we already know j different individuals satisfying A and are asked if a (j+1)st individual, t, also satisfies A. The formula $\sim A(t)$ is then derivable.

4. MINIMAL NUMERICAL QUANTIFIERS

Now consider formulas of the form, $\exists_i xA(x)$, read "There exists at least i x such that A of of x". We will call quantifiers of this form, minimal numerical quantifiers. What useful information does this provide that is not provided by $\exists xA(x)$? If the universe under discussion contains n individuals, and we already know of n-i individuals y such that $\sim A(y)$, we can deduce about any (n-i+1)st individual, t, that A(t). Consider five professors, three of whom are in a meeting. If I know who the five people are, and I've seen two in the hall, I can deduce who is in the meeting.

Since the usefulness of minimal numerical quantifiers depends on some universe of objects, it is convenient to introduce domain restricted minimal numerical quantifiers. We will use the notation $\exists_i x(P(x):Q(x))$, where P(x) and Q(x) are arbitrary formulas with x free, to mean, "of all objects x such that P(x), at least i of them satisfy Q". In a data base without the closed world assumption [5], we can seldom be sure that the objects known to satisfy P are the only ones that actually do. For example, the following corpus, representing the example above, is insufficient for deducing who is in the meeting.

(3) $\exists_3 x(Professor(x):In(x,meeting))$
(4) $\forall x(In(x,hall)\rightarrow\sim In(x,meeting))$
(5) Professor(Pat)
(6) Professor(Gabor)
(7) Professor(Nick)
(8) Professor(John)
(9) Professor(Stu)
(10) In(Pat,hall)
(11) In(Nick,hall)

However, it may be that whoever provided rule (3) knows that there are only five professors. To record such information, we will add another parameter to the minimal numerical quantifiers giving the schema, $_n\exists_i x(P(x):Q(x))$, where n is the number of objects which satisfy P. Notice that this amounts to a closed sub-world assumption. If we replace (3) in the above corpus by

(3') $_5\exists_3 x(Professor(x):In(x,meeting))$

stating that "Of the five professors, at least three are in the meeting", then we can derive In(Gabor,meeting), In(John,meeting) and In(Stu, meeting).

With minimal numerical quantifiers, negative information can be used to deduce positive information. Given the rule $_n\exists_i x(P(x):Q(x))$, and n-i individuals y such that $P(y)\&\sim Q(y)$, we can deduce for any other individual t such that P(t) holds that Q(t) also holds.

5. NUMERICAL QUANTIFIERS

The minimal and maximal numerical quantifiers can be combined into what we shall simply call the numerical quantifiers, $_n\exists_i^j x(P(x):Q(x))$, which are read, "Of the n individuals x such that P(x), at least i and at most j are such that Q(x)", or simply, "Between i and j of the n Ps are Qs". The other quantifiers we have discussed may be obtained by leaving out appropriate parts of this schema.

If a data base contains a rule of the form $_n\exists_i^j x(P(x):Q(x))$ and j individuals are found satisfying $P(x)\&Q(x)$, it may be deduced that the remaining n-j individuals satisfying P(x) satisfy $\sim Q(x)$. However, if n-i individuals are found to satisfy $P(x)\&\sim Q(x)$, it may be deduced that the remaining i individuals satisfying P(x) also satisfy Q(x).

The regular existential quantifier, $\exists xA(x)$, is the same as the numerical quantifier $\exists_1^{\infty} xA(x)$. It is now clear why it seldom helps us determine whether A(t) holds for a fixed individual, t. $\exists_1^{\infty} xA(x)$ cannot derive $\sim A(t)$, since there is no maximum -- all individuals might satisfy A. It can seldom produce A(t), since that would require knowing that all other individuals satisfy $\sim A$, and we rarely have a finite list of all the individuals in the domain. Because of this, the implementor of a deductive QAS may wish to distinguish the existential quantifier from the numerical quantifiers, and continue to prohibit invocation of a rule that would bind an existentially quantified variable to a constant.

6. NUMERICAL QUANTIFIERS IN SNePS

Numerical quantifiers have recently been added to SNePS, the Semantic Network Processing System [6; 8], which already included universal and existential quantifiers as well as a set of non-standard connectives. SNePS accepts numerically quantified formulas of the form

(12) $_n\exists_i^j \bar{x}(P_1(\bar{x}),\ldots,P_k(\bar{x}):Q(\bar{x}))$
(13) $_n\exists_i \bar{x}(P_1(\bar{x}),\ldots,P_k(\bar{x}):Q(\bar{x}))$
(14) $\exists^j \bar{x}(P_1(\bar{x}),\ldots,P_k(\bar{x}):Q(\bar{x}))$

where $k\geq 0$ and $\bar{x}$ represents a sequence of variables $\langle x_1,\ldots,x_m\rangle$ each of which is free in at least one of $P_1(\bar{x}),\ldots,P_k(\bar{x}),Q(\bar{x})$. The meaning of (12) is that there are n sequences of individuals, $\langle t_1,\ldots,t_m\rangle$ such that $(P_1(\bar{x})\&\ldots\&P_k(\bar{x}))[t_1/x_1,\ldots,t_m/x_m]$ is true and that at least i and at most j of these n sequences also satisfy $Q(\bar{x})$. The meanings of (13) and (14) are the appropriate simplifications of this.

As an example of (12), consider the many-many relationship of dog ownership. Several people may jointly own one dog, and several dogs may be owned by the same person. The formula $_5\exists^4_2 x,y(Person(x),Dog(y),Owns(x,y):Spoils(x,y))$ says that of the five dog ownership relations (e.g. <John,Rover>, <John,Spot>, <Jane,Spot>, <Mary, Lassie>, and <Jim,Lassie>), between two and four involve spoiling the dog.

Rules of the form of (12) are represented in the SNePS network by a node with: an auxiliary arc labeled EMIN to i; an auxiliary arc labeled EMAX to j; an auxiliary arc labeled ETOT to n; descending arcs labeled PEVB to the nodes representing the variables in $\bar{x}$; descending arcs labeled &ANT to the nodes representing the formulas $P_1(\bar{x}),\ldots,P_k(\bar{x})$; a descending arc labeled CQ to the node representing $Q(\bar{x})$. In SNePS, auxiliary arcs may connect semantic network nodes to arbitrary data structures, including numbers. A descending arc goes from a network node to another network node and has a paired ascending arc in the reverse direction.

7. EXAMPLES

In this section, we will show SNePS runs of the three major numerical quantifier examples from above. Lines beginning with "**" or "*" were typed by the user. The character ";" indicates that the rest of the line is a comment. Input is in SNePSUL, the SNePS User Language, [8]. Each input and each deduced fact is commented by its English translation. Each rule is also commented by its translation into the logical syntax used previously in this paper. The runs were transcribed to make them easier to read, and edited only to add the comments and to remove some trace printing. SNePS is written in Lisp and runs interactively on a CYBER 173. A compiled version was used for these examples.

7.1 Example 1

We assert that Jane is John's mother and that everyone has at most one mother. Then we ask if Mary is John's mother, and SNePS responds that she is not.

```
**;Jane is a person.
*(BUILD MEM JANE CLASS PERSON)
(M13) ;The SNePS node representing the assertion.
8 MSECS
**;John is a person.
*(BUILD MEM JOHN CLASS PERSON)
(M14)
8 MSECS
**;Jane is John's mother.
*(BUILD A JANE R MOTHER O JOHN)
(M15)
12 MSECS
**;Every person has at most one mother.
*;∀x[Person(x)→∃1y(Person(y) : Mother(y,x))]
*(BUILD AVB $X
* ANT (BUILD MEM *X CLASS PERSON)
*  CQ (BUILD EMAX 1 PEVB $Y
*       &ANT (BUILD MEM *Y CLASS PERSON)
*         CQ (BUILD A *Y R MOTHER O *X)))
(M21)
65 MSECS
**;Mary is a person.
*(BUILD MEM MARY CLASS PERSON)
(M22)
7 MSECS
**;Is Mary John's mother?
* (DESCRIBE (DEDUCE A MARY R MOTHER O JOHN))
(M24 (MIN(0)) (MAX(0)) (ARG(M23)))
     ; It is not the case that
(M23 (A(MARY)) (R(MOTHER)) (O(JOHN)))
     ; Mary is the mother of John.
(DUMPED)
1120 MSECS
```

7.2 Example 2

At least three of the five professors are in the meeting. We see Pat and Nick in the hall. When we ask who is in the meeting, SNePS deduces that Pat and Nick are not, but Gabor, John, and Stu are.

```
**;At least 3 of 5 professors are in a meeting.
*;5∃3x[Professor(x)→In(x,meeting)]
*(BUILD ETOT 5 EMIN 3 PEVB $X
* &ANT (BUILD MEM *X CLASS PROFESSOR)
*   CQ (BUILD A *X R IN O MEETING))
(M4)
44 MSECS
**;Whoever is in the hall is not in the meeting.
*;∀x[In(x,hall)→~In(x,meeting)]
*(BUILD AVB $X
* ANT (BUILD A *X R IN O HALL)
*  CQ (BUILD MIN 0 MAX 0
*       ARG (BUILD A *X R IN O MEETING)))
(M8)
50 MSECS
**;Pat is a professor.
*(BUILD MEM PAT CLASS PROFESSOR)
(M9)
10 MSECS
**;Gabor is a professor.
*(BUILD MEM GABOR CLASS PROFESSOR)
(M10)
8 MSECS
**;Nick is a professor.
*(BUILD MEM NICK CLASS PROFESSOR)
(M11)
8 MSECS
**;John is a professor.
*(BUILD MEM JOHN CLASS PROFESSOR)
(M12)
8 MSECS
**;Stu is a professor.
*(BUILD MEM STU CLASS PROFESSOR)
```

```
(M13)
9 MSECS
**;Pat is in the hall.
*(BUILD A PAT R IN 0 HALL)
(M14)
11 MSECS
**;Nick is in the hall.
*(BUILD A NICK R IN 0 HALL)
(M15)
10 MSECS
**;Who is in the meeting?
*(DESCRIBE (DEDUCE A %X R IN 0 MEETING))
(M17 (MIN(O)) (MAX(O)) (ARG(M16)))
(M16 (A(PAT)) (R(IN)) (O(MEETING)))
     ; Pat is not in the meeting.
(M19 (MIN(O)) (MAX(O)) (ARG(M18)))
(MI8 (A(NICK)) (R(IN)) (0(MEETING)))
     ; Nick is not in the meeting.
(M20 (A(GABOR)) (R(IN)) (O(MEETING)))
     ; Gabor is in the meeting.
(M21 (A(JOHN)) (R(IN)) (0(MEETING)))
     ; John is in the meeting.
(M22 (A(STU)) (R(IN)) (O(MEETING)))
     ; Stu is in the meeting.
(DUMPED)
1427 MSECS
```

7 - .3 Example 2

We assert that between two and four dog owner inp relations involve spoiling, and assert four such spoiling relations. SNePS deduces that Jim does not spoil Lassie.

```
**;Of 5 dog ownership relations,
*  ,between 2 and 4 involve spoiling.
* , 532Xy member(x,person),Member(y,dog) ,
          Owns(x,y) : Spoils(x,y)]
•* (BUILD ETOT 5 EMIN 2 EMAX 4 PEVB($X $Y)
*  6ANT ((BUILD MEM *X CLASS PERSON)
*        (BUILD MEM *Y CLASS DOG)
*        (BUILD A *X R OWNS 0 *Y))
     CQ (BUILD A *X R SPOILS 0 *Y))
(M5)
81 MSECS
**;John is a person.
*(BUILD MEM JOHN CLASS PERSON)
(M6)
10 MSECS
**;Jane is a person.
*(BUILD MEM JANE CLASS PERSON)
(M7)
10 MSECS
**;Mary is a person.
*(BUILD MEM MARY CLASS PERSON)
(M8)
9 MSECS
**;Jim is a person.
*(BUILD MEM JIM CLASS PERSON)
(M9)
9 MSECS
**;Rover is a dog.
*(BUILD MEM ROVER CLASS DOG
(M10)
9 MSECS
**;Spot is a dog.
*(BUILD MEM SPOT CLASS DOG)
(M11)
12 MSECS
**;Lassie is a dog
*(BUILD MEM LASSIE CLASS DOG)
(M12)
10 MSECS
**;John owns Rover.
*(BUILD A JOHN R OWNS 0 ROVER)
(M13)
11 MSECS
**;John owns Spot.
*(BUILD A JOHN R OWNS 0 SPOT)
(M14)
11 MSECS
**;Mary owns Lassie.
*(BUILD A MARY R OWNS 0 LASSIE)
(M15)
13 MSECS
**;Jane owns Spot.
*(BUILD A JANE R OWNS 0 SPOT)
(M16)
11 MSECS
**;Jim owns Lassie.
*(BUILD A JIM R OWNS 0 LASSIE)
(M17)
12 MSECS
**;John spoils Rover.
*(BUILD A JOHN R SPOILS 0 ROVER)
(M18)
10 MSECS
**;John spoils Spot.
*(BUILD A JOHN R SPOILS 0 SPOT)
(M19)
12 MSECS
**;jane spoils Spot.
*(BUILD A JANE R SPOILS 0 SPOT)
(M20)
12 MSECS
**;Mary spoils Lassie.
*(BUILD A MARY R SPOILS 0 LASSIE)
(M21)
11 MSECS
**;Who spoils whom?
*(DESCRIBE  (DEDUCE A %X R SPOILS 0 %Y))
(M18 vA(JOHN)) (R(SPOILS)) (0(ROVER)))
     ;John spoils Rover.
(M19 (A(JOHN)) (R(SPOILS)) (O(SPOT)))
     ;John spoils Spot.
(M20 (A(JANE)) (R(SPOILS)) (O(SPOT)))
     ;Jane spoils Spot.
(M21 (A(MARY)) (R(SPOILS)) (O(LASSIE)))
     ;Mary spoils Lassie.
(M23 (MIN(O)) (MAX(O)) (ARG(M22)))
(M22 (A(JIM)) (R(SPOILS)) (O(LASSIE)))
     ;Jim does not spoil Lassie.
(DUMPED)
1341 MSECS
```

8. SUMMARY

We have discussed the roles of existential and numerical quantifiers in reasoning programs. The roles are different and both are important. The existential quantifier is most useful for supplying referents for designating phrases with no previously explicitly mentioned referent. Numerically quantified rules are concise representations of rules that govern reasoning by the process of elimination and can introduce explicit negatives into a data base or can use negative statements for deriving positive statements. The most general schema for numerical quantifiers that we have discussed is $_{n}\exists^{j}_{i}x(P_1(\bar{x}),\ldots,P_k(\bar{x}):Q(\bar{x}))$, which says that at least i and at most j of the n sequences of individuals that satisfy $P_1(\bar{x})\&\ldots\&P_k(\bar{x})$ also satisfy Q(X). We showed how rules of this form can be represented in SNePS, the Semantic Network Processing System, and gave examples of SNePS runs that used such rules for carrying out inferences.

Two aspects of numerical quantifiers might limit their immediate usefulness. One is the n parameter, required whenever the minimal parameter is present. In formulating numerically quantified statements, we have found specifying n to be bothersome. The parameter could be eliminated if the inference system had another means of determining how many individuals satisfy the restriction, for example if the closed world assumption held. The other problem is that inherent in any counting argument is the assumption that any two individuals are, in fact, distinct. If this assumption does not hold, the use of numerical quantifiers depends on a solution to the identity problem mentioned in Sec. 3. Except for these two problems, numerical quantifiers seem to be useful additions to the tool kit of representation and inference.

ACKNOWLEDGEMENTS

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A SCRABBLE CROSSWORD GAME PLAYING PROGRAM

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A program that plays the SCRABBLE Crossword Game has oeen designed and implemented in SIMULA 67 on a DECSystem-10 and in Pascal on a CYBER 173. The heart of the design is the data structure for the lexicon and the algorithm for searching it. The lexicon is represented as a letter table, or trie using a canonical ordering of the letters in the words rather than the original spelling. The algorithm takes the trie and a collection of letters, including blanks, and finds all words that can be formed from any combination and permutation of the letters. Words are found in approximately the order of their value in the game.

1 INTRODUCTION

The SCRABBLE Crossword Game is a well known game considered to require a fair amount of intelligence, strategic and tactical skill, facility with words, and luck. Unlike most games in the artificial intelligence literature, it can be played by two or more players and is neither a zero sum game nor a game of perfect information. For these reasons, minimax searching procedures do not seem applicable. When humans play the game, a large easily accessible vocabulary seems to be the most important determiner of victory. One might, therefore, think that it would be easy to write a program that plays the SCRABBLE Crossword Game at the championship level. We are examining this question by concentrating our efforts on the design of the lexicon and the algorithm for searching it and paying much less attention to the strategies and tactics of actual play.

Our lexicon differs from those usually used in natural language processing programs because of the use to which it is to be put. Usually one is confronted with a possible word. One must determine if it is a word, and, if so, segment it into affixes and stem, and retrieve lexical information associated with the stem. The problem for the SCRABBLE Crossword Game lexicon is, given a set of letters, find all the words that can be made from any combination and permutation of them. This is a very different problem.

We have designed a program that plays the SCRABBLE Crossword Game and implemented two versions. At Indiana University, Howard Smith implemented a program in SIMULA 67 [2,3] on a DECSystem-10. At SUNY/Buffalo, Michael Morris and Karl Schimpf implemented a version in Pascal [6] on a CDC CYBER 173 that manages a game between any number of players, and each wrote a program player.

In the sections that follow, we will briefly describe the game manager, basing the description on the Pascal version, which is more general than the SIMULA version. We will then describe the lexicon data structure and search algorithm in more detail. Finally, we will briefly describe the three program players that have been written.

2. THE GAME MANAGER

Figure 1 shows the overall organization of the system, assuming one human player and one program player. In reality, there may be any number of human players and any number of program players as long as there are at least two players.

The game manager module handles all interaction with human players and either deals tiles or accepts tiles picked by human assistants. After

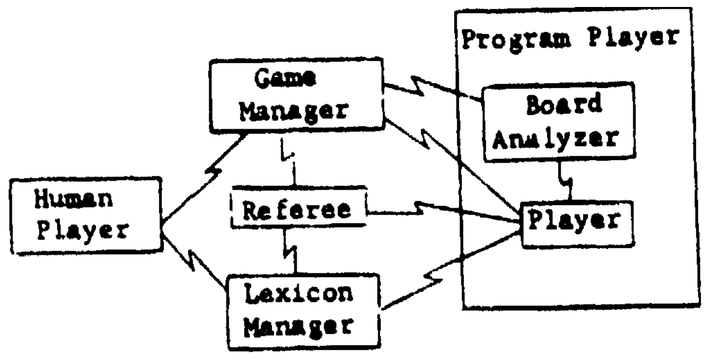

Figure 1: Overall system organization

each move, it reports the move to the board analyzer modules of all program players in the game, so they may "start to think about their next plays" while the humans are playing.

2.1 The Referee

The referee checks proposed plays for legality

and computes the score of legal plays. If a human proposes a word not in the lexicon, the referee asks if it is really a word. If the human says it is, it is added to the lexicon. Otherwise the play is considered illegal.

Program players may use the referee to find legal plays and to choose the best among several legal plays.

2.2 The Human Opponent

A human player interacts with the game manager in a notation close to the official notation of the SCRABBLE Crossword Game Players, Inc. [1]. The word is typed with each letter already on the board preceeded by a "$". When a blank tile is played, a "@" is typed followed by the letter it is being used as. The location of the word is indicated either by a row and the beginning and ending columns (e.g. 8K-N), or by a column and the beginning and ending rows (e.g. C2-7).

2.3 The Lexicon Manager

The lexicon manager is used by the referee to check whether words and crosswords are contained in the lexicon, and to add words which a human player claimed are words, but were not already in the lexicon. The program players use the lexicon manager to find words to play. A human player may use the lexicon manager to interact with the lexicon without ending the game.

3. THE LEXICON

3.1 The Data Structure

The lexicon was designed for the particular problem, "given a collection of letters, find all words that can be formed from any combination and permutation of the letters, and find these words in approximately the order of their value in the SCRABBLE Crossword Game". Two key ideas were combined in the design of the data structure - letter tables [4, 5, 8], or tries [7], and canonical ordering.

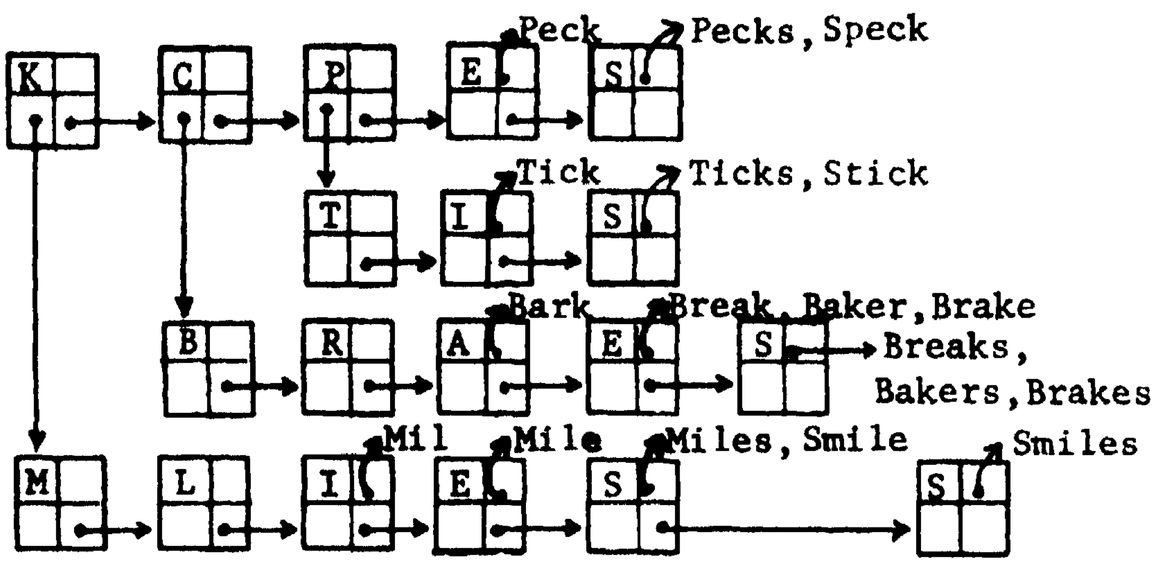

Figure 2: An example lexicon trie

Key:

letter	words
fail	success

Each node in the lexicon trie contains a letter, a list of words, a success pointer and a fail pointer. If L is the sequence of letters contained in all nodes on the success path from the root to some node, n, excluding the letter in n, and l is the letter in n, then the list of words in n is all words that are permutations of the letters in L plus £, the success pointer points to a subtrie containing words formed from L, £, plus other letters, and the fail pointer points to a subtrie containing words formed from L, other letters, but not l. The order of letters on both success and fail paths is the canonical order discussed below. Figure 2 shows a small lexicon trie.

3.2 The Search Algorithm

Briefly, the algorithm for searching the lexicon is to take a set of tiles, order them according to the canonical ordering, search the fail path of the root until the letter of the first tile matches the letter in a node, then search the success subtrie with the remaining tiles of the set. Then, to get words formed from subsets of the original set, ignore the letter that matched the node and also search the fail subtrie. So, if the lexicon of Figure 2 is searched with the letters KCPTIE, "peck" will be found, and then, ignoring "p", "tick" will be found.

So that words can be found in approximately the order of their values in the SCRABBLE Crossword Game, the major sort used in the canonical ordering is the value of the letters in that game. Since when a letter of a lexicon node is in the search set both its success and fail subtries are searched, but if it is not only its fail subtrie is searched, the secondary order is frequency of the letter in the game set, least frequent first. The tertiary sort is frequency in English, most frequent first, to help minimize the size of the lexicon trie. Contrary to this ordering, "S" was placed last, because of the large number of words that can have "S" added and remain words. For example, Figure 2 has 21 nodes, but if "S" were placed before L » where it belongs, the same lexicon would have 32 nodes. The final ordering used was ''QZXJKHFYWVCMPBGDLUTNRIOAES".

Four details were ignored in the above brief description of the search algorithm. First, longer words, like "smiles" are more valuable than shorter words using the same letters, like "mil", so words on the same success branch are collected in the order of leaf toward root, rather than root toward leaf. Second, the search set of tiles may contain blanks, which can match any letter. Blanks are initially placed first in the search set so they can match nodes high in the lexicon trie, and later

shuffled down in the search set to match lower nodes. Third, the search set can contain letters that are required to be in found words, so are never ignored by the search algorithm. Fourth, the search terminates after each word is found in case that word is acceptable to the player and no further search is required. If this is not the case, the search can be resumed from where it left off. The SIMULA 67 version uses the detach facility for this purpose. Space precludes presenting the complete algorithm here. It can be found as procedure findwords2 in [9") .

3.3 Use of Secondary Storage

We have used two different schemes for maintaining the lexicon on disk. The SIMULA 67 version uses a sequential file of characters and digits. The letter of each node is followed by the list of words, if any, and then by one of the digits 0-3 indicating which kinds of subtries the node has. If both are present, the success subtrie proceeds the fail subtrie. This organization allows the lexicon to be searched while the file is read in the forward direction only. However, a node's entire success subtrie must be read to find its fail subtrie. The SIMUIA version, with a lexicon of about 1500 words, averaged about 42 CPU seconds per pair of moves (program and human).

The Pascal version uses a segmented file of records, where each record is a lexicon node containing at most one word. If necessary, successive records with dummy letters contain additional words. Except for this, the root of the success subtrie of a node immediately follows the node. A node with no success subtrie is followed by an end-of-segment mark. The root of the fail subtrie of a node is the first node of some segment later in the file, so that to find a node's fail subtrie, the entire success subtrie needn't be read, just the first node of each intervening segment. Currently, this lexicon contains 2126 words, in 4262 node records and 1666 segments. The Pascal program averages about 29 CPU seconds per pair of program vs. program moves when run in batch, but has been too slow to run interactively due to system overhead.

4. PROGRAM PLAYERS

Three program players have been written, SIMSCRB, written by Howard Smith in SIMULA 67, and two Pascal programs -- Gerry, by Michael Morris, and Joanne, by Karl Schimpf. SIMSCRB only plays across existing words, never extending a word or playing parallel to a word. Joanne also considers parallel plays, but not extending words. Gerry considers all types of plays. Each board analyzer maintains a list of playable positions ordered by expected value of a play there. The programs consider the best P positions and the first w words found in the lexicon for each position. The chosen play is the first that is worth at least m points, or the best of the Pw plays, or, if these are all illegal, they exchange their racks. Joanne first tries playing parallel to existing words, considering upto w2 words formed entirely from the rack.

Table 1 shows the results of interactive games of SIMSCRB against humans DRF and SJ, and batch games of Gerry against itself and Joanne against itself. The programs play approximately at human level. The major difference is the number of times the programs exchange tiles. This is partly due to small vocabularies, and partly to wasting many of the limited pw tries on positions for which legal moves could not be found.

TABLE 1
Summary of Four Games

Player	Number of Moves	Number of words played	Score Before Reduction	Avg. Score per word played	Final Score
DPF	26	25	347	13.88	339
SIMSCRB	25	16	210	13.13	208
SJ	20	18	216	12	212
SIMSCRB	19	15	211	14.07	198
Gerry 1	12	6	71	11.83	61
Gerry 2	11	6	76	12.67	63
Joanne 1	30	13	135	10.38	119
Joanne 2	30	20	208	10.4	204

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Ben Shneiderman, Margaret Ambrose and Barbara Rasche cooperated on an early version of the program. Howard R. Smith implemented the SIMULA 67 version, and was partially responsible for the lexicon search algorithm, Michael Morris Jr. and Karl Schimpf implemented the Pascal version.

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SPEECH TRAINING SYSTEMS USING LATERAL SHAPES OF VOCAL TRACT AND F1-F2 DIAGRAM FOR HEARING-IMPAIRED CHILDREN

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Three speech training systems for hearing-impaired children were designed and constructed using a minicomputer and a microprocessor. The first system displays the lateral shape of the vocal tract for each vowel estimated from the speech sound. In this system, three storages are prepared. One of them can be used to store a reference shape which may be estimated from a teacher's voice or a prepared standard shape. A child can articulate seeing the reference shape and re-articulate comparing his own first articulation with the reference shape. The system can also compare the estimated shape with the reference one and produce instructions with animated cartoons which show where any articulatory defects exist. The second system displays successively the lateral shapes for articulation of any phoneme sequences containing consonants. The third system displays the first two formant frequencies extracted from speech as a spot on the F1-F2 plane, where the regions of vowels are shown in color. Preliminary use of these devices has shown that they complement each other to form a more effective system of speech training.

1. INTRODUCTION

If hearing-impaired children can see their articulation and compare it with a reference articulation in order to bring their articulation closer to the reference, or if they can see the formant frequency locus for their utterance on a F1-F2 plane, where the regions of the vowels are shown, they might be able to understand how they articulated or how they should articulate. In addition, teachers might be more able to teach them how to articulate or know where their articulatory defects exist. Therefore, we have constructed three speech training systems using a minicomputer and a microprocessor. For vowel articulation the first system estimates a lateral shape of the vocal tract from the speech sound and displays it on a storage CR-tube. And it can compare the estimated shape with the reference one and produce instructions with animated cartoons which show where any articulatory defects exist. For consonant articulation we cannot yet estimate a vocal tract shape from the speech sound, but our second system can display successively the lateral shapes of the vocal tract for the articulation of any phoneme sequence containing consonants. Our third system displays the first two formant frequencies extracted from a speech sound as a spot on the FI-F2 plane, where the regions of the vowels are also shown in color. It can also display pitch frequencies.

2. SYSTEM 1

This system estimates shapes of the vocal tract for vowels by evaluating PARCOR coefficients and instructs where any articulatory defects exist and also indicates how a child should correct his articulation. Fig. 1 shows the main flow of our procedures. The operation of this system is simple, and one has only to type a number or YES/NO in reply to the system inquiry " = " or " ? " shown in the state of this diagram. Then the system proceeds to the next state executing the action described along the line, types the characters shown in the new state and waits for the next reply. Referring to the marks in the diagram we will explain what this system can do chiefly.

(a) In order to avoid disturbance from the room noise, you can specify a threshold value in reply to the inquiry "Cut level=" at which the system begins to store the input speech wave for 3.2 sec.

(b) The system displays the reduced input speech wave on a storage CR-tube as shown in Fig. 2 by typing "N" at the state (ii) Again? Therefore you can examine the speech wave envelope and select the places where you want to obtain the vocal tract shape.

(c) At the state (iii) you can enlarge the wave form at any specified place and find its pitch period as shown in Fig. 3.

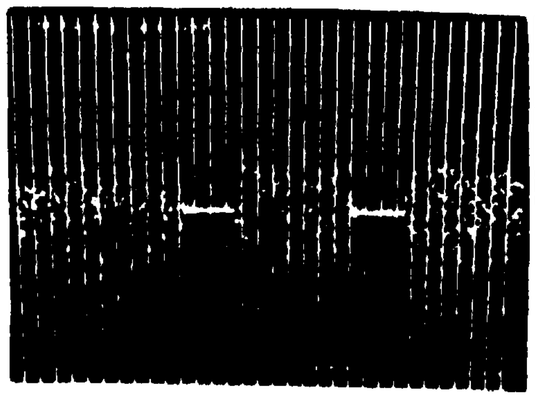

Fig. 2 Display of the uttered speech wave.

Fig. 3 An enlarged speech wave.

(d) Two storages labelled "1,2" for storing the estimated shapes are prepared and you can respond with one of them to the inquiry "Pattern=" at (v). While, in the third storage labelled "0" you should store the shape which you want to use as a reference.

(e) For the inquiry "Display shape=" at (vi) you can specify any storage containing the shape. Then the specified shape is displayed.

(f) At the state (viii) Reference = 0,..? , if you input "0" then the estimated shape is compared with the content in the storage "0", and if you input "1" or "2" then the estimated shape is compared with the standard reference shape which was specified at the state (vii) Present vowel= . Comparison between the estimated shape and the reference one is done for the two features: the place of articulation and the lip-opening. If the difference between the places of articulation of both shapes is over a certain threshold value, an instruction such as "Draw back your tongue" is shown and the estimated lateral shape moves gradually toward the reference shape as shown in Fig. 4. And if the difference between lip-openings of both shapes is large, an instruction such as "Open your lips" is written and the lips represented by an ellipse move gradually toward the reference opening (Fig.4). If the difference is a little, the instruction "OK" is written as shown in Fig. 5. The reference shape stored in the storage "0" can be the prepared standard shape or the estimated shape which has been estimated from the teacher's voice through the above-described routine.

(g) Going along the route 3 by inputting "3" at the state (i) Link order= , we can estimate and display successively the vocal tract shapes of the vowels at the pre-specified places.

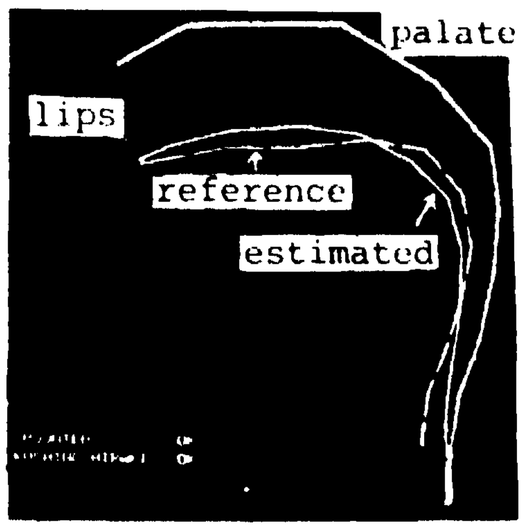

Fig. 5 An example of practice. One can articulate seeing the reference shape shown by broken line. In this case both instructions for articulation of /a/ are "OK".

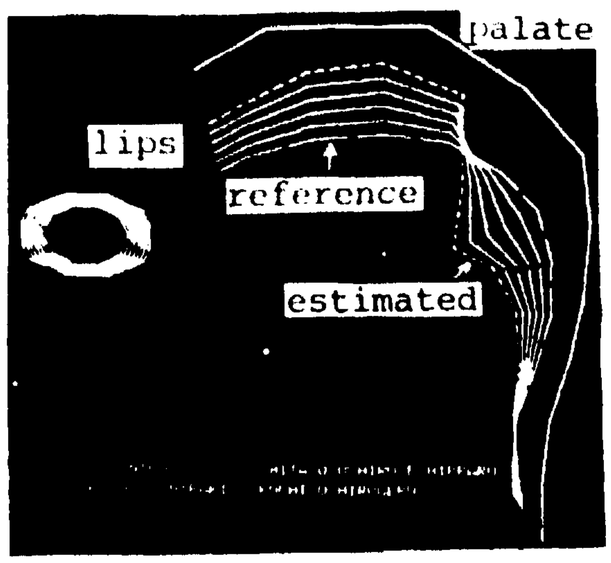

Fig. 4 An example of instructions for articulation. In this case /i/ was uttered and the estimated shape shown by dotted line was moved toward the prepared reference shape /a/ shown by broken line. The lip-opening was also moved. The instructions mean that place of articulation: Draw back your tongue, lip-opening: Open your lips.

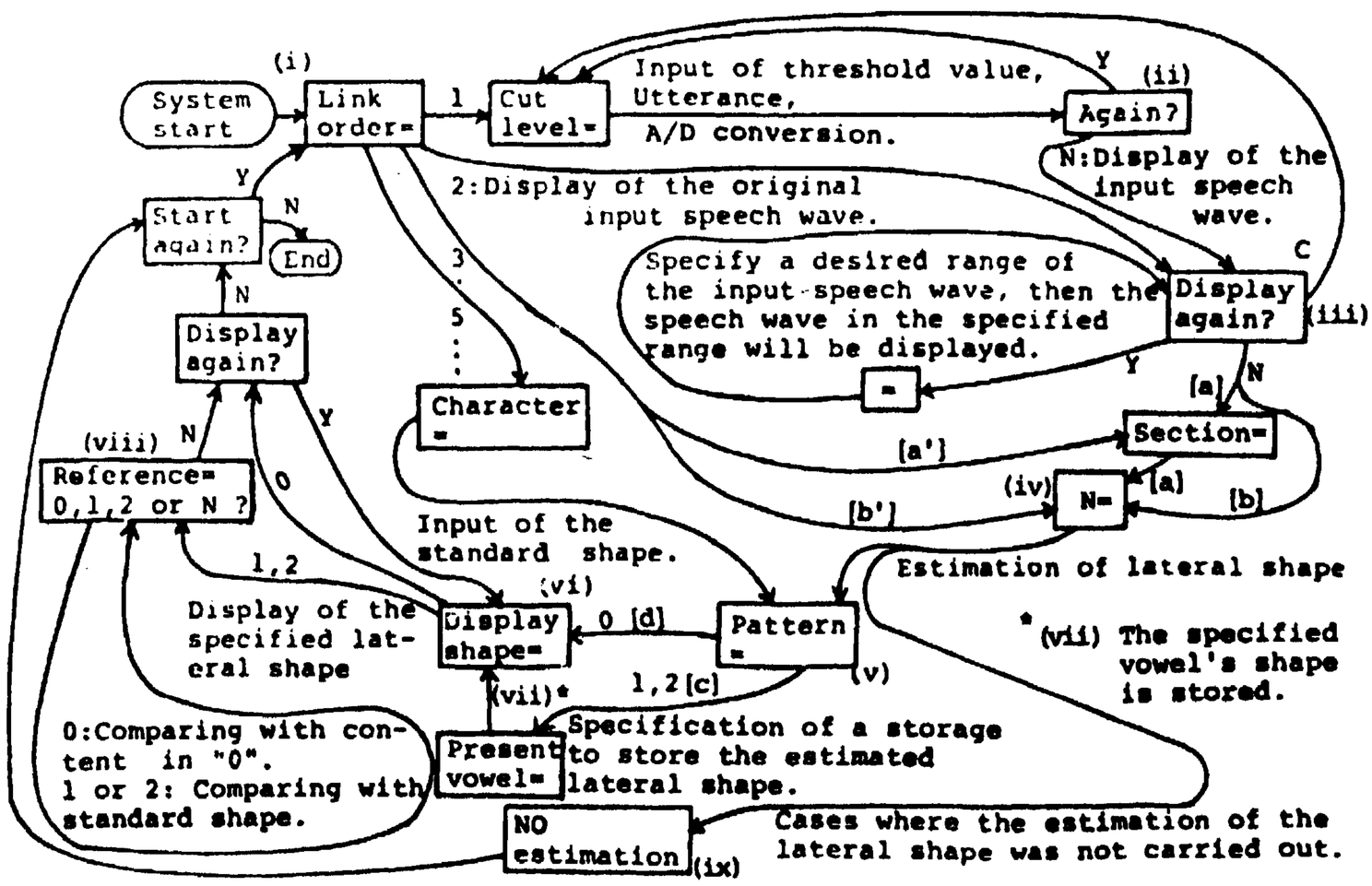

Fig. 1 Flow diagram of the speech training system which estimates the lateral shape of the vocal tract from the speech wave and instructs how one should articulate.

For practice, at first you should display a standard shape prepared previously or a shape estimated from your own utterance. Then a child can articulate seeing the reference shape, and re-articulate comparing his own articulation with the reference shape (Fig. 5). The practice shapes of the child should be stored in either storage "1" or "2", then he can successively compare his articulation with the previous articulation or the reference shape, if he wants, looking at instructions.

3. SYSTEM 2

We have prepared a system which displays synthetic articulatory movements for monosyllable utterances or words containing consonants, because it is very difficult to estimate a vocal tract shape from a speech wave for any of the consonants. The lateral shape of the vocal tract for Japanese phoneme sequences are produced by our speech synthesizer using an articulatory model [1]. The synthesized lateral shapes are stored on a drum storage and displayed with arbitrary speed. A child can easily look at the articulatory movements containing stop or fricative consonants. Fig. 6 shows the synthesized shapes in the sequence /ika/.

4. SYSTEM 3

This system displays the first two formant frequencies extracted from speech as a spot on the F1-F2 plane, where the regions of the vowels are shown in color as shown in Fig. 7. It can also display pitch frequencies. This system uses a microprocessor and a color TV set.

This system is useful by itself, and also helpful in order to know the quantative vowel quality.

5. DISCUSSION AND CONCLUSION

Our estimated shapes of the vocal tract are not accurate, but we can approximate the place of articulation for vowels and point out the defect of articulation and, of course, the systems function properly for hearing-impaired children. But an infant is unable to understand instructions such as "Draw back your tonque body", so these systems should be used to offer .information to a teacher.

We also hope that these systems are used by older persons for self-teaching.

Though we have not yet evaluated the effectiveness of these systems, preliminary use of these devices has shown that they complement each other to form a more effective system of speed: training. Especially it is instructive to use the systems 1 and 3 simultaneously, because we can get articulatory information in both articulatory and frequency domains.

Authors would like to express their gratitude to 0. Tanaka, T. Nishide, Y. Furuya and other students in our laboratory for their help.

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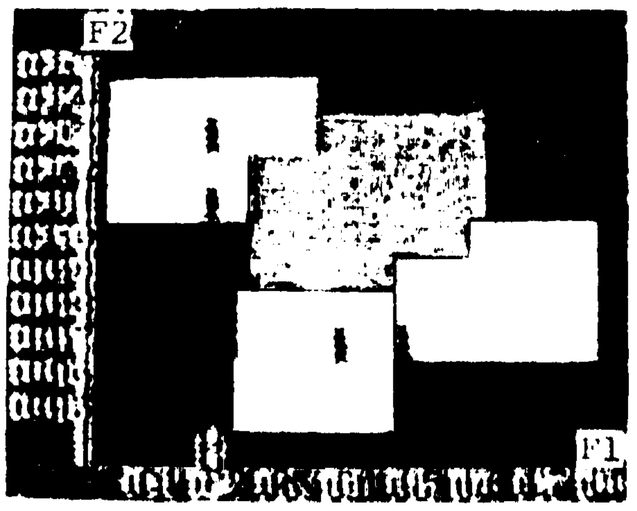

Fig. 7 An output in the system 3 for /aoi/.

(a) from uniform tube to /i/ (b) from /i/ to /k/ (c) from /k/ to /a/

Fig. 6 Synthesized lateral shapes of the vocal tract for /ika/. In our synthesizer the shape of the vocal tract begins to move from a uniform tube, therefore in (a) it starts from the shape parallel to the upper wall and moves toward the reference shape of /i/.

EXPERIMENTAL JAPANESE LANGUAGE QUESTION ANSWERING SYSTEM MSSS78
- Use of Case Patterns with Procedures -

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MSSS78 is an experimental computer system made in a series of research efforts to construct a natural language man-machine interface. The system accepts sentences about arithmetic or geography, and then responds to the queries on the basis of its own knowledge and dialogue context.
The system analyzes sentences, using Case Patterns, in which procedures are embedded. Case Patterns are linguistic knowledge associated with main words. The system uses Case Patterns for syntactic and semantic analysis. Additionally, Parsing is controlled by the utilization of a pushdown stack and a list.
The system generates somewhat intelligent responses, considering results of the database reference or lack of input information.

1 INTRODUCTION

Various natural language understanding systems r sentence analysis programs, including those for Japanese language, uses case frames[1) (2], The method using case frames seems to benefit problems such as modularity and extendability to many components, which construct an intelligent understanding system.

Mainly from such the case frame viewpoints, an experimental Japanese language question Answering system, MSSS78, was made in a series f research efforts intended to construct a natural language man-machine interface. The system uses Case Patterns, which are linguistic knowledge associated with main words. Case Patterns can be regarded as a new style of case frames. There are three features concerning the parsing mechanism.

(1) Case Patterns are used for both syntactic and semantic analysis.
(2) Procedures are usually embedded in Case Patterns to accomplish fine analysis and construct semantic structure.
(3) A list, called RLIST, is introduced to effectively control parsing as to reanalysis.

As another feature, the system generates somewhat intelligent responses, considering results of the database reference, or lack of input information. A deduction program based on a PLANNER-like pattern matching method uses three logical values, true, false and unknown to make sensible responses.

MSSS78 accepts sentences about arithmetic or geography, and responds to the sentences from its own knowledge and context of dialogue (Fig.I). Input sentences are typed in KATAKANA, a square form of KANA (the Japanese vowel and consonant combination syllable symbols), or ROMAJI (a method of writing Japanese language using the Western alphabet). The system responds by output sentences spelled in KATAKANA. Additionally, the system displays KANJI-KANA-MAJIRI-BUN (Japanese ordinary style of writing, spelled in KANJI (Chinese ideographs) and KANA) for both input and output sentences.

2 SENTENCE ANALYSIS OUTLINE

The MSSS78 analyzes a sentence by Case Patterns, carrying out syntactic and semantic analysis, and then solve a problem, which the system has to deal with.

The analysis process, roughly speaking, consists of two phases. First, the system analyzes all the possible sentence structures. Second, the system performs processing, such as composition and execution of a command to search database, composition of equations, etc. In the first analysis, the system fills case slots with return values of procedures embedded

in Case Patterns, In the second analysis, another procedure, embedded in the Case Patterns, interprets the filled case slots for the system purpose from its own knowledge and dialogue context.

3 BUNSETSU ANALYSIS (MORPHOLOGICAL ANALYSIS)

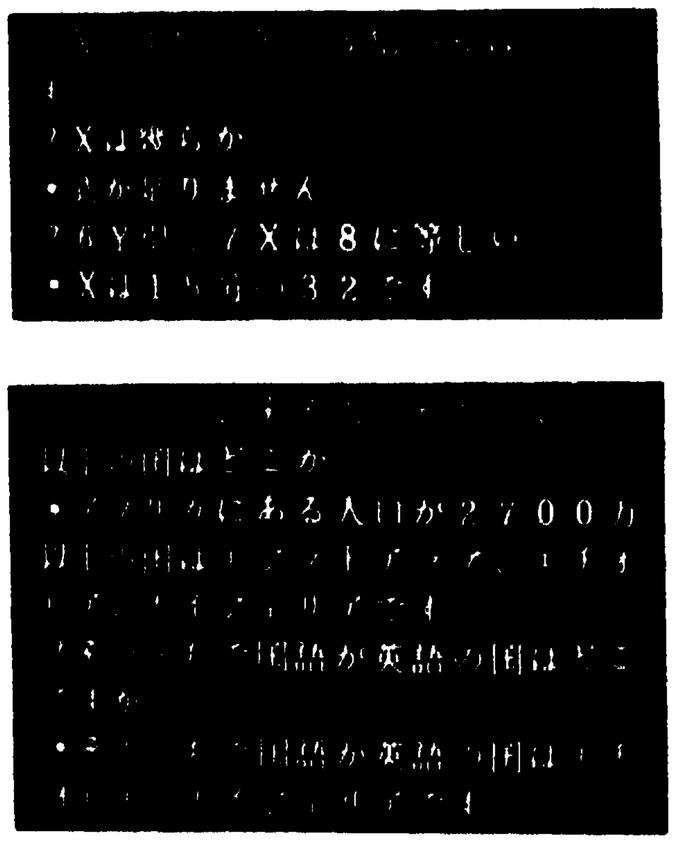
A Japanese sentence can be divided into a sequence of BUNSETSUs, a kind of syntactic unit. A BUNSETSU consists of two parts, a main part and an auxiliary part. The main part is a MEISHI (Japanese noun), a root of a DOUSHI (verb) or KEIYOUSHI (adjective), a FUKUSHI (adverb), or a RENTAISHI etc. The auxiliary part is a JOSHI (postpositioned word), KATSUYOU-GOBI (inflectional ending of a verb or an adjective), or JODOUSHI (auxiliary verb). They convey miscellaneous information, such as case information, tense information, or modal information. In addition, they show how a focused BUNSETSU modifies a succeeding BUNSETSU.

ｶﾞﾎﾞﾝﾊ ﾄﾞｺﾆ ｱﾘﾏｽｶ。 is a sentence written in KATAKANA, which means "where is Gabon", where ｶﾞﾎﾞﾝﾊ, ﾄﾞｺﾆ and ｱﾘﾏｽｶ。 are BUNSETSUs. Each BUNSETSU is internally transformed to a BUNSETSU spelled in ROMAJI, GABONWA, DOKONI and ARIMASUKA. BUNSETSU analyzer separates a BUNSETSU into main and auxiliary parts, that is, GABON-WA, DOKO-NI and AR-I-MAS-U-KA-. where GABON, DOKO, and AR are main parts, and WA, NI, and I-MAS-U-KA-. are auxiliary parts. In detail, GABON (noun) is a place name, DOKO (pronoun) means "where". AR is a root of a verb ARU which means "be" or "lie". WA and NI, usually connected to a noun, are JOSHI. I-MAS-U-KA-. is a composition of I (KATSUYOU-GOBI of ARU), MAS (root of an auxiliary verb MASU which indicates politeness), U (KATSUYOU-GOBI of MASU), KA (JOSHI which represents a question) and (period). We can expresses such relations between main parts and auxiliary parts, or between auxiliary parts, by a transition network dictionary.

In Japanese written language, it is not a recognized custom to leave a space between BUNSETSUs. In MSSS78, Input sentences can be typed while not leaving a space between BUNSETSUs. The network dictionary has special symbols, which designate an ending of a BUNSETSU element. BUNSETSU analyzer can identify a BUNSETSU by the special symbols.

4. CASE PATTERNS WITH PROCEDURES

Case frames of many case systems can be viewed more or less as frame-like linguistic knowledge. Case Patterns in this paper can be regarded basically as a new member of case frames. Case Patterns accomplish various kinds of processing, including syntactic and semantic analysis. Especially, elaborate analysis is



#Quadruple X plus thrice Y is 20. What is X?

The number of equations is insufficient.

#6Y minus 7X equals 8.

X is 32 over 15.

#What are African countries whose population is 27 million or more?

African countries whose population is 27 million or more are Egypt, Ethiopia, Nigeria.

#What are the countries among them whose language is English?

The countries among them whose language is English are Ethiopia, Nigeria.

Fig.l An actual dialogue with MSSS78. Left is the displays of the KANJI-KANA-MAJIRI-BUN for input and output sentences. Right is the translated English, where # is a prompt for input sentences.

possible by procedures embedded in Case Patterns. Case patterns are given in advance to main words, such as noun, verb and adjective. Case Patterns are constructed as follows.

```
Case-Patterns = (Case-Pattern
                 ...
                 Case-Pattern )
Case-Pattern = (slots [procedure-1])
slots = (slot ... slot)
slot = (slot-name
        syntactic-conditions
        semantic-conditions
        procedure-2
        [procedure-3] )
```

The parser locates dependent BUNSETSUs or phrases by matching RUNSETSU sequence with slots. The evaluation of slot constituents; syntactic conditions, semantic conditions and procedures, carries out the matching. Each slot may be regarded as a surface case.

The following is an explanation of Case Pattern constituents.

d) slot name provides a tag, by which the slot is associated in the succeeding analysis.

(2) Syntactic conditions provide conditions as to whether or not a BUNSETSU modifies a focused BUNSETSU. The focused BUNSETSU invokes the Case Patterns used. The modifier BUNSETSU is the right most BUNSETSU of a phrase, and the right most BUNSETSU represents the phrase. Syntactic conditions are generally JOSHI, or BUNSETSUs connection information in case a main part of BUNSETSUs is a verb or an adjective. Conjugation form of a verb or an adjective, or auxiliary parts of the BUNSETSU determins connection information. A special tag in syntactic conditions shows an obligatory or optional category for a slot.

(3) Semantic conditions provide semantic or conceptual conditions which a main part of a modifier BUNSETSU has to satisfy. These conditions make more detailed analysis, and exclude syntactically correct but semantically meaningless sentences. BUNSETSU main parts normally show semantic information to be examined. Semantic information is given in advance by the dictionary. In some cases, procedure-2 changes the information later on.

(4) Procedure-2 carries out, miscellaneous processing: the examination of other conditions, which the above syntactic conditions or semantic conditions cannot cover; the utilization of context information; or the extraction of semantic structure, etc. Syntactic conditions and semantic conditions provide conditions of a modifier BUNSETSU itself, rather than a phrase, although the BUNSETSU represents the phrase implicitly. Procedure-2 can examine the phrase structure explicitly, if necessary.

If a procedure-2(3) returns a non NIL value, the parser judges that the examined BUNSETSU (phrase) satisfies the slot, that is, the BUNSETSU modifies the focused BUNSETSU. In addition, if the value is non NIL value other than T, the value fills the slot. This slot is kept with the focused BUNSETSU, and is used by the succeeding analysis.

(5) Procedure-3 is a kind of procedure-2 for use when a connective form of a BUNSETSU to a focused BUNSETSU is RENTAI modification, a kind of a participial modification.

(6) Procedure-1 is invoked for a phrase (in MSSS78, a sentence) interpretation, when there aren't any more BUNSETSUs which modify the phrase. The procedure-1 interprets slots filled by evaluation of Case Patterns slots, and accomplishes processing, which the system has to deal with. The processing by procedure-1 may be considered as problem solving processes, or as a sort of deep structure analysis.

5 PARSING MECHANISM

5.1 Matching by PSTACK

The parser analyzes a sentence from left to right and from bottom to top, matching Case Patterns to a sequence of BUNSETSUs, or phrases put in a pushdown stack called PSTACK[3].

5.2 Reanalysis by RLIST

Parsing by case patterns doesn't necessarily succeed in a forward direction. In some cases, the parser must examine the rest part of a sentence to determine whether or not a BUNSETSU modifies a focused BUNSETSU. Augmented Transition Network grammar shows a similarity in the selection of several paths from a state[4]. In MSSS7B, the parser uses a list, called RLIST, to reanalyze an input sentence.

If a sentence can be segmented into different BUNSETSU sequences, or some word has a homonym, the parser can reanalyze the sentence on the same framework.

6 ANALYSIS EXAMPLES BY CASE PATTERNS

(1) Syntactic conditions: In the following sentences,

820WO 79DE WARUTO IKURAKA.
(Divide 820 by 79, what do you get?)

WO and DE (auxiliary parts of BUNSETSUs) make a difference between a dividend and divisor. The next Case Pattern to WARU (divide) provides the syntactic conditions.

```
(((TSY1 (WO ZERO) (KAZU HENSUU) (F-S-SIS0KU2))
  (TSY2 (DE RNT)
        (KAZU HENSUU)
        (COND
         ( (AND
            (EQ GVN-SYNTYP 'DRENTAI)
            (CDDR TREE)
            (EQ (SYNTYPE (CAAAR (CDDR TREE)))
             'ZERO ))
           NIL )
          ((F-S-SISOKU2)) )
        (S-ASSOC 'ATAI (CDDR SS)) ))
 (SISOKU) )
```

(2) Semantic conditions: In the next two phrases, which have the same meaning,

KOKUGOGA HURANSUGONO KUNI
(the country whose language is French)
HURANSUGOGA KOKUGONO KUNI
(the country where French is its language)

the concepts expressed by the underlined phrases are both language, but one, HURANSUGO (French), which is a compound of HURANSU (France) and GO (language), is an instance of languages, and the other, KOKUGO (language), is a generic concept. Procedure-2 of a Case Pattern to GO or KOKUGO determines a modifier of the underlined phrase by the next inner representations of modifiers.

```
(GNN KOKUGO)              ;KOKUGO
(TSB KOKUGO (IDN 2))      ;HURANSUGO
```

(3) Context: The following dialogue in MSSS78 shows an example concerning context processing.

#YO-ROPPADE MOTTOMO ZINKOUNO 001 KUNIWA DOKO DESUKA.
(What is the most heavily populated country in Europe?)
YO-ROPPADE MOTTOMO ZINKOUNO 001 KUNIWA NISHIDOITSU DESU.
(The most heavily populated country in Europe is West Germany.)

#[S0N01 ZINKOUWA DOREKURAI DESUKA.
(About how larqe is the population?)
ZINKOUWA 61830000 NIN DESU.
(It is 61830000.)

where # is a prompt symbol to accept input sentences, and words surrounded by [and] can be omitted. ZINKOUWA (the population) in the underlined sentences implicitly indicates the population of West Germany. If there is SONO (its) before ZINKOUWA, SONO explicitly indicates West Germany. Procedure-2 to SONO recognizes this indication from the context information in STM (short-term memory). The Japanese language contains no articles, but it seems that the function, which corresponds to the work done by an article, covers many different modes of expression. In this example, WA in ZINKOUWA functions as a definite article to indicate the context.

In the next sentence,

1W0 2NI TASHI 3W0 KAKERUTO IKURA DESUKA.
(Add 1 to 2 and multiply the result by 3, then what do you get?)

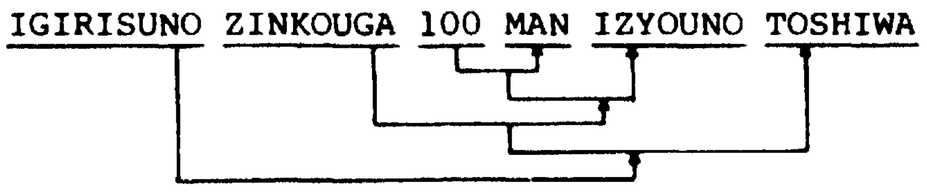
the result of "1WO 2NI TASHI" (add 1 to 2) implicitly indicates the multiplicand of KAKERU (multiply). Procedure-2 to KAKERU references the result through a slot attached to the phrase.

(4) Compound nouns: The parser analyzes the phrase,

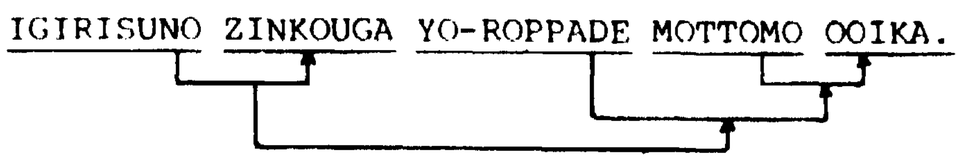
100 MAN NIN IZYOU
(one million persons or more)

as a compound of 100 (one hundred), MAN (ten thousand), NIN (person), and IZYOU (or more). In Japanese language, we normally consider IZYOU as a word like a suffix, but here the system treats IZYOU as a noun whose concept is a suffixal number. Procedure-2 to IZYOU changes the concept of the right most BUNSETSU, IZYOU, which represents the phrase, to a number. In the suceesing analysis, the BUNSETSU, IZYOU, is treated as a number.

(5) Reanalysis: In the next two sentences,



(British cities of a million or more population)



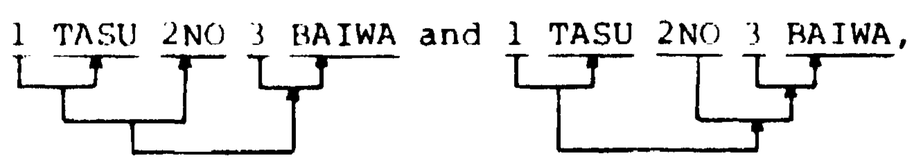
(Is British population the largest in Europe?)

when the parser focuses on ZINKOUGA (population), there is a possibility that 1GIRISUN0 (British) either modifies ZINKOU, or not. Procedure-2 to ZINKOU reports the alternative possibilities to the parser by the flag setting. At this stage, the parser takes the relation, wherein TGIRISUNO modifies ZINKOU. as the first selection, and holds the information about the other relation, wherein IGIRI5UNO does not modify ZINKOU, in RLIST with the environment information. Later on, the parser picks out the element from the RLIST, and reanalyzes the sentence from the state reset by the element.

(6) Ambiguity: Ambiguity is an interesting problem for an understanding system to deal with, from various viewpoints, such as syntax, semantics and pragmatics. In MSSS78, the system parses the underlined phrase in

1 TASU 2NO 3BAIWA IKURA DESUKA.

into two phrases,



where each phrase has either meaning of (1+2) x 3, and 1 + 2 x 3. At present, the system responds to the sentence as an ambiguity sentence, and asks for reinput.

As an ambiguitiy dependent upon the knowledge of the problem domain, the system interprets the underlined phrase in

1 TASU 2 KAKERU 3WA IKURA DESUKA.

as either meaning (1 + 2) x 3, or 1 + 2 x 3, from arithmetic knowledge. Procedure-2 in a Case Pattern to a number detects this ambiguity at the stage of the underlined phrase analysis.

(7) A variety of expressions: The following are among those which can be analyzed by Case Patterns to words whose concept is an equality, a number or a variable.

4WA X KAKERU 2NI HITOSHII.
4T0 XNO 2BAIWA HITOSHII.
(4 is equal to twice X.)

3X TASU 2YWA INI HITOSHII.
3XT0 2YN0 WAWA INI HITOSHIIDESU.
(3X plus 2Y is equal to 1.)
INI 2W0 TASUTO 3N1 HITOSHII.
INI 2W0 TASUTO SONO KEKKAWA 3NI HITOSHII
(1 plus 2 is equal to 3.)

7 SEMANTIC INTERPRETATION

7.1 Interpretation by Procedure-1

The parser analyzes a sentence by evaluation of Case patterns slots towards the solution of the problem, which the system has to deal with. Procedure-1 of a Case Pattern to a BUNSETSU, which represents a phrase(in MSSS7B, a sentence), interprets the resulting filled case slots to set up an equation, or construct and execute command to query database, etc.

From the underlined part in the next sentence,

AHURIKANI ARU ZINKOUGA 1000 MAN NIN IZYOUNO KOKUGOGA EIGONO KUNIWA DOKO DESUKA.
(What are countries in Africa, whose population is ten million or more, and whose language is English?),

the parser recognizes three phrases, such as the country in Africa, the country whose population is ten million or more, and the country whose language is English. The inner representation including filled slots to the phrases is as follows.

```
(GNN KUNI
 (RNT ARU (TSY1 (TSB TAIRIKU (IDN 2)))
 (ZMK (TSB KAZU
        (ATAI "G10000000")
        (GNN ZINKOU) ) )
 (ZMK (TSB KOKUGO (IDN 212))) )
```

Procedure-1 to DESU constructs the next command by interpretation of the filled slots, and executes the command.

```
(TEST ((KUNI 2 (V KUNI))
        (WAWA (V KUNI) KUNI)
        (ZINKOU (V KUNI) "G1000000")
        (WAWA (V KUNI) KUNI)
        (KOKUGO (V KUNI) -3) ))
```

The TEST commmand searches into database by means of PLANNER-like procedural deduction mechanism (no backtracking unlike PLANNER). According to the return value of the command, a sentence generator constructs response sentences. (The sentence generator reconstructs an output sentence from a parsed tree of an input sentence, supplementing or

replacing necessary words according to the input sentence pattern or the result of a problem solving.)

7.2 Interpretation by World Knowledge

Complete set of objects and relations in the geography world is unknown[5]. In MSSS78, the answer to the question

KANADANO SYUTOWA MONTORIO-RU KA.

(Is the capital of Canada Montreal?),

turns out to be

HE, KANADANO SYUTOWA MONTORIO-RU DEWAARIMASEN. KANADANO SYUTOWA OTAWA DESU.
(No, the capital of Canada isn't Montreal. The capital of Canada is Ottawa.),

or

KANADANO SYUTOWA MONTORIO-RU KA WAKARIMASEN.
(I don't know that the capital of Canada is Montreal.)

according to whether or not the fact that the capital of Canada is Ottawa is in the database. For the above responses, the deduction program uses three logical values, true, false and unknown. Procedural type knowledge prepares logical value and additional information.

8 CONCLUSION

The experimental Japanese language question answering system, MSSS78, was made in a series of research efforts intended to construct a natural language man-machine interface. The system uses Case Patterns for syntactic and semantic analysis. The Case Pattern method seems to produce modularity and extendability of syntactic and semantic programs, and the readiness of system making.

Procedures in Case Patterns are a good tool for testing various processings. However, from a viewpoint of easy descriptiveness and system stability, it would be better to describe various functions absorbed in the procedures, using the so-called declarative style.

MSSS78 generates a response based on three logical values as well as additional information as to the result of the reference to the database. Such responses can be thought to place reliance on database. For the reference to a database, it seems convenient to be able to utilize the previous reference result in accordance with the context indication.

For written Japanese, it is better to display KANJI-KANA-MAJIRI-BUN for input and output sentences. In KANJI-KANA-MAJIRI-BUN display, output sentences are redundant at present.

MSSS78 was implemented on PDP11/55 with extensive utilization of disk memory capacity. The language used for the implementation is mainly LIPX, an extended version LIPQ16], plus a little bit of assembler. The dictionary contains more than 600 words at the time. To analyze and respond to each sentence, takes from a few seconds to a few minutes, where most of the latter is search time for data in the database.

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RESOLUTION IN A NEW MODAL LOGIC

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This paper proposes a new logic called manner logic(ML) and considers resolution techniques for mechanical theorem proving in the ML. The ML deals with statements which contain adverbs or verbs representing manner such as possibility, uncertainty and causality. Manner is expressed by a manner operator "*", which is a monadic operator. By using manner operators, a postulate can be four-valued; true(T), true in the sense of "*" (T*), false in the sense of "*" (F*), or false(F). In the ML, an atomic formula is assigned a value T or F, but a well-formed formula is assigned a value T, T*, F*, or F. Therefore, the ML can represent more complicated statements than the ordinal predicate logic. Its logical manipulation is quite simple, since it can be considered an extension of the oridinal binary logic. This paper also discusses resolution techniques in a refutation process. In our method, an additional valid clause is used in a refutation process to resolve clauses with manner operators which cannot be resolved directly.

1. INTRODUCTION

In the real world, the situation is often encountered where a postulate can be many-valued rather than two-valued. However, the many-valued logic is too complex to be applied to predicate calculus in artificial intelligence.

There are some other interesting logics such as a modal logic, tense logic or fuzzy logic. The modal logic [2], [3] had its effective beginning with work of C.L. Lewis[3] some sixty years ago, and is known as the logic of necessity and possibility. The tense logic [4], [6] deals with statements containing tensed verbs or explicit temporal references, and is logically similar to the modal logic. In these logics, the mode and tense are represented by two monadic symbols, and a postulate can be two-valued; true or false.

The present paper proposes a new logic which falls under the heading of the ordinal modal logic in a wide sense. The proposed logic deals with statements which contain adverbs or verbs representing manner such as possibility, uncertainty and causality. Monadic operators called manner operators are introduced to express such manner. A postulate in the logic can be four-valued; for example, true, possibly true, possibly false, or false. That is, a value T or F is assigned to each atomic formula in a well-formed formula(wff), but a value T, T*, F*, or F is assigned to the wff as described in the following sections. Consequently, we call the new logic the multi-binary logic or manner logic(ML). The manner logic can represent more complicated statements than the ordinal predicate logic, since it is essentially a four-valued logic.

Thus we are interested in the application of the ML to solve intellectual difficult problems. As is well known, the resolution principle due to Robinson[7], [8], [9] is a simple but extremely useful technique for mechanical theorem proving. It is difficult, however, to apply the Robinson's resolution principle to the ML, because clauses contain manner operators. To circumvent this difficulty, additional clauses which are valid are used in a refutation process. The present paper considers some fundamental properties of the ML, and gives a new rule of inference for mechanical theorem proving.

2. FUNDAMENTAL PROPERTIES

This section is devoted to consideration of fundamental properties of the ML. We shall introduce the symbol "*" with intention of interpreting it as a manner operator, which is placed on the shoulder of well-formed formulas. Suppose a proposition P is interpreted as "She is beautiful". Then P* is "She is possibly beautiful", "She will be beautiful", or "She seems to be beautiful" or "She is very beautiful", in the sense of the modal, tense or fuzzy logic, respectively.

The symbols such as P, Q and R, that are used to denote propositions are called atoms.

Definition 1 Well-formed formulas (wff) or formulas for short in the ML are defined recursively as follows:

1. An atom is a formula.
2. If G is a formula, then so are ~G and G*.
3. If G and H are formulas, then so are G∨H, G∧H, G→H.
4. All formulas are generated by applying the above rules.

In the ordinal logic, a well-formed formula can be either true or false. Here we represent "true" by T and "false" by F. Therefore, ~G is T when G is F, and is F when G is T. In the similar manner, G* is T* when G is T, and is F* when G is F. Consequently, a well-formed formula G can be T, T*, F* or F; that is, true, true in the sense of "*", false in the sense of "*", or false. For example, G is true, G is probably true, G is probably false, or G is false.

We begin by defining some logical symbols used here by means of Table 1. They are ~ (negation), *(manner), ∨(disjunction), ∧ (conjunction), and →(implication). This table expresses the truth value of the statements. It is seen from Table 1 that the implication can be represented by a negation and disjunction as follows:

$$X \rightarrow Y = \sim X \vee Y$$

where X and Y are wffs.

Some examples of statements containing manner operators are shown below. Let P and Q be propositional symbols interpreted as

P : She is young.
Q : She is beautiful.

Then the expression X→Y asserts as follows:

P→Q : If she is young, then she is beautiful.

P	F	F	T	T
Q	F	T	F	T
~P	T	T	F	F
P*	F*	F*	T*	T*
(P*)*	F*	F*	T*	T*
~(P)*	T*	T*	F*	F*
(~P)*	T*	T*	F*	F*
P∨Q	F	T	T	T
P∨Q*	F*	T*	T*	T*
P*∨Q	F*	T	T*	T
P*∨Q*	F*	T	T	T*
P∧Q	F	F	F	T
P∧Q*	F	F	F*	T*
P*∧Q	F	F*	F	T*
P*∧Q*	F*	F	F	T*
P→Q	T	T	F	T
P→Q*	T	T	F*	T
P*→Q	T*	T	F*	T
P*→Q*	T	T*	F	F

Table 1 Truth table

P→Q*: If she is young, then she seems to be beautiful.
P*→Q : If she seems to be young, then she is beautiful.
P*→Q*: If she seems to be young, then she seems to be beautiful.
(P→Q)*: It seems that if she is young she is beautiful.

As shown in the above examples, more complex statements can be represented if manner operators are employed.

Now, we consider the fundamental properties of the ML. Let P, Q, and R be atoms, and X, Y, and Z be well-formed formulas. From the truth table, Table 1, we have the following laws:

Idempotent laws

$$X \vee X = X, \quad X \wedge X = X \tag{1}$$

Absorption laws

$$X \vee (X \wedge Y) = X, \quad X \wedge (X \vee Y) = X \tag{2}$$

Commutative laws

$$X \vee Y = Y \vee X, \quad X \wedge Y = Y \wedge X \tag{3}$$

Associative laws

$$X \vee (Y \vee Z) = (X \vee Y) \vee Z, \quad X \wedge (Y \wedge Z) = (X \wedge Y) \wedge Z \tag{4}$$

Distributed laws

$$X \vee (Y \wedge Z) = (X \vee Y) \wedge (X \vee Z), \quad X \wedge (Y \vee Z) = (X \wedge Y) \vee (X \wedge Z) \tag{5}$$

Involution laws

$$\sim(\sim X) = X. \tag{6}$$

De Morgan's laws

$$\sim(X \vee Y) = \sim X \wedge \sim Y, \quad \sim(X \wedge Y) = \sim X \vee \sim Y. \tag{7}$$

Contradiction laws

$$X \vee \sim X = T, \quad X \wedge \sim X = F. \tag{8}$$

Complement laws

$$X \vee F = X, \quad X \wedge T = X \tag{9}$$

$$X \wedge F = F, \quad X \vee T = T. \tag{10}$$

These laws are the same as those in the ordinal logic, but the following laws are peculiar to the ML.

- $(P^*)^* = P^*.$ (11)
- $\sim(P^*) = (\sim P)^*.$ (12)
- $P^* = (P \wedge T^*) \vee (\sim P \wedge F^*), \quad (\sim P)^* = (P \vee T^*) \wedge (\sim P \vee F^*).$ (13)
- $(X \vee Y)^* = (X^* \vee Y^*) \wedge T^* \vee (X^* \wedge Y^* \wedge F^*).$ (14)
- $(X \wedge Y)^* = (X^* \wedge Y^* \vee F^*) \wedge (X^* \vee Y^* \vee T^*).$ (15)

Using the laws (1) - (15), we have the logical equivalences as follows:

- $P \wedge P^* = P \wedge T^*, \quad \sim P \wedge \sim P^* = \sim P \wedge T^*,$ (16)
- $P \wedge \sim P^* = P \wedge F^*, \quad \sim P \wedge P^* = \sim P \wedge F^*.$

[Proof] The proof is obtained from Eq. (13).

- $P \vee P^* = P^* \vee F^*, \quad \sim P \vee \sim P^* = \sim P^* \vee F^*,$ (17)
- $P \vee \sim P^* = P \vee T^*, \quad \sim P \vee P^* = \sim P \vee T^*.$

[Proof] The proof is obtained from Eq. (13).

- $(\sim P \vee P^*) \wedge (P \vee \sim P^*) = T^*,$ (18)
- $\sim P \wedge P^* \vee P \wedge \sim P^* = F^*.$

[Proof] The proof is obtained from Eqs. (16) and (17).

- $(P \wedge P^*) \vee (\sim P \wedge \sim P^*) = T^*,$ (19)
- $(P \vee P^*) \wedge (\sim P \vee \sim P^*) = F^*.$

[Proof] The proof is obtained from Eqs. (16) and (17).

- $(P \vee Q)^* \wedge (\sim P \vee \sim Q)^* = (P \wedge \sim Q \vee \sim P \wedge Q) \wedge T^*,$ (20)
- $(P \vee \sim Q)^* \wedge (\sim P \vee Q)^* = (P \wedge Q \vee \sim P \wedge \sim Q) \wedge T^*.$

[Proof] The proof is obtained from Eqs. (14) and (15).

- $(P^* \wedge \sim Q^*) \vee (\sim P^* \wedge Q^*) = (P \wedge \sim Q) \vee (\sim P \wedge Q),$
- $(P^* \wedge Q^*) \vee (\sim P^* \wedge \sim Q^*) = (P \wedge Q) \vee (\sim P \wedge \sim Q).$ (21)

[Proof] The proof is obtained from Eqs. (14) and (15).

- $(P^* \vee Q)^* = (P^* \vee Q^*)^* = (P \vee Q)^*,$
- $(P^* \wedge Q)^* = (P^* \wedge Q^*)^* = (P \wedge Q)^*.$ (22)

[Proof] The proof is obtained from Eqs. (14) and (15).

- $P \wedge Q \wedge (P \wedge Q)^* = P \wedge Q \wedge P^* \wedge Q^* = P \wedge Q \wedge T^*,$ (23)
- $P \vee Q \vee (P \vee Q)^* = P \vee Q \vee P^* \vee Q^* = P \vee Q \vee F^*.$

[Proof] The proof is obtained from Eqs. (14) and (15).

- $P^* = P^* \wedge (P \vee F^*) = P^* \wedge (\sim P \vee T^*)$
  $= P^* \vee P \wedge T^* = P^* \vee \sim P \wedge F^*,$ (24)
- $\sim P^* = \sim P^* \vee \sim P \wedge T^* = \sim P^* \vee P \wedge F^*$
  $= \sim P^* \wedge (\sim P \vee F^*) = \sim P^* \wedge (P \vee T^*).$

[Proof] The proof is obtained from Eqs. (18) and (19).

- $(P \rightarrow Q)^* = (P^* \rightarrow Q^*) \wedge (P \rightarrow Q^*) \wedge (P^* \rightarrow Q).$ (25)

[Proof] The proof is obtained from Eqs. (14) and (15).

Now, we will show that a formula Y can be represented in the conjunctive and/or disjunctive normal form.

Definition 2. A formula Y is said to be in a conjunctive or disjunctive normal form if and only if Y has the form

$$Y = Y_1 \wedge \ldots \wedge Y_n$$

or

$$Y = Y_1 \vee \ldots \vee Y_n,$$

where each of $Y_1, \ldots, Y_n$ is a disjunction or conjunction of literals with and without manner operators, respectively.

Let $P_1, P_2, \ldots, P_m, Q_1, Q_2, \ldots, Q_n$ be atoms, and $Y(P_1, P_2, \ldots, P_m, Q_1^*, Q_2^*, \ldots, Q_n^*)$ be an (m + n)adic formula.
Then we have

$$\begin{aligned}
&Y(P_1, P_2, \ldots, P_m, Q_1^*, Q_2^*, \ldots, Q_n^*) \\
&= P_1 \wedge Y(1, P_2, \ldots, P_m, Q_1^*, Q_2^*, \ldots, Q_n^*) \\
&\quad \vee \sim P_1 \wedge Y(0, P_2, \ldots, P_m, Q_1^*, Q_2^*, \ldots, Q_n^*) \\
&\quad \vee \ldots\ldots\ldots \\
&= (P_1 \wedge P_2 \wedge \ldots \wedge P_m \wedge Q_1 \wedge Q_2 \wedge \ldots \wedge Q_n \\
&\qquad \wedge Y(1, \ldots, 1, 1^*, \ldots, 1^*)) \\
&\quad \vee \ldots\ldots\ldots \\
&\vee (\sim P_1 \wedge \sim P_2 \wedge \ldots \wedge \sim P_m \wedge \sim Q_1 \wedge \sim Q_2 \wedge \ldots \wedge \sim Q_n \\
&\qquad \wedge Y(0, \ldots, 0, 0^*, \ldots, 0^*)).
\end{aligned} \tag{26}$$

$$
\begin{aligned}
&Y(P_1, P_2, \ldots, P_m, Q_1^*, Q_2^*, \ldots, Q_n^*) \\
&= (P_1 \vee Y(0, P_2, \ldots, P_m, Q_1^*, Q_2^*, \ldots, Q_n^*) \\
&\qquad \wedge (\sim P_1 \vee Y(1, P_2, \ldots, P_m, Q_1^*, Q_2^*, \ldots, Q_n^*)) \\
&= (P_1 \vee \ldots \vee P_m \vee Q_1 \vee \ldots \vee Q_n \\
&\qquad\qquad \vee Y(0, \ldots, 0, 0^*, \ldots, 0^*)) \\
&\qquad\qquad \wedge \ldots\ldots\ldots \\
&\qquad \wedge (\sim P_1 \vee \ldots \vee \sim P_m \vee \sim Q_1 \vee \ldots \vee \sim Q_n \\
&\qquad\qquad\qquad Y(1, \ldots, 1, 1^*, \ldots, 1^*)) .
\end{aligned}
\tag{27}
$$

The former is the disjunctive normal form and the latter is the conjunctive normal form. As mentioned before, Y(.....) can be T, T*, F* or F, and then T* and F* appear in Eqs. (26) and (27). Using Eqs.(18) and (19), however, we can eliminate T* and F*. Therefore, any formula can be represented by using

$\sim$, *, $\vee$, and $\wedge$.

3. RESOLUTION TECHNIQUES

As is well known, the resolution principle is a useful technique for making deduction in the system of the first-order predicate calculus. Here we consider techniques based on the resolution principle for the ML system. Some important definitions of terminology are given as follows:

Definition 3 A formula G is said to be satisfiable or semi-satisfiable if and only if there exists an interpretation I such that Y is evaluated to T or T*, respectively. In this case, we say I satisfies or semi-satisfies Y.

Definition 4 A formula is said to be unsatisfiable or semi-unsatisfiable, if and only if it is F or F* under all its interpretation. A formula is said to be satisfiable or semi-satisfiable if and only if it is not unsatisfiable or not semi-unsatisfiable, respectively.

Definition 5 A formula G is said to be a logical consequence or semi-consequence of a given set of formulas S, if and only if every interpretation satisfying or semi-satisfying S also satisfies or semi-satisfies G, respectively.

Definition 6 Given a formula G, a formula G obtained by removing all manner operators in G is said to be a reduced formula of G.

Definition 7 Given a clause C, a clause C obtained by removing all manner operators in C is said to be a reduced clause of C.

Definition 8 A clause which takes F or F* is said to be an empty or semi-empty clause, respectively.

Processes for showing the unsatisfiability or semi-unsatisfiability are called refutation processes. The following theorems give basic properties used for refutation processes.

Theorem 1

The following clauses C_1 and C_2 are valid

C_1 : $(\sim P \wedge P^*) \rightarrow F^*$

C_2 : $(P \wedge \sim P^*) \rightarrow F^*$.

[Proof]

From Eq. (17), we have

$$
\begin{aligned}
(\sim P \wedge P^*) \rightarrow F^* &= P \vee \sim P^* \vee F^* \\
&= T,
\end{aligned}
$$

which gives the proof. q.e.d.

Theorem 2

Given formulas $Y_1, \ldots, Y_n$ and a formula G, G is a logical consequence or semi-consequence of $Y_1, \ldots, Y_n$ if and only if the formula $(Y_1 \wedge \ldots \wedge Y_n \wedge \sim G)$ is unsatisfiable or semi-unsatisfiable, respectively.

[Proof]

($\Rightarrow$) Suppose G is a logical consequence or semi-consequence. In an interpretation I satisfying or semi-satisfying $Y_1, \ldots, Y_n$, G is T or T* and then $Y_1 \wedge \ldots \wedge Y_n \wedge \sim G$ is F or F*, respectively.

($\Leftarrow$) Suppose $Y_1 \wedge \ldots \wedge Y_n \wedge \sim G$ is unsatisfiable or semi-unsatisfiable. For any interpretation I, if $Y_1 \wedge \ldots \wedge Y_n$ is T or T*, then G must be T or T* in I. Therefore, G is a logical consequence or semi-consequence of $Y_1, \ldots, Y_n$.

Now, we consider the application of the resolution principle due to Robinson to the theorem proving in the ML.

The resolution principle is essentially an elegant technique to check whether a given set of clauses is unsatisfiable or semi-unsatisfiable.

Consider the following set of clauses

$S_1 = \{C_1, C_2, C_3\}$

C_1 : P

C_2 : $P \rightarrow Q^*$ or $\sim P \vee Q^*$

C_3 : $\sim Q$.

The resolution technique is very similar to that of Robinson except that clauses may contain manner operators. In this case, the resolvent Q* (clause C_4) is obtained by deleting the pair of literals P and $\sim P$ from clauses C_1 and C_2:

C_4 : Q* from C_1 and C_2.

However, we have no way to get the resolvent from clauses C_3 and C_4. Thus, a new set of clauses S_2 is introduced such that

$$S_2 = S_1 \cup C_5$$
$$= \{C_1, C_2, C_3, C_5\}$$

$$C_5 : Q \vee \sim Q^* \vee F^*.$$

Since C_5 is a tautology from Theorem 1, S_2 is equivalent to S_1 from the point of view of refutation processes. Thus we have

C_6 : $\sim Q^* \vee F^*$ from C_3 and C_5

C_7 : F^* from C_4 and C_6.

Therefore, S2 is semi-unsatisfiable and so Is S1

In the above example, however, if *C3* = Q* is used instead of C3, then we have the empty clause as the resolvent of C3 and *C4.*

Here a question arises : In what case a set of clauses is semi-unsatisfiable ? As described before, a formula G is a logical semi-consequence of Y], ,.., Yn if a semi-empty clause is obtained as a resolvent in a refutation process. This means, therefore, thnt 0 is true in a sense of "*". For example, consider the case where "G*" asserts "It possibly rains". If a semi-empty clause is obtained, the proof is possibly true or the inference is possibly correct. That is, it is possibly true to conclude that it rains. On the other hand, the proof is true if an empty clause is obtained. The following sets of clauses are also semi-unsatisfiable and give the same results as above.

$\{P, \sim P \vee Q, \sim Q^*\}$

$\{P^*, \sim P \vee Q, \sim Q\}$

$\{P, (\sim P \vee Q)^*, \sim Q\}$.

Now we will show some important properties of a resolvent in the following theorems.

Theorem 3

A resolvent of given two clauses C1 and C2 is a logical consequence or semi-consequence of *C1* and C2.

[Proof]

Let C}, C2 and C3 be denoted as follows:

C1 - XvC1, C2 «~XVC2, C3 - CivC2.

The proof will be made in the case (i) X * F, (ii) F*, (iii) T*, and (iv) T. Suppose there exists an interpretation 1 for which *C1* and C2 are T or T*. In cases (i) and (ii), cj must be T or T*, and thus C3 = T or T*. In cases (iii) and (iv), C2 must be T or T*, and thus C3 - T or T*. This gives the proof. q.e.d.

Theorem 4

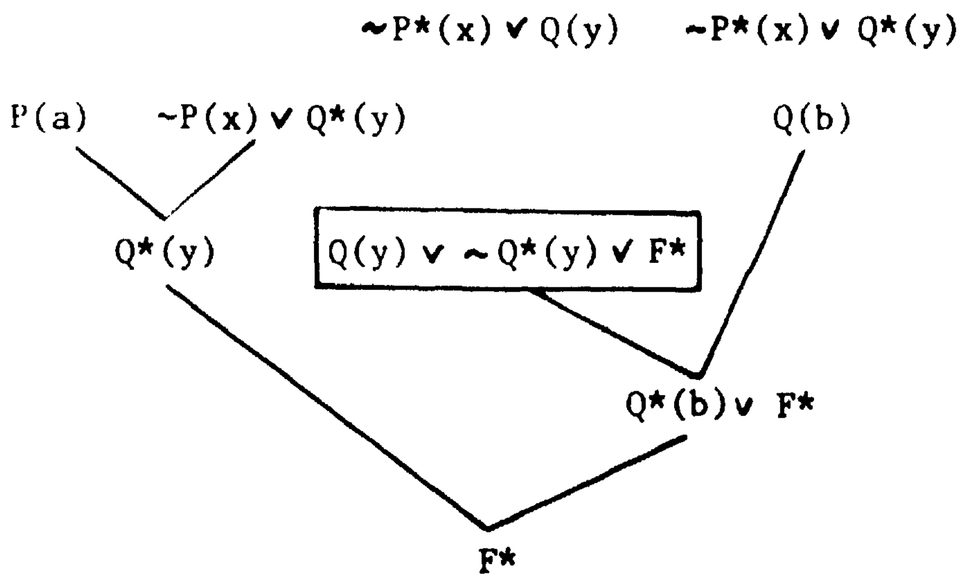
Let S be an unsatisfiable or semi-unsatisfiable set of clauses and $\bar{S}$ be a reduced set of S. If an empty clause is obtained from $\bar{S}$ by applying the resolution principle, then either an empty or semi-empty clause is obtained from S.

[Proof]

Let $\bar{C}_3$ be a resolvent of reduced clauses $\bar{C}_1$ and $\bar{C}_2$. If $\bar{C}_1$ and $\bar{C}_2$can be resolved, then they must be indicated as follows: $\bar{C}_1 = L \vee C_1'$, and $\bar{C}_2 = \sim L \vee \bar{C}_2'$, where L is a literal. Therefore, we have (i) $C_1 = X \vee C_1'$, $C_2 = \sim X \vee C_2'$, or (ii) $C_1 = P \vee C_1'$, $C_2 = \sim P^* \vee C_2'$.
It is clear that an empty clause is obtained as the resolvent in the case (ii) and that an empty or semi-empty clause is obtained in the case (i).

Fig. 1 illustrates an example of refutation graphs for a set of clauses as follows:

$S = \{P(a), (P(x) \rightarrow Q(y))^*, \sim Q(b)\}$
$= \{P(a), (\sim P(x) \vee Q(y))^*, \sim Q(b)\}$
$= \{P(a), \sim P(x) \vee Q^*(y), \sim P^*(x) \vee Q(y),$
$\sim P^*(x) \vee Q^*(y), Q(b)\}.$



~P*(x) ∨ Q(y) ~P*(x) ∨ Q*(y) : unused clauses

Q(y) ∨ ~Q*(y) ∨ F* : tautology

Fig. 1 A refutation graph for S = {P(a), (P(x) → Q(y))*, ~Q(b)}

4. CONCLUDING REMARKS

We have, considered a new logic called the ML and derived its mathematical properties. Due to manner operators introduced here, the ML can express more complex statements than the ordinal logic. Since the ML can be considered an extension of the ordinal binary logic, its logical manipulation is quite simple, although it is a four-valued logic. Four values are true(T), true in the sense of "*" (T*), false in the sense of "*"(F*) and false (F). Furthermore, we have developed some interesting applications of the ML to mechanical theorem proving in artificial intelligence. A refutation process for the ML system is similar to that of the ordinal propositional or predicate logic. The idea of semi-unsatisflability is introduced in the refutation process. That is, a semi-empty clause is obtained as a resolvent if a set of clauses is semi-unsatisfiable. In the refutation process for mechanical theorem proving, therefore, the appearance of a semi-empty clause means that the inference is not completely true but true in the sense of "*". This is one of the advantages of our system.

Several directions seem to be interesting for furthering investigations.of the ML from both a mathematical and applicational point of view. The author believes that the ML system is quite useful for solving complex problems.

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TOWARDS MINIMAL DATA STRUCTURES FOR DETERMINISTIC PARSING

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The determinism hypothesis suggests that natural language may be parsed in a single pass w'thout resort to backtracking techniques. The PARSIFAL system, developed by Marcus, incorporates this philosophy in an English language parser. Here, we show that the data structures used by this parser may be considerably simplified resulting in more elegant grammatica1 spec il 1cat ions.

Keywords: artificial intelligence, natural language processing, deterministic parsing

[1] • IM DETERMINISM HYiHJTH^SIJS

Marcus [1][2] proposes that natural language may be parsed in a fully deterministic manner. Under this determinism hypothesis portions of the parse-tree, once constructed, necessarily become part *of* the final parse-tree output. This is in contrast to the traditional back-tracking paradigm in which "guesses" are made about the syntactic structure ot the input sentence; and, when the guess proves later to be Incorrect, any parse-tree structures re-sulting from that guess must be erased prior to testing alternate hypotheses.

An important discovers' was that English could be parsed determin1stically by using an, at most, three-constituent look-ahead strategy. This differs from the k-token look-ahead strategy used by an LR(k) parser in that the bounded look-ahead is with reference to parsed constituents rather than to individual words of the sentence. For example, the sequence <auxverb ' <noun phrase- appearing at the beginning of the sentence would indicate that a yes-no question was being parsed. Note that in order for this sequence to appear in the look-ahead buffer, it would have been necessary to first parse the noun phrase in the second position. This is accomplished by means of an atLention shifting rule in the grammar. In the example above, the attention si)ifting rule would detect the beginning *of* a noun phrase starting in the second position of the look-ahead buffer. It would then shift the look-ahead window one position to the right, just past the ^{c}auxverb>, and activate grammar rules suitable for parsing noun phrases. The noun phrase parse then operates only with respect to words in the input sentence to the right of the <auxverb>. When the noun phrase parse is complete, attention shifts back to the original look-ahead window position with the <auxverb^{s}> in first position and the new <noun phrase^{v}- in the second position.

By using such an approach it is possible to parse natural language in a time on the order of the length of the input sentence. A more detailed discussion, including arguments for the psychological reality of the determinism hypothesis can be found in [1][2],

This deterministic mechanism has been incor-porated as part of the PARSIFAL system devel-oped by Marcus. In this paper we propose a simplification of the data structures employed by PARSIFAL. The change significantly lessens the amount of detail which must be explicitly specitled in the rules of the grammar. This results from the fact that this detail can now be implicitly embedded in the control structure of the parser.

The new approach will be presented after a cursory overview of the current PARSIFAL mechanisms.

"Is the boy John saw yesterday going to the party?"

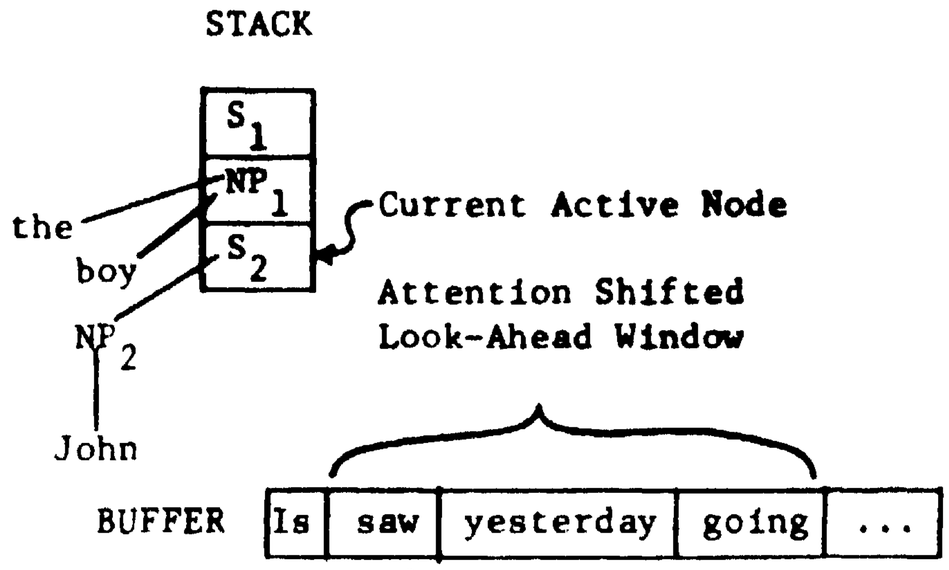

Figure 1. PARSIFAL's STACK and BUFFER

2. THE PARSIFAL APPROACH

2.1 Data Structures

PARSIFAL uses two data structures to record parsing progress (Fig. 1). These are the Stack and the Buffer. The Buffer is the look-ahead buffer discussed in the previous section. The Stack is used to hold partial structures which have already been parsed by the system. The Buffer contains only terminals and complete sub-trees, while the Stack contains sub-trees under construction. (Note that the Stack differs from the pushdown stack used by backtracking parsers in that structures once parsed and placed on the Stack are always used later as subordinates of larger structures.) Instructions to move nodes between the Buffer and the Stack must be explicitly stated in the system's grammar rules. Grammar rules build the structures on the stack by removing elements from the Buffer and attaching them to the most recent node on the Stack, this may be a newly created non-terminal node or a previously created non-terminal which already has some subordinate structures attached to it. When a complete sub-tree has been built on the stack, the parent node is dropped from the stack back into the buffer to be used there in the construction of higher-level constituent structures.

2.2 Attention Shifting Rules

Attention shifting rules are responsible for adjusting the look-ahead window of the Buffer to the proper position for parsing a new sub-constituent. They must be treated as a special case since they need to be able to scan the buffer to locate the beginning of the sub-constituent. Once this has happened, the new node is created, pushed on the stack and the look-ahead window is explicitly advanced. Special attention must also be given to the problem of restoring the look-ahead window after the sub-constituent parse is complete.

2.3 Node Reactivation Rules

An additional type of grammar rule is the node reactivation rule. Its function can perhaps best be explained through an example. Consider the case of a noun phrase which includes an attached relative clause. During the processing of the relative clause it is sometimes necessary to access the attributes of parent nodes of the noun phrase under construction. However, since the noun phrase sub-tree has not yet been completed at the time the relative clause is being parsed, the noun phrase is not attached to a parent. Thus, access to parent attributes from the relative clause would be impossible. To remedy this situation, the noun phrase parse tree is prematurely taken to be complete just prior to parsing the relative clause. The noun phrase can then be attached by its parent node. A node reactivation rule is then called into play. It "reactivates" the noun phrase processing in order to parse the relative clause. Now, the grammar rules for processing the relative clause are able to reference the parents of the noun phrase.

Thus, in figure 1, if it were desirable to attach the NP1 to S1 as its subject, NP1 would have to be prematurely marked complete and later reactivated to continue parsing the phrase.

Node reactivation rules were intended to be only a temporary solution to certain parsing problems. The data structuring approach described in the next section eliminates the need for such a reactivation mechanism.

3. THE UNIFIED APPROACH

3.1 The Unified Data Structure

Under the proposed strategy, the former Stack and Buffer are combined into a single Buffer.

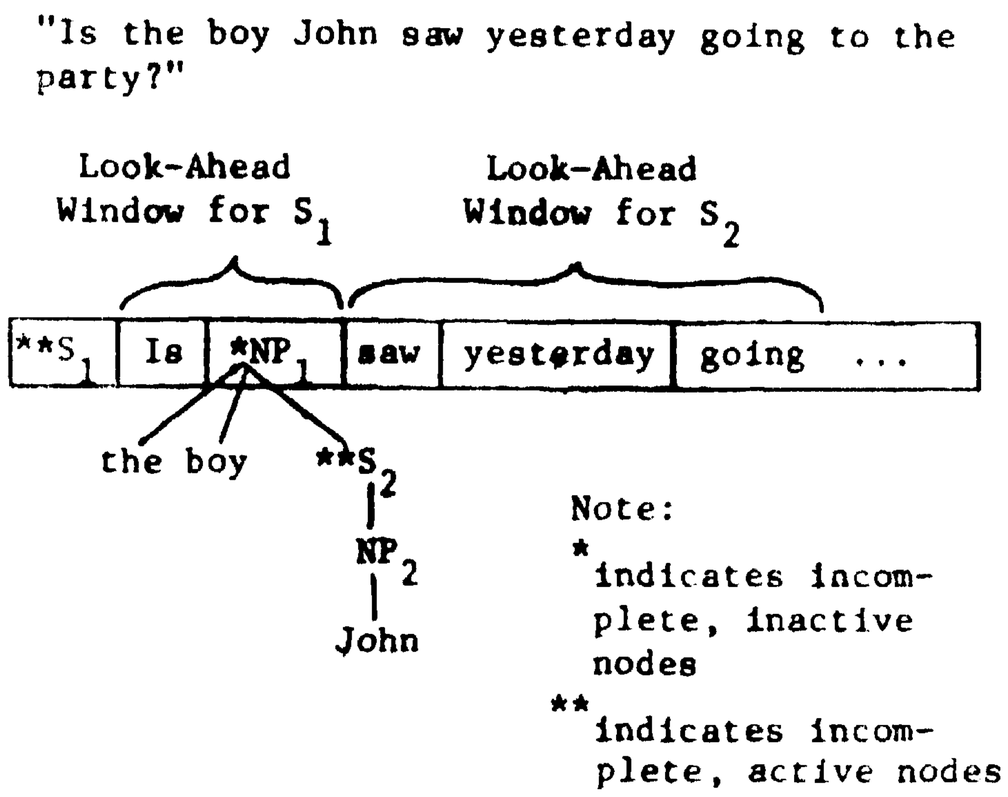

Figure 2. Unified BUFFER Organization

This buffer holds both complete and incomplete sub-trees (see Fig. 2). For each incomplete sub-tree, the most subordinate incomplete node is considered to be the active node for that subtree. A parsing process is associated with each active node. This parsing process operates over a look-ahead window consisting of the three Buffer cells following that Buffer cell which contains the active node.

Because the new Buffer structure now contains all the information previously contained in the Stack as well, the explicit instructions which transfered data between the two structures are no longer necessary.

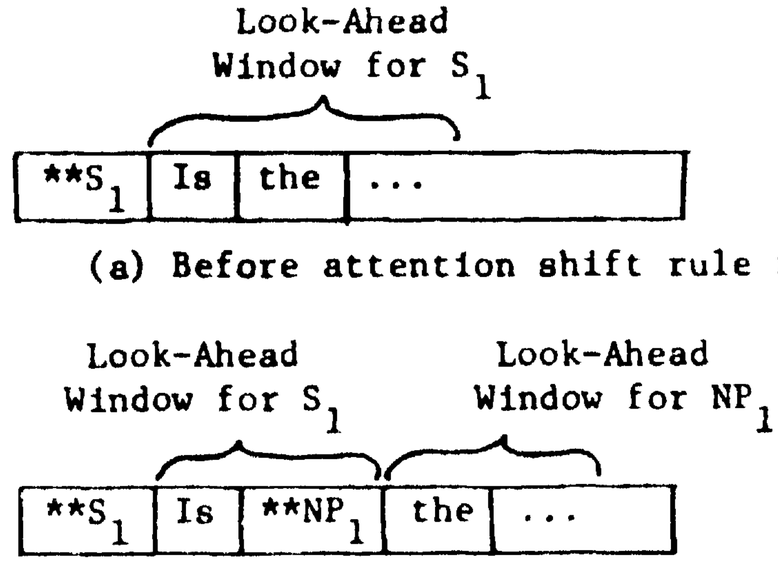

Figure 3. Automatic Attention Shifting

3.2 Automatic Attention Shifting

Under this scheme, the attention shifting rules simply insert a newly created node into the Buffer (see Fig. 3). Since a newly created node is necessarily an incomplete node, It is automatically active. The look-ahead window for the new node, as for any active node, is defined to be the next three cells in the Buffer. No explicit mechanism for shifting attention is needed.

3.3 Automatic Node Reactivation

All active nodes are considered to be parsing their look-ahead windows in parallel. Note however that the look-ahead may not extend beyond an incomplete node. This is because this portion of the buffer is actively being considered for attachment by the incomplete node.

Thus, in figure 3b, it would be possible for S_1 to attach NP_1 as its subject without a deactivation and subsequent reactivation of NP_i.

The mechanism can be thought of as a kind of linear cellular automaton where each cell has access to the contents of up to three cells to its right. Because multiple cells can be active at the same time, there is no need for an explicit reactivation mechanism.

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A COMPACT RELATIONAL STRUCTURE REPRESENTATION

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This paper is concerned with the representation of objects by computer. It presents a compact relational structure representation derived by generalizing the properties of objects. Objects are described by means of surface primitives (basic descriptive elements) and relations between the primitives. The essence of the representation is the use of a single primitive to describe all identical parts. The representation involves abstracting properties of individual scene elements. Similarly, relations between parts of objects that hold for particular instances of the objects are generalized to ensure that they will be valid for all instances. Common primitives and relations are shared both within and across models. This leads to a compact representation that has many desirable properties. A computer implementation oi a version of the representation has been developed. It is used to illustrate the descriptive power of the representation. A recognition system has been developed that takes advantage *of* the representation in its operation. It is described elsewhore (Shneier (1977),Shneier (1978)).

1. INTRODUCTION

The way in which information is represented is critically important to the effectiveness of any system in Artificial Intelligence. Using a good representation, tasks that would otherwise be intractable become amenable to solution, In machine vision, representations have usually been tailored to specific, small domains. Recognition algorithms have been developed that depend lor their effectiveness on specific knowledge about the objects in the domain. This paper presents a new representation for describing objects. The system is intended to be generally applicable, but was developed primarily for; the domain of three-dimensional machine vision. It has also been applied to a second domain, that of spelling correction. The presentation of the system will be in terms of machine vision.

The representation takes advantage of similarities in the descriptions, or models, of objects. 11 two parts of an object, or two parts *of* different objects, have the same description, then these parts are represented by a single description in the representation. The basic idea is to share descriptions that are common within models and across models. When this sharing is accompanied by a comprehensive indexing scheme, it leads to a representation that has many advantages over previous representations (e.g. Barrow and Popplestone (1971), Falk (1972), Ambler et al. (1975)) and suffers few disadvantages.

Some constraints were placed on the implementation of the system. The first constraint was that the descriptions of objects should be acquired automatically from visual data. This is a sensible constraint because it allows the domain to be changed easily and confronts the problems of representing objects from the real world, rather than those of representing artificially-created objects. The second constraint was thatthe representation should not be domain-dependent. It should be possible to change or expand the domain with as little effort as possible, and the information known about objects should be acquired entirely from the objects themselves rather than being partly dependent *on* built-in assumptions about the domain. This constraint would be useful in a robot assembly domain, where different assembly tasks might use widely different parts. Instead of having to re-program the system for each new task, it would be preferable for it to acquire descriptions of the parts visually.

Some of the problems to be confronted when a

representation and a recognition system are being designed become amenable to solution in a more natural way using tiie new representation than using earlier representations. It becomes easier to compare descriptions of objects, the domain of objects may be changed or expanded with very little effort, and the problems oi matching symmetrical objects disappear. There is a great deal oi flexibility in the choice of how to describe objects, and the form o1 the :epresentation makes rec:ognition of objects eaSier.

A reropnition algorithm based on the represent .it ion has been developed and implemented, it xikts use of the form of the representation to > ;"iab 1 e it to recogn 1 ?.e objects in a robust and efficient manner. An earlier version of the algorithm appears in Shneier (1977). It is dis cussed in more detail in Shneier (19/8), and examples are presented of its use in three-dimensional vision and in spelling correction.

. . COMPACT MODELS

Tiie approach taken here differs from earlier *\.'*"k in two major respects. The first differ- r.iiu' concerns the nature of models. Those authors who have previously made use of models ■ >t objects (e.g. Falk (1972), Barrow and Pop- plestone (1971), but not Waltz (1975)) have „iven the term "model" certain implicit char- acteristics. A model has been defined as a description ot an object with a one-to-one relationship between parts of the object (e.g. a„iges, surfaces, volumes) and parts of 11le model. For example, the model for a cube con- sists of a separate description of each >1 the six sides of the cube, and d relationships between the sides.

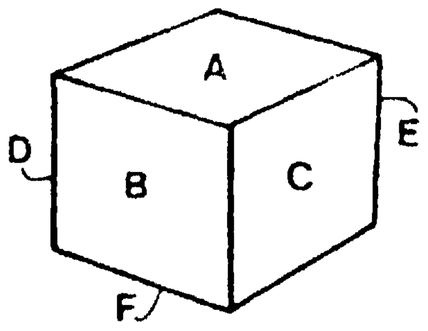
There are a number of reasons why this concept of model, while natural, is not the best for machine vision. It means that each model has to be treated as a separate entity because there is no sharing of structure between models or parts of models. Most systems have performed matching separately on each model in turn, with models being rejected one by one until a match was found. It was desired to be able to match with all possible models in parallel, finding the best match in the most efficient manner possible. Grape (1973) attempted to match in this way by compiling a central list oi feat- ures against which to match. He was not en- tirely successful, however, because he had to match, against each element of the feature list in turn.

Another reason for re-examining the notion of model concerns the analysis of models of sym- metric objects. Underwood and Coates (1972) were unable to deal with symmetric objects because of problems of finding the correct correspondence between parts of the scene and parts of the model. Other authors have had to content themselves with finding all possible correspondences between the scene and a model, and then choosing one of these arbitrarily (e.g. Barrow and Popplestone (1971), Ambler et a] . (1975)). The problem arises because the model of a symmetrical object contains several parts that are described in a very similar fashion. When an object model is being con- structed from several views, it is not clear when to construct a new part in the model and when to assume that all parts have already been seen. Similarly, when trying to recognize an object, it is not clear which of a number of parts of a model should be matched against a scene fragment. If the system is to work in a world of man-made objects, it seems advisable to be able to handle symmetry in a more accept- at: i e manner .

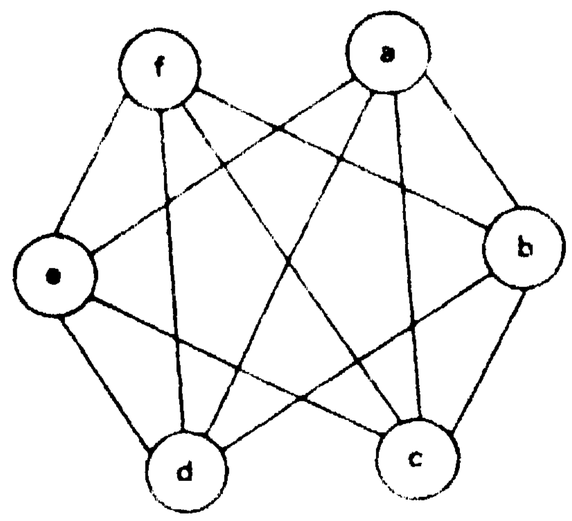
Our solution to these problems with models is t broaden the concept of a model. A model is defined as a collection of descriptions of the kind of parts that make up an object and the set of the relations between them. There is no requirement of a one-to-one correspondence be* tween object parts and model parts. Rather, there is one model part for each distinguish- ably different object part. This is similar to systems of mathematical logic, where a model is a collection of axioms describing a world, and where no axioms are repeated,

So, for example, a model of a cube consists of only one part description—that of a square plane. Relations are defined between instances of the part, so that a form of relational structure is the basis of the representation.

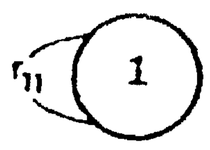
Figure 1 depicts the difference between the conventional relational structure model of a cube ^nd the model described in this paper. The conventional model has one node for each surface in the cube, whereas the new model has a single node describing all the surfaces. Similarly, while there are many relations de- f ined between the surfaces in the conventional model, the new model needs only a single, rela- tion to represent them all. There is a great saving in the size of the model.



"cube"



Conventional Model



New Model

Figure 1

In fact, the models are even more like those of the Logician than has been described so far. A logician describes a whole world with one set of axioms. Similarly, the models in this representation all share one structure, instead of the usual separation of models of different objects. The advantages of such a system are manifold. Matching is enormously simplified and matches occur with all possible models at once. Models are compact and are easily compared. Similarities are evident in shared structure, and differences are reflected by structure that is not shared.

The second difference between the new system and earlier work is more specific, and arises as a result of the formulation of the models as relational structures. A relational structure is defined as a set E of elements, together with a set of properties P and a set of relations R over E (Ambler et al, 1975)). Scene analysis based on relational structures has been concerned with the following kind of matching: Given two relational structures $\langle E_1,P,R\rangle$ and $\langle E_2,P,R\rangle$ define a match between them as a set $T_1 \subseteq E_1$, a set $T_2 \subseteq E_2$, and an isomorphism between T_1 and T_2 preserving properties and relations. That is, $e_1 \tilde{} e_2$ implies $p(e_1)$ iff $p(e_2)$ for each $p \in P$. Also, $e_1 \sim e_1'$ and $e_2 \sim e_2'$ implies $r(e_1,e_1')$ iff $r(e_2,e_2')$ for each $r \in R$. A match represents a common substructure in the relational structures.

This definition will be changed to allow the two relational structures to have a different relationship. For recognition, the structure of models and the structure obtained from the scene being recognized are described in terms of different basic elements. That is, the structure obtained from the scene (called the scene graph) represents the parts of the scene as they actually appear, whereas the structure of models (the graph of models) represents a meta-description of the objects possibly in the scene. Several parts of the scene graph may map into a single node of the graph of models. There is an isomorphism from the scene graph to a structure derived from the graph of models, but not to the graph of models itself. The structure derived from the graph of models is a conventional relational structure with each part of the object described individually, even if the parts have similar descriptions. Relations between the parts are also made explicit.

Thus it is necessary to distinguish three levels in the representation. There is the representation of the actual sense data in the scene graph, there is the structure representing the models of the objects known to the system, and in between there is a structure instantiated from the graph of models to aid in the analysis of the particular scene being studied. The relationship described above for matching relational structures holds between the scene graph and the intermediate structure, but this intermediate structure is only one of many possible such structures that can be instantiated from the graph of models.

Winston (1975), with his TYPICAL-MEMBER labels, went some way towards this position. He did not explore the potential of such a representation, but relied on the conventional structure representation.

3. REPRESENTATION

A representation has been implemented that is simple to construct and is powerful enough to describe a large class of objects. The representation is based on primitives and relations. Ideally, primitives could be descriptions of any scene elements that are easy to extract, have a canonical description, and have sufficient variation to allow the representation of an interesting class of objects. A small set of easily calculated relations is desired that succinctly describe the relationships between instances of the primitives in an object.

Relations are stated as schemata; their arguments are abbreviated surface descriptions instead of full surface descriptions. The form of the representation is a network whose nodes are primitives, and in which an arc is drawn between nodes if a relation is defined between the primitives at those nodes. Arcs are labelled with the set of relation schemata that justifies them. An object will be described by some set of these nodes and arcs, but many nodes and arcs in the network may be common to several object models. A primitive is represented by a single node, so should an instance of a primitive occur in several objects, the models produced from these objects would share that node. In addition, models may share relations, should common primitives occur in similar relationships in both models. The only thing that two models may not share is a name.

The network for the two objects of Figure 2 is given in Figure 3. The objects are a cube (called "cube"), and a rectangular parallelepiped ("rect") whose model shares a side with the cube.

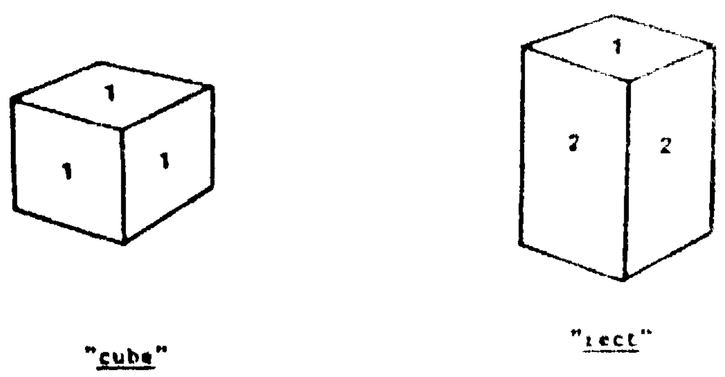


Figure 2

r_{11} = {<RELANGLE P1 P1 90°>, <RELANGLE P1 P1 180°>}

r_{12} = {<RELANGLE P1 P2 90°>}

r_{22} = {<RELANGLE P2 P2 90°>, <RELANGLE P2 P2 180°>}

Figure 3

Definitions

The definitions are of the terms used to describe the representation. They are in terms of labelled graphs.

1. Let $P = \{p_1, p_2, \ldots, p_n\}$ be a set of primitives. Each p_1 forms one (and only one) node of the graph.

2. Let $R = \{r_1, r_2, \ldots, r_m\}$ be a set of relation schemata. Each r_1 is of the form: <function name, $arg_1, arg_2, \ldots, arg_n$, value>. The arguments $arg_1, arg_2, \ldots, arg_n$ are typed variables which may take as values instances of individual elements of P (possibly repeated). The value FALSE (0) is not considered legal for a relational schema. The labels on the arcs of the graph are sets of relation schemata, subsets of R, called label sets.

3. Let $M = \{n_1, n_2, \ldots, n_k\}$ be a set of names of models.

4. The graph obtained from modelling objects is called the graph of models.

5. A model in the system is represented by a subgraph of the graph of models. The nodes in the subgraph are those primitives that occur in the model. The arcs in the subgraph are those that have relation schemata in their label sets that occur in the model. The label set of an arc in the subgraph consists of the subset of relations that occur in the model.

A rich indexing structure is maintained by the representation. Each primitive indexes the models in which it occurs. If a primitive forms part of the description of an object, it must index the model for that object.

Relation schemata index the models in which they occur and the primitives that form their arguments. To test whether or not a relation is satisfied requires finding instances of its arguments, while to derive any benefit from such a test requires that the information obtained be available to the models that can use it.

The models index both the primitives that form their parts and the relation schemata that describe how the parts are related.

4. THE MODELLING PROCESS

4.1 Extraction of surfaces

The implementation discussed here makes use of range data obtained from a triangulation ranging system (Popplestone et al. (1975)). An object to be modelled is placed on a turntable (Figure 4). The object is passed under a plane of light, and scanned at fixed intervals. When the scan is complete, the object is rotated by a known amount, and scanned again. This process is repeated until all desired views of the object have been scanned (Figure 5).

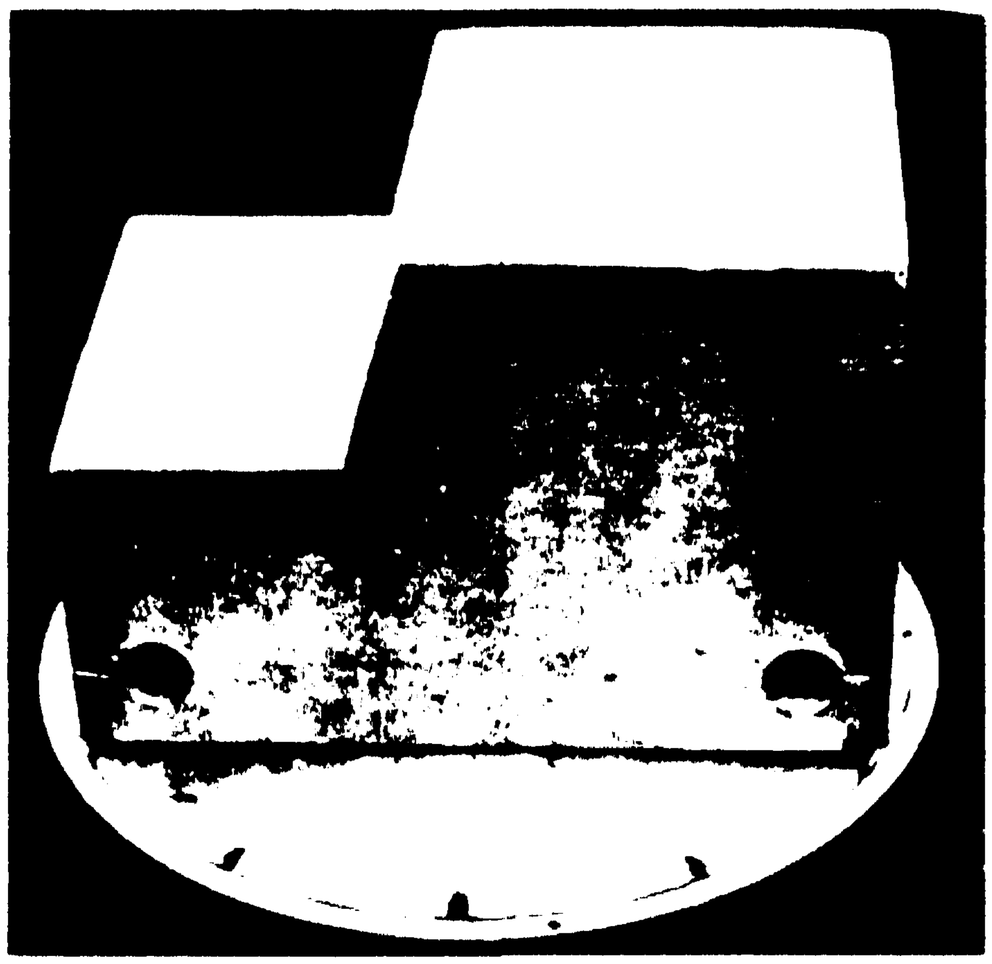


Figure 4

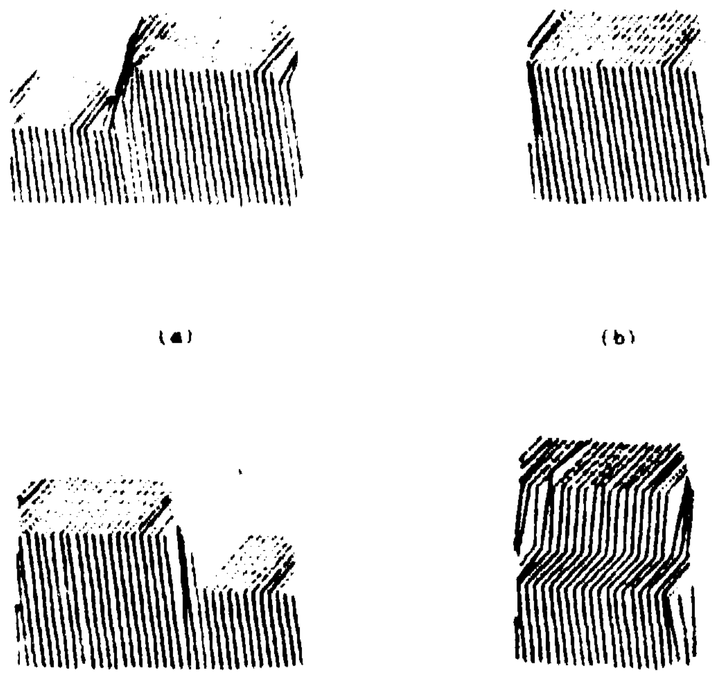


Figure 5

The result of processing the data obtained in this way is a set S of surfaces, each described by:

1. The surface type (plane or cylinder).
2. The equation of the surface.
3. The three-dimensional coordinates of the centroid of the surface.
4. The radius of a cylindrical surface.
5. The segments of lines that make up the surface.

Some further processing is done on this information before a model is produced. The aim of this processing is to derive simple, non-coordinate-specific information about the surface, which can be used to form primitives. The information chosen is a measure of the dimensions of the surface.

4.2 Primitives and relations

From the set S of surfaces, a list P' of surface descriptions is constructed, one for each surface. Elements of P' may be repeated. The elements of P' will be used to construct the set P of nodes in the graph of models. The descriptions are constructed from the surfaces by extracting the type of surface and its dimensions. All coordinate-specific information is discarded when forming the descriptions. This information is, however, still available to the rest of the system, and will be used to construct the relation schemata. At the same time, the set

$$SP = \{\langle s,p\rangle \; s\in S, p\in P\}$$

of pairs of surfaces and their associated descriptions is constructed. SP links the surfaces in the image with the descriptions in the model world. The three-dimensional positions of the surfaces and their relationships with other surfaces will be used in building the model.

The next step is to determine the relationships between the surfaces in the object being modelled. In the implementation, relations have been restricted to having at most two arguments, for ease of acquisition and because the number of relation schemata produced for n-ary relations can be very large. In practice, binary relations are adequate for the domains under consideration, although Shneier (1978) presents an argument to show that this is not true in general.

The choice of the relations with which to model an object is left to the user, who lists the names of the functions to be applied at the time the model is constructed. The use of a relation requires that an executable function exist which can calculate Values for instances >f its arguments. A number of different functions have been used in experiments. Some of these are:

ADJACENT: if the light plane in some subscan passed over both surfaces at the same time, and the line segments produced by the light plane were touching, then the surfaces are id)acant.

RELDiST: The distance from the centroid of *one* surface to that of another.

RELANCLE: The angle between two surfaces, from the viewpoint of the first.

Whereas ADJACENT is a true relation, in that it has values "true" or "false," RELDIST and RELANGLE can have a large number of values, each of which will give rise to a new schema when it is encountered In an object being modelled. (There will not, however, be an infinite number ■; such values, since a range ot values which ire sufficiently simiLar will be grouped into in equivalence class.)

ihe schemata are constructed as follows. For , ach pair of surfaces in S, the chosen set of functions is applied. ihe result of the appli- ation is used as the expected value slot in the schema. The name of the function that was applied is the value of the function name slot, while the argument slots are filled by the descriptions that correspond to the surfaces used in the evaluation. The correspondence is obtained from the set SP >of pairs of surfaces and their descriptions. Using abbreviated descriptions, rather than full surface descriptions, generalizes the relations to make them valid for all surfaces that match the abbreviated descriptions. If the value of the function is FALSE (0), a schema is not constructed.

4.3 Producing the graph of models

At tills stage there is

1. A list P' of surface descriptions.
2. A set of relation schemata.
3. A model name.

This information must be integrated into the graph of models. Any new information should be retained, but duplication or spurious arcs should not be introduced.

Each of the descriptions in P' is matched against the primitives in P, the set of nodes of the graph of models. Only if there is no match (i.e. if a description is sufficiently different) is a new primitive node created for the description and added to P. Primitives are described in exactly the same way as surface descriptions, but there is only one primitive with a particular description. The result is a set PUP[1] of primitives. Matching requires that the surface types be the same in the primitives and the surface descriptions, and that the dimensions be within some fixed tolerance of each other (currently, dimensions are allowed to vary by about 20% before the match fails).

When a surface description matches with a primitive already in the graph, the values of the primitive in the graph are updated. The mean of each description in the surface and the primitive becomes the dimension for the primitive in the graph.

The name of the model is added to the set of names if it is not already a member. The new set of relation schemata is added to the set R of schemata that already exist as follows. If a new schema is not already a member of R, it is added to R, and indexes only the new model. If a relation scheme alneady exists in R, it is not duplicated. Instead, the schema is altered so that it indexes the new model in addition to any others it might already Index. The model indexes the primitives and relation schemata that occur in it, and the primitives index the new model.

4.4 Example

Figure A shows a picture of a toy car resting on the turntable. The car was scanned by the ranger, rotated through 90 degrees, and scanned again. This process was repeated four times, giving four views, each perpendicular to its predecessor. The four views cover all surfaces of the car except its base (Figure 5).

After scanning the car, the range map produced from the scans is processed to find the surfaces of the car. There are seven of these, corresponding to the roof, two sides, back, front, windshield, and bonnet of the car. Some of these surfaces were visible in more than one view of the car. The roof appeared in all four scans, and the bonnet in three (Figure 5). Notice that the sides of the car appear smooth

because the axle holes were not large enough to be perceived by the ranger.

From the set of surfaces, the program must produce a description of the car. To be able to do this, three pieces of information are necessary. The first is a name for the object—it will be called "CAR". The second requirement is a file containing the surface data, and the third requirement is a list of functions to be applied to pairs of surfaces to produce the relation schemata. In this example, a single function that finds ADJACENT relationships between surfaces will be used.

The first thing that the program does is to work out descriptions for each surface. It finds the type of the surface (in this example, all surfaces are planes) and two numbers that describe the dimensions of the surface.

When the program tries to find the dimensions of the roof of the car, it discovers that there are several views of the surface, that is, the roof was scanned more than once by the ranger. Each of these views is processed separately, and the results are merged. The bonnet of the car is treated similarly.

Having described the surfaces, the next stage is to construct the relational structure to describe the object. First, the program examines the surface description. If two descriptions are similar, they are represented by a single primitive node (PRIMITIVE) in the graph of models. In the example, three primitives are found to be sufficient to describe the seven surfaces. This is less than half the number that would be required by a conventional representation, illustrating the compactness of the representation. The three primitives describe the following surfaces:

Primitive PI describes the roof and back of the car.

Primitive P2 describes the windshield, bonnet, and front of the car.

Primitive P3 describes the two sides of the car..

The dimensions stored for each of the primitives are the means of the dimensions of each surface that matched with the primitive. In addition to describing the surfaces, the primitives also index the model CAR of which they are parts.

The next step in building the model is to link the primitive nodes by means of ADJACENT relation schemata. An arc is constructed between two nodes if <u>any</u> of the surfaces described by one of the nodes is adjacent to <u>any</u> of the surfaces described by the other node. Thus, the side of the car is adjacent to the back of the car, giving rise to the schema <ADJACENT PI P3 1>. The side of the car is also adjacent to the roof of the car, but this gives rise to the same schema, because the roof and the back are dear* cribed by the same primitive and one schema is used to represent both relationships. All pairs of surfaces are examined, and five relation schemata are found sufficient to describe the relationships between the surfaces in the car.

The three primitives and five relation schemata, together with the name of the car, are all the information needed to model the car (Figure 6).

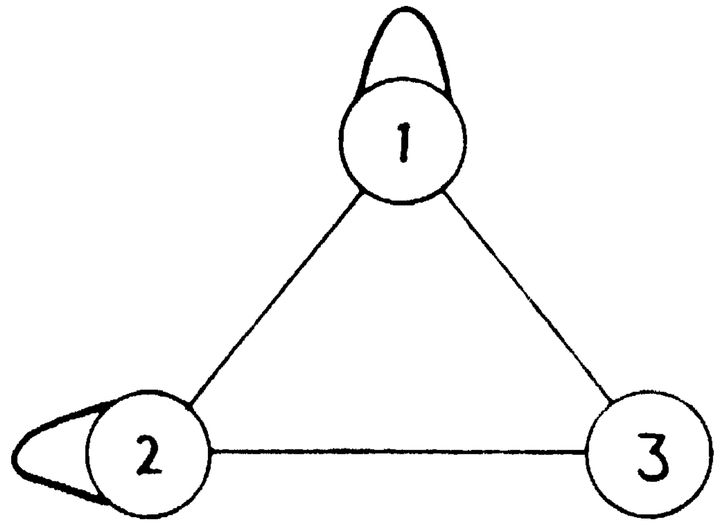


Figure 6

Note that the bottom of the car was not scanned, and so does not appear in the model. To incorporate it, two sets of scans would be necessary. The model as shown would first be constructed, and then another set of views of the car, this time on its side or its roof, would be produced. Presenting the modeller with the new set of views and the old object name would result in the model for CAR being updated to include the new surface and any new relations that were discovered.

The situation is more complex when several objects are modelled. If the descriptions of some of the surfaces of an object being modelled match with primitives already in the graph of models, the new model will share that primitive in the graph. The node is made to index the new model in addition to any others it already indexes. Similarly, relation schemata may be shared by several models, and must be indexed accordingly.

5. <u>DISCUSSION</u>

The advantages of the representation are as follows. The representation is compact because nodes are shared by parts of several objects. This allows the space required to store models to be reduced, and has valuable implications for recognition. Models can be constructed easily

from visual data, and new models can be integrated into the network without affecting those models already in existence.

Because of the sharing in the structure, all models that are described by a part of the structure are made available simultaneously when that part of the structure is accessed. Instead of matching with each model individually, all of them are available at once and the work that is done to discriminate between models can be tailored by the context. This allows less work to be done when a scene is analyzed.

The representation is flexible. It was easy to change the domain to which the system was applied from three-dimensional vision to one-dimensional spelling correction without changing the form of the representation. It is also possible to describe objects within a domain in different terms.

The ability to compare descriptions is one of the criteria for a useful recognition. In the past, objects have each been described separately and compared by finding correspondences between two structures. In the representation presented here, a single structure is shared by all models, with parts of models that are similar being represented by the same part of the structure. Thus, instead of painfully comparing two structures and finding points of correspondence, the single structure can be examined and similarities and differences between object models can be found immediately. Similarities are indicated by shared structure, and differences are indicated by structure that is not shared.

An important requirement for a representation and recognition system, especially one that is to work with man-made objects, is an ability to deal with symmetry. Many objects have some degree of symmetry, and this has led to problems in previous systems. The difficulty arises when a symmetrical object is matched with its model description. It is not clear what parts of the object should be matched with what parts of the model because there is no unique way of matching when several parts have the same description. This problem has either been avoided by not allowing symmetric objects in the domain (Underwood and Coates (1972)), or it has been solved by resorting to finding all possible correspondences between the object and its model and choosing one of them (e.g., Barrow et al. (1972)). When there is a large amount of symmetry, as in a cube, this method can be very expensive. Using the representation in this paper, the problem of symmetry disappears. There is a single description for all the similar parts, so that there is no confusion when matching. Symmetric objects can thus be recognized with the same effort as non-symmetric objects.

The representation has been successfully applied to two domains. The first, machine vision, used surface descriptions as primitives, and relations like adjacency. The second, spelling correction, used letters as primitives and ordering relations like "precedes" and "follows". Shneier (1978) provides a full discussion of each domain. He also discusses an elegant recognition algorithm that takes advantage of the form of the representation in its analysis. The modelling and recognition systems have been fully implemented and tested. Their performance underlines the advantages of the compact representation.

6. CONCLUSIONS

This paper has presented a new representation that takes advantage of similarities in the descriptions of objects. By sharing descriptions that are common within models and across models, a compact representation was obtained that had numerous advantages over other representations. The system was implemented and applied to two domains, those of machine vision and spelling correction. In both cases, it proved possible to represent the objects in the domain in a compact manner that was especially useful for recognition. The simplification of the representation is a direct result of a generalized concept of model.

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Overview of the Programmer's Apprentice

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ABSTRACT - This note gives an overview of the Programmer's Apprentice system being developed at MIT. This system is conceived as being midway between an aid to improved programming methodology *and* an automatic programming system. A programmer and the apprentice work together throughout all phases of the development and maintenance of a program. The programmer does the difficult parts of design and implementation, while the apprentice acts as a Junior partner and critic, keeping track of details and assisting the programmer wherever possible. A key feature of the apprentice is its ability to understand the logical structure of a program so that It can interact with the programmer In e meaningful way.

1. Introduction

The Programmer's Apprentice (PA) is an interactive system for helping programmers manage the complexity of evolutionary programming. It is being designed and implemented at MIT by Charles Rich, Howard Shrobe and Richard Waters (only some of *the* modules in the system are actually running at the present time). The intent is that the programmer will do the hard parts of design and implementation, while the PA will act as a junior partner and critic, keeping track of details and assisting the programmer in the documentation, debugging, and modification of nis program. In order to cooperate with the programmer in this ,, shion, the PA must be able to "understand" what is going on. The central achievement of the Programmer's Apprentice project has been the development of a "plan* representation which facilitates the cataloging of basic programming knowledge.

The "plan" for a program is a network of operations inter connected by data flow and control flow links. This representation is a better vehicle for expressing the logical interrelationships in a program than the programming language source code. A plan is segmented into a hierarchy of subsegments, each corresponding to a conceptual unit of Lchavior. The plan specifies how each non-terminal segment is constructed out of the segments contained within it. Explicit dependency links are used to record the goal-subgoal and prerequisite relationships between a segment and its subsegments. Taken together, these links summarize how the behavior of a segment follows from the behavior of its subsegments and the way they *are* connected by control flow and data flow. A final aspect of the plan representation is that there may be more than one plan for a program or part of a program, representing different points of view.

The plan representation is also used in the PA system to construct a library of common algorithms *and* data structure implementations. In general, the PA attempts to understand a programmer's code in terms of these familiar plans.

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2. A Scenario of Use of the PA

The following imagined dialogue between a programmer and the PA is presented in order to illustrate the intended operation of the system. (Comments discussing the scenario are printed in italics.) The scenario illustrates the following basic areas in which the PA can assist a programmer:

1) DOCUMENTATION: The PA provides automatic, permanent, and in-depth documentation of the program. The PA remembers not only explicit commentary supplied by the programmer with the code, but also a substantial body of derived information describing the logical structure underlying the program.

2) DEBUGGING: Any discrepancy between the PA's understanding of the programmer's intent and the actual operation of the program is reported to the programmer as a potential bug.

3) MANAGING EVOLUTION: Based on its knowledge of the logical relationships between parts of a program, the PA is able to determine what parts of a program are affected by a proposed design change. It can use this information to warn the programmer of impending difficulties.

The scenario traces the design, coding, and subsequent modification of a program which deletes an entry from a hash table. The scenario picks up in the middle of a session at a point where the programmer has already made many design choices and told them to the PA In particular, he has stated the input-output specifications for the subroutine DELETE and chosen the basic data structures to be used. The hash table is implemented as *an* array of linked lists called "buckets*. Each of the entries in a bucket is a dot ted-pair whose CAR is the key for the entry.

Programmer: The plan for the routine DELETE has three main steps: the first one hashes the input key to get an index) the second one fetches the bucket corresponding to that index from the table; and the third splices out the entry in the bucket whose key part is equal to the input key.

[The only feature of this scenario which is not $ current research goal of the Programmer's Apprentice project is the use of natural English dialogue. Although the system should be able to support a sophisticated natural language "front-onf, no effort has been expended in tNs direction to date.

The PA uses the programmer's outline of the design in order to build a plan representing the program's intended structure. References to basic programming techniques such as "splicing out" (deleting elements from a linked list) trigger the retrieval of plans from the plan library.)

PA: I think that there is • bug in this design. If the input key is equal to the key part of the first entry in a bucket then the first entry will not be spliced out.

[After constructing a plan, the PA uses its reasoning abilities in order to check for bugs. Above, the PA finds a bug and reports it to the programmer, framing its response In terms of the "splicing plan, !n general, it is the responsibility of the programmer to supply corrections.)*

Programmer: Modify the plan *as* follows. Add a final step which compares the bucket after splicing with the bucket before splicing and stores the new bucket in the table under the index if the two initial cells are not identical.

PA: OK, the plan now seems correct.

[*The programmer then types in the code for* DELETE.]

Programmer:

```
(defun delete (key) ; hash table delete routine.
  (prog (bkt1 bkt2)
        (setq bkt1 (tbl (hash key))
              bkt2 (bkt-delete key bkt1))
        (cond ((not (eq bkt1 bkt2))
               ; check if first entry deleted.
               (store (tbl (hash key)) bkt1)))))
```

[The PA analyzes the code written by the programmer in order to construct a plan for it. Comparing this plan with the plan directly described by the programmer, the PA discovers en implementation bug. The bug is so simple that the PA can suggest a correction.)

PA: This code is not consistent with your plan. When the first entry is deleted, the code stores the bucket before spiking, rather than the bucket after splicing. Did you mean:
•(STORE (TBI (HASH KEY)) BKT2)7

Programmer: Yes, fix the code.

[Some time later it is necessary to make a modification to the original design. The PA helps the (perhaps new) programmer maintain consistency.)

Programmer: I want to make a change in the representation of buckets in the hashing programs. A bucket now has two parts: a count field and a list of entries as before. The count field will contain an integer equal to the length of the list of entries. Let a bucket be a dotted-pair whose CAR is the count and whose CDR is the list of entries.

[The PA inspects the logical dependencies in the plans for the programs being worked on in order to determine the specific ways in which the programs can be affected by the proposed changes.)

PA: The proposed change will affect DELETE as follows: After the bucket is fetched, it is passed to BKT-DELETE which does the actual deletion. However, BKT-DELETE requires e list of entries while in this new implementation, a bucket it no longer Just a list of entries.

Programmer: Change the specifications of BKT-DELETE so that it expects as input a bucket of the new type, rather then e list of entries.

[... *and so the session continues with the PA looking over the programmer's shoulder.)*

3. Current Status of the PA

Rich and Shrobe [1] laid out the basic idea of a plan and the initial design of the PA. Since that time Rich, Shrobe end Waters have been working together on further aspects of the theory along with design and implementation of the PA system.

Rich*s work [2] centers on the plan library. He is using the plan representation to formalize a number of common techniques in non-numerical programming involving trees, lists, end errays. Ha is also studying the use of this library in the PA system for analyzing already-written programs *and* to provide high level abstractions for interactive program synthesis.

Shrobe [3] has implemented a deductive module, called REASON, which can reason about programs represented by plans. REASON is a dependency based system which maintains *an* explicit record of its control information within the seme formelism as is used to represent facts. An accompanying article in these proceedings describes how REASON reasons about destructive modifications to complex end potentially shared data structures.

Waters [4] has implemented a system which can analyze the code for a program and produce a structured plan for the entire program. The basic idea behind Waters' work (which is described in detail in an accompanying article In these proceedings) is that *p\an% tor* most programs *are* built up in a small number of stereotyped ways, and that features in the code for a program can be used to determine the structure of the plan for the program.

Our goal for the immediate future is to construct a prototype system which exhibits the kind of behavior shown in the scenario. To do this, an interactive module must be built, and the modules which have already been constructed must be connected together into an integrated system. Looking further ahead, additional modules (such as a simple program synthesis module, and one dealing with efficiency issues) will be added to the PA, and the existing ones strengthened so that the PA cen take over more responsiblity from the human programmer.

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Dependency Directed Reasoning in the Analysis of Progra Which Modify Complex Data Structure*

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Abstract

REASON is the deductive component of a larger program understanding system called the Programmer's Apprentice *[*\\ REASON') key features are : (1) Its use of the Truth Maintenance System [2] to record end manipulate the justifications for its deductions, (2) A discipline of explicitly recording control information in a form which may be manipulated by the reasoning system itself and (3) Its goal of producing a a "common sense" explanation of how a program functions, as opposed to the formal proofs common in verification. One particularly difficult problem which such a system must face is the analysis of program which allow destructive modifications of potentially shared data structures. Our observation is that experienced programmers tend to make simplifying assumptions when analyzing such programs; even if these assumptions are found to be false they can be useful in guiding a more accurate analysis. Thb paper shows how REASON mimics thb behavior of expert programmers.

Introduction

REASON is the deductive component of the programmer's apprentice system, a 'program understander" which is not mainly concerned with providing a rigorous proof of a program's correctness, but rather with giving a "common sense" explanation of how the intended behavior of the whole program results from :h© kr.own (or assumed) behaviors of its parts. REASON is able to analyze the effect of a proposed change to a program, viewing the modification at a pertubation rather than as a whole new program requiring a new proof.

One particularly difficult problem which REASON faces is the analysis of programs which allow destructive modifications to complex and shared data structures. Apparently simple operations can produce non-trivial results: a modification of one part of a structure can change properties of the whole structure. Thus, in reasoning about the results of a particular action, a program analyzer must assess what properties besides those explicitly stated will also change. Suzuki [3] attacked the problem of verifying PASCAL programs which allow such opertions; however, the formal approach of his work is not easily adapted to the interactive, and common sense context of the programmer's apprentice.

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This general problem of knowing what change* and what remains the same has been termed the "frame problem" in *[4*\ In the case of common sense reasoning, one has to assume that most things don't change unless there is reason to believe otherwise. When such assumptions lead to trouble, a belief revision process is necessary. In the case of program understanding, similar techniques can also be applied. Consider the following procedure which deletes all elements of a list which are also members of a hash table.

```
(eefun removt (I1it-1 hashtablt)
       (mapc
          '(laabtfa (x)
                    (and (lookup x haihtablt)
                         (Mtq 11it-I (dtIttt x 11it~I))))
           Hit-1))
```

This program has a bug which few programmers (even experts) spot when examining the code. (The reader might try to figure out what the problem is now before proceeding).
Suppose that the hashtable is implemented as an array of lists (the lists are called buckets) as is typically done in LISP. Suppose also that the parameter list-1 is bound to a list which shares some structure with one of the buckets of the table. In this case the above program will have the unintended effect of removing elements from the hashtable as well. This is because DELETE operates by side effect.

Most readers will feet cheated by this example. It doesn't seem fair to bring in the issue of structure sharing out of the blue. Quite so. This illustrates a difference between formal verification and common sense reasoning: In a verification system one must consider the most general case of a program's behavior; this is typically done by considering all input

parameters of the program to be objects which *might* share structure. This forces the verifier to consider all cases of possible identity. However, the very fact that the example above seems like a trick indicates that this is not the way programmers routinely think about their code. Quite the contrary, the *tacit calculus* of expert programmers assumes that, unless otherwise stated, sharing of structure does not take place.

There is a good reason for this tacit calculus; in common sense reasoning and also in engineering disciplines we find that there is a trade off between ease of comprehension and accuracy. Simplifying assumptions are made to reduce the cognitive complexity of a problem to the point where a solution can be developed In general the simplifying assumptions are chosen so that the solution reached is "close enough". In those rare cases where the solution b not close enough, it is debugged; however, it still plays a guiding role in the formation of the improved solution.

Our observations above indicate that programmers use more than one strategy for analyzing the effect of an action. In the more reckless strategy, one assumes that things are not changed unless there is reason to believe they do. This has the advantage of being right most of the time, requiring less effort, and allowing the programmer to form a "first order" theory of what the code does. In the more careful strategy, one does the opposite, assuming things are effected unless evidence to the contrary exists. This, has the advantage of never allowing a false conclusion to be drawn, but the disadvantage of requiring much greater effort, to the extent that it can prevent one from forming a "first order" understanding.

REASON is designed to conduct both of these forms of reasoning. More significantly, however, it is a dependency based system which can use information gathered during the "common sense" analysis to guide the "formal" analysis. Frequently, all one desires from the formal analysis is the statement that there are "screw cases" in which the behavior inferred during the informal analysis no longer obtains.

The Pepewdewc* Bated Formalism

REASON is implemented in a variant of the language AMORD [51 a formalism which records both facts and the reasons for believing them. AII goal states and the reasons for their existence are recorded within the same formalism. *Justifications* are a crucial form of information in REASON. When an assertion is entered into REASON'* data base, it is always accompanied by a justification explaining why the new assertion is believed. To make this convenient, each assertion is assigned a unique "fact-name". For example;

Asttrtlon	Syitee-Swep1iad-ract*RiM
(< x Y)	r-l
(< Y z)	r-l

The transitivity rule can be applied to F-I and F-2 and a newly deduced fact entered into the system using the ASSERT function:

```
(Assert '(< X Z) '(Transitivity F-1 F-2))
```

ASSERT takes two arguments: the new assertion to be added to the data base and the justification for the assertion: a justification is a list whose first element is a justification name and whose remaining elements are the fatt-names upon which the new assertion depends.

REASON makes deductions using *rules* which consist of two elements: a *trigger set* and a *body.* The trigger set is a list of patterns each of which has two parts: a fact-name variable and an assertion pattern. The body is a LISP expression which is evaluated in an environment in which the variables of the patterns are bound to the objects which they matched. The following is a fairly typical REASON rule:

```
(rule ((:f (Rest :list-1 :list-2))
       (:g (Member :list-2 :obj-1)))
      (assert '(member :list-1 :obj-1)
              '(List-Membership :f :g)))
```

Variables are indicated by a leading colon (:).

In these triggers, the leading single variable (:f or :g) is the fact-name variable, the remaining part of each trigger (Rest :lisM :list-2) or (Member :list-2 :obj-I)) is the assertion pattern. A rule is applicable if all its patterns are matched by facts which have currently valid justifications (see below). The body is then executed in the environment of the match.

As each trigger is matched to an assertion, the fact-name variable of that trigger is bound to the fact-name of the matched assertion. This allows the body of the rule to refer to its triggering facts. In particular, assert statements in the body of the rule may include a justification mentioning these facts.

Assertions have one of two statuses in REASON, they are either *in* or *out.* A fact which is *in* is believed to be true. An assertion whose negation is *in* is believed to be false. If both an assertion and its negation are *in* then the data base is contradictory and corrective action is required. If neither the assertion nor its negation is *in,* then the fact is simply unknown.
The meaning of justifications such as the transitivity justification shown above is that whenever F-I and F-2 are *in* then F-3 should also be *in.* If for some reason either F-I or F-2 became *out,* then F-3 would lack support and would also become *out.* The "ting and *outing* of facts is managed by the Truth Maintainence System [2] which ensures that no fact is in unless it has well founded support

It is frequently necessary to *assume* that some fact holds even though no reason exists for believing it This is often done in hypothetical reasoning as when one proves that A implies B by assuming A and deriving B. One assumes a fact because there is

no apparent reason not to believe it; thus, the assumed fact is justified by making it depend on the Outness of its negation. This is done by the function ASSUME:

```
(Assume '(Made-of The-Moon Green-Cheese) '(Bill F-23))
```

which states that the system will believe that the moon is made of green cheese as long as it has no reason to believe that the moon is not made of green cheese and as long as it believes fact F-23, The function ASSUME builds a justifiction which has two parts: A list of assertions upon whose inness the fact depends and a list of assertions upon whose Outness the fact depends. When the above ASSUME form is invoked it creates the assertion:

```
(Not (Made-of The-Moon Green-Cheese))        F-1001
```

and then justifies its argument assertion by stating that it depends on F-1001's being *out* and on F-23's being *in.*

```
F-1002  (Made-of The-Moon Green-Cheese) (Bill (F-23) (F-1001))
```

where the first list in the justification is the list of facts whose inness supports F-2 and the second list is the *out* list. Whenever an assertion changes its status, the Truth Maintenance system propagates the change until only assertions with well-founded support remained *in.* It is, therefore, always safe to make an assumption since if this introduces an inconsistency, the TMS will cause the improperly assumed fact and all other facts which depend upon it to go *out.*

Reasoning About Simple Side-effccts

A program segment is thought of as forming a *transition* between its input and output *situations.* Situations are representations of the state of affairs which obtain at a particular point of the computation. When appropriate, assertions may be situationally tagged to indicate at what points of the computation they are true. For example, to state that the first element of List-1 is Obj-22 when Segment-41 is entered we would assert

```
(Input-Situation     Segment-41  S1tuat1on-l)
((First List -1 Obj-22) Situation-1)
```

A side-effect is indicated as follows:

```
(Side-effect <object> <in-sit> <out-sit> <new-fact>)
```

Which says that the <object> has been subjected to a side-effect during the transition from the <in-sit> to the <out-sit> with the result that <new-fact> is made true in the <out-$it>. The new fact can be any relation (primitive or not). Side-effect processing consists of deducing which properties can safely be moved along the transition from <in-sit> to <out-sit> safely; I refer to this process as *transition analysis.* My general approach of explicitly recording dependencies dictates that REASON should provide a justification whenever it decides to move a fact across a transition. Similarly, if it decides not to move a fact it should justify this decision as well. These recorded dependencies allow REASON to make an initial decision based on a cursory analysis of the circumstances, while still reserving for itself the option of reconsidering in more detail at a later time. If it should reconsider, the recorded dependencies can rapidly indicate which properties depend on the simplifying assumptions of the cursory analysis.

The basic protocol is as follows: An assertion in the input situation of a transition can be moved to the output situation of the transition only if there is an explicit assertion declaring it *safe* to do so. In phase one of the analysis, simple rules are run to find reasons for not moving a fact. If such cause is found, these rules assert that it is *unsafe* to move the fact. At the end of this process each assertion is asserted to be safe to move; however, the justification for this safe assertion depends on the *outness* of the corresponding unsafe assertion. Thus, if any reason for considering the assertion unsafe had been found, the unsafe assertion will be *in,* causing the safe assertion to be *out.* If at the end of this process a safe assertion is *in* for a particular fact, then the fact will be asserted in the output situation with its justification pointing to the safe assertion. The following rules carry out these operations:

```
The Default Assumer for the Careful Protocol
(rule ((:f (side-effect :object :in-sit :out-sit :new-fact))
       (:g (:old-fact :in-sit))
       (:h (transition :in-sit :out-sit)))
      (assume '(not (safe :g))
              '(safety-first :f :g :h)))

The Default Assumer for the Fast and Dirty Protocol
(rule ((:f (side-effect :object :in-sit :out-sit :new-fact))
       (:g (:old-fact :in-sit))
       (:h (transition :in-sit :out-sit)))
      (assume '(safe :g :in-sit :out-sit)
              '(reckless-abandon :f :g :h)))

The Safe Fact Mover
(rule ((:f (safe :old-fact :in-sit :out-sit))
       (:old-fact (:fact :in-it))
       (:g (transisiton :in-sit :out-sit)))
      (Assert '(:fact :out-sit)
              '(safe-from-side-effect :f :g)))
Make The Side-effect Appear In The New Situation
(rule ((:f (side-effect :object :in-sit :out-sit :new-fact)))
      (assert '(:new-fact :out-sit)
              '(side-effects-happen :f)))
```

where the last of these merely asserts that the relation stated in the side-effect assertion is true in the output situation; this is, of course, independent of the safe assertions.

REASON has a set of rules for determining whether a particular fact is affected by a particular side effect If the fact is not affected then the rules assert that the fact is *safe-from* this particular side effect (and conversely). If a fact is safe-from all side effects at a particular transition then it u *safe* The simplest such rule is the rule of direct negation which says that a fact which is explicitly negated by a side-effect is unsafe:

```
(rule ((:f (side-effect :obj :in-sit :out-sit (not :fact)))
       (:g (:fact :in-sit)))
      (Assert '(not (safe-from :f :g))
              '(direct-negation :f :g)))
```

Another simple side-effect rule concerns objects (like records) which are composite structures with several distinct fields, called *parts.* Suppose that we modify a particular record to change one of its parts to a new value. It follows, that assertions stating the old value of the affected part of the record are not safe from this side effect However assertions mentioning other fields of the structure are safe.

```
(rule
 ((:f1 (side-effect :object-1 :s-1 :s-2
                    (:new-part-name :object-1 :new-part)))
  (:f2 ((:old-part-name :object-2 :old-part) :s-1)))
 (cond
  ((eq :old-part-name :new-part-name))
  (t
   (assert '(safe-from :f1 :f2)
           '(diff-part-side-effect :f1 :f2)))))
```

The next rule is for side-effects to objects such as arrays which have indexed-parts. Suppose we have an object with an indexed structure (for example, an ARRAY, a HASH-TAHE, or a record structure including an ARRAY) and that this object is modified to change the part indexed by INDEX-s. Also suppose that we have an assertion saying what is the part indexed by INDEX-I. Then, the side-effect should make the assertion unsafe if the two indices are identical and leave it unaffected otherwise, as expressed in the following rule:

```
(rule
 ((:f (side-effect :object :in-sit :out-sit
                   (:ip :object :new-index :new-value)))
  (:i ((:ip :object :old-index :old-value) :in-sit)))
 (assert '(if    ((equal :old-index :new-index) :input-sit)
           then  (not (safe-from :f :i))
           else  (safe-from :f :i))
         '(indexed-part-side-effect :f :i)))
```

Notice that it is altogether possible that neither the premise of the IF-THEN-ELSE, nor its negation are present in the data base and thus, that neither a -from assertion nor its negation will be created. In the first pass, "fast and dirty" analysis, this lack of an unsafe assertion will be taken as grounds for assuming that the assertion is safe; it will, therefore, be moved across the transistion. This will not be logically incorrect, since the justifications for the assumption are explicit and can be withdrawn; it is, however, not a very useful strategy. Even for a fast and dirty pass this strategy is a little too dirty. We would rather say that if it is *passible* that the two indices are equal, then we should not consider the assertion SAFE, but should rather do a case analysis, considering separately the two possibilities of equality and non-equality.

Since the conclusion that the assertion is not SAFE is based on the *possibility* that the indices are equal, we need a way of asserting that this possibility exists; this *possibility assertion* can then be included in the justification. I have developed some syntactic mechanisms to facilitate the use of the concept. The starting point is the observation that an assertion is possible as long as its negation is *out,* of course, if the assertion is *in* it is also possible. Thus, the following support structure captures the notion of possibility (the wavy line indicates that the dependency is on the outness of the assertion, this is called non-monotonic support).

```
        F-3   (Possible ((Equal Index-0 Index-1) S-1))

 F-2 (Not ((Equal Index-0 Index-1) S-1))

                F-1 ((Equal Index-0 Index-1) S-1)
```

As a syntactic convenience, I have added an IF-POSSIBLE-THEN-ELSE construct, which is invoked as follows:

```
(if-possible (:f fact-1)
        then body-1
        else body-2)
```

This expression is interpreted in two stages. First the support structure shown above is created for an assetion which states the possibility of FACT-I. If this assertion stays *in,* then body-I will be executed in a binding environment where *f* is bound to the possibility assertion for F-1. If the negation of FACT-1 is *in* (i.e. FACT-I is impossible) then BOOY-2 is executed in a binding environment in which :F is bound to the negation of F-I.

Given this, the appropriate body for the rule dealing with tide effects to indexed-part stuctures is:

```
(if-possible
 (:f (equal :old-index :new-index) :input-sit)
  then (assert '(not (safe-from :f :i))
               '(careful-indexed-part :f))
  else (assert '(safe-from :f :i)
               '(careful-indexed-part :f)))
```

This says that if it is at all possible that the indices are equal, the system will decide that the indexed-part assertion is not SAFE. If REASON decides that moving this assertion is important it can try backward chaining rules on the IF-THEN-ELSE assertion to create a case analysis.

More Complicated Effect!

So far the analysis of side-effects has been quite simple considering only assertions about PARTS and INDEXED-PARTS. These are the most primitive notions in the system However, there are a host of more complex defined notions which have been developed to allow programs to be thought of in more high level terms.

The relations which are used in describing programs are complex in the sense that they are a logical combinaton of assertions which ultimately depend on the PART structure of the objects implementing the more abstract notion. For example, in

hashing systems there is a notion of membership in the table which is defined in terms of membership in one (or more) of the INDEXED-MATS (BUCKETS) of the table. Similarly, since we frequently implement these BUCKETS as LISTS, membership of an object in the BUCKET reduces to whether the object is the FIRST part or a MEMBER of the REST part of the list. Thus, simple side-effects to the part structure of an object can result in side-effects to derived properties of the object. For example, side-effecting a TABLE to set one BUCKET to the EMPTY-LIST will (potentially) delete several members of the table. The processes handling side-effects, therefore, must examine the way in which facts in the input situation of a transition depend on one another and use this as a guide to the transition analysis.

For example, let us define LIST membership in the standard way: an object is a MEMBER *of* a LIST if it is either the FIRST of the LIST or a MEMBER of the REST of the LIST.

```
(Members Hit objects <■>  (Or (First List Objtct)
                              (Mtmbtr [Rut L1st] Objtct))
```

The brackets indicate a *reference expression,* they are read "the object which is ...". REASON extracts the component clauses of the right hand side of this definition, building a network of *potential dependency* assertions, which links assertions to those side-effects which might make them UNSAFE. For example, from the definition for LIST membership we can get the following potential dependency assertions:

```
(potential-dependency (member   :list   :objtct-l)
                      (firit    :11ft   :objtet-7))
(potential-dependency (members :11st object-1)
                      (rest   :List-l   :11st-*))
(potential-dependency  (mtmbtr  :11st  :objtct)
                      (not (mtmbtr  :List-l  .objtet)))
```

Potential dependency assertions are the information used to determine that there *might* be a logical connection between a fact and a side-effect. These say that if (I) There is an assertion in the input situation which matches the first pattern and (2) There is a side-effect on the transition which matches the second pattern, then it is *possible* that the assertion is rendered UNSAFE by the side-effect Notice that in the case of dependencies on many-to-many relations (such as MEMBER) the dependency is on the negation of the relation. If functional relationships (such as PART or INDEXEDPART) assertions are involved, a side-effect asserting a new value for the relation, such as (First List Foo), implicitly negates any previous value of the property, such as (First List Btr); for these relations the dependency pattern is not negated. The network of potential dependency assertions is completed by using a transitivity rule.

The information in the potential dependency assertions is used by a rule which monitors transitions in which facts might be made UNSAFE by a side-effect. If such situations are noticed, the rule asserts that the fact is *possibly-unsafe* Any fact which is POSSIBLY-UNSAFE is expanded, i.e. the right-hand side of its definition is added to the data base.

```
(rule ((:f (potential-dependency :a :b))
       (:g (side-effect :object :a-in :a-out :b))
       (:h (:a :a-in)))
      (Assert '(possible (not (safe-from l:g l:h)))
              '(pd :f :g :h)))

(Rule ((:h (Possible (not (safe-from :f :g)))))
      (Assert '(Expand :g) '(pd-expand :h)))
```

Two points about these rules for determining potential dependency should be noted. First, these rules only signal the *possibility* that an assertion is affected by a side-effect; it is for other more thorough rules to explore whether or not the assertion actually is SAFE or not This allows a many layered control structure in which one set of rules notices candidates for examination, and other sets of rules chose to examine these candidates at a level of detail deemed appropriate.

The second point to be made here, is that the potential dependency rules shown so far are actually of the "fast and dirty* variety. Remember that our earlier example showed that different local variable names might, in fact, name the identical object Usually people rule out this possibility of "aliasing" to facilitate their analysis. However, to be completely accurate one must examine all possibilities.

The careful version of a rule for LIST membership, for example, is:

```
(rule ((:f (side-effect :obj :a-in :a-out (first :obj :new-first)))
       (:g ((member :obj-2 :old-first) :a-in)))
      (If-possible (:h (id :obj :obj-2))
                   then (Assert '(possible (not (safe :g from :h)))
                                '(poss-or-se-careful :f :g :h))))
```

Once it has been determined that an assertion is possibly affected by a side-effect it remains to be determined whether the assertion is SAFE or UNSAFE. When a defined relation is possibly unsafe it is expanded into its definition; thus, the only remaining analysis is that associated with the logical connectives. Rules for these connectives are given in *[6]*

Once an assertion has been determined to be UNSAFE, it is then treated as a side-effect itself. This initiates a consideration of derived side-effects, propagating the side-effect through the various levels of definition.

Reducing Complexity in Side Effect Analysis

Much of the complexity in reasoning about side effects occurs in recursively defined structures which share substructure. Suppose that we know of the existence of two lists, and one of these is modified; given what we have developed so far, we must consider the possibility that this modification will also change some properties of the second list as well. However, if we knew that the two structures were *disjoint,* then this possibility would be eliminated, reducing the complexity considerably. Burstall [7], introduces some techniques for reasoning about side-effects which use this notion of disjointness to advantage. I will extend that notion in this section.

Suppose that we know that LIST-I and LIST-2 do not share any structure and that one of these lists has an element spliced into it; since neither list can be a sub-list of the other it is not necessary to conduct a thorough investigation as outlined in the preceding sections. It is immediately obvious that the modification to the first list cannot affect the second.

The notion of list-structure can be generalized to that of recursive data structures; having made this generalization we can create a hierarchy of classification for side-effects, properties and the degree of sharing exhibited by recursive structures. It will follow that the level of sharing can limit the degree to which side-effects to one structure can effect properties of the other. Similarly, the classification of properties into levels isolates those at a higher level from less powerful side-effects.

For our purposes a recursive structure can be thought of as a labelled digraph with two distinct types of arcs: those labelled as value arcs and those labelled as structure arcs. The set of objects connected to a node by outgoing structure arcs are called the *immediate children* of the node; the set of objects reachable by outgoing value arcs are called the value set of the node. All immediate children of any node of a recursive data structure must be either terminal or non-terminals of the recursive data type. Value nodes may be objects of any type. Terminal nodes may not have outgoing structure arcs.

Actually, we are not as interested in sharing as in the lack of it disjoin tness. We may identify three types of disjointness which have some utility. We have previously defined *structure sharing* as having a node in common. *Structurally disjoint* structures are those which do not share structure. For lists this means that no sublist (the transitive closure of COR) of the two lists is shared.

Often we will have non-recursive structures such as HASH-TABUS whose parts are recursive structures. For such objects, we define structure sharing in the obvious way: namely two objects share structure if there is a part of the first and a part of the second which share structure. Thus, a HASH-TABLE and a LIST share structure if one of the table'* BUCKETS shares structure with the LIST. They are structurally disjoint if there is no BUCKET of the TABLE which shares structure with the LIST.

The next type of sharing is termed *value sharing.* Recall that the nodes of a recursive structure can have parts other than those which represent the immediate children. A list is a recursive structure which has a value at each node called the FIRST. When there is an object which is a value of two recursive structures, we say that there is *fake sharing,* conversely, if there is no such object we say that the structures are *rahie disjoint.* It follows that if two structures are value disjoint, they are also structurally disjoint.

Two objects are *totally disjoint* if (I) The objects are both structurally and value disjoint and (2) All objects pointed to by each node are totally disjoint. It follows that if two RECURSIVE-STRUCTURES are totally disjoint, then side-effects to the one can not effect the other.

Now let us classify side-effects in a manner similar to that used for structure sharing. We call side-effects *strictly structural* if they only affect the immediate children property of some node of the structure, RRLACD is the simplest such side-effect, although LIST-INSERT and LIST-DELETE, etc. are also strictly structural side-effects. Notice that a strictly structural side-effect to one structure will not affect any property of another object from which it is structurally disjoint.

We may also identify *strictly value* side-effects such as RRLACA which only change value properties. If two structures are structurally disjoint, then a strictly value side-effect to one will not affect properties of the other. A *structural side effect* is one which consists only of strictly structural and strictly value side-effects. A SORT program which works by changing both CAR and CDR pointers in a list is an example of a structural side-effect If two objects are structurally disjoint, a structural side-effect to one will not change any property of the second.

Finally, an *indirect side effect* is one which only changes properties of VALUES of the RECURSIVE STRUCTURE. For example, a marking graph traversal procedure which sets the MARK property of the VALUE of each node is such an INDIRECT side-effect procedure. If two objects are VALUE DISJOINT, then INDIRECT side-effects to one will leave properties of the other unchanged.

Finally we come to a classification of properties. We can notice that some properties such as SUBLIST or LENGTH only depend on the recursive structure of the object, and not on the VALUES at each node. We call these *strictly structural properties.* More commonly, properties such as MEMO, depend both on the recursive structure and on the identity of the various VALUES present at each node, but not on any property or sub-structure of these values; these are called *value dependent* properties. Finally, there are properties which depend both on the structure and on mutable properties of the objects present at each node. MEMBER (as opposed to NEMQ), for example, depends on the structure of the list as well as on the structure of the objects pointed to by the list.

We note that a side-effect at one level can not effect a property of a lower level. For example, a VALUE side effect cannot affect a STRICTLY STRUCTURAL property. An INDIRECT side-effect cannot affect a STRUCTURAL property.

These observations can be summarized by several simple rules of the following form:

```
(rule ((:f1 (Side-effect :obj-1 :s-in :s-out :se))
       (:f2 (Structural-Side-Effect :se))
       (:f3 (Structurally-disjoint :obj-1 :obj-2))
       (:f4 ((:fact :obj-2) :s-in)))
      (Assert (Safe-from :f1 :f4)
              (Structure-disjoint :f1 :f2 :f3 :f4)))
```

```
(rule ((:f1 (Side-effect :obj-1 :s-in :s-out:se))
       (:f2 (Structural-Side-Effect :se))
       (:f3 (Structurally-isolated :obj-2))
       (:f4 ((:fact :obj-2) :s-in)))
      (Assert (Safe-from :f1 :f4)
              (Structure-isolation :f1 :f2 :f3 :f4)))
```

Notice that since these rules assert that a particular property is SAFE, they remove the need to engage in the more complicated analysis shown earlier. A large percentage of side effects have very limited range of effect precisely because there is a strong limit on structure sharing. Thus, most of the time one of the above rules will fire and REASON's work will be done. In some rare cases, the more complex and thorough analysis will be required.

Given these ideas we can extend our fast and dirty protocol for side effect analysis even further. It appears that most programmers assume by default that the inputs to a program segment are structurally disjoint. In our first pass analysis we will assume that all recursive structures are structurally disjoint unless otherwise indicated. This is coded by making rules of the following general form:

```
(rule
 ((:f (side-effect :list-1 :sin :sout :se))
  (:g ((P :list-2) :sin)))
 (if-possible (:h (structurally-disjoint :list-1 :list-2))
        then (assert '(safe-from :f :g)
                     '(loose-living :f :g :h))
        else (assert '(possible (not (safe-from :f :g)))
                     '(careful :f :g :h))))
```

Sussman [8] argues for the importance of "almost correct theories" and debugging as a means of reducing the complexity of problem solving tasks to levels within human limits. My approach to analyzing side effects follows in this tradition. REASON's first pass analysis is not rigorous, but it is useful. Much of the time it just happens to give the right answers (for incorrect reasons). The dependencies recorded during the first pass analysis can help guide an accurate and complete investigation in a second pass analysis if the problem is considered to be worth the effort. Often, however, the first pass analysis is adequate to allow the apprentice to help analyze the consequences of proposed program modifications and to generate high level common sense explanations of the code.

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A FRAMEWORK FOR DISTRIBUTED PROBLEM SOLVING

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Abstract

The contract net framework for distributed problem solving is discussed. Task distribution is viewed as a mutual selection process, a discussion carried on between a node with a task to be executed and a group of nodes that may be able to execute the task. This leads to the use of a control formalism based on a contract metaphor, in which task distribution corresponds to contract negotiation.

The three primary components of the framework are described: communication, control, and knowledge organization. The use of the framework is illustrated for a distributed sensing system. We then discuss suitable applications and limitations of the framework.

1 Distributed Problem Solving

Distributed Problem Solving ie the cooperative solution of problems by a decentralized and loosely coupled collection of knowledge-sources (KSs), each of which may reside in its own distinct processor.[1] Decentralized means that both control and data are logically, and sometimes geographically, distributed—there is neither global control nor global data storage. The KSs cooperate to solve problems by sharing tasks and/or results. Loosely coupled means that individual KSs spend the great percentage of their time in computation as opposed to communication. Such problem solvers offer advantages of speed, reliability, extensibility, the ability to handle applications with a natural spatial distribution, and the ability to tolerate errorful data and knowledge. In addition, as a result of their modularity, they offer conceptual clarity and simplicity of design.

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2 The Contract Net Framework

The central result of the research reported here is the contract net framework for problem solving in a distributed processing environment. The framework has three major conceptual components: a control component that specifies the possible modes of interaction between processor nodes; a knowledge organization component that specifies how knowledge is organized in individual nodes and distributed throughout the collection of nodes; and a communication component that provides the basis for node interaction.

2.1 Communication And Control

2.1.1 Connection And Contract Negotiation

In the design of the communication and control components of the framework, our emphasis to date has been placed on facilitation of task-sharing as a means of cooperation for problem solving. The computational load for execution of subtasks of the overall problem is distributed among the nodes. To enable this distribution, there must be a means whereby nodes with tasks to be executed can find other idle nodes with KSs capable of executing those tasks. We call this the connection problem. (In centralized problem solvers it is called the invocation problem; that is, which KS to invoke at any given time for the execution of a task.) In a distributed

problem solver, both sets of nodes can proceed simultaneously, engaging each other in a process of negotiation to solve the connection problem. Task distribution can thus be considered as a process of contract negotiation, or mutual selection based on a two-way transfer of information. This process gives rise to the name—the contract net framework [Smith, 1978b].

The collection of nodes is referred to as a contract net and the execution of a task is dealt with as a contract between two nodes. Thus, each node in the net takes on one of two roles related to the execution of an individual task: manager or contractor. A manager is responsible for monitoring the execution of a task and processing the results of its execution. A contractor is responsible for the actual execution of the task. Individual nodes are not designated a priori as managers or contractors. These are only roles, and any node can dynamically take on either role. During the course of problem solving, a particular node normally takes on both roles (perhaps even simultaneously for different contracts).

The normal method of negotiating a contract is for a node that generates a task to advertise the existence of that task to other nodes in the net with a task-announcement message. It then acts as the manager of that task for its duration. Many such announcements are made over the course of time as tasks are generated for execution.

Nodes in the net have been listening to the task announcements and have been evaluating their own level of interest in each task with respect to their specialized hardware and software resources. When a task of sufficient interest is found, a node submits a bid. A bid message indicates the capabilities of the bidder that are relevant to execution of the announced task. A manager may receive several such bids in response to a single task announcement; based on the information in the bids, it selects one (or several) node(s) for execution of the task. The selection is communicated to the successful bidder(s) through an award message. These selected nodes thus become contractors for that task.[1]

[1] This is ^simplified version of the actual process (and does not work, for example, in the case of a task that cannot be executed due to insufficient data). We have also ignored the use of focused addressing and more specialized interactions like directed contracts. See [Smith, 1978b] for the specification of the full set of message types in the protocol and a complete discussion of the processing associated with each of the message types.

2.1.2 The Contract Net Protocol

The use of communication protocols in networks of resource-sharing computers, such as the ARPAnet, is by now quite familiar. The primary function of these protocols is to effect reliable and efficient communication between computers. Such low-level protocols are, however, only a start—a prerequisite for distributed problem solving. They enable bit streams to be passed between nodes but do not consider the semantics of the information being passed. We require a high-level protocol, which we call a problem-solving protocol (PSP), to assign problem-solving interpretations to the bit streams—to control the processes used to solve problems as opposed to the processes used to effect communication. This enables the applications programmer to focus on what the nodes must say to each other, as opposed to how to say it.

The contract net protocol is the PSP that governs all problem-solving interactions between nodes in a contract net. Task-dependent information is placed in typed slots in the messages of the protocol and is encoded in a common internode language. Task-independent information is encoded directly in the protocol; that is, in the specification of message types and their associated slots.

A task announcement message, for example, has four slots for task-dependent information. The eligibility specification is a list of criteria that a node must meet to be eligible to submit a bid. It enables a node receiving the message to decide whether or not it is able to execute the task. The task abstraction is a brief description of the task to be executed. It enables a node to rank the announced task relative to other announced tasks. The bid specification is a description of the expected form of a bid. It enables a node to include in a bid only the information about its capabilities that are relevant to the announced task. Finally, the expiration time is a specification of the time period during which the announcement is valid.

The common internode language provides the primitive elements for encoding task-dependent information in the task abstraction, eligibility specification, bid specification, and so on. The implemented language enables

statements of the form Respond with <value> of <attribute> of <object> to be encoded, where some of the objects are node, task, procedure, and contract. Objects are linked together by attributes, each of which has a value (which may be another object). A oontraot object, for example, has a manager attribute whose value is a node object. The language has a grammar and a core vocabulary of terms that appear to be of use in a wide variety of applications. The vocabulary is also extensible; that is, new terms can be added for specific applications.

2.2 Example

The following is an example of the negotiation for a task that involves gathering of sensed data and extraction of signal features. It is taken from an INTERLISP simulation of a distributed sensing system (DSS) [Smith, 1978a].

The managers for this signal task attempt to find a set of sensor nodes such that the set has an adequate spatial distribution about the surrounding area and has an adequate distribution of sensor types. Sensor nodes, on the other hand, attempt to find managers for the signal task that are closest to them.

The eligibility specification in the signal task announcements Indicates that only those nodes located in the same area as the announcer and having sensing capabilities should bid on this task. This helps to reduce extraneous message traffic and bid processing. The task abstraction indicates the type of task and the position of an individual signal group contractor. It enables a potential contractor to determine the manager to which it should respond. The bid specification indicates the information that a manager needs to select a suitable set of sensor nodes—the position of the bidder and the number of each of its sensor types.

The potential contractors listen to the task announcements from the various managers. They respond to the nearest manager with a bid that contains the information specified in the task announcement. The managers use this Information to select a set of bidders and then award signal contracts. The award messages specify the sensors that each contractor is to use to provide raw data to its manager.

Sample messages that are transmitted during negotiation of the signal contracts are shown below. Terms written in upper case are included in the core common internode language, while terms written in lower case are specific to the DSS problem. The ^{wiH} indicates a broadcast message.

To: * <Managers make announcements
Prom: 25 of this form.>
Type: TASK ANNOUNCEMENT
Contract: 22-3-1
Message:
laak Abstraction;
TASK TYPE »signal
NODE NAME '25 POSITION 'p
Eligibility Specification;
MUST-HAVE DEVICE TYPE 'sensor
MUST-HAVE NODE NAME 'SELF POSITION area 'A
Bid Specification:
NODE NAME 'SELF POSITION
EVERY DEVICE TYPE 'sensor TYPE NUMBER

To: 25 <Sensor nodes respond to
From: M2 the nearest manager.>
Type: BID
Contract: 22-3-1
Message:

NODE NAME 'H2 POSITION 'q
sensor TYPE 'S NUMBER '3
sensor TYPE 'T NUMBER '1

To: 42 <Several similar awards
From: 25 are transmitted.>
Type: AWARD
Contract: 22-3-1
Message:
Xaak Specification:
sensor NAME 'S1
sensor NAME 'S2

2.3 Knowledge Organization

The knowledge organization component of the framework specifies mechanisms for retrieval and distribution of knowledge in a distributed problem solver. Retrieval can be further broken down into two parts: partitioning and indexing. Partitioning indicates the ways in which the knowledge is broken up into modules; indexing indicates the handles placed on the knowledge modules so that they can be accessed.

2.3.1 Partitioning

It is common in AI problem solvers to partition expertise into domain-specific knowledge-sources (KSs), each of which is expert in a particular part of the overall problem. KSs are typically formed empirically, based on examination of different types of knowledge that can be brought to bear on a particular problem. In a speech-understanding problem, for example, knowledge is available from the speech signal itself, from the syntax of the utterances, and from the semantics of the task domain [Erman, 1975]. The decisions about which KSs are to be formed is often made in concert with the formation of a data hierarchy for a problem. KSs are typically chosen to handle data at one level of abstraction or to bridge two levels (see, for example [Erman, 1975] and [Nil, 1978]).

In a distributed processor there is an additional consideration: The KSs themselves will likely be distributed to different nodes, and their interactions will therefore often be more expensive than in a uniprocessor. As a result, the kernel size of the KSs must be chosen carefully, based on the characteristics of the distributed processor. KSs that are too small will result in a large amount of communication between nodes, thus reducing the speedup that can be achieved via a distributed approach. Matching of kernel size to distributed processor characteristics must at present be done via trial and error by the applications programmer.

2.3-2 Indexing

In the contract net framework, the main issue in indexing of knowledge is connecting nodes with tasks to be executed to nodes with KSs that are appropriate to execute those tasks. Two major types of knowledge are recognized for indexing: task-centered knowledge and knowledge-source-centered knowledge (KS-centered knowledge). Task-centered knowledge is useful for finding nodes capable of executing tasks and KS-centered knowledge is useful for finding tasks to be executed by a node. The contract net appears to be the first use of both kinds of knowledge at the same time.

In the DSS, for example, the task-centered knowledge used by the manager for the signal task specifies that contracts should be awarded so that the area surrounding the manager is covered with an adequate distribution of sensor types. The KS-centered knowledge used by a sensor node specifies that a signal task should be selected from the closest manager that offers such a task.

2.3*3 Distribution Of Knowledge

Distribution also has two aspects: static distribution, how knowledge is initially loaded into the nodes, and dynamic distribution, how knowledge is transferred between nodes as work on the overall problem proceeds.

The criteria for a good static distribution of knowledge are minimization of message traffic and avoidance of critical function nodes that could reduce processing speed and create reliability problems. In the DSS, for example, KSs with expertise at a particular level of the data hierarchy were placed in different nodes. This enabled nodes to carry on simultaneously with computation specific to those levels of the data hierarchy that concerned them (without the need for frequent interactions with nodes operating at different levels of the hierarchy).

In the contract net framework, dynamic distribution of knowledge can be effected in three ways. First, a node can transmit a request directly to another node for the transfer of the required knowledge. The response is the knowledge requested (e.g., the code for a procedure). Second, a node can broadcast a task announcement in which the task is a transfer of knowledge. A bid on the task indicates that another node has the knowledge and is willing to transmit it. Finally, a node can note in its bid on a task that it requires particular knowledge in order to execute the task. The manager can then send the required knowledge in the contract award if the bid is accepted. Each of these interactions is simplified by the use of a common internode language.

Dynamic distribution enables effective use of available computational resources: A node that is standing idle because it lacks information required to execute a previously announced task can acquire that information as indicated above. Dynamic knowledge distribution also facilitates the addition of a new node to an existing net; the node can dynamically acquire the procedures and data necessary to allow it to participate in the operation of the net. This is especially useful in the DSS application.

3 Discussion

There are several reasons for adopting a distributed approach to problem solving. These Include speed, reliability, extensibility, and the ability to handle applications that have a natural spatial distribution. The design of the contract net framework has taken Into account each of these considerations. We relate here design choices made in the framework to their underlying motivations.

In order to achieve high speed we wish to avoid bottlenecks. Such bottlenecks can arise in two primary ways: by concentrating disproportionate amounts of computation or communication at central resources, and by saturating available communications channels so that nodes must remain idle while messages are transmitted.

To avoid bottlenecks we facilitate the distribution of control and data. This is a major motivation for the use of local contract negotiation to achieve connections and task distribution, and to provide a means for dynamic distribution of procedures and other data. System concurrency is also enhanced because both managers and contractors simultaneously seek each other out, finally achieving connections by mutual selection.

To avoid communications channel saturation we attempt to maintain loose-coupling. The framework is well-suited to loosely coupled systems in three respects. First, it provides a very general form of guidance in determining appropriate partitioning of problems: the notion of tasks executed under contracts is appropriate for a kernel size larger than that typically used in parallel systems. Second, the framework attempts to be efficient with respect to its use of communications channels by reducing the number and length of messages. The Information in task announcements, for instance, helps minimize the amount of channel capacity consumed by communications overhead. Extraneous traffic is eliminated by the eligibility specifications of the task announcements and the bid messages are reduced in length because of the bid specifications. Finally, the framework enables dynamic distribution of procedures and other data. Thus the option exists to distribute information only when required;

Reliability is also enhanced by the distribution of control and data, together with shared responsibility for tasks (by managers and contractors). The failure of a contractor, for example, Is not fatal, since its manager can re-announce the appropriate contract and recover from the failure. This strategy allows the system to recover from any node failure except that of the node that holds the original top-level problem.[1]

Extensibility is facilitated by the use of a common internode language and dynamic distribution of knowledge.

The ability to handle applications with a natural spatial distribution is facilitated by the use of local contract negotiation to achieve connection and task distribution.

4 Suitable Applications

The framework is particularly well-matched to problems that use a hierarchy of tasks and levels of data abstraction. Heuristic search problems are examples of the former, and applications that deal with sensed data (e.g., audio or video signals) are examples of the latter.

The manager-contraotor structure provides a natural way to effect hierarchical control and the managers at each level in the hierarchy are an appropriate place for data integration and abstraction. The contract links between nodes assist in coordination of KSs (i.e., a manager can coordinate the actions of contractors working on related subtaaks).

It also follows that the framework is primarily applicable to domains where the subtaaks are large (in the loose-coupling sense) and where it is worthwhile to expend a potentially nontrivial amount of computation and communication to invoke the best KSs for each subtask. (The aame basic mechanism can, however, be used simply as a means of task distribution with distributed control and shared responsibility for tasks to maintain reliability and avoid bottlenecks.)

The framework has also been designed to

[1] At the top level, contracting can distribute control almost completely, hence removing the bottlenecks that centralized controllers create. There still remains, however, the reliability problem inherent in having only a single node responsible for the top-level problem. Since this cannot be handled directly by the manager-contractor links, standard sorts of redundancy are required.

provide a more powerful mechanism for transfer of control than is available in current problem-solving systems (see [Smith, 1978b] for a complete discussion). The announcement-bid-award sequence of contract negotiation enables more information and more complex information to be transferred in both directions (between caller and respondent) before KS-invocation occurs. In addition, information about the complete collection of candidate KSs is available before a final selection is made. The computation devoted to the selection process, based on the information transfer noted above, is more extensive and more complex than that used in traditional approaches, and is local in the sense that selection is associated with and specific to an individual KS (rather than embodied in, say, a global evaluation function). As a result, the framework is most useful when the specific KS to be invoked at any time is not known a priori and when specific expertise is required.

5 Limitations And Extensions

We have proposed a framework that offers some ideas about what information is useful for distributed problem solving and how that information can be organized. There is still a considerable problem involved in instantiating the framework in the context of a specific task domain. The contract net protocol provides a site for embedding particular types of task-dependent information (e.g. an eligibility specification), but does not specify, for a particular problem, the content, nor how to instantiate it in a particular domain. We require more experience with the framework to better understand its utility as a mechanism for helping a user structure and understand distributed problems.

We have emphasized task-sharing as a means of internode cooperation and have attempted to provide some structured mechanisms for the communication required to effect this mode of cooperation. We have, however, not yet adequately studied result-sharing as a means of cooperation; that is, nodes assisting each other through sharing of partial results, based on somewhat different perspectives on the overall problem. Different perspectives arise because the nodes use different KSs (e.g., syntax vs acoustics in the case of a speech understanding system) or different data (e.g., data that is sensed at different locations in the case of a DSS). This type of cooperation appears to be of use in dealing with problems where errorful data or knowledge lead to conflicting views of the problem at individual nodes (see [Lesser, 1978] for a preliminary discussion). It is our intention to examine the structure of communication for this mode of cooperation with a view to extending the contract net framework so that a synthesis of the two approaches to distributed problem solving can be attempted.

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THE X-0-0 HEURISTIC IN GAME TREE ANALYSIS

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Programs for two-person games, such as chess or Go, are heavily dependent on Minimax evaluation of large game trees, which is combined with heuristics in an attempt to prune these trees as severely as possible* In particular, alpha-beta pruning, usually combined with the killer heuristic, is used in all major minimax-based programs* In this paper we shall propose a new heuristic which could be incorporated into minimax-based programs, and which should significantly increase the pruning possible during the analysis of game trees* This new heuristic, which can be combined with alpha-beta and the killer heuristic, is called the X-0-0 heuristic. The development of the heuristic was prompted by the difficulty of analyzing large game trees in Go, and is based on a formalism and extension of the Go proverb "the enemy's play is my own key play[11]*

1* Introduction*

Current programs for complex two person games such as chess or Go rely heavily on minimax-based lookahead to evaluate board positions and to select moves* In chess programs this is usually an analysis performed over good moves throughout the whole board, while in most Go situations lookahead must be restricted to local battles* In order to increase the number of nodes that can be analyzed with the computing resources available, alpha-beta tree pruning is invariably utilized, usually in conjunction with the killer heuristic [1,4]*

In this paper we will introduce a new heuristic named the X-0-0 heuristic* The purpose of this heuristic is to anticipate and protect against the opponent's strong moves, both offensive and defensive* In section 2 we will informally describe the heuristic, and will give examples of it in use in chess and Go* We will then define the algorithm for the heuristic precisely in section 3* We will assume that the reader knows the basic rules of chess and Go*

2* The X-0-0 heuristic*

There is a Go proverb "The enemy's play is my own key play" [3]• A simple example of this is shown in Figure 1*

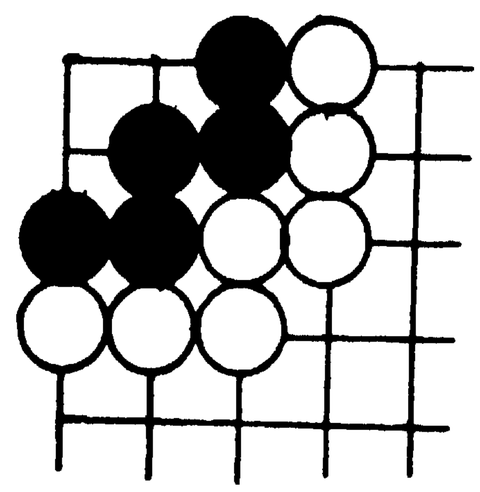

Figure 1

If it were black's move, he would play in the corner, guaranteeing the safety of his group* If it is white'8 move he uses the proverb to play in the corner* In its simplest form, the X-0-0 heuristic Is similar to the proverb in that it attempts to recognize the opponent's strongest move, and to take it away from him*

A chess example Is shown in Figure 2.

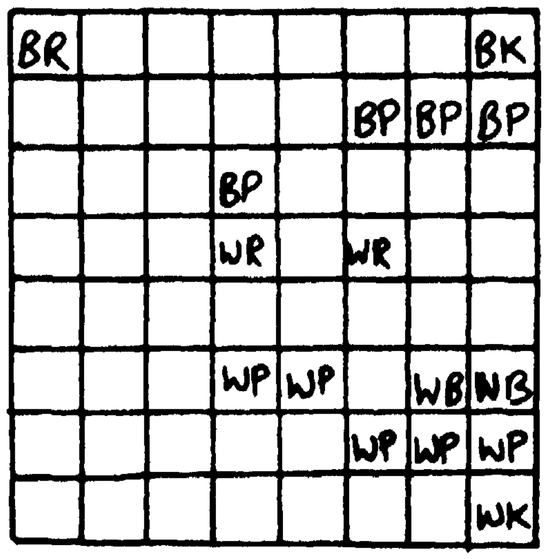

Figure 2

It is White's move. In this situation current chess programs will perform extensive lookahead analysis attempting to find a mating sequence. In the same position, even a poor human player will quickly recognize the R-R8 threat, and will decide that the only way to block that move is R-R5, and so the block move is forced. No lookahead is necessary to make the move* The thought process that has occurred is:

> "If it were black's move instead of mine, does he have any obvious strong moves? Yes, he would move his rook to R8 and check me. Would I then be able to do anything about that? No, it would be checkmate. How can I stop that move? I must either capture the rook, block its path, delay him by putting him in check, guard RI, or block the path between RI and my king. The only one of these that I can do is to block the path of the rook with R-R5, and so this is a forced move*[11]

Figure 3 shows a similar board position.

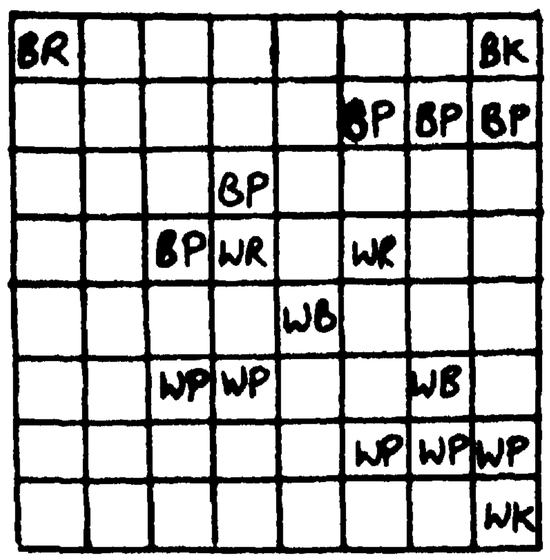

Figure 3

Here the threat is the same as before, but if *xack plays R-R8, white needs two moves to block the threat; either P-R3 or P-R4 followed by K-R3. The X-O-0 heuristic compels white to play either P-R3 or P-R4 at this move.

Figure 4 shows a Go position called the nose tesuji. It is black's turn to play, and he wants to capture the two white stones on the right. A tesuji pattern matching program decides that the probable best play is the stone marked with an X, on top of the white "nose". Black must now confirm that the white pieces cannot escape. Tackett [2,5] analyzed this position, and decided that its solution would take nearly a month on an IBM 360/67, using standard lookahead techniques. Using the X-O-0 heuristic the analysis is very inexpensive. White can only escape in two directions, to the left or right. Consider an escape to the right: if it were black's move he would immediately play to the right of the two white stones, blocking all possibility of escape. Therefore the X-O-0 heuristic compels white to block that move by playing there. A simple template pattern match should now show that white is trapped. A similar analysis on the left shows that white cannot escape that way either, and so black's nose tesuji is confirmed.

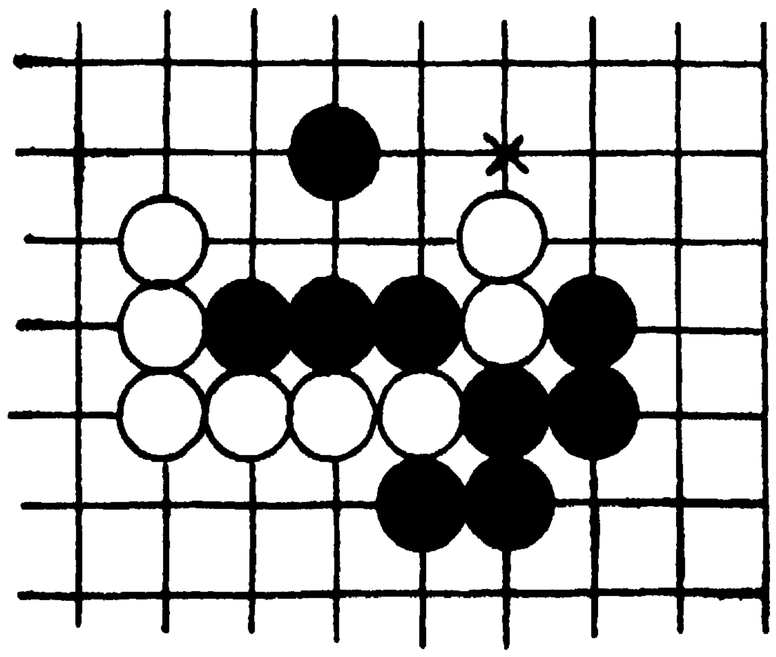

Figure 4

3- The X-O-0 algorithm.

We are now ready to give the formal algorithm for the heuristic. Assume that the two players are X and 0, and that it is O's turn to play.

The algorithm can then be written:

Find all very strong X moves, XI, ••• , Xn.

For each XI
(a) If there is an 0 move which nullifies the effect of XI then XI can be ignored.
(b) If XI must be blocked now, add blocking 0 move8 to the forced move list for XI*
(c) If two 0 move8 are needed to nullify the effect of Xi, say 0' and 0"$_t$ then add 0* to the forced move list for XI*

If there are no forced move lists, then use alpha-beta lookahead as usual*

If there are forced move lists, then play a move which is in the intersection of all of the forced move lists*

4. Summary

The success of the heuristic in any given game will depend on the care with which the good X moves are selected* The list of moves should be kept as small as possible, and n should usually be much smaller than the branching factor of the mintmax game .ce. We are currently experimenting using the game of Go-Moku in order to obtain a good estimate of the improvements which can be expected using X-O-0.

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AN EXAMINATION OF A FRAME-STRUCTURED REPRESENTATION SYSTEM

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The Unit Package is an interactive knowledge representation system with representations for individuals, classes, indefinite individuals, and abstractions. Links between the nodes are structured with explicit definitional roles, types of inheritance, defaults, and various data formats. *This* paper presents the general ideas of the Unit Package and compares it with other current knowledge representation languages. *The* Unit Package was created for a hierarchical planning application, and is now in use by several AI projects.

1 INTRODUCTION

When the MOLGEN project was started, many ideas about frame systems and semantic networks were being widely discussed, buj^ no software was available. In collaboration with other members of the MOLGEN project, the author developed a representation system called the "Unit Package" which became operational in July 1977. In some cases (and usually in ignorance), this work has duplicated other representation work that was happening at about the same time. *The* Unit Package is now being used by several other projects including two away from Stanford. It is written in INTERLISP and runs under the TENEX and TOPS20 operating systems. It is an interactive system for building knowledge-based programs. It also provides a substantial virtual memory so that knowledge bases of several thousand nodes can created without sacrificing the INTERLISP environment.

*M0LGEN is a joint project between the Stanford Computer Science Department, several departments of the Stanford Medical School, and the Computer Science Department at the University of New Mexico. It is active in the computer planning of molecular genetics experiments ([71, [17]). MOLGEN is supported by grant NSF MCS 78-027777 from the National Science Foundation.

**Nancy Martin and Peter Friedland made substantial contributions to the Unit Package, especially in the first year.

2 ELEMENTS OF TOE REPRESENTATION

Knowledge in the Unit Package is organized as a partitioned semantic network. Following KRL [3] terminology, the nodes are alternatively called units and the links are called slots. A built-in generalization relationship provides a hierarchy with several modes of property inheritance. Conspicuous for its absence is a comprehensive inference mechanism. While the Unit Package provides some built-in inferential facilities — notably the property inheritance mechanism, the pattern matchers, and the attached procedure mechanism — most of the inference control must be provided by application-specific methods. *The* ideas in the Unit Package will be presented in the following order.

1) Partitions — *The* boundaries in the network which divide it into (possibly overlapping) explicit sets of nodes.

2) Units — *The* nodes in the network. The Unit Package has nodes for constant individuals and classes as well as for undetermined and abstract entities. For the latter it permits naming them, anchoring them to constants, adding details to them, and indicating whether they are the same or different (without necessarily anchoring them) •

3) Slots — The links between the nodes. The fine structure of links is defined by a set of "aspects" %*iich define their inheritance and definitional roles, datatypes, defaults, and attached procedures. These aspects provide declarative meta-knowledge which indicates how a slot is to be interpreted.

4) Attached procedures — Procedures may be attached to units, slots, or datatype units, depending on what they are used for. They are activated by messages and have explicit purposes. A small set of purposes is recognized by the Unit Package to allow automatic activation under specified circumstances. Attached procedures are the chief mechanism for making inferences in the Unit Package.

2.1 Partitions

While a knowledge base is ultimately composed of nodes and links, it is often useful to consider larger organizations of units. For this purpose the Unit Package provides a facility for partitioning a network into explicit sets. This £s the same idea as the spaces in Hendrix's partitioned semantic networks [91. The unit Package simply prov^es an efficient notation for explicit sets and a mmber of functions which act on all members of sets.

2.2 Nodes

In our planning application, it is helpful to have open-ended descriptions for abstract entities and to be able to refer to individuals whose identities have not yet been determined. To represent this information the Unit Package provides four kinds of nodes as in Fig. 1 along with the computational machinery for their interpretation.

We have not yet exploited the set notation for handling quantification.

This could have been indicated with a member-of slot. Our implementation makes it possible to tell whether a unit is in a set without requiring that the unit be core resident.

	Constant	Variable
Individual	Instance	Indefinite
Class	Schema	Description

Figure 1. Kinds of nodes in the Unit Package

These kinds of nodes are listed here briefly and discussed in the following sections.

1) INSTANCE — Constant node that stands for a unique individual. An instance is analogous to a constant in predicate calculus.

2) SCHEMA — Constant node that stands for a class. A schema describes all of its potential progeny in the generalization hierarchy.

3) INDEFINITE NODE — Variable node that stands for an individual. Analogous to an existentially quantified variable in "predicate calculus with equality". Fundamental links for reasoning about equality are (1) "anchor" links which tie indefinite nodes to instances and (2) "co-reference" and "not-co-reference" links which tie indefinite nodes together.

4) DESCRIPTION NODE — Variable node that stands for a class. These nodes are used for matching and reasoning about abstractions, that is, incompletely described entities.

Section 3.1 compares these node types to other work on representation.

2.2.1 Nodes for Constants

An "instance" is the simplest kind of node in the Unit Package. Instances are analogous to constant terms in predicate calculus and are used to represent distinct entities, that is, "individuals" Examples of instances in the our application would be domain objects like Culture-133, a particular culture of organisms. Schemata stand for classes, that is, implicit sets and may have subclasses and instances below them in the hierarchy. Because instances do not stand for classes, they can have no nodes below them. A schema describes all of its potential progeny by expressing all of the

attributes that are required for members of the class.

2.2.2 Indefinite Nodes

"Indefinite" nodes are the simplest variable nodes in the Unit Package; they stand for individuals whose identity may be unknown. They allow us to indicate that two variables are equal (or not equal) without knowing their values. This is like the augmentation of predicate calculus to predicate calculus with equality except that it is a three-valued logic permitting the logical possibility that equality may be "unknown". For example, we could have indefinite nodes for Martha's-husband or The~first-president. We may equate these indefinite nodes to each other by marking them as "co-referential". We may also "anchor" or ground them to an individual unit (e.g., George-Washington), Two indefinite nodes are said to be equal if they have the same anchor or if they are tagged as being co-referential. Two indefinite nodes are not equal if they have different anchors, if they are marked as "not co-referejjtial", or if their scopes do not intersect . In all other cases, equality is "unknown". Co-reference and anchor relationships are represented by slots with standard names. *The* need for such nodes in natural language processing (sometimes termed "intentional" nodes) has al90 been recognized [20]. Our experience has been that the potentially difficult parts in reasoning with these entities are (1) deciding when there is enough evidence to conclude about equality of identities and (2) combining the (possibly conflicting) attributes of the various hypothetical objects once their common identity has been concluded.

2.2.3 Description Nodes

Description nodes are variable nodes which stand for classes instead of individuals. These nodes are used in our planning application to represent open-ended goals. Whereas "anchoring" is the key to equality of indefinite nodes, matching is the key to equality of description nodes. The class defined by a schema is the set of its specializations in the hierarchy; the class defined by a description node is the set of nodes within a specified scope that match the description node. Two description nodes are said to be#equal if they potentially match the same units or if they are indicated as being co-referential. This limits the expression of match conditions to a conjunction of slots. We have found it convenient in our planning application to augment this notation with additional "constraint" units that can express arbitrary predicates involving several nodes. In our planning application, the refinement of abstract goals is accomplished by the addition of constraints to descriptions and the matching of descriptions to the knowledge base. The interpretation and manipulation of these constraints is done by our planning program and not by the Unit Package.

Scopes, in the Unit Package, are simply a branch of the generalization hierarchy. Extending this to a more flexible form of quantification is part of the planned future work on the Unit Package.

2.3 Links

As the Unit Package has been developed, it has become necessary to provide structure for the links between the nodes. Several different "aspects" have been created to accommodate this:

1) NAME — Name of the slot.

2) VALUE — Stored value of the slot. Typically this is the name of a unit but it may be a different data-structure if the datatype aspect is other than "unit". Tlie Unit Package distinguishes between values that are valuejrestrictions and those that are "terminal"

3) DEFINITIONAL R0I£ — The role that the slot plays in the definition of the unit. Tlie roles "PART-OF", "PROPERTY", "RELATION", "SUPER-UNIT", "EQUIVALENCE", and "DOCUMENTATION" are recognized by the Unit Package. Definitional roles are explained further in Section 2.3.1.

4) INHERITANCE ROLE — The mode of inheritance of the slot by progeny. Four distinct roles, ("S", "R", "0", and "U") are recognized in the Unit Package, Criteriality is determined from this role. Inheritance roles are discussed further in Section 2.3.2.

*The operational test for deciding whether two descriptions potentially match the same units is that the descriptions match each other.

**In an analogy with units, descriptions are like schemata and terminal values are like instances.

5) DEFAULT — Default value for the slot to be used in the absence of specific information. This aspect was much less frequently used than we originally expected.

6) DATATYPE — A link in the Unit Package need not go to another unit; it may go to an atom, integer, string, list, lambda expression, or to a value with some other "datatype". "Unit" is probably the most important datatype and is used for most of the links usually associated with semantic networks. The datatype aspect facilitates treating different kinds of values uniformly. The factoring of procedures to support this is discussed in Section 2.4.

2.3.1 Definitional Roles

A retrospective examination of how slots were being used in our genetics knowledge base made us aware that indistinguishable notations were sometimes used where distinct meanings were intended. Pig. 2 illustrates some of the slots from the representation of an organism in one of our knowledge bases. The slot chromosome is used to refer to a part of the organism; the slot gramstain refers to the visible character of the organism when a particular staining agent is applied. Without the definitional role, a general procedure to separate or remove the parts of a unit may try to "remove the gramstain" from an organiam. Thus, the exosomes slot in Fig. 2 indicates (1) what exosomes the organism has (i.e. EXOSOMES (0RGANISM1) = (PMB9, P9C101)) and (2) that the exosomes are to be considered parts of the organism (i.e. PART-OF (PMB9, 0RGANISM1) =T T).

The idea of distinguishing between kinds of links is not new with our work. Woods [20] distinguished between "assertional" and "structural" links. We differentiate between the definitional roles "PART-OF", "PROPERTY", "REIATION", "SUPER-UNIT", "EQUIVALENCE", and "DOCUMENTATION". The role "SUPER-UNIT" has the inverse meaning of "PART-OF" and is used to annotate slots which point back from the parts of a larger concept. The role "EQUIVALENCE" is used to label the special "co-reference" and "anchor" slots used in description and indefinite units. The role "DOCUMENTATION" is used to tag slots like the modifier slot which are part of the automatic documentation of a knowledge base. More definitional roles will probably emerge as the Unit Package is used in additional applications.

Slot Name	Value	Definitional Role
EXOSOMES:	(PMB9, PSC1Ø1)	PART-OF
CHROMOSOME:	DNA-Structure-92	PART-OF
MORPHOLOGY:	COCCUS	PROPERTY
GRAMSTAIN:	POSITIVE	PROPERTY
CAN-EAT:	NUTRIENT-GEL	RELATION
KILLED-BY:	TETRAMYCIN	RELATION
MODIFIER:	Feitelson	DOCUMENTATION
MODIFIED:	12-MAR-79	DOCUMENTATION

Figure 2. Definitional Roles

2.3.2 Inheritance Roles

The idea of the hierarchical inheritance of properties has its roots in the inferential machinery discussed in Quillian's thesis [14]. In its simplest form, a value is defined in the most general schema to which it applies. Nodes corresponding to descendants of the schema inherit the value. As Brachman [6] points out, while a slot in an individual is intended to assert a property of the individual, a slot in a schema is often intended to restrict the legal values of corresponding slots in its potential progeny. These alternative meanings of slots (slots used to define properties versus slots used to instantiate properties) are important for the understanding of inheritance and are not always clearly differentiated in network formalisms.

In the Unit Package we have identified five standard "inheritance roles" for slots. Four roles (termed "S", "R", "0", and "U") that have been useful in the Units Package are described below. A fifth role (termed "M"), which is probably useful but which has not been implemented, is also discussed.

1) The simplest role is for direct inheritance of values by all progeny. This is termed the "S" role because the slot has the same value in the defining unit and all of its progeny.

2) The "R" role is for the inheritance of requirements; it is for slots that are criterial to the definition of a schema. The

values in schemata are interpreted as value-restrictions for the corresponding slots in progeny. The values in slots of progeny need not be the same as jp the schema, but may be further restricted • Usually the value of the slot in an instance will be "terminal", that is, an actual value instead of a description of a value. If every "R" slot in an instance has a terminal value, then the instance is fully instantiated.

3) The "0" role is similar to the "R" role except that the slot is optional (ie. not criterial). The slot in an Instance need not be filled in with a terminal value. For example, in the molecular genetics domain, the organisms slot of the Culture unit has role *B* arid the exosomes slot of the Bacteriun unit has role "0". This is meant to In3Tcate that every culture must have organisms, but every bacterium need not have exosomes.

4) The "U" role is for information about a node that is not inherited by its progeny. The slot value is unique at each level in the hierarchy. As with the other roles, the slot name, datatype, and role are inherited by offspring. However, the value is not inherited or used to limit the value of the slot in offspring. This role is used mainly for our bookkeeping purposes in the network such as for the creator slot in units.

The first three roles can be seen as decreasingly strict. With the "0" role, a value is optional in instances; with "R" it is required; with "S" it is directly inherited. In contrast, the "U" role ignores the nesting of values in progeny altogether. *One* additional role for inheritance, which we have not implemented, would allow slots in progeny to have values that override restrictions from above. (This might be termed the "M" role meaning modifications allowed). This idea was originally disallowed because it was seen as counter to the spirit of unit specialization.

Like definitional roles, inheritance roles provide meta-knowledge about the interpretation of slots. They indicate (1) transmission instructions for the information and (2) whether the value is criterial to the definition of the slot. Inheritance roles are also used by the interactive component of the Unit Package to determine what checking is performed when knowledge is entered by a user.

Before leaving the subject of inheritance, it is worth emphasizing that a generalization hierarchy should be distinguished from other hierarchical relationships from everyday life which do not indicate inheritance paths. Some common ones are "subset-of", "element-of", "part-of" and "abstraction-of". These relationships are represented in a semantic network by explicit links independent of those used for the superclass taxonomy.

2.4 Attaching Procedures

The attachment of procedures to frames is one of the representational ideas common to the new knowledge representation languages. Several older languages (such as LISP) support arbitrary attachment of procedures to data structures; the approach in frame-structured languages is more disciplined. This discipline in the Unit Package has two main elements: (1) standardized points for attachment and (2) an explicit purpose for procedures. The "purpose" of a procedure indicates when a procedure should be activated.

The Unit Package provides three standard places for attaching procedures: (1) unit attachment (2) slot attachment and (3) datatype attachment. Unit attachment is used for operations that act on a unit as a whole. Slot attachment is used for operations on a particular slot of a unit. Datatype attachment is useful for operations on slots located in units throughout the knowledge base that have values of a particular datatype. Although datatype attachment has not been reported in other frame systems, it has been used extensively in the Unit Package [17] and is similar to ideas from SIMULA.

We have adapted some terminology from SMALLTALK to describe the activation of attached procedures. A procedure is activated by "sending it a message" with a token that matches its purpose. This is an indirect form of procedure call — where the purpose of the procedure is known to the caller but the name of the procedure need not be known. The "purpose" of a procedure is usually associated with standardized activation conditions (e.g. "To-Get"); it also indicates where the

*The meaning of "further restricted" is determined by a function associated with the datatype of the slot. For the "number datatype, the value-restrictions are numeric ranges or lists. For the "unit" datatype, the value-restrictions may be description nodes or ancestor specifications.

procedure's name is stored. For unit attachment, the purpose is the name of a slot containing the procedure name; for slot attachment, it is the name of an aspect; for datatype attachment, it is the name of the slot in the unit for the datatype. Functions like the matcher, which must work for all datatypes, operate by activating datatype-specific procedures using the message mechanism.

3 RELATIONSHIP TO OTHER WORK

During the period when the Unit Package was developed, many other frame-structured representation systems have also appeared. In some cases, our work has duplicated that of other groups. This section compares the Unit Package to related systems.

3.1 Other Work on Node Types

The idea of distinguishing between node types in a knowledge representation language has important implications for the design of interpreters and matchers. If node types are not distinguished, then the semantic information about abstractness and equality must be carried by some other means. Node types similar to our four categories have appeared in other contemporary representation languages. Fig. 3 summarizes what they are called in AIMDS ([15], [16]), FRL [8], KLONE ([5], [19]), KRL-0 ([1], [3]), Levesque's System [11], and OWL ([18],[13]). This is not to say that the node types correspond exactly in these systems, but that the ideas seem to be very similar.

Several other types of nodes have appeared in representation languages. For example, KRL-0 supported the additional node categories "relation", "proposition", and "basic". The relation category was used to represent an abstract relationship between entities and a proposition was an instantiation of a relationship specifying its truth value. (In our planning application, constraints serve some of this function although their interpretation is by the planning program instead of a general interpreter for the representation language.) "Basic" categories partition the world into simple non-overlapping categories. Categories are meant to allow quick tests (by category comparison) to decide whether an object fits a description. This partitioning is partially (but inadequately) achieved in the simple hierarchical systems by the approximate rule that two schemata are in distinct categories if neither is an ancestor of the other in the superclass hierarchy . It is not clear that such categories can be assigned to domain objects once arv3 for all. Further aspects of this are discussed in two recent critical examinations of KRL ([10], [1]).

One of the shortcomings of the Unit Package is illustrated by this example. There is no annotation to indicate which branches in the generalization hierarchy are mutually exclusive.

System	Instance	Schema	Indefinite	Description
AIMDS	instance	template		
FRL	instanti-ated frame	generic frame		
KLONE	individual nexus	generic concept	variable nexus	parametric individual
KRL-0	individual	special-ization	manifestation	abstract
Levesque's System	instance	class	indefinite	
OWL	instance	species		

Figure 3. Node types in other representation systems

The node types in KLONE ([4]$_r$ [5]) shown in Fig, 3 do not fit perfectly into the categories used in the Unit Package; KLONE distinguishes between patterns (also called descriptions or concepts) and representations of things. A generic concept in KLONE is a pattern because it does not stand directly for its potential progeny; the class is its extension in solhe context. Similarly, an "individual concept" in KLONE is an individualized pattern; it describes a potentially unique individual which may or may not exist (e.g. "the current king of Prance"). A nexus is more like the sort of individual in the Unit Package. A nexus is either constant or variable. A nexus has an "existence value" which can be "does not exist". It can have "coreference wires" to other nexuses and "description wires" to individual concepts. Thus KLONE distinguishes individualized patterns (individual concepts) from representations of individuals (nexuses). The matrix in Fig. 1 does not make this distinction. KLONE's "parametric individual" is not quite the same as a description node (i.e. variable class node) in the Unit Package. Parametric individuals are still patterns — they describe potentially many individuals — but they are not arbitrary generic descriptions; some of their values are bound by the context in which they appear, and thus they are "parameterized".

3.2 Other Work on Property Inheritance

Hie recognition of different forms of inheritance is not unique to the Unit Package. Goldstein and Roberts [8] distinguished two kinds of inheritance in FRLH0 — additive and restrictive. Additive inheritance permitted a specialization to add new non-contradictory facts. This corresponds to the "R" and "0" roles above. Restrictive inheritance is used when a specialization overrides the information in a more general schema. This corresponds to the "M" role above, which we have not implemented, FRL-0 also encouraged the use of "idiosyncratic forms" of inheritance by the use of attached procedures. These procedures effected the transmission of values from frames other than the parent. This seems to be an attempt to capture some of the "multiple-perspectives" idea of KRL using less machinery.

An elaborate proposal inheritance was proposed by Brachman [6] and then substantially elaborated by Brachman and Woods ([5], [19]). Brachman connects nodes not by a single generalization link, but rather by a complete bundle of links (called a "cable") which ties together the parts with different kinds of links. The details of these links require more explanation than is convenient here but the main insight is that inheritance of complex structures must be supported by a rich vocabulary of relationships for the parts of the inherited structure. While the scope of their developing system (KLONE) is broader than our own, the philosophy is essentially the same, namely, to develop a concise and structured representation in which the important kinds of relationships are explicit and uniformly represented for processing by general purpose network routines.

4 SUMMARY

The Unit Package is a frame-structured representation language whose main elements are partitions, nodes, links, and attached procedures. Our goal has been to develop a concise and structured representation language in which the important kinds of relationships are explicit and uniformly represented for processing by uniform network processing routines. This has led to formalisms for kinds of nodes, links, inheritance, and attached procedures. Some of these formalisms have been inspired by and instrumental for the MOLGEN planning application. Probably the most important example of this is the idea of a hierarchical variable to which one can add information and constraints. These variables provide a notation for hierarchical planning.

Some shortcomings of the Unit Package have been noted in passing. These include a need for allowing multiple generalizations, a need for explicit indication of mutual exclusion, and a more adequate use of quantification. These problems are not difficult to fix. Space does not permit discussion of more substantial representational problems beyond the current research, such as the structured representation of processes and causal relationships. The reader interested in a discussion of some unsolved problems is referred to [17].

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AUTOMATIC DISCOVERY OF HEURISTICS FOR NONDETERMINISTIC PROGRAMS

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This paper discusses one way to limit the cost of executing declaratively specified nondetermin istic programs. The approach we take is to develop control heuristics for a family of problems from traces of sample solutions generated during a training session with a human expert. Algorithms have been developed which recognize a set of patterns in the sequence of 'knowledge applications' and which compile descriptions of these patterns in a control language, called CRAPS. The CRAPS descriptions generated are then used for guidance in solving subsequent problems. We describe an implementation of this approach and give the results of several experiments.

1. INTRODUCTION

During the last few years, a number of relatively effective Artificial Intelligence programs have been written incorpprating considerable amounts of knowledge, and the problem of encoding such knowledge in a useful form has emerged as one of the central problems of AI. Recently, attention has turned towards mechanisms which facilitate incorporating limited procedural or heuristic information into a primarily declarative framework (for example, Rychener's approach [4] is to build a rational "goal" structure into declarative rule-based systems, while Davis [2] favors a separate set of "meta-rules", specifying control information). The problem of acquiring, debugging and extending control information has become increasingly important. We believe that there are a number of important areas in which it might be possible to deduce control information automatically from a declarative program. These include declaratively specified problems: (1) for which there exists a relatively simple algorithmic procedure> or (2) whose performance can be improved in frequently occurring or particularly important special cases? or (3) in which particular subproblems can be solved by simple algorithmic procedures. This problem has been discussed by a number of previous workers in various forms (for example [1,3,7]); space does not permit a complete review here (see [5] for such a review and comparisons with the present work).

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2. APPROACH

In our experiments, we have been working on a (slightly idealized) jigsaw puzzle, in which each piece has an average color, and four sides described by unique integers (with side i fitting side -i). A nondeterministic algorithm written in production language form for this problem can be found in [6].

The representation contains 33 productions, and is highly nondeterministic, and if executed would be hopelessly inefficient. It does not even "know" that it will find a solution (i.e. terminate) if it can repeat the production which puts a piece in the puzzle as frequently •♦s possible, so even the crudest goal-subgoal structure is absent. (However, there is no production to remove a piece from the puzzle, which serves as a clue to an intelligent observer). It is even possible for the program to pick up a piece and then put it down immediately without doing anything with it.

However, sufficient productions are present to permit simple sequencing heuristics to reflect the usual strategies used by experi-

enced puzzle-solvers:

o work on the outside edges first (build a pile of outside edges); repeat the put-piece-in-puzzle sequence until this pile is empty;

o separate the pieces in the heap into piles of the same average color, and search the appropriate pile first;

o search first for pieces which have more than one neighbor of the same average color (e.g. work on the sky first);

It may appear that automatic detection of such heuristics is a task of great difficulty. Below we outline an approach to this problem which appears to be quite successful, describe a system which has been embedded in a production system language and give some experimental results.

Our procedure is as follows: we select a •typical[1] input to the program and run the program repeatedly on this input, recording the sequence of rules selected. This is repeated for other typical inputs. We then attempt to describe the better (i.e. shorter) successful sequences in a language, CRAPS, designed for this purpose and described in the next section. We then use this description to guide the program's subsequent decisions. The analysis of the solution sequences also produces a set of meta-rules which are used to dynamically alter the sequencing in the event the description does not behave properly.

Inherent in this approach is the assumption that good decision-making procedures or heuristics can be inferred from the performance of the program on only selected inputs. In general, as suggested by work on inductive inference and information theory, we give preference to short CRAPS descriptions which will generate a high proportion of short successful solutions and few long or unsuccessful solutions. We anticipate that the selection of inputs will be critical and that eventually we will want to be able to handle new inputs incrementally. Initially, however, we have concentrated on the simpler problem of getting a good solution for the non-incremental case.

As suggested by sample experiments, the execution time of a completely declarative program will usually be too long to permit a solution except in the simpler cases. Accordingly, we run the program in "training mode" in which its decisions can be observed and if necessary corrected. In initial experiments this was done by a trainer who was aware of the structure of the program; subsequently we anticipate the necessity of using techniques similar to those of Davis [2], which will enable the trainer to deal only with the external behavior of the program.

It should be noted that we have deliberately chosen to exclude information about sequences which end in failure. It is clear that, as found by Winston [8], counterexamples will be extremely valuable. However, as the reader will note below, even this simpler problem poses considerable technical difficulties, and it was our feeling that a clearer picture would emerge from the simpler approach. Furthermore, the experiments suggest that useful results can be obtained without counterexamples.

3. THE CRAPS LANGUAGE

The CRAPS language provides a semantic framework with which to specify or describe sequences of rule applications in the execution of the non-deterministic program. The operators of CRAPS are Concatenation, Repetition, Alternation and Permutation of Sequences, with enabling conditions which are DNF expressions of rule applicability. Concatenation corresponds to sequential execution of statements, and repetition corresponds to iteration statements with 'while' and 'until' termination conditions. The alternation operator specifies alternative sequences of actions much like an ALGOL-68 'case' statement or LISP 'cond' expression. The permutation primitive represents a form of concurrent execution similar to the specification of collateral expressions in ALGOL-68.

The algorithms which compile CRAPS descriptions are based on standard optimization techniques and divide and conquer pattern recognition algorithms. The input to the program consists of a sequence composed of the rules which were fired on each cycle together with the associated input/output information and the list of rules which were applicable on each cycle. The analysis also produces a set of meta-rules whose objective is to suggest productions to fire in the event the CRAPS description is inappropriate. Complete details of these algorithms can be found in [5,6].

4, EXPERIMENTS

The experiments were performed on 5 puzzles with 25-30 pieces. Over 400 productions were fired to solve a puzzle. The CRAPS description generated from a training session using one puzzle consisted of 75 concatenations and 15

repetitions. A total of 192 meta-rules were generated. The original puzzle used in the training session was easily solved using the CRAPS description? no metarrules were needed. The second puzzle was solved in 10 1/2 minutes but required 5 meta-rule calls. The third puzzle failed to be solved because of an incorrect choice specified by the meta-rules after 193 cycles. A fourth puzzle was solved in 11 1/2 minutes with one meta-rule call. A fifth puzzle was run with the meta-rules alone and it failed to make correct decisions after 80 successful cycles were executed. Complete details of these experiments can be found in [5J.

5. CONCLUSION

It is believed by many researchers that an important quality of intelligent behavior is the ability to improve performance with experience, and that generalizing a concept is a critical aspect of learning. In CRAPS, a form of generalization occurs when a repeating subsequence is collapsed into a repetition. Although quite restricted in scope, CRAPS shows how a system might learn procedures, a form of learning which we believe is very important. Although there are a number of very difficult technical problems, it seems to us that with more powerful pattern recognition techniques and more powerful generalizations of control statements, this approach could be very fruitful.

With less ambitious designs, CRAPS can be viewed as a programming aid for the designer and implementer of a large AI problem-solving knowledge base. The CRAPS approach might be useful in fine-tuning a declarative knowledge base as opposed to 'hand-compiling* control elements to effect competent performance in such a system.

The power of the descriptions produced is limited by both the expressive power of the CRAPS primitives, and the level of sophistication of the pattern recognition algorithms th,at have been developed. For example, during repetition detection no notion of similar subsequence is used; furthermore, it is not possible for alternation to appear within repetitions. Despite this, the algorithms are powerful enough to detect interesting patterns and subsequently interesting heuristics.

Our experiments suggest that this approach will have the best chance of success when the encoding of the knowledge of the problem domain is such that on any execution cycle a small number of productions and only one instantiation of each production is applicable. This suggests one way in which CRAPS should evolve: the execution traces should include not only productions but also the instantiations of productions (i.e. contextual or even goal information should be included). However, recognizing patterns in such sequences is much more difficult. We view our approach as an initial step in the understanding of this more general problem.

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A FACSIMILE BASED TEXT EDITOR USING HANDWRITTEN MARK RECOGNITION

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A fundamental study on a facsimile based text editor using handwritten mark recognition is described with some experimental results. Every information for editting is given to the computer via facsimile. First, texts (handwritten, typed or printed) and five kinds of handwritten marks are input to the computer as binary pictures. Second, the marks are recognized to make the picture allocation list. Third, the fair copy of the text is constructed by rearranging the binary picture according to the list, and is output to the facsimile receiver. Manuscripts using almost any kinds of languages including English, Chinese, Japanese etc. are editted by this system. Moreover, the method described here can be combined with usual text editors or word processors, in order to reduce the keyboard based man machine interaction. Experiments based on a minicomputer controlled facsimile produced unexpectedly good results, and the report 11] was actually made using this method, with less than a half of efforts required in the usual way of Japanese manuscript writing with black ink, scissors and paste.

1. Introduction

It is usually a hard work to prepare documents, especially in Japan, where more than 2,000 kinds of kanji characters are commonly used.

Kanji text editors are available, however, the inconvenience of Kanji input operation is yet essentially unsolved.

Consequently, the greater part of documents used in Japan is still handwritten, and the development of text editors free from Kanji input operation is expected.

This paper describes a fundamental study on a text editor using only facsimiles as input and output devices. The method described here is not based on character recognition, but on mark recognition.

2. Assumption

The following conditions are assumed, in order to make the practical consideration.

(a) Characters must be handwritten, typed or printed with the color easily detected by the facsimile transmitter(e.g. black).

(b) The ruled lines of the manuscript paper should be printed with the color which is not detected by the facsimile transmitter(e.g. light blue or green).

(c) Characters must be placed according to the ruled lines.

(d) Marks are drawn by one of the following two methods:

(d-1) drawing marks directly on the manuscript paper together with characters,
(d-2) drawing marks on the other papers.

In case of (d-1), the overlapping of marks with characters or with other marks should be avoided except for the delete or space marks stated later, while the method (d-2) do not suffer from this limitation.

Fig.l shows an example of the manuscript paper format and five kinds of marks employed here.

(1) Position mark:

The position mark is defined as a set of short lines drawn according to the ruled lines of manuscripts. The format and block size of manuscripts are estimated from this mark.

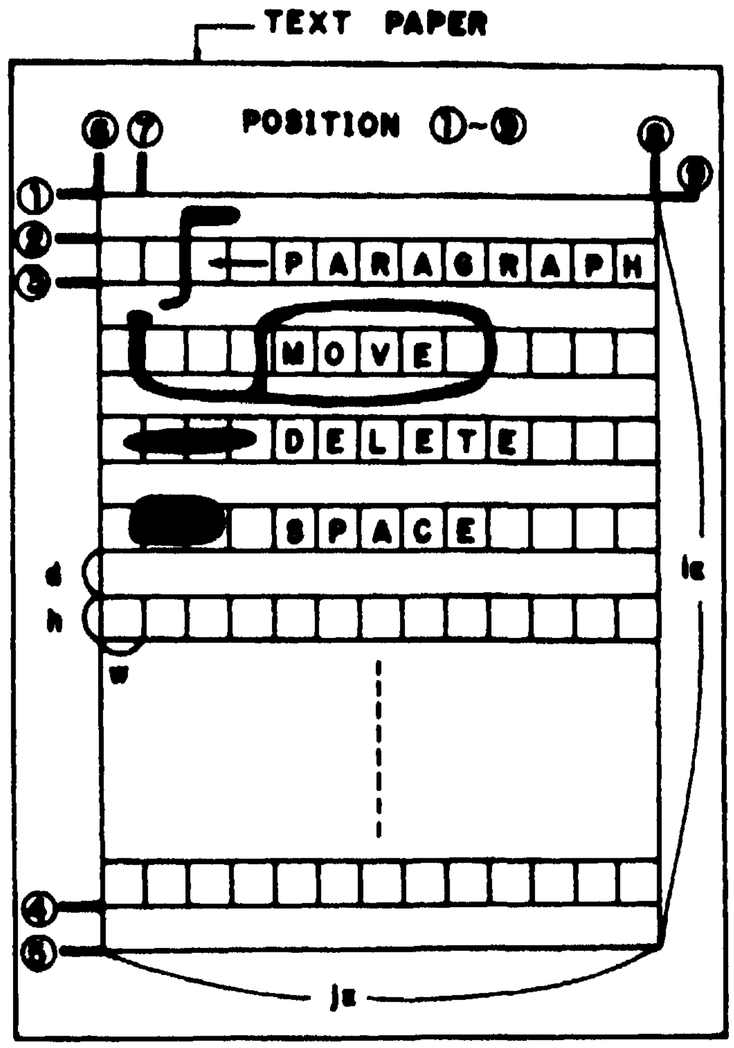

Fig.1 An example of the manuscript paper format and handwritten marks.

(2) Delete mark;

The delete mark is defined as a mass figure drawn on the character string within the blocks. The characters covered with this mark are deleted.

(3) Space mark:

The space mark is defined as a mass figure drawn on the character string, which is similar to, but wider than the delete mark. The characters covered with the space mark are replaced by the equal numbers of spaces.

(4) Paragraph mark;

The paragraph mark is defined as a hook shaped line figure which crosses the blocks vertically This mark indicates the beginning of the new paragraph.

(5) Move mark:

The move mark is defined as a line figure which consists of an arm and a loop. The character string within the loop is extracted and inserted to the position indicated by the arm.

3. Procedure

Referring to Fig.2, the procedure of text editting is described below.

3.1 Input of texts

Original manuscripts and handwritten marks are input to the minicomputer from the facsimile transmitter. At this time, the position mark is detected, and the parameters on the text size and format are calculated.

3.2 Detection of marks for text modification

At first, the paragraph marks and the move marks are detected by searching along the center line of the space between lines.

Then the delete marks and the space marks are detected by testing the inside of blocks. In case of method (d-1) stated in 2, detected marks are completely removed from the binary picture of the manuscript.

3.3 Generation of the picture allocation list

The picture allocation list (PAL) is generated according to the detected marks. PAL consists of block numbers and addresses indicating the order. Character strings of the manuscript are virtually deleted, moved and combined in PAL.

3.4 Reconstruction of the binary image

Finally, the fair copy of the manuscript is made by rearranging the binary picture according to PAL, and output to the facsimile receiver. Put line procedures for Japanese and English are different from each other.

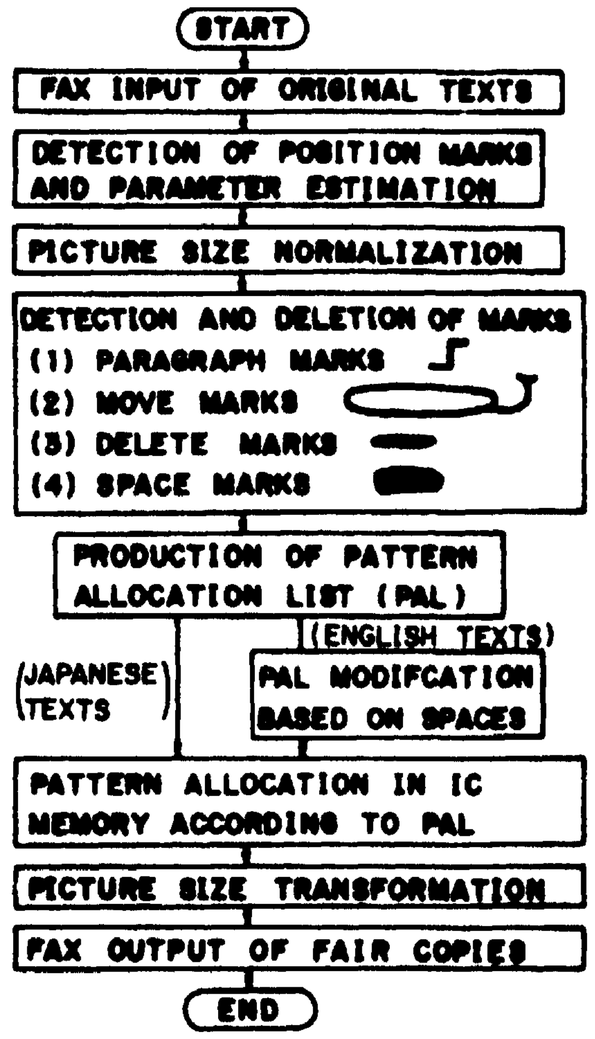

Fig.2 Flow diagram of text editting.

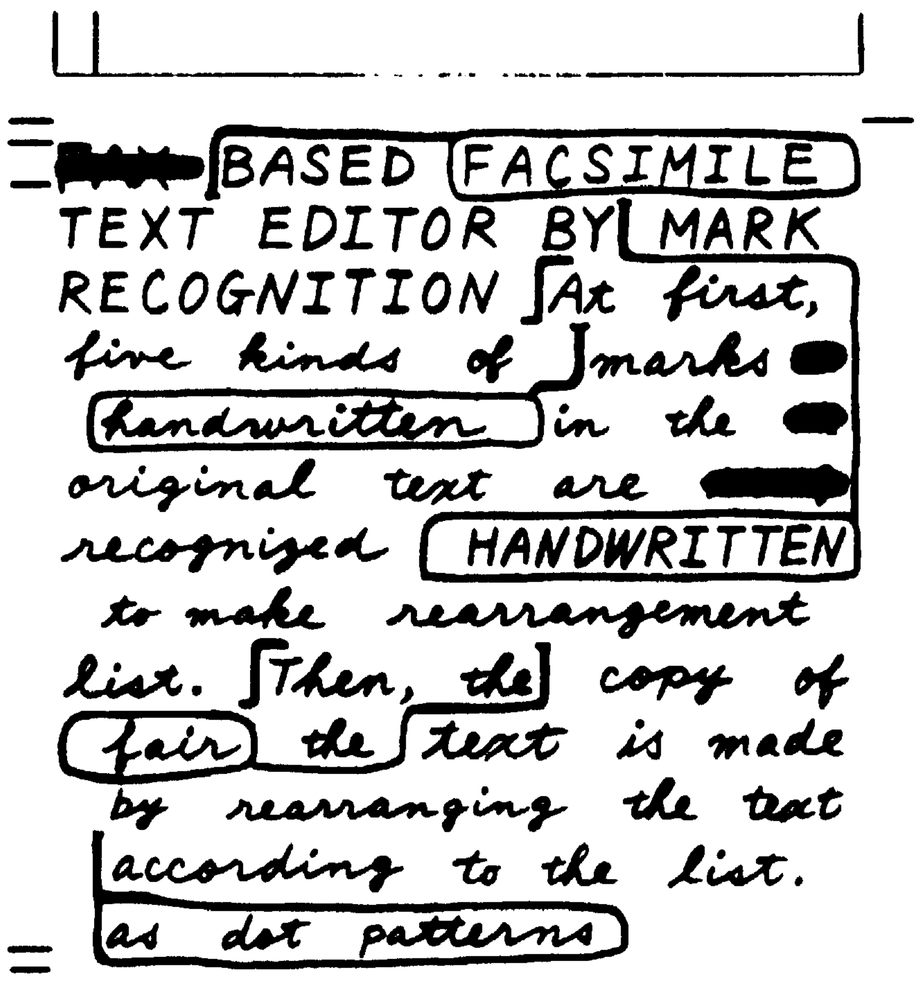

Fig.3(a) An original of a handwritten text. A common manuscript paper and an HB pencil are used.

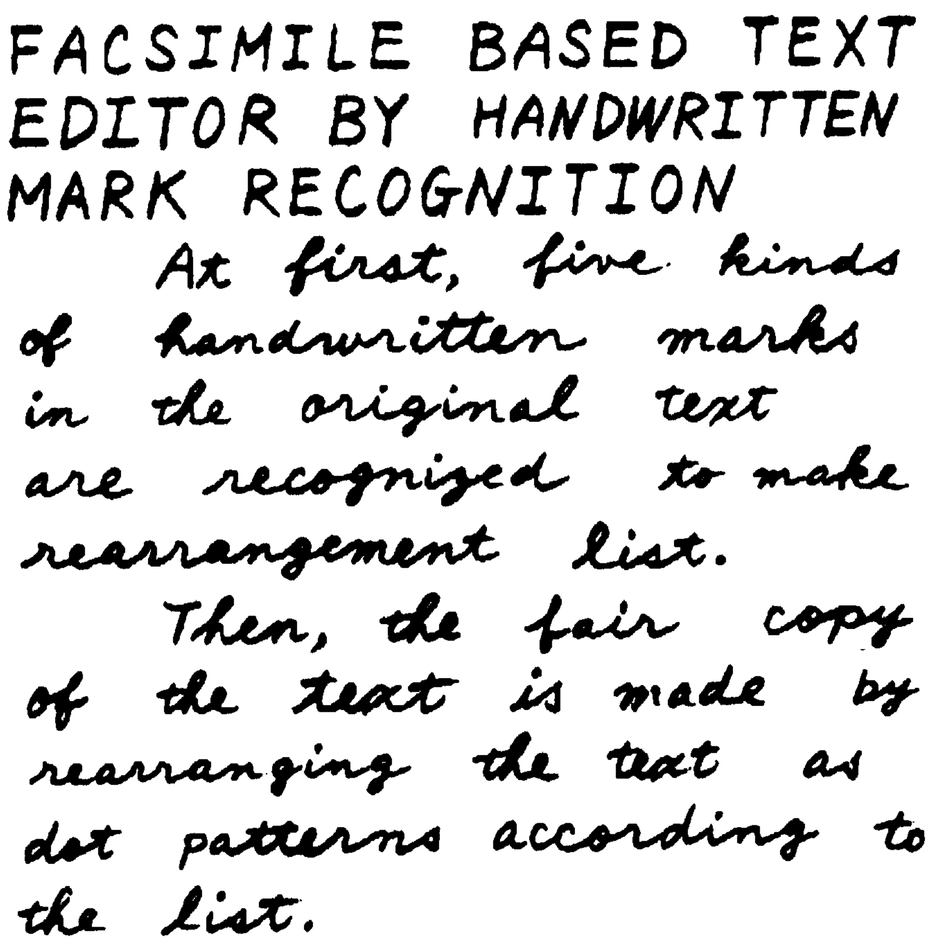

Fig.3(b) Resultant binary pattern of the manuscript made from Fig.3(a).

4. Experimental results

Fig.3(a) and (b) show an example of text editting by the system stated above. One page of the manuscript is handled as a 512 x 512 dot binary picture.

Most programs of the experimental system are made using FORTRAN-IV, and only some special input or output routines are written with an assembly language.

The total processing time is about three minutes per one page of the manuscript: one minute for facsimile input, one minute for mark recognition and the rearrangement of binary picture, and, one minute for facsimile output.

5. Conclusion

The fundamental experiments of text editting by the system described here produced unexpectedly good results. Actually, the report[1] was made by using the system, with less than a half of efforts required for ordinary way of manuscript writing with black ink, erasers, scissors and paste.

The notion and techniques stated here will be very useful for the the modification of various kinds of texts written in almost any kinds of languages.

Moreover, the method employed here can be used in combination with usual text editors, or, in future, with some Kanji OCR's, to reduce the keyboard based man machine interaction.

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AUTOMATIC CONSTRUCTION OF JUNCTION DICTIONARIES AND THEIR EXPLOITATION FOR THE ANALYSIS OF RANGE DATA

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A knowledge-guided system is presented for the analysis of range data obtained from the three-dimensional world. A model of the world is defined by a finite set of prototypes of three-dimensional objects, from which the system establishes its own knowledge about the world in the form of a "junction dictionary". Next the system exploits the dictionary for the prediction of missing edges in the analysis of range data originated with real three-dimensional scenes, and thus constructs concise descriptions of the scenes in terms of vertices, edges, faces and spatial relationships among them. The system is flexible in the sense that the only thing an operator has to do when the world is changed is to replace the model by a new one; the system constructs its own knowledge about the new world and utilizes it for the analysis of range data.

1. INTRODUCTION

It is known that the nature of the three-dimensional objects world places great constraints on line drawings of those scenes, and these constraints are exploited for the analysis of scenes. Huffman [1] and Clowes [2] enumerated all of the permissible junctions in line drawings of a certain fundamental class of polyhedra, and used them for categorizing line-segments according to their physical types (i.e., convex edges, concave edges and contours). Walts [3], Sugihara [A] and Kanade [5] extended Huffman-Clowes method to drawings with shadows and cracks, to drawings with hidden lines and to Origami world, respectively. Those methods work well for perfect drawings. However, if drawings are imperfect, an unmanageable number of permissible junctions should be considered. Therefore, the knowledge about permissible junctions has been used for the categorization of extracted lines, but not for the extraction of missing lines.

On the contrary, the author, utilizing the advantage of range information, proposes an approach to the use of junction knowledge for the extraction of missing edges in the analysis of range data [6]. The basic idea of the approach is the following. In the analysis of range data we can distinguish convex, concave, obscuring and obscured lines from each other without using any additional information; the junction knowledge is not necessary for the line categorization. Therefore, this knowledge can be used for another purpose, that is, for the prediction of missing edges. Comparing a line drawing extracted from the range data with the list of the permissible junctions, we can tell whether the present drawing is consistent with the physical world or not, and we can, in the latter case, predict the locations and physical categories of missing edges. Thus the extraction of edges can be efficiently guided by those predictions. This approach is practical, since "noisy" raw range data can be dealt with.

One of the greatest shortcomings of the above approach (as well as other approaches to the exploitation of the junction knowledge) is the trihedral-vertex condition, that is , it is assumed that every vertex of a body in the scene has exactly three faces. If we would simply remove this assumption, there would occur an infinite number of permissible junctions, which could not be stored in a finite size of the computer memory.

The present study aims at circumventing the above shortcoming, that is, we represent the knowledge about nontrihedral junctions as well as trihedral ones. The approach we shall take is automatic compilation of the junction knowledge. A model of the world is defined by a finite set of prototypes of polyhedra, and the junction knowledge associated with this world is constructed automatically and is incorporated in the system for range-data

analysis* Since the world Is restricted to a finite number of polyhedra, the number of permissible junctions is also finite and the knowledge about the world does not swell out*

2. OUTLINE OF THE SYSTEM

The outline of the functions of our system is shown in Fig.l, where rectangles denote system components, circles denote information and arrows denote flow of information. It is assumed that the real world is composed of polyhedra which are taken from a finite set of prototypes. The system consists of the four subsystems:

1. Range Finder———a subsystem which obtain range data from real scenes by triangulation,

2. Model Generator———an interactive subsystem by which an operator can generate a model of a real world as a finite set of polyhedra,

3. Knowledge Compiler———a subsystem whose input is a world model and whose output is a junction dictionary,

4. Range Analyzer———a subsystem which analyzes range data and establishes concise descriptions (in terms of vertices, edges, faces and spatial relationships among them) of the scenes; in each step of the analysis the subsystem consults a junction dictionary in order to predict missing edges.

We shall go into details of those subsystem in the following sections.

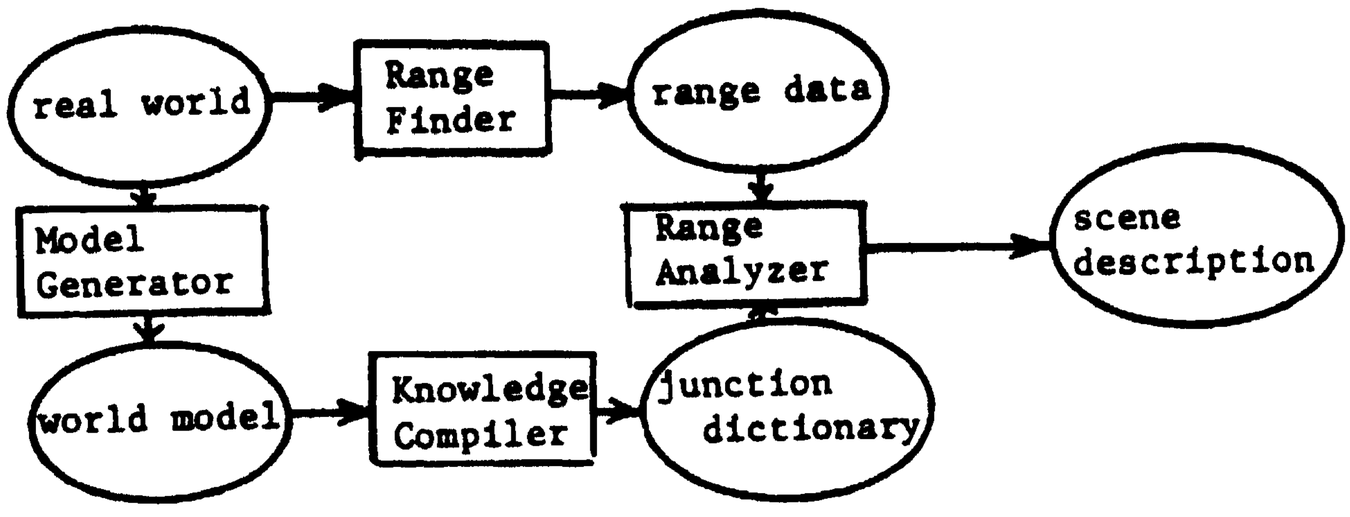


Fig.1. Outline of the system

3. RANGE OBSERVATION

Fig.2 shows a triangulation method for obtaining range information about a scene. A light beam is projected from a source 0 to the scene and the illuminated spot is observed from another angle by a TV camera 0'. The direction of the beam is specified by the point (i,j) at which the beam intersects a fixed plane S. Let d(i,J) denote the distance of the image $P^f(i,j)$ of the illuminated spot P(i.j) from the left margin of the TV image plane, as is illustrated in Fig.2. A three-dimensional location of the point P(i,j) can be easily calculated by simple geometry, if we know d(i,j) and the spatial relation among the light source 0, the TV camera 0' and the plane S. We shall call the array of the data d(i,j)'s (1=1, ..., m, j-1, ..., n) a range picture (though d(i,j) is not a range itself). For practical purpose, a vertical slit light can be used Instead of a spot light (see Oshima and Shirai [7]).

Note that we can not always observe the range of a given point (i,j), because the range is obtained only when the illuminated spot P(i,J) can be seen from the TV camera. The line-segment AB in Fig.2, for example, is hidden from the TV camera by another object in front of it, and thus the range data associated with this line-segment are unknown. Therefore, in the range picture (i.e., the two-dimensional array of d(i,j)'s) there are usually a few regions whose values are undefined.

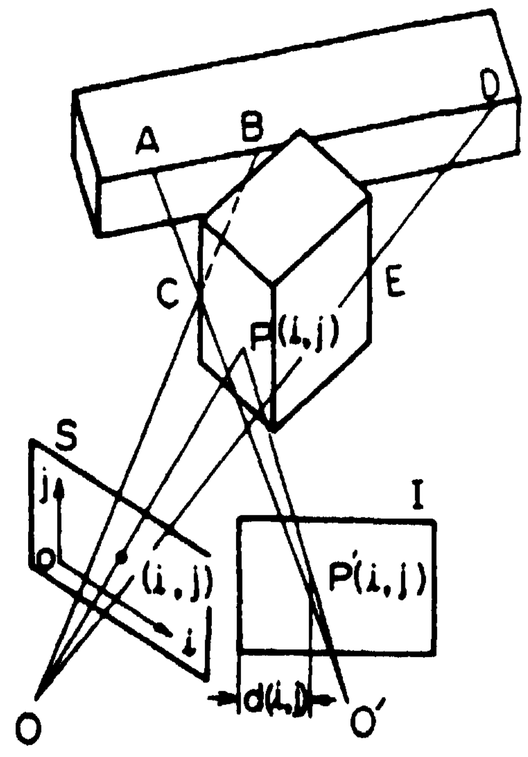
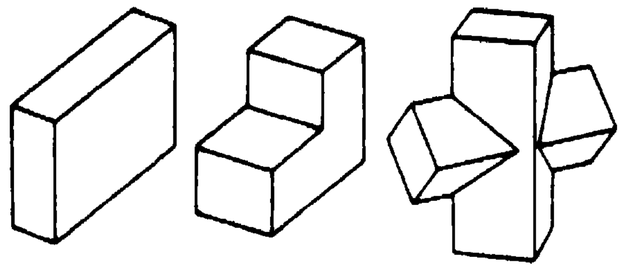
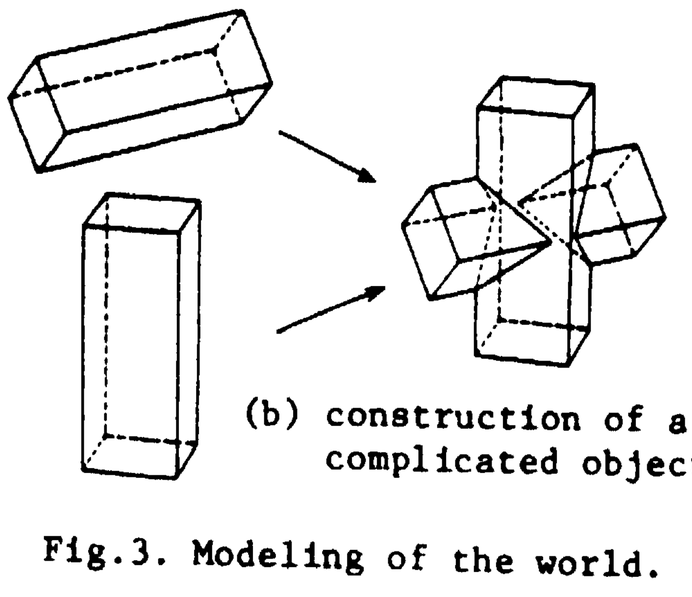


Fig.2. Range observation.



(a) example of a modeled world



(b) construction of a complicated object

Fig.3. Modeling of the world.

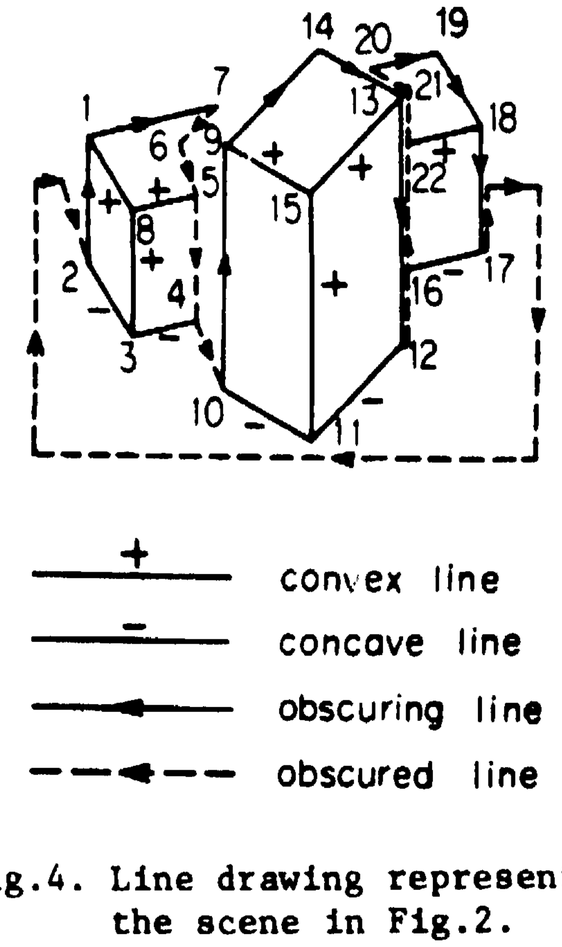


Fig.4. Line drawing representing the scene in Fig.2.

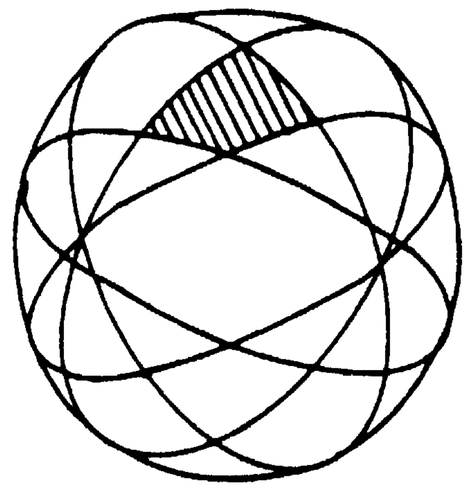


Fig.5.Spherical polygons.

4. MODELING OF A WORLD

The basic part of Model Generator is written in a high-level language named GEOMAP, which is a FORTRAN subroutine package for handling descriptions of three-dimansional solids developed by F. Kimura of Electrotechnical Laboratory [8]. This subsystem is used interactively for the construction of a world model as a set of prototypes of polyhedra. In order to construct a model of each polyhedron, an operator first (1) generates primitive polyhedra such as a rectangular brick, a wedge and a prism/cone with a polygonal base, and next (2) modifies and combines them into a required shape by set-theoretical operations such as a union, an intersection and a subtraction and/or affine transformations. An operator can also obtain two-dimensional projections of the modeled objects seen from an arbitrarily specified viewpoint.

Fig.3(a) shows an example of a modeled world. The process for the construction of the rightest object is shown in Fig.3(b), where two rectangular bricks are generated first and then they are merged into one by a set-theoretical union operation.

5. CONSTRUCTION OF JUNCTION DICTIONARIES

5.1. Line Categories

Fig.4 shows a line drawing of the scene in Fig.2, where two blocks are put on a desk surface. The lines in the drawing are classified according to their physical properties into the four categories: convex lines, concave lines, obscuring lines and obscured lines. While the first three categories occur in usual line drawings, the last category is peculiar to range pictures obtained by triangulation. For example, the right side of A in Fig.2 is obscured by C when seen from the camera 0', and consequently A is on an obscured line and C is on an obscuring line, as is illustrated in Fig.4.

5.2. Enumeration of Possible Junctions

We will assume that (1) the scene is composed of polyhedra taken from a finite set of prototypes, and that (2) accidental alignments do not occur in the scene. We will call a junction possible if it can appear in a line drawing of the scene under those assumptions, and call it impossible if otherwise.

Suppose that a vertex of a polyhedron (made of solid material) is put on the center of a unit sphere. Each face around the vertex, when extended, intersect the unit sphere at a great circle, as is shown in Fig.5. These great circles divide the surface of the sphere into a finite number of spherical polygons. Then, some of the spherical polygons are in solid material and the others are in an empty space; we will call the former polygons occupied polygons and the latter ones empty polygons. A vertex of a cube, for example, generates eight

spherical polygons, one of which Is an occupied polygon and the other seven are empty polygons.

The light source and the camera are supposed to be put on (the same or distinct) empty polygons. Then, the subsystem classifies the area of surfaces around the vertex Into the two groups: the area which Is visible from both the light source and the camera (i.e., the area whose range can be observed) and the area which is invisible from either of them. And finally, the subsystem constructs a perspective view of the vertex (seen from the camera) in terms of the four categories of lines, and thus obtains a possible junction.

Special types of junctions occur when the camera or the light source is on one of the (extended) face plane. For the enumeration of such kinds of junctions, we have to consider putting the camera and/or the light source on an edge or a corner of a spherical polygon. Once the positions of the camera and the light source are fixed, the processing for the construction of a junction is the same as the above case.

The polyhedron shown in Fig.6(a) has 24 vertices (including hidden vertices which are not shown in the figure), and they are classified into three types 1, 2 and 3 as are shown in the figure: the vertex of type 1 consists of three faces which meet at three convex edges, the vertex of type 2 consists of three faces which meet at one convex edge and two concave edges, and the vertex of type 3 consists of four faces which meet at two convex edges and two concave edges. All the possible junctions associated with the vertices are listed in Figs.6(b), (c) and (d), where an arc connecting two arrowed lines denotes an obscuring/obscured relationship.

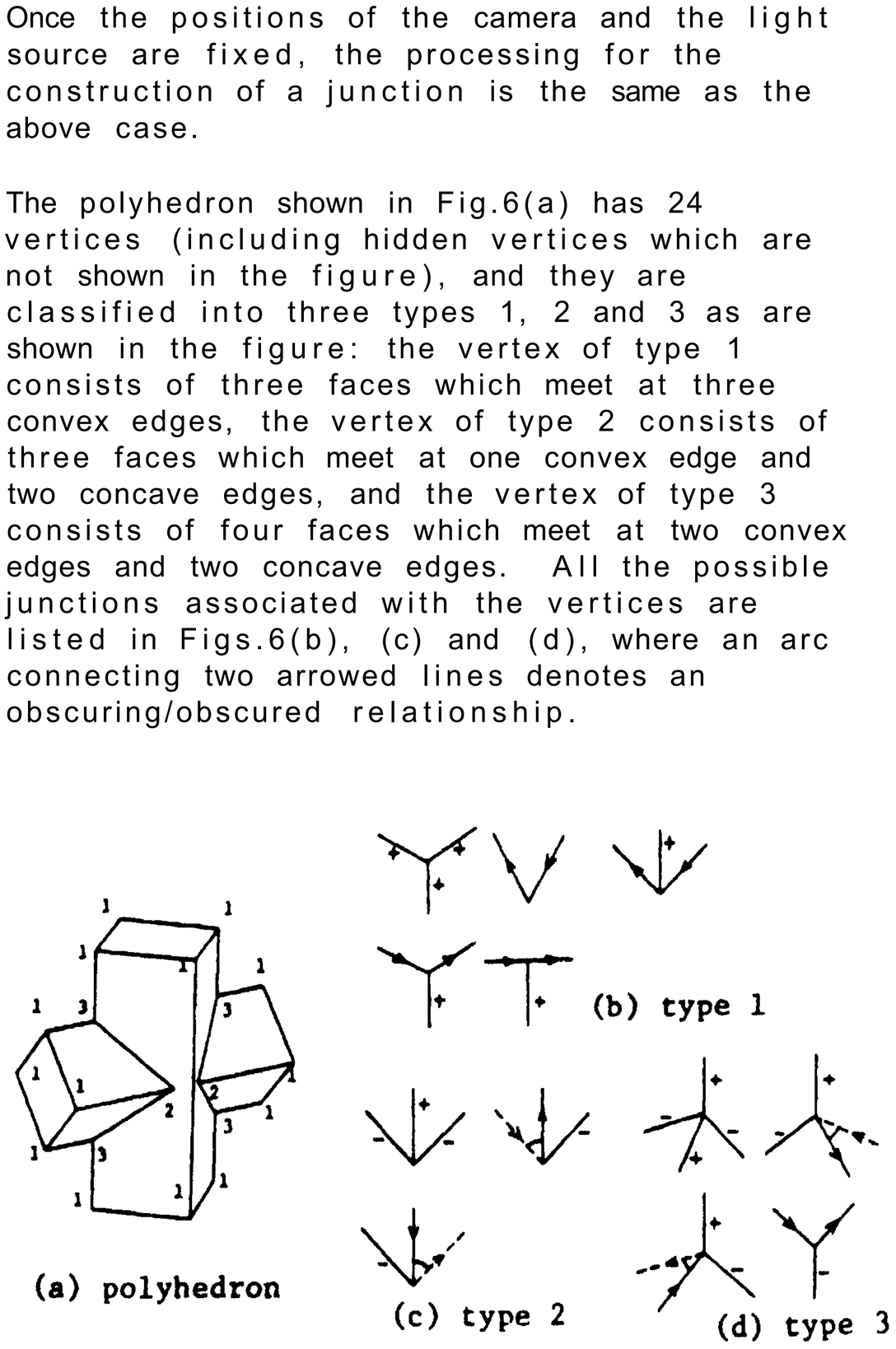


Fig.6. Construction of possible junctions.

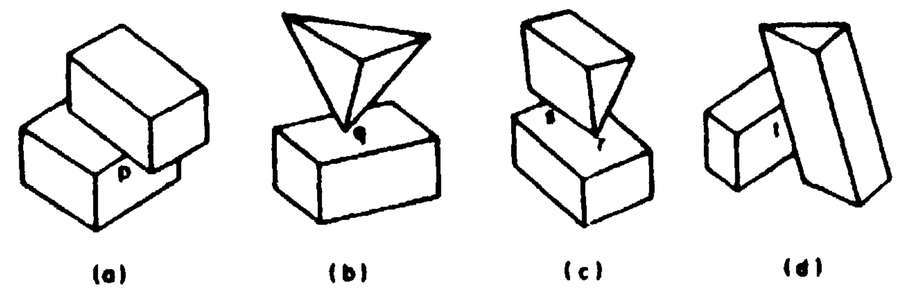


Fig.7. Possible ways of the contact of two bodies.

The above enumeration is sufficient for isolated bodies, but in real scenes several bodies contact each other. Because of the assumption (2) permissible ways of contacts of two bodies are (a) face to face, (b) point to face, (c) edge to face and (d) edge point to edge point as is shown in Fig.7. The subsystem generates the possible junctions associated with the vertices such as q and r as well as the pseudo-vertices such as p, s and t.

5.3 Junction Dictionary

A junction dictionary is constructed in a form of a directed graph whose nodes are all sub-configurations of possible junctions and whose arcs represent the relationships that the initial node can be changed into the terminal node by an addition of one line.

Part of the junction dictionary is shown in Fig.8, where seven junctions and relationships between them are illustrated. The three junctions in rectangles (t, v and y) are impossible ones and the four in circles (u, w, x and z) are possible ones. The drawings beside the possible junctions show the examples of the situations in which the junctions occur. An arrowed arc connecting two junctions denotes an addition of a line. If, for example, we add a convex line in the shaded area of the junction t in Fig.8, we get another junction u. Adding, furthermore, a concave line to u, we obtain w and thus we get the path (t, u, w) from t to w. When we exchange the order of addition of the two lines, we get another path (t, v, w). Those paths suggest the existence

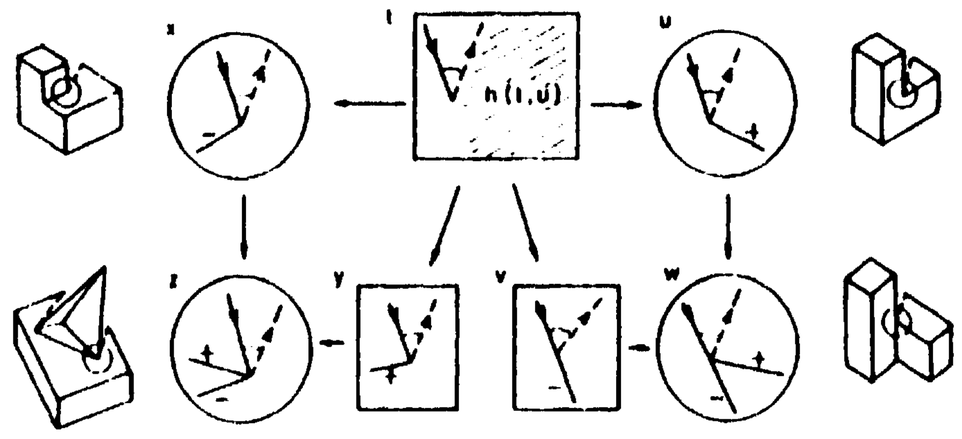


Fig.8. Part of the junction dictionary.

of new lines and guide the analysis of the range data. If a junction of the type u is found in range-data analysis, the dictionary tells us that a concave line "may" exist at that junction. If, on the other hand, a junction of the type v is found, the dictionary says that a convex line "must" exist because v is impossible and w is the only possible junction that has v as a sub-configuration.

6. RANGE DATA ANALYSIS

6.1. Experts for the Analysis

The subsystem for the range data analysis is called DARP (Dictionary-guided Analyzer for Range Picture). The input to DARP is a range picture originated with a real scene and the output is a collection of labeled line drawings of all the objects in the scene.

DARP is composed of many experts: a line predictor, when a junction is given, consults a dictionary and predicts missing lines around the given junction; a prediction tester judges whether predicted lines really exist or not; a line tracker, when a new line is found at a junction, tracks it as far as possible and extracts the whole part of the line; a straight-line adjuster finds straight lines which approximate to the strings of points extracted by the line tracker; a body partitioner, using the knowledge of what types of junctions occur when two bodies contact each other, decomposes the line drawing into smaller ones; a vertex-position corrector revises a position of a junction whenever a new line is connected to the junction.

The processing of DARP is divided into the two parts: a pre-processing and the main processing. The pre-processing consists of several routines which are executed one by one sequentially. In the main processing, on the other hand, the experts interact each other and the system chooses its next step in such a way that the information at hand is used most efficiently [6]. The control structure is based on the idea of a heterarchical program by Shirai [9]).

6.2. Example

Fig.9 shows a range picture (represented by light-stripe images) of the scene composed of two objects———a supporting block and a complicated body consisting of two bricks; both of them are in the world model in Fig.3(a). Fig.10 shows how the system analyzes the scene.

DARP, in its preprocessing, extracts contour lines and locates junctions on them. In the main processing DARP first focuses its attention to junction Jl in Fig.10(a), where junction Ji is represented by i. Jl is a junction of type t in Fig.8. (Note that the internal lines J1J3 and J3J2 have not yet been found.) The line predictor generates predictions about new lines around Jl, and the prediction tester finds a concave line. The line tracker follows it and extracts the whole line (as a string of points), and the straight-line adjuster finds a new junction, say J3, on the new line and replaces the string by two straight line-segments J1J3 and J3J2. Thus the type of Jl is changed to x in Fig.8. Since no other lines are found around Jl, DARP terminates the analysis of Jl.

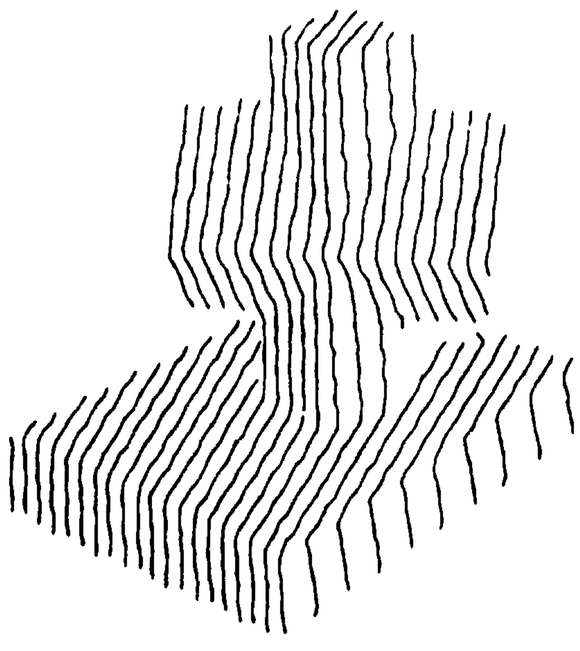


Fig.9. Example of range data.

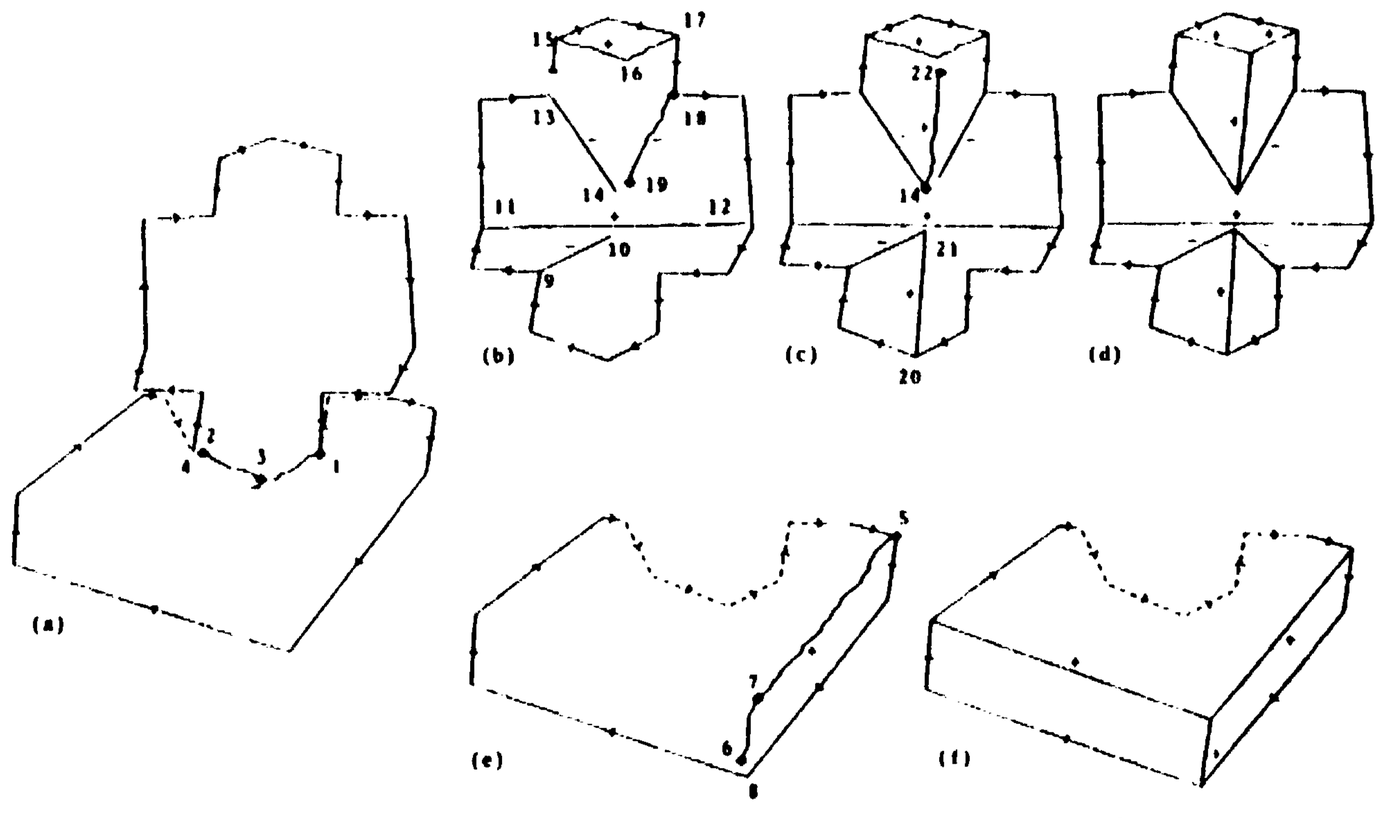


Fig.10. Analysis of the scene shown in Fig.9.

Next DARP picks up junction J A and the line predictor suggests a concave line in the right side of the junction. The prediction tester finds that the predicted concave line has already been extracted, and consequently the two junctions J2 and J 4 are merged into one, which is renamed J2. Then, the drawing is decomposed along the concave lines J1J3 and J3J2, because Jl and J2 are the junctions that occur at the contact of two bodies (Fig.10(b) and Fig.10(e)).

When J5 is examined, a new convex line J5J6 and a new junction J7 are found (Fig.IO(e)), and when J8 is examined, J8 and J6 are merged into one. By similar processing DARP establishes a concise description of the supporting block as is shown in Fig.10(f). The other body is analyzed similarly and DARP obtains the final line drawing shown in Fig.10(d). The numbers assigned to junctions show the order in which the lines and the junctions are extracted.

Though seven edges come close to each other around the central portion of the scene, DARP can construct a perfect line drawing, because the data processing is supported by appropriate predictions of missing lines based on the junction dictionary.

7. CONCLUDING REMARKS

We have studied the dictionary-guided system for the analysis of range data obtained from three-dimensional scenes. Once a world model is given as a set of polyhedra, the system enumerates all of the possible views of vertices and compiles a junction dictionary associated with the given world, and uses it for the analysis of real scenes. Since the junction dictionary suggests missing lines at each step of the analysis, the edge detection is executed efficiently and reliably. Moreover, since the dictionary suggests how to organize the extracted lines, the output is not merely a collection of lines but a structured description of vertices, edges and faces, which is useful for later processings such as the identification and/or the manipulation of objects. The system is flexible in the sense that the only thing an operator has to do when the world is changed is to replace the model of the world with a new one, from which the system generates its own knowledge about the new world and uses it for the scene analysis.

The present system has week points. First, the junction dictionary conveys only local knowledge. Therefore, the system is sometimes insensitive to global inconsistency of the drawing, and it decomposes the scene into pieces smaller than the modeled prototypes. Secondly, obscured lines can not be identified if they are caused by the edges which are out of the picture; this difficulty seems to be essential to triangulation.

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THE EXPERIMENTAL LISP MACHINE

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This machine is specially designed powerful enough to implement an efficient LISP interpreter in microcodes. A LISP processor module and a main memory module are connected to the unibus of a LSI-11 system. The LISP processor module is the microcoded device with a writable control storage that interprets a LISP program in the main memory. Four microprocessor slices(Am 2903) and one microprogram sequencer(Am 2910) are used.

1. INTRODUCTION

The LISP is widely used in the artificial intelligence research community. However LISP processing systems have several nontrivial problems to be solved. One of the most important problems is that the computing time of getting solutions of the problems is much slower than the case of numerical problems. The main reason for the slow speed of computation is due to an unfitness of LISP and a conventional computer architecture at present.

An approach to this problem is to design a machine whose architecture is LISP oriented and code structure more closely reflects that of the language. The machine proposed here is an experimental microprogramable computer system for LISP. This machine is specially designed powerful enough to implement an efficient LISP interpreter in microcodes.

2. THE LISP MACHINE SYSTEM

Our LISP machine is a stand alone personel computer, and Fig.1 illustrates the structure of the machine.
The LISP processor module and the shared main memory module are connected to the UNIBUS of the LSI-11 system(DEC Co). The LSI-11 acts as the master processor of the system and plays the roles of system initialization, input and output, and controls of the LISP processor module. The LISP processor module is a microprogramed device with a writable control storage(WCS) that interprets a LISP program stored in the main memory. The main memory module is a 64k words(32-bit words) semiconductor memory and its access time is about 75 nsec. The main memory module is also accessible from the LSI-11 using a page mode access mechanism. A data transfer unit between the LISP processor module and the main memory module is a 32-bit word.

3. THE LISP PROCESSOR MODULE

The LISP processor module is implemented with a microprogrammed architecture(Fig.2).
Its kernel consists of an arithmetic and logic unit(ALU) and a computer control unit(CCU). The CCU has a WCS(4k of 56-bit words) to accommodate the specialized microcodes to support the LISP.

It has hardware for extracting specialized fields in a word, called field extractor, and the mapping memory which converts a main memory address into 3-bit code.

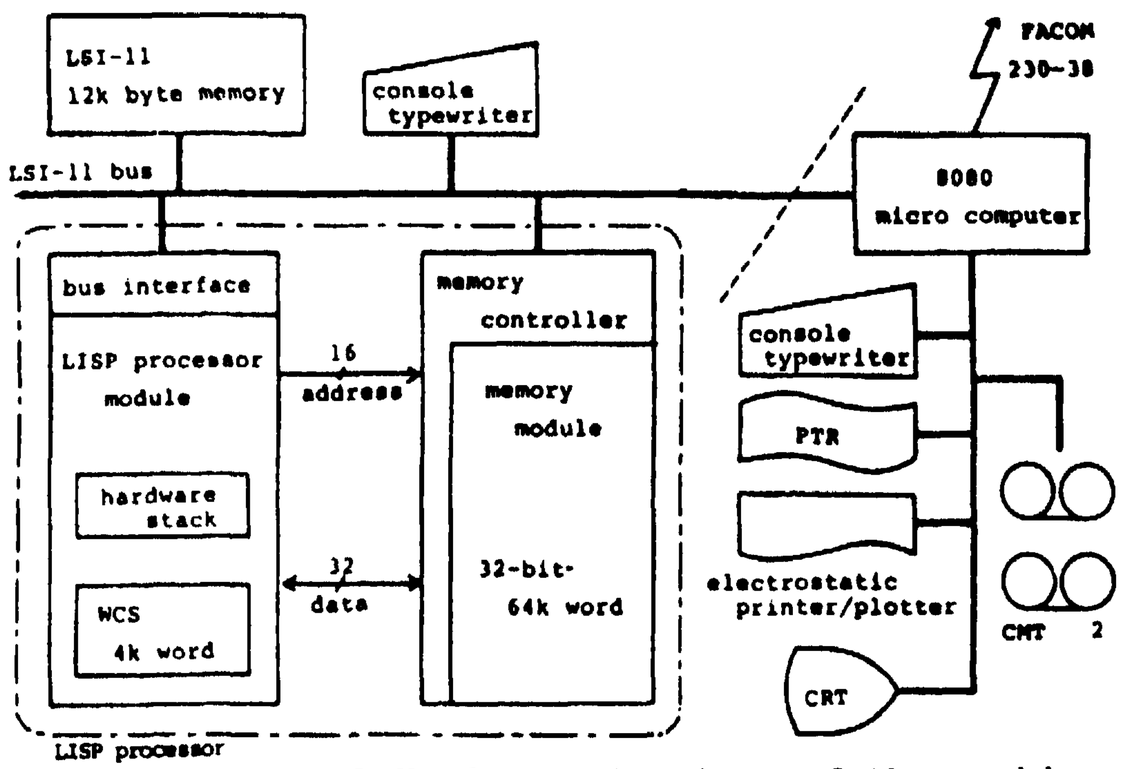

Fig.1 Hardware structure of the machine

It has not a cashe, but has a high speed stack(4k of 16-bit words) acts as a high speed main memory area for a stack, which is where most of the memory references go in LISP.
It has also three buses called A bus, Y bus and B bus. A bus is the data bus, Y bus is the destination bus and B bus is the data bus between the CCU and ALU through which a constant value is supplied to the ALU.

3.1 The ALU and CCU

The ALU is an array of four 4-bit expandable bipolar microprocessor slices(Am P903). And the CCU is a control unit of the machine and consists of a microprogram sequeneer(Am ?910), WCS, and other circuits. The Am 2910 is an address sequencer intended for controlling the sequence of execution of microinstructions stored in the WCS(access time is about 150 nsec). Besides the capability of sequential access, the sequencer provides conditional branchings to any microinstructions within its 4096 microwords range. The flag register contains ALU's flags, the mapping memory flags and other flags. All these flags are available for conditional branching under the microprogram control.

3.2 The Hardware Stack, Field Extractor, Mapping Memory and Bit Addressing Unit

The hardware stack is a 4096 16-bit word memory (access time of the memory chip is about 70 nsec). Two pointer registers STP and SAR are provided for stack operations.

The field extractor locates on the A bus and all data to the ALU flow through the unit. This unit is useful to extract a fixed specified field of data.

The mapping memory is a Ik 3-bit word memory. Whenever the main memory references are made the address is gated to the unit. Ik 3-bit word memory is considered as a tag table whose entries are associated with every 64 words sections of the main memory. The supplied address is converted into three bits code which indicates the data type of the object. By using this three bits code rapid conditional jump is possible in the microcode:-).

The bit addressing unit is a functional unit which tests and sets a bit on a predefined bit table in the main memory. This unit is prepared for realizing the rapid garbage collection.

3.3 Microprogram Instructions

All operations to the ALU, CCU, hardware stack,

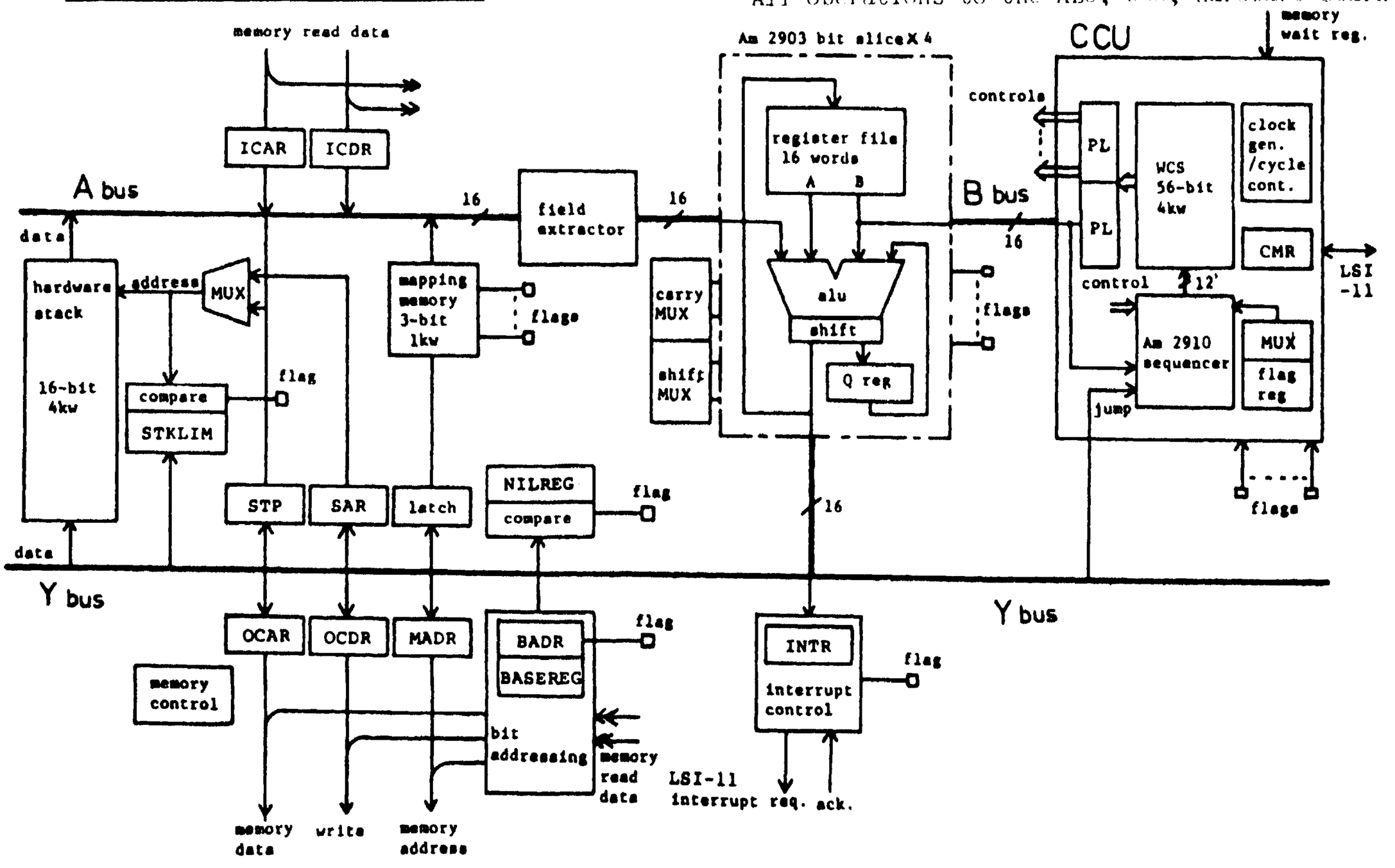

Fig. 2 LISP processor module.

mapping memory and other circuits are entirely under the control of microcode words of the WCX[1]. The microinstruction is a 56-bit word divided into fields. Two types of microinstructions are provided. The type 1 instructions can provide a constant value to the ALU through the B bus, type ? instructions are conditional branching instructions which can transfer controls to any microcode locations depend on condition flags.

4. DATA AND FUNCTION TYPES

There are four data types, small integer, integer, symbolic atom and list. Small integer, +8191 to -8192 doesn't occupy any memory words. Integers are represented in two's complement notation. Symbolic atom are stored as four consecutive words, each of which is divided into two 16-bit cells termed the function body cell, attribute cell, argument cell, top-value-eel], property list cell, print name cell and two unused cells.

Three types microeoded subroutine functions, MSUBR, MRSUBR and MRFSUBR are provided. MRSUBR and MRFSUBR are recursive functions and MSUBR is not.

MRSUBR: EVAL, APPLY, MAP, GET, EQUL, etc.
MRFSUBR: COND, PROS, AND, DE, SETQ, etc.
MSUBR: CAR, CDR, CONS, EQ, NULL, ATOM, etc.

5. INTERPRETER

In our system the user program is reconstructed into a binary tree structure and interpretation of the program is made by traversing the tree in the endorder fashion.

The functional calling is the basic main control structure in LISP. As mentioned above, the LISP machine function calling is made fast through the use of the hardware stack and microcodes. The stack is formatted into frames; each frame containes a header, arguments, local variable value slots, and a push down list for intermediate results. The header gives the function which owns the frame, a pointer to the function body, links this frame to previous frames, and remembers the program counter and microprogram counter.

6. SYSTEM REALIZATION AND EVALUATIONS

The hardware of the LISP processor module and the main memory module consist of about 650 IC chips and 17 universal printed circuit boards(8x7 square inches). The LTSP interpreter of the machine is entirely microeoded and stored in the WCS. The program size of the first version is about 1200 microinstruction steps.

In order to evaluate our LISP machine, we executed the benchmark programs of the second LISP contest of IPSJ(Information Processing Society of Japan). Our interpreters execution times of these programs were shorter than those of any participants of the contest(almost all typical LISP systems in Japan such as HLISP installed IIITAC-8800 and OLISP installed NEC system 800-2 were attended).
Examples of typical two benchmarks(e.g. TARAI and TPU) are shown in Table 1. TPU is a theorem prover based on the unit binary resolution priciple written by C.L. Chang and TARAI is a very short program which does almost recursions only except the very simple functions GREATERP and SUB1.
These measurements showed that the architecture of our machine nicely fits in the control structure of the LISP language and realizes a very rapid execution of LISP programs.

	-----INTERPRETER-----			-----COMPILER-----	
	FAST-LISP KOBE UNIV.	HLISP	OLISP	HLISP	OLISP
TARAI-3	55	78	197	17	36
TARAI-4	1,013	1,443	3,727	330	670
TARAI-5	27,538	39,068	100,734	8,905	18,934
TARAI-6	1,011,732	---	---	322,347	---
TPU-1	904	4,790	2,262	1,029	658
TPU-2	3,426	13,411	10,262	2,871	2,064
TPU-3	1,365	5,684	3,932	1,227	850
TPU-4	1,815	8,025	5,042	1,707	1,161
TPU-5	238	866	759	181	132
TPU-6	6,728	22,849	20,241	4,893	3,617

Table 1 Execution times of the benchmark programs of the 2nd LISP contest of IPSJ (unit time is msec.)

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PREDICTIVE CONTROL PARSER: EXTENDED LINGOL

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We have developed a flexible parser called Extended LINGOL which is an extended version of Pratt's LINGOL. Although original LINGOL has several advantages, the results of our experiments revealed that it has some deficiencies. One of them is that each augmented context-free rule does not enable us to examine their applicability in case of some situations. Another is that the morpheme analyzer of original LINGOL is too simple to analyze aggulutinative languages such as Japanese. With respect to the former problem, we have introduced predictive control mechanism which has offered us flexible methods to implement a precise grammar with a small set of rules. Furthermore, as the mechanism avoids generating unnecessary partially parsed trees we have obtained high speed parsing. On the other hand, with respect to the latter problem, we have implemented a more powerful morpheme analyzer.

1. INTRODUCTION

The LINGOL, which was developed by V. Pratt, is a research tool for natural language processing. We implemented LINGOL on our T-5600 computer system about four years ago and used it for a while. The advantages of the LINGOL arc its program size, speed, and its neat format of grammar and dictionary. It is interesting to note that the semantic interpretation method of the LINGOL is simlar to that of Montague Grammar.

The result of our experiments, however, has revealed that Pratt's LINGOL has several deficiencies mainly with respect to syntactic processing. One of them is that each augmented context-free rule does not enable us to examine their applicability. Another is that the morpheme analyzer of original LINGOL is too simple to analyze aggulutinative languages such as Japanese. In order to cope with these deficiencies, we have revised some portions of original LINGOL and added new programs to it.

2. PREDICTIVE CONTROL MECHANISM

2.1 <Advice> and <delayed-advice>

The Extended LINGOL incorporates a predictive control mechanism which enables us to examine the applicability of each rule in case of some situations. The string parser developed at New York University had implemented the same mechanism in their top-down parser [1].

However, as the LINGOL uses both top-down and bottom-up parsing algorithms, the predictive control mechanism differs from that of New York University. Descriptive format of our dictionary is,

[<word> <syntactic-category>
(<message-list> <cog>) <sem>]

Message-list is considered to be attached to the syntactic category of the <word> and is used later by predictive control mechanism as messages. (Fuctions of <cog> and <sem> are the same as described in [3] and [4]). The format of an augmented context-free rule in Extended LINGOL is,

[<left> <right> (<advice> <cog>) <sem>]

The <left>-<right> pair represents a context-free rule of A——>B (C). The <advice>, which is introduced in our Extended LINGOL, is an arbitrary LISP function for controlling parsing process. The evaluator of predictive control mechanism works as follows:

For each <advice> or <delayed-advice> in rules,
if the evaluation value is true
then do not apply the rule
else apply it;

Suppose a Partially Parsed Tree with a root node E (PPT:E) is created at some intemediate stage of parsing. There are six possibilities to extend the tree. Four of them depend on the evaluation of <advice> in the following rules;

(RI) A——>E or
(R2) A——>E F.

(See Fig.1).

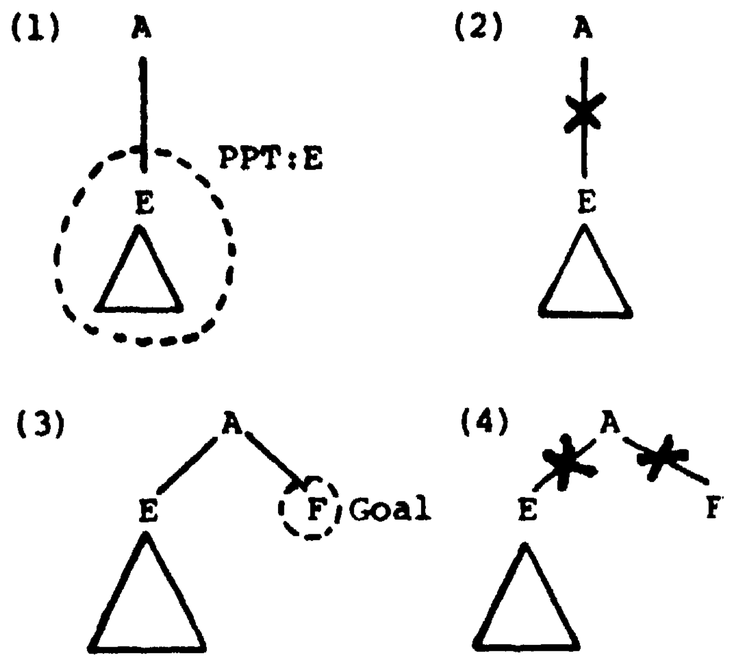


Fig. 1 The result of the evaluation of advice

"X" in Fig.I indicates that (RI) and (R2) fail to apply. Fig.I(1) indicates that (RI) applies to PPT:E. Fig.1(3) indicates that (R2) creates a new goal which predicts the next syntactic category F In (4), a new goal is explicitly cancelled, while in (2) it is implicitly cancelled.

When a new goal is created as in Fig.1(3), we can record <delayed-advice> in the goal by using the Memo-Advice (MA) function in <advice> in the following way:

(MA <delayed-advice>)

The execution of <delayed-advice> is postponed until PPT:F will be created. (See Fig.2). With respect to <delayed-advice>, there are two more possibilities in growing PPTs depending on the evaluation value of <delayed-advice>. The <delayed-advice> acts as though it were a look-forward demon which would be activated when a goal is satisfied later.

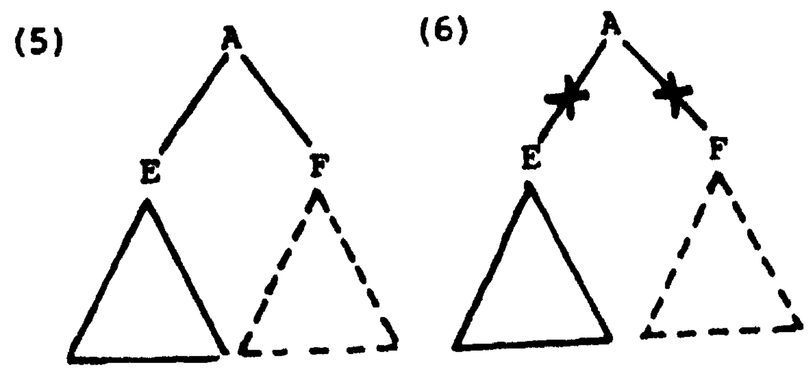


Fig.2 The result of the evaluation of <delayed-advice>

2.2 Control of Messages

Tn the field of advice and delayed-advice , we use messages to control parsing process. About 10 primitive functions are prepared.

A. Creating and Passing Messages: In <advice>, users can crcat and pass any kind of messages from node to node upward in accordance with the growth of PPT. There arc six primitive functions as shown in Fig.3. The effects of the evaluation are also stated in Fig.5.

CF rules	Primitive Functions for creating and passing messages	Message "M" sent to Node A.
A ⟶ B	(PM 'a)	(CONS 'a X)
A ⟵ M B ⟵ X	(PM1 'a)	(NCONS 'a)
A ⟶ B C	(PML 'a)	(CONS 'a X)
A ⟵ M	(PMR 'a)	(CONS 'a Y)
X Y B C	(PMRL 'a)	(CONS 'a (APPEND X Y))
	(PM2 'a)	(NCONS 'a)

Fig.3 Prmitive functions for creating and passing messages.

B. Checking Messages: When applying a context-free rule to some PPTs and goals created so far, users can ask for messages at the root node of PPTs by using the function named QM. Recall the cases of Fig.I where (RI) and (R2) have a very simple <advice> (QM 'm).

```
[A E ((QM 'm)..)  ]      ;A———-E
[A (E F) ((QM 'm)..)..] ;A———->E F
```

If a message m exist at the node E, (EVAL (QM 'm)) becomes true and two rules under consideration can not be applied ((2) and (4)), otherwise PPT:E grows in (1) or a new goal is created in (3).

C. Removing Messages: To remove a messages in the root node of PPTs, the function named KM is used.

3. EXAMPLES

In order to show how the predictive control mechanism works, we discuss two very simple examples, which inhibits the recursive application of rules of left and right recursive definitions.

Example (a)

Let us consider the following rule.

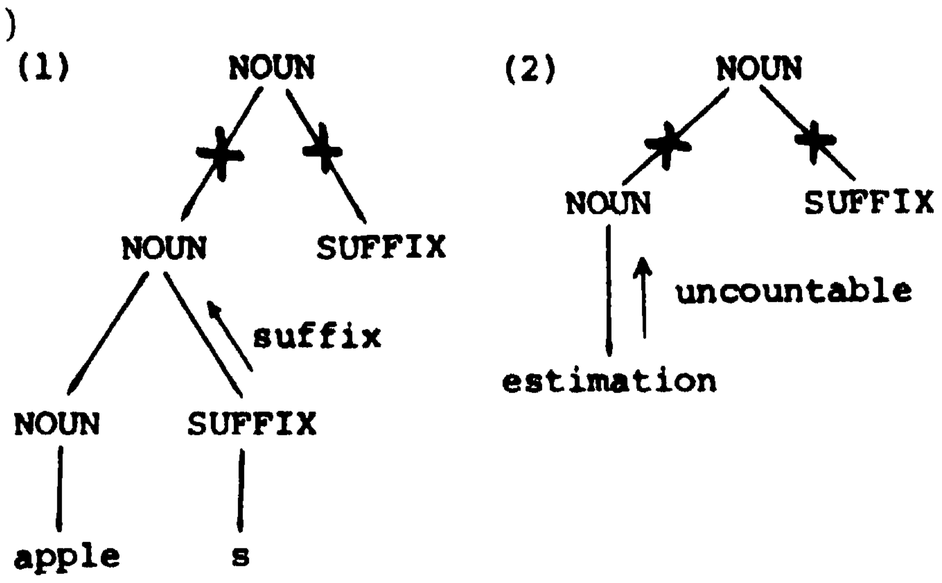
```
(R3) [NOUN (NLUN SUFFIX)
          ((OR (QM 'uncountable)
               (QM 'suffix) (PMR 'suffix))..)..]
and [estimation NOUN ((uncountable)..)..]
    [apple NOUN(()..)..]
    [s SUFFIX ((suffix)..)..]
```

Notice that the rule (R3) is left recursive, but it should not be applied recursively. The predictive control mechanism avoids the situation. The last three are from a dictionary.

The <advice> in (R3) works as follows:

If NOUN is not an uncountable noun
and Noun is not followed by a suffix
then create a goal by applying (R3)
and pass a message named suffix
upward if a goal SUFFIX is satisfied;
else do not apply (R3);(See Fig.4(a)).

(a)



(b)

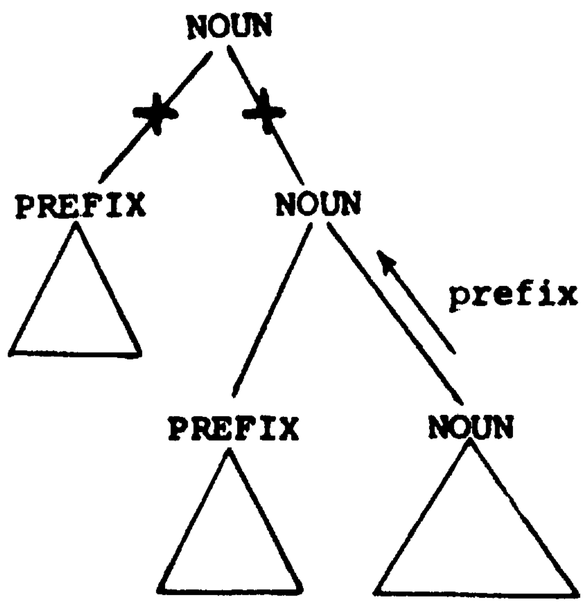


Fig.4. Example (a) and (b)

Example (b)

The following rule (R4) is right recursive.

```
(R4) [NOUN (PREFIX NOUN)
           ((MA (OR (QM 'prefix)
                    (PM 'prefix)))..)...)
```

The <advice> creates a <delayed-advicc> (OR (QM 'prefix) (PM 'prefix)). By using lig.4(b), it is easy to follow how the delayed-advice prevents the right recursive application of (R4).

4. CONCLUSION

We have discussed a new parser called Extended LINGOL which has been used in our laboratory for about 3 years. Predictive control mechanism has offered us flexible methods to implement a grammar. As described in the preceding section, each context-free rule works as an active process that can pass messages to another process or creat a new process. The process can also notify the parser the applicability of the rule attached. The newly created process works as if it were a look-forward demon. The <advicc> attached to each (context-free) rule expresses an action of the rule (or process). Semantic information will become available during parsing process through the message control mechanism if necessary.

Automatic segmentation algorithms in our Extended LINGOL are reported in [6]. Various experiments have been carried out in our laboratory using Extended LINGOL. Some of them are reported in [5].

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INDUCTIVE LEARNING OF CATEGORIES FROM EXAMPLES USING MINIMUM COST REPRESENTATIONS

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The problem of learning categories from a sequence of examples is considered in terms of maintaining a minimum-cost representation for the set of categories. Categories here are subsets of a set of natural numbers. Computational aspects of the following problems are addressed: (1) how are the category representations updated as an incremental change is made to one category, (2) how can a minimum cost representation for a new category be obtained in terms of existing ones? and (3) how does the enlargement of the known universe of objects affect representations of known categories? We then discuss extensions of our methodology to domains which include structure in the categorical descriptions.

1. INTRODUCTION

1.1 Motivation

Machine acquisition of concepts from experience is an important goal for artificial intelligence. Knowledge bases, the primary source of limitation as well as power in "expert systems" should be able to grow and thus permit the systems to improve [2]. The automation of this growth of system knowledge is then of obvious interest. In this paper we focus on a simplified learning scenario where the concepts are restricted to be categories.

1.2 Past Work

The process of learning categories from examples has been studied from several different approaches including (a) trainable pattern classifiers working with real-valued features [6] and (b) discovery of classification rules using variable-valued logic [5], and (c) formation of structural descriptions in terms of known substructures [7]. Here we discuss the learning of categories in the simple mathematical framework of countable sets as is done by Lenat [4] so as to make clear some of the computational issues involved.

1.3 Problem Formulation

The kind of learning we wish to understand is the acquisition of new "concepts" (categories of objects) and the continual refinement of the representations for known categories as new examples of old categories are encountered. For example, suppose a person Sue previously unexposed to computers is shown a personal computer and told "This computer, the ACME 1, is a home system". Sue should then know that there is a category "computer", a category "home system" and that the ACME 1 is an example of each. She may also be able to infer that the category "home system" is included in the category "computer" if the context supports that inference, e.g. if she had previously been told "Let's discuss types of computers". After being shown several more home systems she may understand "home system" to be the set {ACME 1, Apple 15, JETSETTER, ACME 21. Suppose she is then told that the following are "cheapo's": {ACME 1, Apple 15, ACME 2}. Being unfamiliar with the computer domain, we would not expect Sue to be able to distinguish the cheapo's from the non-cheapo's except by using the Information she has been told. If Sue is thinking, we would naturally expect her to infer that JETSETTER is an example of a home system that is not a cheapo. In fact, if she remembers which are the home systems, then she has an easy method for remembering the cheapo's in:

cheapo's = (home systems) - {JETSETTER}.

We would like computer programs to make similar inferences in the course of learning categories.

2. MINIMUM COST REPRESENTATIONS

2.1 Representation Scheme

Given a set S of natural numbers, a representation for S written R(S) is any one of the following forms (as applicable) and C(R(S)), the cost of R(S), is as given. (1) if S is known

to be empty, then R(S) = {} and C(R(S)) = 1. (2) if S is a singleton, then R(S) = $\{a_j\}$ and C(R(S)) = 1. (3) if S is the extension of an initial predicate, then R(S) = $\{x|P_j(x)\}$ and C(R(S)) = 1.
(4) if S is a union of two other sets, then R(S) = $(R(S_1) \cup R(S_2))$ and C(R(S)) = $C(R(S_1)) + C(R(S_2)) + 1$. (5) if S is an intersection, then R(S) = $(R(S_1 \cap R(S_2))$ and $C(R(S)) = C(R(S_1)) + C(R(S_2)) + 1$. (6) if S is a complement, then R(S) = $(\sim R(S_1))$ and $C(R(S)) = C(R(S_1)) + 1$.

The cost of S is the minimum cost over all representations of S. Our cost function, while arbitrarily chosen, yields cost values that roughly reflect the amount of symbology necessary to store representations.

2.2 Updating a Single Category

The amount of the change in cost for assimilation of a new fact is bounded (when only one category is represented). The following proposition describes the cost change for updating S to S' according to $S' = S \cup \{a_i\}$ where $a_i \notin S$.

Proposition 1: $C(S') - C(S) \leq 2$
and $C(S) - C(S') \leq 3$
where C(X) denotes the cost of X.

As will become clear from subsequent discussion, when several categories are simultaneously represented, an incremental change in one may affect the total cost of representation beyond the bounds of proposition 1.

3. COMPUTATIONAL CONSIDERATIONS

3.1 Computing Minimum Cost Representations

Even the problem of transforming a list representation of a category into a minimum cost representation is a nontrivial problem in combinatorial optimization. The computational complexity of this and related problems of minimum cost representation is of interest because the high cost of such processing illustrates the subtlety in learning even simple concepts.

3.2 Multiple Categories

Suppose that there are initial predicates $P_0, \ldots, P_k$ and existing categories $S_0, \ldots, S_m$. Given a new category S_{m+1} we wish to find a minimum cost representation for $\{S_0, \ldots, S_{m+1}\}$. One approach is to find a minimum cost rep. for S_{m+1} in terms of the rep's. for $S_0, \ldots, S_m$. However it is possible that the rep's. of some or all of $S_0, \ldots, S_m$ should change with the assimilation of S_{m+1}. We shall address this subsequently.

As we permit LS to handle multiple categories we need an additional representation form: $R(S) = R(S_1)$. However we now must modify our cost rules so that any given category only gets charged once.

C(R(S)) = the number of occurrences of all of the following in R(S):

$$\cap, \cup, \sim, \{a_i\}, \{\}, \{x|p_j(x)\}, R(S^1),$$

where a_i is any integer, P_j is any predicate and S^1 is any category whose representation is charged separately. Note that the assimilation of new information may require changing representations for old information.

3.3 Circularity in Representation

As category representations are updated, care must be taken to avoid circular representations If at time 1 we have S_2 represented as or in terms of $R(S_1)$, then we may not at a later time (2) change the representation of S_1 to be in terms of S_2 unless S_2 is first made independent of S_1. Prevention of circularity may be handled by maintaining a partial order on the categories, implemented as a directed acyclic graph. The algorithm below builds the representation for a collection of categories in a non-circular way by representing the simplest (least costly) categories first and building up to "inherently costly" categories (those that would be expensive if expressed independently of other categories), thus progressiving throug a "topological sort" of the partial order.

3.4 Brute-force Method

The "exhaustive" computation scheme follows: FINISHEDREPS ← set of extensions of initial predicates; I ← 1; WHILE categories remain to be represented DO BEGIN ADD representations for all categories having cost at most I (in terms of representations already in FINISHEDREPS; I ← 1; END.

In order to determine whether (and how) a category S_i can be represented in terms of the members of FINISHEDREPS with a cost of I, we can simply generate all representations (finitely many when U is finite) and test to see if any represent the category under consideration. It is not hard to see that the combinatorial explosion is severe here. If the size of the universe is N, and the number

of representations on FINISHEDREPS is q, then $O((N + q)^{(I + 1)/2})$ representations must be considered using this scheme.

3.5 Reducing the Computational Effort

If q, the number of complete representations is much less than n, the size of the universe, then the following approach is economical. Combinations (of the existing q categories) of successively greater cost are generated using ~, ∪, and ∩ but no singleton sets. The category S_i which is to be represented, is "matched" to each of these categories as it is generated. In matching S_i with an S_j (set represented using some combination of existing Categories), compute $S_{ij1}=S_i-S_j$, the set of numbers in S_i missing from S_j and $S_{ij2}=S_j-S_i$, the set of numbers which need to be removed from S_j in forming a representation for S_i in terms of S_j. We call $d_{ij}=|S_{ij1}|$ the deficiency of S_j (for S_i) and $e_{ij}=|S_{ij2}|$ the excess of S_j (for S_i). If $C(R(S_j)) + (2d_{ij} - 1) + (2e_{ij} + 1) \leq I$ then we have a representation for S_i of the form

$$((...((R(S_j) \cup \{x_1\}) \cup \{x_2\}) \cup ... \cup \{x_{dij}\}) \cap \sim (\{y_1\} \cup \{y_2\}) \cup ... \cup \{y_{eij}\}) .$$

The operation of determining the deficiency set and the excess set is analogous to a process referred to as "interference matching" [3]. The above algorithm can take advantage of an additional short cut (without changing its solutions). From I and $C(R(S_j))$ the permissible deficiency plus excess is easily computed. As S_{ij1} and S_{ij2} are being computed it may be apparent that the limit will be exceeded. At such a point, further consideration of S_j can be aborted for the current value of I.

3.6 Supporting Categories

In some cases a collection of categories may have their cost reduced by introduction of a new category. If we let our system construct one, we term it a supporting category. While we have heuristics to generate supporting categories that reduce costs in specific situations, the problem of finding them in general is an open one.

3.7 Extensions

Our study has primarily been concerned with sets of natural numbers. There exist straightforward means to represent and to compute costs for structured objects such as n-tuples, labelled graphs and strings. Once again, computational complexity is a problem as one confronts the problem of subgraph isomorphism [1].

4. IMPLEMENTATION

A preliminary implementation has shown that additional heuristics and/or parallel processing are needed to make minimization of cost computationally feasible. Approximate solutions would be acceptable in most AI applications and this area is open for future work.

5. CONCLUSION

The maintainance of a minimum cost representation for a set of categories is desirable because relationships among categories are clarified and space requirements for the stored information are low. However, the complexity of computing the representations is high. Some heuristics have been given here and more are needed to simplify such computations.

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Experience with the Evaluation of Natural Language Question Answerers*

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Research in natural language processing could be facilitated by thorough and critical evaluations of natural language systems. Two measurements, conceptual and linguistic completeness, are defined and discussed in this paper. Testing done on two natural language question answerers demonstrated that the conceptual coverage of such systems should be extended to better satisfy the needs and expectations of users.

None of the natural language papers presented at IJCAI77 reported on their programs[1] performance as language understanders. The reader has very little hope of thoroughly understanding the capabilities of the systems and techniques described.

The most critical dimensions of natural language performance are the range of concepts understood and the accommodation of diverse forms of expression. In this work on evaluation I have concentrated on these two aspects of performance and restricted the study to natural language question answering systems. In the paragraphs that follow, I will describe performance goals and measurement in more detail, then discuss the findings to which their use has led.

1.0 Performance Goals and Measurement

A natural language processor can be seen from two points of view: that of the designer and that of the user. The designer examines the domain of discourse of a particular application and maps out the range of concepts that are within it. The range of concepts is the CONCEPTUAL COVERAGE of the system. The designer must also accommodate the diversity with which the users will generate their statements and requests. The range of linguistic phenomena handled by the system is the LINGUISTIC COVERAGE of the system. The gauge of the success of the designers is how well the coverage has anticipated the needs of the users.

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Users see a natural language question answering system and the database to which it interfaces through the perspective of their own needs and habits. They approach a database question answerer expecting it to include certain concepts, and forming utterances in their accustomed ways. The degree to which the concepts expected by a set of users can actually be found in the system's conceptual coverage is the CONCEPTUAL COMPLETENESS of the natural language processor, with respect to the set of users. Similarly, the degree to which the language of a set of users is appropriately analyzed by the system is the LINGUISTIC COMPLETENESS with respect to that set of users.

It is interesting to consider the current description techniques for natural language processors in terms of conceptual and linguistic coverage and completeness. When a paper presents twenty or so questions that are appropriately analyzed, the questions include concepts from the system's conceptual coverage, and their forms and features suggest elements of the system's linguistic coverage. Unfortunately, the conceptual and linguistic coverage of the system is not fully specified by what is found in the examples, and one cannot generalize from them. If no claim is made that the examples were in some sense typical of user inputs, nothing can be inferred about conceptual or linguistic completeness. If the paper goes on to explicitly mention handling features such as ellipsis or pronoun reference a comment is being made about the elements of linguistic coverage. Since this is not being related to the needs of a set of users, it says nothing about linguistic completeness.

2.0 Performance Testing

The ideas for testing conceptual and linguistic completeness were exercised on two natural language question answering systems, PLANES[9] and, to a lesser extent, the Automatic Advisor[7]. The performance of PLANES will be described in [8],

One tests the general competence of the natural language system by simply giving database problems to users and letting them attempt to solve them. Conceptual completeness if. tested by giving database problems to subjects who are very familiar with the system, eg., the system designers. If a problem can be solved at all, the conceptual coverage must include the concepts indicated by the problem. Linguistic completeness is tested by giving users the problems that were solved in the conceptual completeness test. If a user utterance cannot be handled appropriately by the system, it is probably due to a limitation of linguistic coverage. It could, however, be due to a limitation of the conceptual coverage that was not discovered in the conceptual completeness test. For this reason, tests for conceptual completeness and linguistic completeness are not entirely independent.

3.0 Conceptual Completeness

Much work has been done and discussed in the literature on identifying the elements of linguistic coverage for improved linguistic completeness. The user testing has not led to the discovery of new elements of linguistic coverage.

The most interesting findings were in the area of conceptual completeness. Papers describing natural language processors frequently concentrate on linguistic coverage with the implicit assumption that the database determines the range of conceptual coverage. However, we found that the subjects thought in terms of the activities that the database described. The activities orientation is evidently the one that should be supported for casual users.

The activities orientation is helpful for identifying a broad class of erroneous presuppositions that may be embedded in user's queries. In the question "Which planes that flew on March 2, 1970 had maintenance on March 3?", one presupposition is that there were in fact some planes that flew on March 2. If the database lists the planes that flew on particular days, this would be a Kaplan-type presupposition [2]. However, if there was no information on flights in the database, it would be a more general form of presupposition.

Another result relating to conceptual completeness was evidence against the common assumption that users' utterances are limited to database queries. Most natural language question answerers rely on the assumption that the user will ask a question, the system will query the database to answer it, then the user will ask another and so on. This is not the way conversations work. In testing PLANES and the Automatic Advisor, users frequently made utterances that were not intended to be interpreted as database queries. Various examples follow.

1. About the database:
    1. "What do you know"?
    2. "Is that everything you know about math 195?"
2. About vocabulary:
    1. "What is a buser?"
    2. "What does howmal mean?"
3. Context setting:
    1. "Now I am talking about the year 1970".
    2. "Year is 1970".
    3. "I am interested in a7's".
4. Reference to discourse objects:
    1. "What was the last plane I talked about?"
    2. "Now combine the two"
    3. "The other ones I just mentioned"
5. Verifying or summarizing results:
    1. "Then infe 210 and infe 211 must be taken at the same time".
    2. "So all I need is junior standing and math 195".
6. Multiple query utterances:
    1. "What parts failed and what were the parts removed or installed".
7. Multiple utterance queries:
    1. "How many aircraft flew more than 10 flights in 1973? in 1972? in 1970? List aircraft by number of flights for 1970."

Each of these examples was actually typed in by users using one of the natural language processors. Many more examples in each of these categories could be imagined. A few additional examples can be found in Malhotra's work [3] on a hypothetical management information system. These examples show clearly that question answerers cannot operate on a one-database-query-per-sentence basis.

A third result was discovered while testing the Automatic Advisor. It pertains to pragmatic relationships between elements of a database

domain.

One of the data domains of the Automatic Advisor is that of the topics that are covered by the engineering courses in the database. The topics covered in the lower level courses were general, those in the upper level courses were more specific. The Automatic Advisor included no pragmatic relationships among the elements of the topics domain. Consequently, when asked for the courses that dealt with computers, it returned one course, the only one which explicitly mentioned "computers" as a topic. It failed to return about ten higher level hardware and software courses and a host of others that made extensive use of computers.

The problem of misleading answers due to missing pragmatic relationships is not peculiar to the Automatic Advisor, but is common to "portable" natural language processors. Harris states that "[the portability of ROBOT] is largely possible because of the way ROBOT makes use of the database as an existing semantic structure" [1]. Indeed, ROBOT, the Automatic Advisor, and other systems are evidence that much semantic and pragmatic information does lie in the structure of the database, but the tests have illustrated the limitations of relying solely on the database for this information. This suggests that conceptual coverage should include the pragmatic relationships between data elements even though these relationships may not be expressed in the database.

4.0 Conclusion

There is a clear need for natural language processors to be evaluated. The measures and measurement techniques described in this paper suggest that meaningful testing can be performed and that its results can promote the engineering of better systems.

The findings discussed above suggest that in addition to the study of the elements of linguistic coverage, attention should be focused on conceptual coverage. Without extending conceptual coverage beyond the limits of the database contents, a natural language question answerer can do little more than a formal query language. One mainstay argument in favor of natural language processors over formal query languages is that the use of natural language processors can be learned quickly and recalled easily after a period of disuse. These claims have not been substantiated, however.

The LADDER system [6] was evaluated [4] as a query language, and users were able to use the system with some facility after "moderate training (approximately 1.5 hours) in LADDER syntax and vocabulary" [4] (they were selected to be familiar with the activities described by the database). The LADDER users were trained because, "LADDER is sufficiently demanding in its syntax and lexicon so that if no training were provided, the outcome could be predicted with certainty — namely, the technology would be severely limited as a tool for accessing a Naval command and control database." But tests of formal query languages have shown similar performance after familiarization [5].

It seems clear that the role that natural language question answerers should play is in providing the user with more complete conceptual coverage than he can have using a formal query language. The user has gained little if he avoids the rigors of learning a formal query language only to be subjected to the rigors of learning the details of the structure of the database. If he must know the minutia of either, he will not be able to use the system effectively on an occasional basis.

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NETWORK TRUTH-MAINTENANCE FOR DEDUCTION AND MODELLING **

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truth functional connectives which attempt to maintain consistency in the network. The use of context layers in addition to dependencies allows more accurate world-modelling than previous dependency-based modelling schemes. Focus of attention in deductive search and planning is accomplished by the propagation of control information through the network in addition to normal truth values.

1. The Development of Truth-Maintenance

1.1 Introduction

The problem of modelling the consequences of an action has been central to the development of automated symbolic problem solving. Selection of proper strategies for accomplishing goals may be done only when the machine has an accurate model of the state of the world at each decision point (or else has a model of its own uncertainty). Early systems required a programmer to associate with each action description a complete representation of the changes that should be made to the world model when the execution of the action was simulated. In highly coupled problem* domains where single actions may alter large numbers of states,* this requirement can lead to a difficult programming problem. If an unrestricted hierarchy of definitions is allowed, the consequences of actions may become highly context dependent, and the problem of simply enumerating the affected states can easily become intractable.

In integrated problem-solving systems, in which planning and world-modelling are combined with automatic inference from logical relations, it becomes highly desirable for the modelling component to employ the same logical relationships used by the inference process. Thus, if some planned action changes a state that had been inferred from previous states, then its supporting antecedents must also be changed ("refuted support"). Similarly, if the changed state had previously been used as the justification for another state, then the dependent state may no longer be Justifiably believed ("lost support"). Also, the new state may provide a justification for logically dependent states ("discovered support"). These concepts led to the notion of logical dependency as a means of maintaining the justifications of derived states and of a process of "Truth Maintenance" (TM) as a means of determining the state of belief or disbelief in expressions as a consequence of changes to the database.

1.2 Previous, releated work

The most complete recent systems employing TM techniques are those of Doyle [2] and London [5]. Although these systems are based on similar theoretical grounds, they differ widely in implementation and application. Doyle's system uses dependencies to determine the consequences of assumptions, to identify inconsistent sets of assumptions and to control backtracking. London's system is designed for modelling the consequences of proposed action sequences. Both of these systems allow knowledge to be expressed in localized "chunks" with the coupling to other chunks accomplished by the dependency network. Both systems depend upon a separate inference module to compute the initial justifications for states, which are then used by the TM process. In both cases, the dependencies must be explicitly declared by the inference process in clause form, i.e., as (the conjunction of) a list of the antecedents of the derived state.

A thorough background discussion on the use of logical dependencies may be found in the referenced works; this discussion is restricted to certain generalizations of the earlier methods and with the solutions to certain difficulties encountered in the use of dependencies for world-modelling. Only examples in propositional logic will be illustrated; the methods have been extended to first-order, but are not implemented as of this writing. (This is an abridged version of the original paper, which can be obtained from the author.)

1.3 Motivation and Features of the JPL System

The "ERIS"+ system being developed at JPL is designed to generalize and improve the the TM and deductive processes in several respects.

ERIS was the Greek goddess of discord.

The following definitions apply to this discussion: A statement is represented as an (normally a Predicate Calculus formula;. Expressions are stored in an indexed (associative) database as nodes. A states is the truth state (represented by a truth value (TV), such as true, false, etc.) of a node (or its associated statement). axioms or rules, are statements of known truth value whose state may not be changed. Statement connectives include the normal truth-functional connectives (AND, OR, etc.) plus connectives for representing causality.

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The propagation of logical support, one of the primary functions of truth maintenance (discovered support), is also required by deduction; as deduction pursues potential proofs, the discovery of an actual proof should result in marking the valid line of support. In addition, by removing the restriction that dependencies 6e explicitly declared in clause form, considerable structural manipulation could be avoided during TM processing. In ERIS, generalized TM procedures have been developed that are combined with the deductive process, resulting in a significant reduction in symbol/structure manipulation during deduction.

Rule-based systems often have the restriction that knowledge be expressed in clause form, with inference (and therefore logical support) directed only from the antecedent to the consequent of implicative rules. Since this syntax restriction can often prove burdensome, especially to non-programmers, a more general representation was desired, in which domain axioms could be expressed using any combination of relational connectives. The SRI "SNIFFER" system employed such a representation, but required '•extraction" rules to place the term to be proved in the consequent of an implication 13]. In ERIS, by defining TM behavior for each statement connective the need for applying rewrite rules to reformulate domain axioms as implications during deduction has been eliminated by a graph labelling procedure that determines logical support. Also, there is no need to conduct a separate search for a proof of a statement's negation, since the TM process may result in the discovery of a line of support for either result.

Previous work has demonstrated the advantages of dependency methods over linear (chronological) context layer schemes for the control of backtracking (see [4], [5], [2]), but context switching for purposes of hypothetical reasoning or multi-world modelling requires considerable computation using dependencies alone, as compared to typical "context-list" schemes. Although ERIS uses dependencies to control backtracking (by identifying the particular assumptions responsible for conflicts), the use of context layers is available for these other activities. Furthermore, by allowing the definition of a particular subcontext for modelling purposes, the combined dependency/context scheme permits the same TM procedures to be used for both deduction and modelling, even though different behavior results. This method has resulted in greater accuracy in world-modelling than London's dependency-based technique, upon which it is based.

When the truth value of a statement is not known, the deductive process may have to examine all applicable axioms for a derivation. Focus of attention during the search is the key factor in determining the effectiveness of a deduction method when the number of domain axioms is large. In a manner analogous to the propagation of logical support for known truth values, focus of attention during deduction is propagated through the network of expressions using "meta" truth values that contain control information, such as the type of search (deduction, planning, etc.), priority, strategy advice, etc. The meta-TV^s allow efficient, uniform treatment of all the propagation rules associated with statement connectives, and, by initial propagation through the domain axioms to possible antecedents of relevant nodes, they provide a way 0r delimiting the subdomain within which the forward (antecedent) reasoning of TM behavior is allowed. This restriction of forward inference is essential in unbounded domains to suppress the generation of irrelevant assertions. Moreover, when domain-dependent deductive strategy information is available (as a supplement to generalized syntactical strategy rules), the control information in the database can be explicitly accessed by modal operators that may be used in strategy advice expressions. Similar use of modal operators for control information was available in the MIT AMORD/TMS system [2, 1].

2. The Method of Network Truth Maintenance

2.1 The Definition of Statement Connectives

The truth-functional connectives of symbolic logic are defined by associating with the name of the connective an encoded set of rules that govern the behavior of expressions formed with the connective. The rules determine the ways in which the expression can provide logical support to the subexpressions it connects (and vice versa) and are responsible for propagating the consequences of changes in support to the affected expressions. For efficiency, the rules are embedded in a procedural specialist for the connective. When a new TV is asserted for an argument of a connective expression or an entire expression, the specialist examines the TV's of the expression and its arguments. Knowledge of the truth table for a connective is embedded in its specialist and is used to find a consistent labelling of the expression and its arguments. If the new TV was assigned to the expression, then the TV's of the arguments may have to be changed; if the new TV was assigned to one of the arguments, then the TV of the expression may change unless the expression is acting as an axiom, in which case the TV of some other argument may have to change. The specialists are also responsible for propagating control information during deduction or planning. Connectives used to represent knowledge of causality are defined to the system similarly, by providing an appropriate procedural specialist.

2.2 The Notion of a "Consistency Context"

Any connective expression may behave as an axiom by having "current" support for its truth value. Truth values are context sensitive; an expression may have one truth value in a given context and a different one in another context or in an earlier "layer" of the given context. A special subcontext. called the "Consistency Context" (CC), defines the subcontext within which logical support for one truth value may not be refuted by a contradictory line of support. Normal TM guarantees that TV's of true or false are well-founded, that is, that they do not depend upon a circular justification [2]. During deduction the CC is identical with the entire context, well-founded TV's may not change, and contradictions result in retracting the offending assumptions (as in [5J). During modelling, however, the CC contains only the current set of axioms and those changes made SINCE the (modelled) execution of the most recent action. Lines of support within the CC may override other support, permitting the network to change so that it reflects the world state after the execution of the action. Truth values in the global plan

context are assumed not to change unless so forced by new support. .Axioms behave as such by the fact that their TV is in the CC, so that even subexpressions may behave as axioms if their TV has well-founded support within the CC. For example, given the axiom (IMPLIES A (OR B O). support for the truth of A will cause the disjunction to behave as an axiom, i.e., if B is known to be false, then C will be labelled true.

2.3 During World-Modelling

There are several problems associated with the use of dependencies for world-modelling, relating to the requirement for refuting all logical support for a changed state. These problems are: local uncertainty, global uncertainty, and the need for adequate domain knowledge. Local uncertainty arises in cases where support derives from mulitple antecedents, so there is more than one possible labelling that refutes the support should the consequent be changed by an action. Suppose that C was originally proved true by the truth of A, B, and the axiom (IMPLIES (AND A B) C). If C is made false by a planned action, it is necessary to refute the conjunction. Since both A and B were true (before the action), it is indeterminate whether one or both should be changed. London outlines two approaches to the problem of local indeterminacy: the introduction of uncertainty into the network by allowing the propagation of a TV for "unknown" to refute the support for both A and B, or else by requiring domain knowledge to be sufficiently complete and, moreover, suitably expressed to determine with certainty all consequences of a state change (by forward (antecedent) inference). These alternatives are generally unacceptable, but the method discussed here offers less sensitivity to the structure of domain axioms and avoids the introduction of uncertainty in most cases.

London pointed out that, in the case of refuting conjunctive support, the spread of uncertainty can in some cases be mitigated by new lines of support emanating from the state originally changed, as would occur in the case of "exhaustive support" with complete domain knowledge [4]. Since with incomplete knowledge such new support is not guaranteed to propagate to the refuted conjunction, some uncertainty may still remain In the net. By using a multiple-level agenda mechanism, the ERIS system defers the propagation of uncertainty to a queue with lower priority than that for known truth values, so that a line of support may be found that eliminates the uncertainty without having to mark nodes as "unknown" unnecessarily.

Furthermore, unlike London's system the CC method provides a way to undo the labelling of nodes marked "unknown" in the event that uncertainty propagates to a well-founded consequence of the original state change or if uncertainty was spread to nodes in a conjunctive antecedent and subsequently one of the nodes was found to have a known refutation. This is accomplished in part by allowing well-founded *TVa* to override the "unknown" TV even within the CC and also by retracing the spread of uncertainty when needed to reconstruct previous support, The CC method has the additional ability to detect instances where multiple antecedents are not linked by the same connective, but in which the network is globally indeterminate following a change.

The remaining difficulty encountered in modelling is the problem of capturing all the consequences of a state change. The above discussion pertains to instantiated structure with initially known truth values, but it is often necessary to invoke deduction to determine whether nodes that could possibly have been providing support before the state change (due to unresolved uncertainty) were in fact providing support. If sucn nodes were supporting a state that is changed by an action, then their support must also be refuted. Failure to determine the support status of indeterminate nodes with respect to a changed state may cause some of the consequences of an action to be ignored. This is the problem of exhaustive support, as described by London [4]. and is a major problem in dependency-based modelling. It is related both to the completeness of the domain knowledge and to deductive search, since the basic problem is that of proving a universal, namely the completeness of the set of consequences (or the non-existence of a line of support from the action consequent to any supposedly unaffected state). The problem of tne completeness of domain knowledge is outside the scope of the system (although indeterminacy following a state change may allow it to detect incompleteness). Deducing the TV's of previously unknown states to determine their support status may place large demands on the deductive component.

3. Concluding Remark;?

By allowing logical support to be determined within existing structure, the restriction that dependencies be explicitly declared in clause form is eliminated. This is accomplished by connective specialists that use graph labelling to maintain consistency in the network, greatly reducing the overhead for symbol manipulation required by the deductive process, as rewrite rules are also eliminated (except for the initial simplification of expressions). The creation of new structure is limited to the instantiation of rules during deduction. By avoiding the structural manipulation of expressions, the network becomes, in effect, a "compiled" knowledge representation, upon which the procedural specialists operate merely by the propagation of normal and "meta" truth value "signals".

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HEURISTICS FOR KNOWLEDGE ACQUISITION FROM MAPS

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Acquiring knowledge from a map depends upon procedures for focusing attention, encoding information, and integrating diverse knowledge. This paper describes the heuristics people use to study and learn maps. Verbal protocols obtained from eight subjects suggested four categories of procedures that were invoked during learning: attention, encoding, evaluation, and control. The use of certain heuristics in each category was highly predictive of learning success. Good learners differed from poor learners in their ability to encode spatial information, to evaluate their learning progress, and to focus their attention in accordance with a learning plan. Many of the successful heuristics appear to be readily trainable.

1. INTRODUCTION

Any image processing system, whether human or machine, must translate the information in the sensory display into a meaningful internal description of the sensory image [1, 3]. This paper investigates how humans acquire knowledge from geographic maps. AI studies of map learning [2] have emphasized the use of cartographic knowledge to guide segmentation and interpretation of map features. The present study, in contrast, focuses on the high-level procedures that people use to select, combine, and encode map information in memory. I shall refer to these procedures as heuristics to emphasize the variety of available techniques and the lack of prescriptive learning methods. The research goal is to develop a theory of expertise in map learning by analyzing differences between good and poor learners in terms of differences in their learning heuristics.

2. THE KNOWLEDGE ACQUISITION PROCESS

Figure 1 schematizes the knowledge acquisition process. The maps used in this study contain a variety of conceptual "elements" (e.g., buildings, roads, parks). Each element has both spatial extent (shape and location relative to adjacent elements) and a linguistic label. Because map learning is an active, intentional process, it resembles a problem-solving task. The goal state corresponds to a complete memory description of the map (shown at the top of the figure), and the problem-solving operators are the heuristics the learner applies to produce the memory representation. These heuristics regulate the flow of information and determine how it will be encoded in memory.

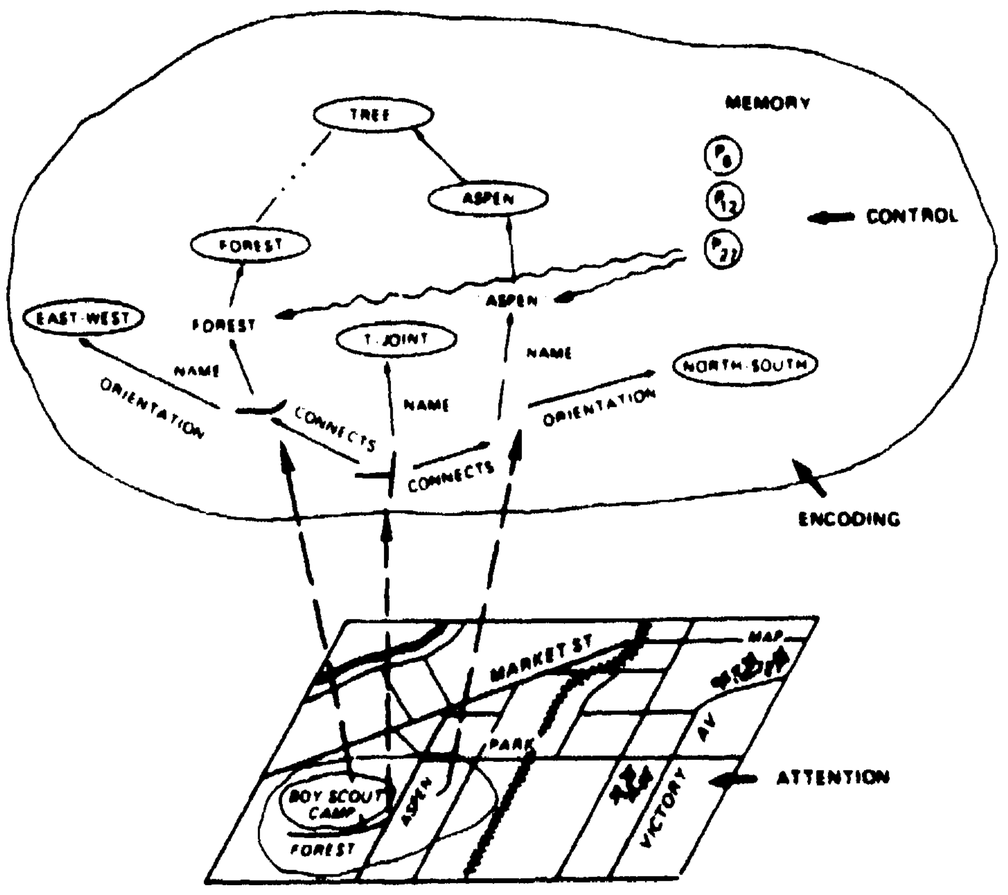

Figure 1. A schematic of the knowledge acquisition process

Attentional heuristics restrict the set of information on the map that the learner focuses on at any point in time, as illustrated in the lower portion of the figure. Encoding heuristics elaborate the information currently in focus and integrate it with other information from the map and knowledge already in memory. For example, one such procedure

(P27) might form a semantic association between the names Aspen Road and Forest Road using knowledge about their common property "trees."

Since the processing capacity (i.e., the upper bound on processing effort, size of working memory, communication channel capacity, etc.) is limited [4], only a subset of the available procedures are concurrently active. Therefore, control heuristics oversee the selection, activation, and scheduling of competing encoding and attentional procedures.

3- ANALYSIS OF LEARNING HEURISTICS

To identify the heuristics that people actually use, Cathy Stasz and I [5] collected verbal protocols from eight subjects attempting to learn real maps. On each of six trials, subjects would first study a map for two minutes and then attempt to reconstruct the map from memory. During the study period subjects thought out loud, describing their attentional focus, their study heuristics, and their evaluations of their learning progress.

Four general types of processes emerged from the protocols: attention, encoding, evaluation, and control. These processes and the heuristics subjects used to implement them are described briefly below.

Attentional processes included those by which subjects restricted eye fixations to a particular subset of the map (focus of attention) and shifted their focus of attention to a new location (attention switching). Two types of attentional heuristics were observed. The first of these, partitioning, was a procedure for focusing attention on a subset of the map information. Since a map contained too much information to be assimilated on any one trial, partitioning the map enabled a learner to attend selectively to a well-defined aspect of the map. Subjects partitioned the map either by (a) spatial region (e.g., by attending only to elements in the north of Market Street) or (b) by conceptual category (e.g., by attending only to the streets on the map).

The second type of attentional process comprised sampling heuristics. These procedures determined shifts in a subject's focus of attention among various map elements. Systematic sampling involved shifting attention according to a subject-defined algorithm (e.g., studying elements from west to east). Stochastic sampling involved shifting the focus of attention to an immediately adjacent element, but in no systematic or consistent direction. In random sampling the focus of attention jumped haphazardly around the map, with the new focus seemingly independent of the previous focus in both location and content. Memory-directed sampling occurred when a subject decided to study particular elements that had not yet been learned. For example, at the beginning of a new study trial, a subject might study the location of a river because s/he could not remember it on the previous recall trial.

When information was in a subject's focus of attention, various heuristics could be used to elaborate and encode the information in memory. These heuristics may be divided into those that operated primarily on verbal or linguistic information and those that operated primarily on shapes and location information.

Three verbal learning heuristics were observed. Counting helped subjects to cluster several elements sharing a particular property (e.g., "there are two parks on Victory Avenue"). Mnemonics were used to generate easily memorable retrieval cues for a set of names, such as "BUD," the order of the three structures on Market Street: bank, undertakers, and department store. The association heuristic involved the elaboration of the map information by association to or embellishment with some related prior knowledge. For example, one subject noted that Forest and Aspen Roads were both names for "trees."

Similarly, several heuristics for learning spatial information were observed. Visual imagery was a learning technique in which subjects constructed mental images of portions of the map. During study some subjects closed their eyes and attempted to draw shapes or name elements in a mental image and reported attempts to form a mental picture of some portion of the map. Labeling involved the generation of a verbal label for a complex spatial configuration. For example, a subject might notice that the three streets in the northwest corner of the map resembled the mathematical symbol pi. In pattern encoding a subject would notice a particular low-level shape or spatial feature of an element, such as Victory Avenue curving to the east. Finally, the relation encoding heuristic refers to the creation of a spatial relation between two or more elements. For example, one subject stated that Victory Avenue is "below the golf course" and is "parallel to Johnson."

The third type of process evident in the protocols was evaluation. Subjects would monitor their learning progress by considering

what they had already learned and what they still needed to study. In particular, they would focus on an element and then determine whether or not they had learned it well enough to recall it later. This evaluation required a search and retrieval of information from memory and a comparison of that information to the representation on the map of the target element. When subjects decided they had not learned the information, they might then decide to study the element using one of the elaboration heuristics.

Finally, control or executive processes presumably directed the overall flow of processing. Since processing capacity is limited. Only a subset of the processes can be active simultaneously. The control processes include a mechanism for selecting from a set of available heuristics those to be activated (selection) and a mechanism for deciding when to deactivate a heuristic and switch to a new one (switching). For example, several subjects began to study a map with an unrestricted random sampling heuristic and then switched to a more selective partitioning heuristic.

4. ANALYSIS OF INDIVIDUAL DIFFERENCES

For each subject, the accuracy of the maps reproduced after each of the six study trials was computed as the proportion of map elements whose name and location were correctly recalled. Performance ranged widely from 94% of the map elements correct after only four trials to 39% correct after six trials.

The protocols of the successful learners (three subjects who recalled at least 90% of the elements correctly) were directly contrasted with those of the other five learners. For each subject the number of occurrences of each heuristic in the subject's six study protocols was computed. While subjects did not vary in how many heuristics they used, they did vary in which heuristics they used. The major differences between good and poor learners' use of heuristics are summarized below for each processing category.

ATTENTION. When good learners used the partitioning heuristic, it was acccompanied by either systematic or stochastic sampling. Once they had decided to focus on a defined subset of the map information, they would sample only elements in the partitioned set. In contrast, poor learners either (a) did not use the partitioning strategy, (b) used random sampling to accompany partitioning, or (c) were unable to restrict attention to elements in the partitioned set.

On later trials, when the basic framework of the map had been learned, good learners relied on memory-directed sampling to determine their focus of attention. That is, good learners knew which details were as yet unlearned and searched for and focused on that particular information. Their heuristic for selecting attentional focus was thus goal-directed. Poor learners, on the other hand, rarely used this sampling heuristic.

ENCODING. All subjects successfully learned the linguistic information; however, subjects varied in their success at learning the spatial information. Effective learners used frequent and varied spatial learning heuristics, while poor learners did not. Good learners reported constructing in memory and rehearsing a visual image of the map. They would also refine their knowledge of spatial location by noticing and encoding explicit shapes (pattern encoding) or spatial relations (relation encoding) among two or more map elements. These heuristics were used significantly more often by good learners than by poor learners. Poor learners frequently reported that they could not think of a technique for learning the spatial information in their focus of attention.

EVALUATION. All learners extensively evaluated their learning progress after each recall trial, but both the accuracy and content of subjects' evaluations differed between good and poor learners. An evaluation resulted in a decision that the subject either did or did not "know" the evaluated information. Good learners evaluated primarily unlearned elements (82% of all evaluation statements), ignoring information they had already learned. Poor learners evaluated a significantly smaller proportion (62%) of unlearned elements, and instead spent some of their study time confirming that they knew certain information. As noted above, good learners appeared to be goal-directed during studying. They would bring to each new learning trial knowledge of what information they had not yet learned, find that information on the map, and then study it using an appropriate encoding strategy. Poor learners seemed more data-driven: they would first focus on a randomly-selected map element, and then evaluate the element in memory to decide whether or not it had been learned.

When subjects assessed whether or not they knew an element, they could be either correct or incorrect in the evaluation. (Accuracy was assessed by comparing the subjects' statements about the elements with the accuracy of the reproductions on the previous trial.) Good learners were

significantly more accurate in their evaluations (96% correct) than poor learners (82%). That is, good learners were superior at determining their current state of learning and "knowing what they know."

CONTROL. When good learners adopted a particular heuristic, they would continue to use it until it had achieved its purpose. For example, when good learners used partitioning, they would sample only information in the partitioned set until all elements had been considered. In contrast, poor learners frequently abandoned this heuristic abruptly and prematurely. This typically occurred when subjects could think of no heuristic for learning the sampled information.

Poor learners also failed to effectively select and use heuristics following evaluations. When a decision had been made that an element had not yet been learned, good learners immediately studied the element. However, poor learners would frequently shift their focus of attention to a new element without studying the unlearned information.

5. CONCLUSIONS

These analyses suggest that the use of powerful heuristics are principally responsible for differences in learning success. We have completed another study that demonstrates directly the utility of using these heuristics [6J. Three groups of subjects, equivalent in map learning ability, were given differential training in the use of learning heuristics. One group learned six of the effective heuristics reported here: three spatial learning strategies (imagery, relation encoding, pattern encoding), two feedback-monitoring strategies (evaluation, memory-directed sampling), and partitioning. A second group learned six heuristics that were uncorrelated with learning success. The third group received no instruction. Subjects trained to use effective heuristics improved their performance on a new map significantly more than subjects in the other two groups. Further, the magnitude of the improvement was a function of the frequency with which subjects used the trained heuristics.

These studies exemplify a growing body of research in cognitive studies of expertise and individual differences. Psychologists are beginning to view expertise as a collection well-tuned, information processes that combine to produce complex task performance. This analytic approach has, of course, been successfully applied in the contruction of knowledge-based systems in artificial intelligence. Based upon the early successes of this approach in cognitive psychology, it would appear to have a promising future in that area as well.

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DESCRIPTION OF TEXTURES BY A STRUCTURAL ANALYSIS

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We introduce a method of a structural analysis for description of textures in natural scenes. The proposed texture analysis system automatically extracts the elements in a texture image, measures their picture properties, classifies them into some discriminable classes (one "ground" and some "figures"), and produces the description of elements in each class and also of their placement rules. This description can be used for learning and recognition of texture images. We also present a new idea for evaluating texture analyzers. In order to directly see what essential features or structurs of the given textures each analyzer extracts, we propose an analysis-by-synthesis method. That is, the synthesis program in our system reconstructs the texture image on the basis of its description. Comparing the reconstructed image with the original one, we can evaluate what information is preserved and what is lost in the description and can improve our algorithms.

1. INTRODUCTION

When we observe objects in a scene, we use the textural information as follows.
(1) identification of objects by the categories of textures,
(2) discrimination of objects by the differences of textures, and
(3) perception of a depth, a curved surface, or a inclination of a surface by the changes of textures.

Endowing machines with these recognition capabilities is not only an interesting problem in computer science but also practically important for automatic analysis of aerial photographs or medical images. Texture has been studied on at least two levels: statistical and structural [1]. On the statistical level, we regard a texture as defined by a set of statistics extracted from a large ensemble of local picture properties. On the structural level, a texture is considered to be defined by elements which occur repeatedly according to placement rules.

We have developed a structural analysis method first to segment an image into differently textured regions [2] and secondly to classify texture samples into several categories [3]. In this paper, we show what kinds of description can be given by the structural analysis and also present a new idea for evaluating texture analyzers. A conventional method for testing performance of analyzers is to evaluate their classification abilities for some texture samples whose categories are specified by a user; a better analyzer is that which gets a higher score of classification [4], The classification ability, however, is highly dependent on both the texture samples and the categories. Since categories of natural textures are not so definite as artificially made characters, the evaluation of texture classification algorithms is dependent on their application fields. Then, in order to directly see what essential features or structures of the given textures each analyzer extracts, we propose an analysis-by-synthesis method. That is, our system first analyzes texture samples and gives their descriptions. Next, the synthesis program reconstructs the texture image on the basis of its description. Comparing the reconstructed image with the original one, we can evaluate what information is preserved and what is lost in the course of the analysis and can improve our algorithms,

2. STRUCTURAL ANALYSYS

A texture is defined as a repetitive pattern in which "elements" are arranged according to "placement rules". The proposed texture analysis system automatically extracts the elements in a texture image and measures their picture properties and their placement rules.

2.1 Preprocessing

An input image is digitized into 64x64 pixels and is quantized into 64 gray levels. Fig. 1 shows digital images of three kinds of textures. Since input conditions may change the first order statistics of brightness distributions, the input image is normalized with respect to gray scale changes so that the mean of the brightness distribution is 32 and the standard deviation is 8. Next, the normalized image is deblurred by an edge preserving averaging method to extract texture elements easily.

2.2 Extraction of Elements

A texture element is defined as a connected area with almost same gray levels. To extract such elements, pixels which are adjacent and whose gray levels are almost same are merged into regions. The merging process used here is as follows.

First, any pixels which are adjacent and whose gray level differences are less than the threshold d(-l) are merged into regions and their gray levels are averaged. Here, the total brightness change caused by averaging is examined. The total change is defined as

$$N(d)- E E |6 (x_f y)|$$

where sd (x,y) is the gray level change at a point (x,y). Next, d is increased by one (d<-d+l) and the merging process is repeated until one of the following conditions is satisfied (d>4).

(1) the total change is very large, which implies that d has become large enough to merge different elements, or

(2) the total change is very small, which implies that there may be a brightness gap between different kinds of elements.

When the process stops at a threshold d* on the condition (1), the regions obtained by merging at d*-l are used for the texture elements. When the process stops on the condition (2), the segmented region by thresholding the brightness histogram are used for the texture elements. For example, Fig. 2 shows the thus obtained elements of the images in Fig. 1.

2.3 Properties of Element

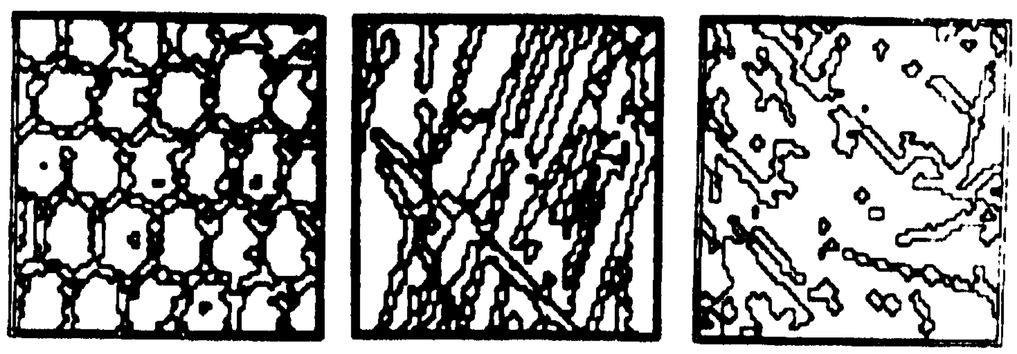
The following five kinds of properties are measured for each extracted element. They are used for global discrimination of elements.

(1) brightness

(2) area

Reptile skin (a) Straw (b) Handmade paper (c)

Fig. 1 Texture images



(a) (b) (c)

Fig. 2 Extracted elements

(3) size

The size of an element is defined as 2 x area/perimeter. For example, when an element is a circle of radius r, the size is r. The value of this size descriptor is not affected greatly by overlap of individuals which may be extracted as one element on the image level.

(4) directionality (direction and magnitude)

The directionality of an element is measured by the principal component analysis. The direction of the element is defined by the slope of the major axis. The magnitude D of the directionality is defined by the eigenvalues λ_1 and λ_2 ($\lambda_1 \geq \lambda_2$) of the covariance matrix for the distribution of (x,y) coordinates of points in the element, as

$$D = \frac{\lambda_1-\lambda_2}{\lambda_1+\lambda_2}$$

When an element is a circle, D=0. When an element is a straight line, D=1.

(5) curvatures along the contour

In the distribution of curvatures along the contour of an element is meaningful information about the complexity of the shape. We measure the k-curvature (k=5) [5] at each contour point. Next, a measured curvature ρ is classified into six zones:

i) high concave curve: $-75° \leq \rho \leq -45°$
ii) low concave curve: $-45° \leq \rho \leq -15°$
iii) straight line : $-15° \leq \rho \leq 15°$
iv) low convex curve: $15° \leq \rho \leq 45°$
v) high convex curve: $45° \leq \rho \leq 75°$
vi) zig-zag line : the other

and the occurence probabilities of curvatures in the first five zones are calculated for the element properties.

2.4 Classification of Elements

On the basis of the distributions of these properties, elements are classified into some discriminable classes. In our system, elements are classified by thresholding the histogram of each property. In computing the histogram of a property, we use the weighted value as its frequency to give large weight to dominant elements. The weighting values are shown in Table 1. For example, the frequency of brightness b is defined as the total area (not number) of elements whose brightness are bo Therefore, the system can stably analyze a texture image in which there are comparatively small number of elements. Since each property has a different domain and range, the histogram is normalized and the thresholds are set automatically at the bottoms of deep valleys between the prominent peaks, if any [3].

2.5 Description of Texture

Statistical Features

Now, the system calculates the following statistical features about elements in each class.
(1) the number of classes: Nc
(2) the mean and the deviation of each property p of elements in each class i: (μ_{ip}, σ_{ip}) (i=1∿Nc and p=1∿Np, where Np is the number of properties). The weighted values in Table 1 are also used for calculating these distributions.

Table 1 Weightings in histogram computation

PROPERTY	WEIGHTING
BRIGHTNESS	AREA
SIZE	PERIMETER
AREA	AREA
DIRECTIONALITY	
.DIRECTION	AREA x MAGNITUDE
.MAGNITUDE	AREA
CURVATURES	PERIMETER

Furthermore, the following features concerning to placements of elements are easily measured.
(3) the density of elements in each class i: Ai (i=1Nc), which is the ratio of the total area of elements in class i to the image area.
(4) the adjacency probability between class i and class k: Pik (i_fk"I-vNc), which is defined as the probability that a boundary point of an element in class i is adjacent to that in class k. When i==k, it is especially called 'auto-adjacency probability'.

Table 2 shows the values of these textural features of the images in Fig. 1.

Figure and Ground

If there is more than one class of elements, one of them can be regarded as the "ground" of the image. The "ground" class is defined as

Table 2 Statistical features of elements and placements

TEXTURE	(a)				(b)				(c)			
No. of class	1		2		1		2		1		2	
properties	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
brightness	19.2	5.2	36.1	1.4	18.5	3.8	35.0	2.4	27.0	0.2	45.4	2.9
size	2.9	0.6	8.2	2.1	3.6	0.9	6.9	3.1	8.9	0.8	3.4	0.9
area	12.9	11.7	73.3	70.0	32.6	36.2	67.4	175.2	2664.5	438.3	144.1	105.2
directionality												
.magnitude (%)	56.6	26.5	34.3	24.4	78.8	28.0	71.4	22.7	7.0	6.9	28.7	29.0
.direction	16.4	4.2	17.7	2.0	17.7	2.7	17.3	1.2	17.9	0.8	23.0	3.8
curvatures												
.[-75°,-45°] (%)	4.4	6.1	5.3	4.5	1.9	3.5	4.4	3.2	9.6	2.1	8.6	5.9
.[-45°,-15°] (%)	21.0	15.2	17.9	7.7	20.8	9.8	19.8	9.9	24.7	5.1	24.3	12.8
.[-15°, 15°] (%)	13.9	13.4	16.0	8.3	32.6	17.5	32.1	16.1	28.8	5.6	22.8	13.7
.[15°, 45°] (%)	24.4	22.1	36.2	13.3	31.4	17.5	24.5	12.8	23.7	8.5	19.6	10.8
.[45°, 75°] (%)	9.1	10.5	18.9	8.5	6.1	8.6	7.0	8.0	9.2	3.1	8.3	9.9
density (%)	30		70		29		71		73		27	
adjacency-probabilities (%)	1 2 1 22 78 2 93 7				1 2 1 10 90 2 60 40				1 2 1 0 100 2 97 3			

(1) a class whose average area of elements is very large (for example, class 1 of (c) in Table 2), otherwise,
(2) a class whose ratio of the deviation to the mean of areas of elements is very large (for example, class 2 of (b) in Table 2), otherwise,
(3) a class which has the largest auto-adjacency probability (for example, class 1 of (a) in Table 2).

The other classes are in turn regarded as the "figures" of the image. If the image has only one class of elements, it is regarded as both the "figure" and the "ground". For example, the "grounds" of the images in Fig. 1 are smeared with black as shown in Fig. 3.

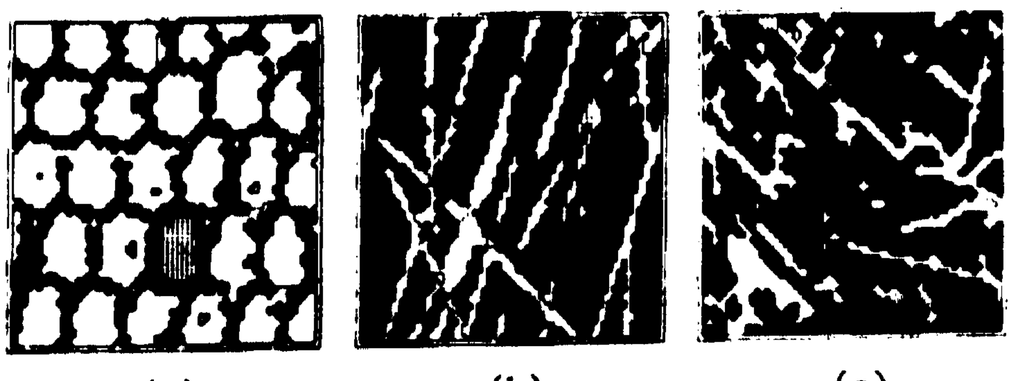
Typical Element

The system selects one typical element from each "figure" class to give a detailed shape description of the elements in that class. The typical element in each "figure" class is the one whose shape properties are the closest to the means of those of that class. The function that evaluates the closeness of an element j in class i is defined as

$$E_{ij} = \frac{\sum_{p=1}^{N'p} \exp\left[-\frac{(x_{jp}-\mu_{jp})^2}{2\sigma_{ip}^2}\right]}{N'p}$$

where xjp is the value of a property p of an element j and the shape properties used are area, size, directionality and curvatures„ For example, the dotted areas in Fig. 3 are the typical elements of the image in Fig. 1.

It is an important problem how a typical element is to be described for a detailed comparison needed in recognition phase of the system. There are many algorithms for shape analysis [6] and we should select a information preserving technique. In this paper, however, only the points in a typical element are memorized in terms of the relative coordinates from the centroid of the element for simplicity.



(a) (b) (c)

Fig. 3 "Grounds" of images (■) and typical elements (⊡) in "figure" classes (□)

Relative Position Vectors

To give a detailed description also of placements of elements, the system measures relative positions among elements in "figure" classes. A relative position between two elements is defined as the relative coordinate between their centroids. The two dimentional histogram Hik of the relative positions of every pair of elements, one in class i and the other in class k (including i=k), are computed. Here, in computing the histogram we use the weighted value as its frequency as follows. Let Eij be the closeness of an element j in class i and Ekl be that of an element 1 in class k. Then the weighted value is defined as min(Eij,Ekl), If the placement is regular, there are significant clusters periodically in the histogram,, In such a case, the mean and deviation of each independent cluster which is nearest to the origin is measured as the placement rule Rik. They are denoted as

$$R_{ik} = [\{\mu_x^n(i,k),\mu_y^n(i,k)\},\{\sigma_x^n(i,k),\sigma_y^n(i,k)\}] \quad (n=1\sim Nik)$$

where Nik is the number of independent clusters. If there is no significant cluster, the placement rule Rik is regarded as random.

For example, Fig. 4 shows the distributions H22 of relative positions of elements in the "figure" class 2 of the image in Fig. 1(a). In this case, the placement is regarded as regular and two independent clusters (whose means are (13,-6) and (0,11)) are measured. On the other hand, those of the other images in Fig. 1 are regarded as randara.

Now, the description of texture is completed. This description can be used for learning and

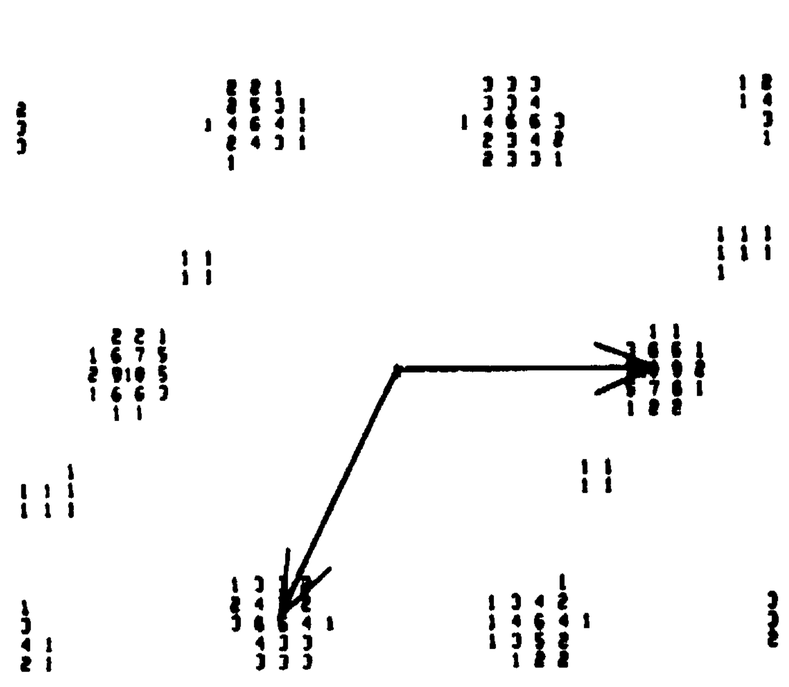


Fig. 4 2-D histogram of relative positions among elements in "figure" class

recognition (classification) of texture images. Classification experiments using only the statistical features are reported in [3].

3. RECONSTRUCTION OF TEXTURES

The synthesis program in the system generates a texture image on the basis of the description of the original texture. It reconstructs a texture image so that the statistical features may be the same as those of the original one.

3.1 Modification of Typical Element

To reconstruct the texture elements, the system uses the typical element in each "figure" class and modifies it according to the distributions of the properties of elements in its class. The properties used for modification are brightness (for light and darkness), size (for magnification and reduction), direction (for rotation), and the magnitude of directionality (for compression).

For example, l (μ_{ip},σ_{ip}) e the nean and deviation of the property p of elements in class i. The typical element is modified so that the distribution of a property p is $N[\mu_{ip},\sigma_{ip}]$ using a normal random number generated.

Modified elements in such a way are then arranged according to the placement rules as mentioned in the next section.

3.2 Placement of Modified Elements

The system determines the positions at which modified typical elements are placed as follows. If there are more than one "figure" class, one dominant "figure" class is selected. That is, the positions of elements of the dominant "figure" class (let it be now i) are at first determined according to the placement rule Rii and those of other class k are determined later according to Rik or Rkk. Our system defines a class i as the dominant one whose average deviation in the placement rule Rii is the smallest. The positions of elements in the dominant class are determined as follows.

When the placement rule Rii is regular, the distributions of relative positions in Rii is used. First, the preliminary positions are determined using the means in Rii

$$\{\mu_x^n(i,i),\mu_y^n(i,i)\}\ (n=1\sim N_{ii})$$

as shown by white points in Fig. 5 (in this case, Nii-2). Next, these preliminary

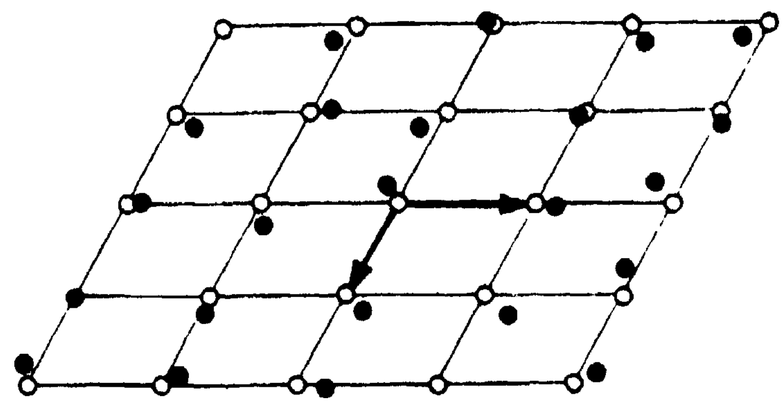


Fig. 5 Position determination in regular placement case (->: mean vector)

positions are fluctuated according to the normal distribution

$$N[(0,0),(\sigma_x/2,\sigma_y/2)]$$

as shown by black points in Fig. 5 using a normal random generator, w h e σ_x a n d σ_y are the average deviations in Rii. These black points are the final positions at which modified elements are placed.

When the placement rule Rii is random, the system uses the density Ai of elements to determine the positions. Since the number of arranged elements Is expected as

$$\text{i}\quad \frac{\text{total area of elements in class i}}{\text{average area of elements in class i}}$$

the system arranges such number of positions randomly over the image using a uniform random number generator.

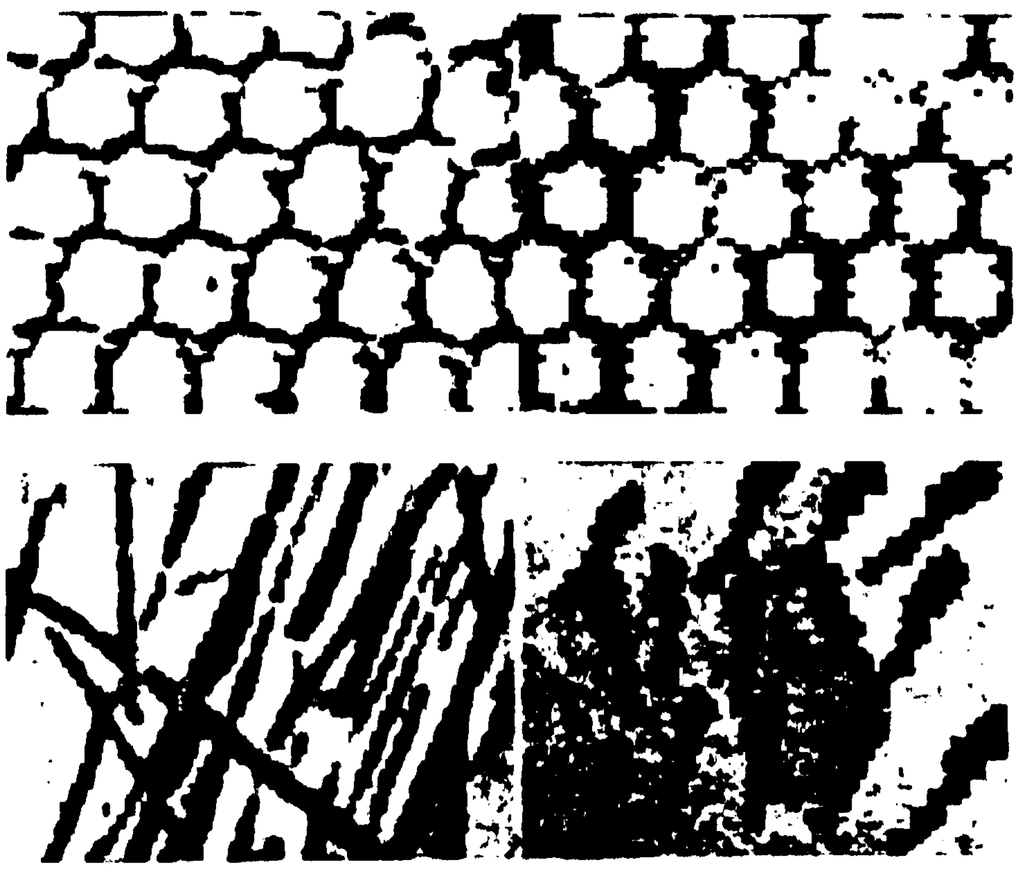
Next, the position of elements in other class k(+i) are determined in almost the same way according to the placement rule Rik or Rkk.

Refering to thus determined positions, modified elements in each "figure" class are placed. After all the "figure" elements are placed, there remains blank space which corresponds to the "ground" of the image. It is filled up with gray values on the basis of the statistical features of the "ground" class by a region growing method.

Now, the reconstruction of texture is completed. Fig. 6 shows examples of the reconstructed images from the original ones In Fig. 1.

4. DISCUSSIONS

For our experiments, we used the same texture samples from Brodatz's photographic album [7] as used in classification [3]. The structural analysis produces anthropomorphic descriptions and therefore they are easily understandable



(c)

Fig. 6 Original images (left) and reconstructed images (right)

and useful* However, we found some important problems by reconstructing those texture images.

Since we only use brightness information to extract texture elements, they do not always correspond to real individuals or what human beings perceive. For example, overlapped individuals with same brightness are extracted as one element on the image level.

Also the "grounds" which the system selects do not always correspond to those which human beings select. This problem relates to the definition of elements.

The placement rules used (relative positions) is the second order statistics and may be still too simple. For example, though the position of an element is considered independently of its properties and those of surrounding elements, there are often correlations among them.

In this paper, we hardly deal with hierarchical textures. A hierarchical texture is such that a set of several elements can be regarded as a unit and many such units are arranged according to their own placement rules. Such hierarchical textures, however, are more often found in artificial textures. If we add aggregation programs [8] to our system, we would be able to describe them in the same way.

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ALVEN: A Study on Motion Understanding by Computer*

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Abstract

This paper presents an overview of a framework for the analysis of motion from sequences of images by computer. The framework includes:
(a) A representation of knowledge for motion concepts that is based on Minsky[f]s frame theory and semantic networks;
(b) Associated algorithms for recognizing these motion concepts. These algorithms implement a form of feedback, by allowing competition and cooperation among local processes. They also allow a change of attention mechanism that is based on similarity links between knowledge units.

The framework is being realized with a system called ALVEN, whose structure and operation are described. The purpose behind this system is to provide an evolving research prototype for experimenting with the analysis of certain classes of biomedical imagery, and for refining and quantifying the body of relevant medical knowledge.

1.0 INTRODUCTION

The main goal of this research, from an AI viewpoint is the development of a framework for Motion Understanding by Computer. This framework is expected to provide:
(a) A representation of knowledge for motion concepts, based on frames [Minsky75] and semantic networks [Brachman79].
(b) The description of basic motion concepts such as verbs, shape transformations and temporal information in terms of the knowledge representation proposed, based on past work in motion representation [Badler75], [Tsotsos76];
(c) The development of algorithms for the analysis of pictorial data in terms of a motion knowledge base. These algorithms will be expected to generate a description of the objects and motions found in the pictorial data at different levels of abstraction, from detailed LV wall kinematics to summary statements using English-like verbs. The recognition control structure is based on the concept of competition and cooperation among local hypotheses [Zucker78] both at the low (image) level [Rosefeld,Zucker, Humel76l and at higher (conceptual) levels.

ALVEN (A Left Ventricular Wall Motion Analysis Computer Consultant), is a system for the analysis of cinecardioangiograms (films of the human left ventricle). Given such a film, the system's job is to generate a conceptual description of the shapes and motions exhibited in the film by the left ventricular wall, noting abnormalities and unusual occurrences.

From a medical point of view, ALVEN*s importance is based on its ability to provide an assessment of the human left ventricle (hereinafter LV), as a functioning muscle. The aim of the research is twofold:
(a) To produce a system that can aid in the analysis of cinecardioangiograms, and which produces consistent and objective descriptions of left ventricular wall dynamics,
(b) To provide a framework for the representation of medical knowledge about the dynamics of the human left ventricle.

ALVEN is a first step towards achieving these objectives. Past descriptions of ALVEN may be found in [Tsotsos78] and [Tsotsos79].

2.0 REPRESENTATION OF KNOWLEDGE

2.1 What Needs to be Represented?

The main concern of this representational formalism is how motion concepts are to be represented and organized into a general motion concept and problem-specific concept knowledge base. There are several types of motion concepts:

a) speed of an object
b) trajectory of motion
c) descriptive motion verbs
d) qualitative trajectory descriptions - directionals
e) changes of an object's properties
f) temporal concepts: duration, start and end time, relative timing of events.

In addition, the representation must be flexible enough to handle "fuzzy" data, different levels of abstraction including linguistic levels, and to represent enough information for approximate regeneration of analyzed motions.

2.2 Representational Building Blocks

The basic entities of the representation are called frames and are used to model abstract concepts such as that of HEART or BEATing. The instantiations of the abstract concepts of the real world are modelled in the representation by frame tokens (or simply tokens). The INSTANCE-OF relationship relates tokens to the frames of which they are instances. Thus, "John's LV", an instance which represents a particular left ventricle, is related to "LV" through the INSTANCE-OF relationship.

* This paper is a summary of [Tsotsos79].

The internal structure of a frame is made up of two distinct components: information on how to instantiate the frame (fill the slots which make up the semantic components of the concept which the frame defines), and information on what concepts must be present in the description derived thus far in the analysis in order for the defined concept to apply. These two components are termed dependant and the prerequisite respectively. Both parts are made up of slots. The difference lies in the default values of the slots. The slot defaults for the dependant slots are made up of references to slots of the prerequisite part and function calls which use these values to calculate the instantiated value of the slot. Defaults in the prerequisite slots give expected values for observed data. Slots have associated with them a name, a frame type, constraints that must be satisfied by any candidate value and exceptions that are to be raised if those contraints are not satisfied.

2.3 Frame Organization

The frames which are part of a knowledge base are organized into an IS-A hierarchy in terms of the (partial order) relationship IS-A [Brachman79].

The prerequisite slots of a frame must conform to specific conditions as well. If frame A defines a motion concept for object C, the prerequisite slots must describe:

a) the motion sequences for C, including any parallel descriptions which must be added together to form the overall motion of C;

b) the motion sequences of all objects C^1 such that C' is a PART-OF C, thus conforming to the PART-OF hierarchy of C.

In addition to these two static organizational concepts, the representation allows the use of similarity links as an aid in transferring control between contexts and classifications during recognition.

Similarity links are associated with the frame concept defined and are based on exceptions which occur in the prerequisite components of that frame. There are three major components to the data stored along with a similarity link:

a) compatibility expression - This Boolean expression contains the necessary conditions which the two linked frames must share in order for the similarity link to be activated (i.e., the "similarities").

b) exception expression - This is a list of Boolean conditions in which the predicates are exceptions which may be raised during matching of the frame. Each of the list's elements has associated with it a time when the exception should occur. In effect, what such an expression defines is the time course of matching failures in one frame which indicate that the other frame is more relevant (i.e., the time sequence of "differences").

c) activate-support list - This is a list of generic frame names which are to be activated or supported by the similarity link.

2.4 Left Ventricular Motion Concepts

The left ventricle is standardly described by splitting up the outline into 3 segments (when viewed in the Right Anterior Oblique projection) - posterior, apical and anterior.

While the form of LV beats is not known precisely, there are some subjective data that are relevant for an initial version of the knowledge base (KB). For example, there is a separate motion frame for each of 7 phases of an LV cycle. Some phases define contraction of the LV (maximum ejection, reduced ejection), others expansion (rapid inflow, diastasis, filling by atrial contraction) and two define a state of rest (isovolumic contraction, isovolumic relaxation - isovolumic is the key here). Therefore the phase frames are IS-A linked to the frames for "contract" and "expand" as is appropriate. In each frame, all of the segments of the LV are associated with the event or sequence of events that define the segment's motions during that phase. Correspondingly, the frame for "normal LV beat" would be made up of the events which represent each phase of the LV, linked in a cycle with appropriate timing information so that together they define the cyclic beats.

Abnormalities are represented using the same structure. The segments which have abnormal motions have separate frames which describe abnormalities expected for that type of motion. Thus, for a particular abnormality, the frame would be made up of the appropriate normal and abnormal segments and phases.

3.0 A KNOWLEDGE-BASED FEEDBACK MODEL FOR ANALYSIS OF TIME-VARYING IMAGERY

There are three main components to the feedback model: (i) image analysis using system expectations; (ii) comparison of the results to the system's expectations; and (iii) adjustment of the system's state and expectations.

3.1 Image Analysis

The starting point for the system is an initial state (say, "NORMAL" LV motion is expected). Thus, the normal LV motion frame is activated along with all of its parts and generalizations (along the IS-A hierarchy). This allows generation of the first set of expectations for the next image. In our case, the first LV outline has been traced in the image. The first expectation is this same outline with a window of acceptable "normal" outlines built upon it. This is reasonable because at end-diastole (i.e., the time when the LV has completed its expansion) there is very little motion in the time spanned by the first 2 or 3 images.

The LV outline is found using an expectation guided relaxation process. Predictions enter the

relaxation process In two ways: the search region and the expected edge orientation. Relaxation Is only applied to the points for which a gradient operator has produced responses, i.e., in the search region. The expected orientation is included in the computation by associating with each sub-region in the region an orientation. This orientation is then used to bias the updating function to favour edge labels of the expected orientation (and those immediately compatible with that orientation). This information is coded into a "strength" function which becomes part of the relaxation updating rule.

We call the resultant outline the "essential trace" of the LV. Motion is detected for the object if the locations of any of its parts differ between the two consecutive images• Correlation of moving shape features between the two LV outlines is done in a heuristic manner. Using the correlation information, values are determined for transformation predicates. The essential kineses for an object are the changes of its physical properties and the changes in its location.

3.2 Change of Attention Mechanism

The system maintains a set of active hypotheses throughout the recognition process. This set is initially filled with the motion hypothesis the user believes is exhibited by a particular object (or objects).

Active hypotheses are organized by their "conceptual adjacency", defined in terms of the primitive relationships used to organize the knowledge base (IS-A, PART-OF and time relationships).

The system adds hypotheses to its list of active ones via activated similarity links and via the "next" temporal constraint. Similarity links are activated when one of the exceptions specified in the exception-expression is satisfied in addition to the hypothesis compatibility expression being satisfied. An active similarity link is also propagated along the motion PART-OF hierarchy in order to ensure the proper new context for the newly activated hypothesis is activated as well.

Hypotheses are deleted from the active list in two ways. If the hypothesis' expected maximum duration is exceeded, it is removed. If the values of its definitional slots can be found, it is instantiated. If the slots cannot be filled It is abandoned completely. The second way of removing hypotheses is by simple thresholding based on the leading hypothesis' certainty. Deletion of a hypothesis is propagated to all of its parts, all parent subjects, and all IS-A sons (recursively).

3.3 Focus of Attention Mechanism

The set of active hypotheses requires further organization. The prediction mechanism needs to know which are the best hypotheses at any instant in the processing, so that it can base its expectations on them. The hypotheses will be ordered by means of the certainty which the system has in them. On activation, all hypotheses are given a 50-50 chances - a certainty of 0.5. For each image afterwards, this certainty is updated using the paradigm of competition and cooperation among conceptually adjacent hypotheses.

The updating is done by a second modified relaxation labelling rule for which compatibility are defined between hypotheses depending on the type of conceptual adjacency they exhibit. For example, mutually exclusive hypotheses are those with a common direct IS-A ancestor. Hypotheses which follow or precede each other in time have large negative compatibilities to aid in their time-wise segmentation. Hypotheses which are the prerequisite slots of another hypothesis have large positive compatibilities with their parent hypothesis. A hypothesis has a compatibility dynamically set with itself for its following time interval depending on its matching progress. Finally, hypotheses linked by similarity links also have dynamically set compatibilities depending on whether one supports the other during that time interval.

4.0 PROJECT STATUS

Currently, we are in the final stage of a prototype implementation of ALVEN. The low level modules (essential trace and essential kineses) have been implemented and are being tested. The data collection module has been implemented and films are being processed. A syntax for the representation of knowledge has been defined and a compiler for entering and maintaining the KB has been implemented.

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AN AUTOMOBILE WITH ARTIFICIAL INTELLIGENCE

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This paper describes an automobile with artificial intelligence, which consists of a road pattern recognition unit and a problem solving unit. The vehicle is completely autonomous and can be driven without a human driver. The road pattern recognition unit involving a pair of TV cameras and a processing unit identifies obstacles in front of the vehicle and outputs data regarding to the locations of the obstacles. The problem solving unit is a microcomputer system and determines control optimal to the environment around the vehicle based on the data. The algorithm employed in it is a table-look-up method, in which the location of the optimal control is addressed in the table by key words generated from the data. The table was heuristically made by means of digital simulation. The vehicle was successfully driven under various road environments at the speed within 30 Km/h.

1. INTRODUCTION

The origins of an automobile with artificial intelligence, called an intelligent car, can be found in both the automatically driven vehicle [1] and the intelligent robot [2]. Due to the guidance system for the automatically driven vehicle, it had one serious defect that it could neither detect nor avoid obstacles on its path. Based on the performance of artificial intelligence the automatically driven vehicle was improved to the intelligent car shown in Fig. 1. It consists of a road pattern recognition unit and a problem solving unit. Then, it involves all the facilities to perform locomotion as an automobile and can move autonomously.

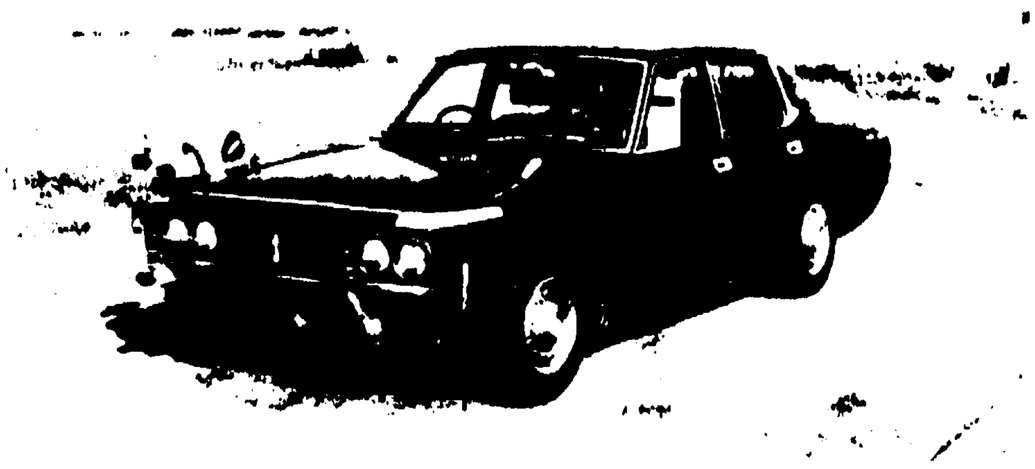

Fig. 1 The intelligent car.

2. ROAD PATTERN RECOGNITION

The road pattern recognition unit functions to clarify presence of obstacles in the view field in front of the vehicle. The unit consists of a pair of TV cameras and a processing unit for video signals from them. The cameras are mounted in the front part of the vehicle with a fixed interval (50 cm) along a vertical line as shown in Fig. 1.

The principle of operation of the unit is shown in Fig. 2, and processing in it is shown in Fig. 3 (a)-(c) which correspond to (a)-(c) in Fig. 2. The two images on the TV cameras, one of which is shown in Fig. 3(a), shift vertically from each other due to the camera positions, and scanning them synchronously and vertically generates two video signals. By processing the signals two pulse trains indicating brightness/darkness changing points (BDCP), one of which is shown in Fig. 3(b), are obtained. One train is delayed for a fixed time corresponding to a distance of a range where an obstacle is to be searched. The delay compensates the shift between the images. Then, the trains are checked if any part of them has same pulse sequences each other, and this results in detection of obstacles as shown in Fig. 3(c), where just real obstacles including some illusion are shown. In Fig. 3(c) the center line is rejected as it does not have any height, and the guard rail is also rejected as it is out of the present range. To cancel the Illusion, height and width of obstacles are checked furthermore.

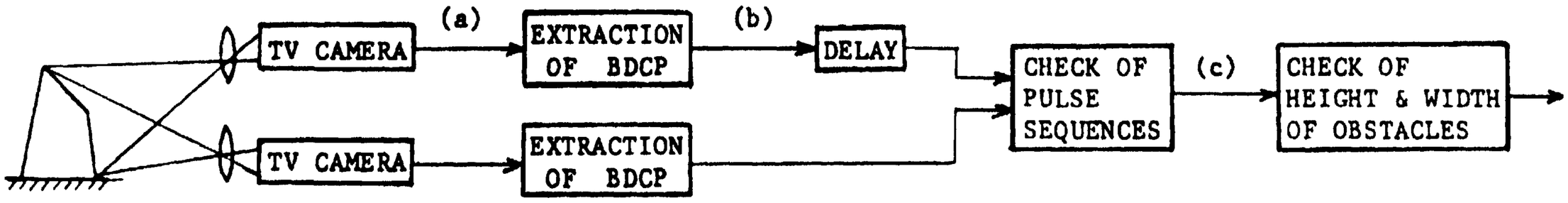

Fig. 2 Principle of operation of road pattern recognition.

Fig. 3(a) A image on a TV camera. Fig. 3(b) Extraction of BDCP. Fig. 3(c) Detection of obstacles.

By employing different delays of more than one and the following circuits, the processing of the pulse trains is performed in parallel to identify obstacles in the whole view field. Processing the images shown in Fig. 4(a) as described above results in identification of obstacles in the view field shown in Fig. 4(b). The view field is quantized according to the ranges, in each of which obstacles are identified, and then the perspective form is converted to a plane figure form. The trapezoid in Fig.4 (b) is the view field in the plane figure and black parts in the center of it are the guard rail, i.e. obstacles.

The area of the view field is between 5 m and 20 m from the vehicle with viewing angle of 40 degree. The time required to identify obstacles is 33.3 msec for scanning one frame and 2.3 msec for processing after scanning.

3. ALGORITHM FOR DETERMINATION OF CONTROL

The problem solving unit determines control by using the data from the road pattern recognition unit. The purpose of the intelligent car is proper locomotion in road environments with safety, quickness and "keep left". Therefore the time required to determine control must be within 100 msec at most, because the vehicle running at 36 Km/h runs 1 m in 100 msec. To satisfy this requirement, a table-look-up method is employed. In the method, control is retrieved by key words from a table. The key words are generated by logical operation upon the data from

Fig. 4(a) A image on a TV camera.

Fig. 4(b) Detection of obstacles in the image shown in Fig. 4(a).

the pattern recognition unit and have relations to the location where the control is stored. The table was made heuristically by computer simulation. Fig. 5 shows the simulation. On the display the vehicle, its view field, its trajectory and the left guard rail are drawn.

After the simulation, the following algorithm was employed in the intelligent car. By defining x_i (i=1 to 16, x_i=5 to 20) and y_i (y_i=-32 to 96) as shown in Fig. 6, the road is classified into five categories: 1) course following, 2) obstacles on the road, 3) left turning, 4) right turning and 5) dead end. In the cases of 1) or 2) a set of (x_i, y_i) maximizing y_i/x_i is the key words. In the cases of 3) or 4) a set of (x_i, y_i) indicating the corner of the turning is also the key words. To make the size of the table small, 16 kinds of x_i are decreased to 8, and 128 kinds of y_i to 32. Therefore the table has 8 x 32 elements.

The problem solving unit consists of a microcomputer system including a micro CPU, RAMs (8 KB), ROMs (3 KB), I/O interfacing LSIs, and A/D and D/A converters. The time required to get control is very short and within 33.3 msec in most cases and 100 msec at most, which include just processing in the microcomputer. A human driver usually requires more than 0.4 sec.

4. EXPERIMENTS

4.1 The Intelligent Car

The automobile is a compact car with a torque converter, some sensors and actuators. The sensors include a speed sensor for the vehicle and a angle sensor for the steering wheel. The actuators include a hydraulic actuator for the steering wheel, an electric motor for throttle valves and vacuum servo brakes.

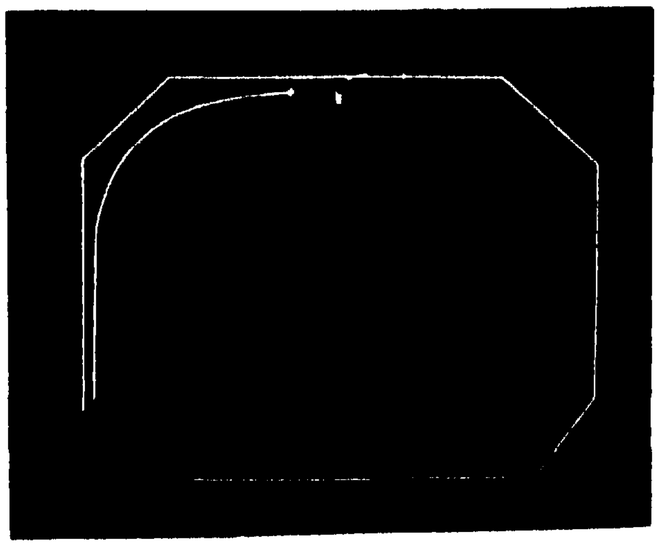

Fig. 5 Digital simulation.

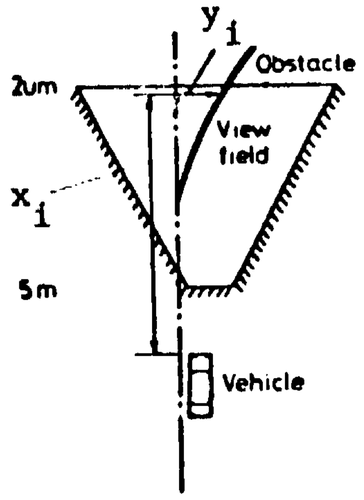

Fig. 6 Definition of x_i and y_i.

4.2 Experimental Results

The experiments were conducted in the test truck of our laboratory. Some results are shown in Figs. 7 and 8.

5. CONCLUSION

Artificial intelligence including both pattern recognition and problem solving for locomotion has been implemented in both software and hardware to the intelligent car. The vehicle was successfully driven under various road environments at the speed within 30 Km/h.

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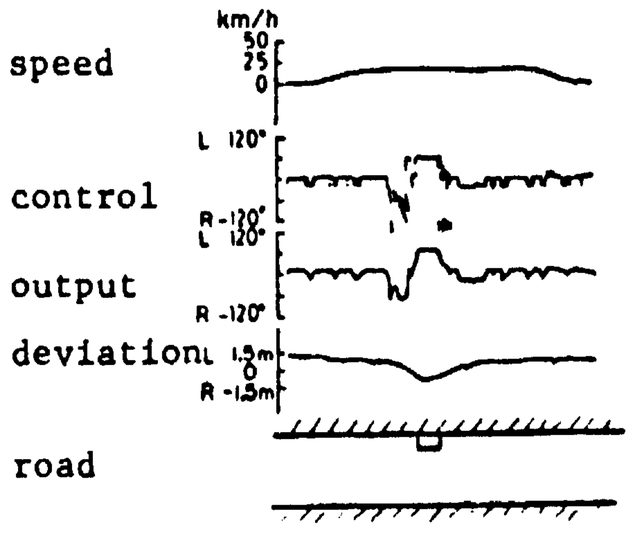

Fig. 7 Obstacle avoiding.

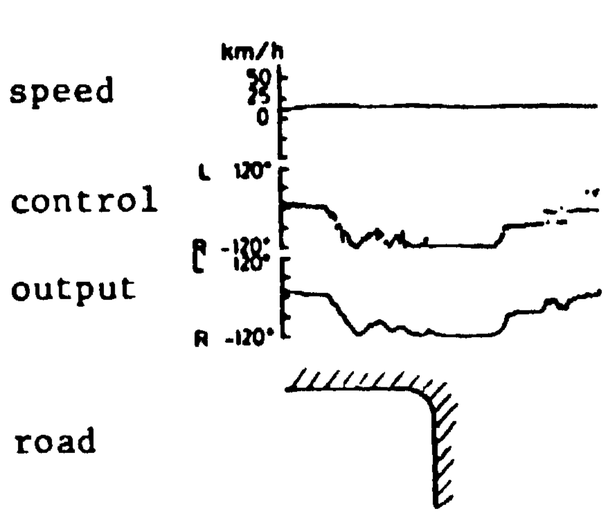

Fig. 8 Right turning.

THREE DIMENSIONAL MOVEMENT ANALYSIS OF DYNAMIC LINE IMAGES

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As a part of a cine-film understanding system, this paper presents a dynamic scene analyzer which separates moving objects from the background and analyzes their motion patterns in dynamic line images such as cartoon films. Finding correspondence of regions and their segments in a sequence of input frames by a new flexible template matching method, the analyzer tracks moving regions and their segments in the dynamic images. Next, a similarity test of segment movements detects the background movement, and classifies the regions into stationary and non-stationary ones. Each in the latter group is further labeled as partly occluded, false, or moving, by examining motion patterns of its segments. Finally, the analyzer merges segments of each moving object into groups having similar motion patterns in order to obtain a meaningful partition corresponding to its components such as hands or legs.

1. INTRODUCTION

In recent years, people have studied dynamic scene analysis, which analyzes a sequence of pictures taken at a constant time interval, such as a cine film or a video record, to interpret it into meaningful descriptions on constituents of the scene and their temporal changes, as well [1,2]. Many papers have been published on detection and tracking of moving objects with [3,4] or without [5] their models in temporal records of natural scenes, interpretation of a sequence of silhouetted images into a model of static and moving constituents [6], and analysis of dynamic line images by utilizing a camera model [7] or by utilizing procedural knowledge about an actor and static objects to describe the dynamic image in terms of meaningful actions [8].

Most systems utilize a priori knowledge and models of the constituents which are very useful to efficiently analyze a large number of consecutive frames, and to solve occlusion problems. They were, however, designed to accept only limited spatio-temporal patterns as inputs; the dynamic image must satisfy both or one of strong restrictions that (1) the constituents show two dimensional movements, and (2) their shapes are almost rigid.

This paper presents a more general motion analysis system that analyzes a sequence of line images, a cartoon film, in which a personified animal moves and rotates freely in a three dimensional world. The analysis is difficult because of the following reasons:
(1) Since the line image of the object consists of curved components, it seems difficult to find strong local features which could be utilized as useful cues for motion analysis or segmentation of the moving object into meaningful parts such as its arms or legs.
(2) Since the moving object and its parts move and rotate in the three dimensional world, and since occlusion often occurs, the shape, size, and structure of each constituent change from frame to frame.
(3) The background or stationary objects may move in the image because of camera movements to track interesting objects.

An approach to overcome the above-mentioned difficulties is to develope a scene analyzer which utilizes effectively temporal patterns. The proposed system has been designed along this approach; knowledge about the shape and structure of each object in the scene, by which usual computer vision systems interpret static scenes, is not utilized, but similarities of both spatial and temporal patterns are iteratively examined with an aim of extracting useful information or cues for higher level analysis of the dynamic scene. In other words, the analyzer is a subsystem of a film-understanding system [8], and its task is to divide the scene into meaningful parts; for example, it separates moving objects from the background, and also subdivides a moving object into components showing similar movement patterns. One can arrange the results into a structural description of the detected objects on properties, spatial relations, and motion patterns.

2. SEGMENTATION OF SCENE BY MOTION ANALYSIS

2.1 INPUT IMAGE

Two animation films containing about 100 frames, in which a personified animal (Moomin) moves freely in a three dimensional world, are used to test the performance of the system. Fig.l displays binary pictures of sampled frames in Film 1; the animal runs from the right side of the picture and then jumps over a stone. Another film, Film 2 shown in Fig.2, is one for testing the effect of the camera movement. We perceive it as if the animal moves

leftwards while it moves its hands and legs but its location is almost unchanged, because objects, trees, in the background translate rightwards at an almost constant velocity.

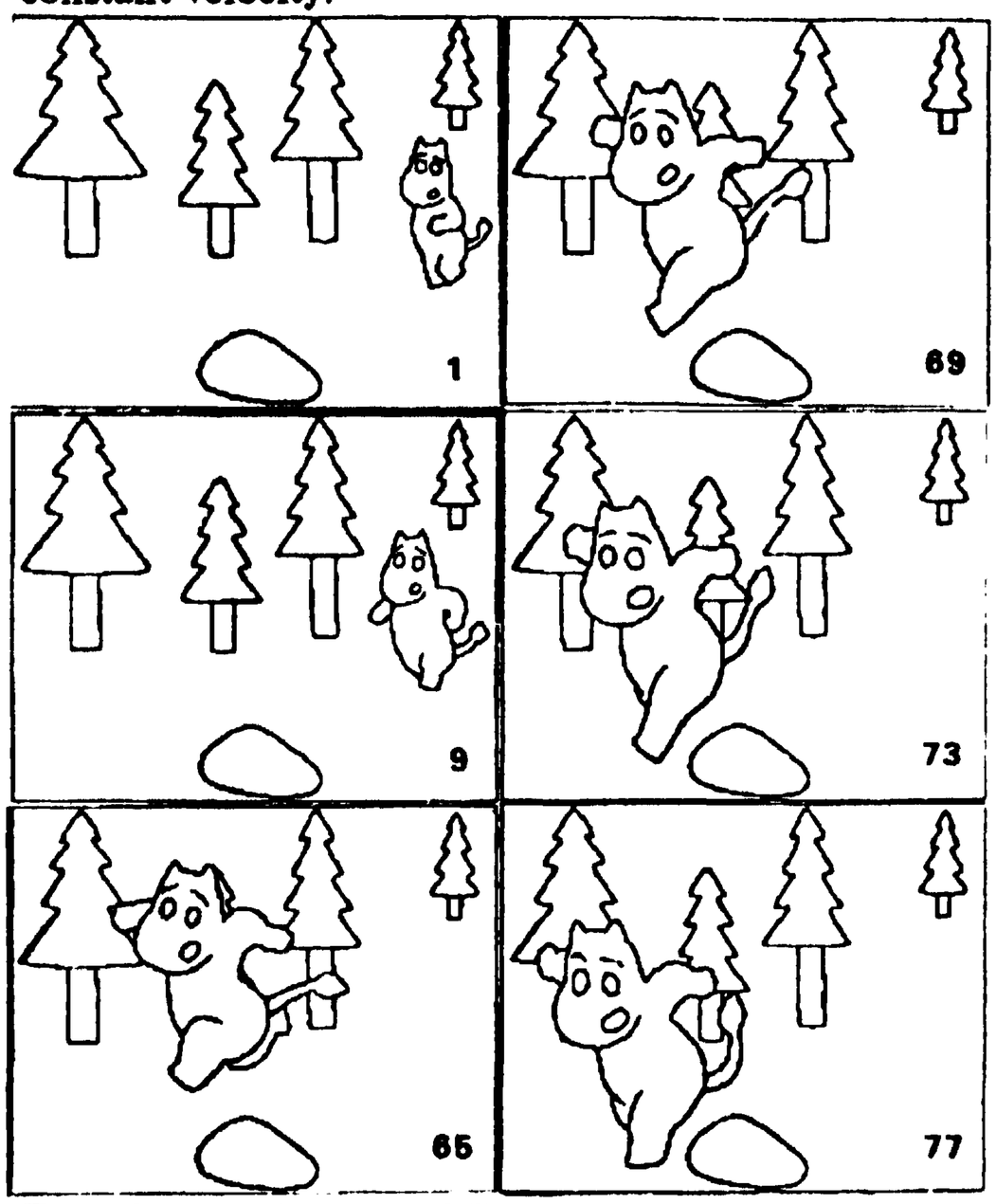

Fig.1 Sample Frames of Film 1.

An animal runs from the left side, jumps over a stone.

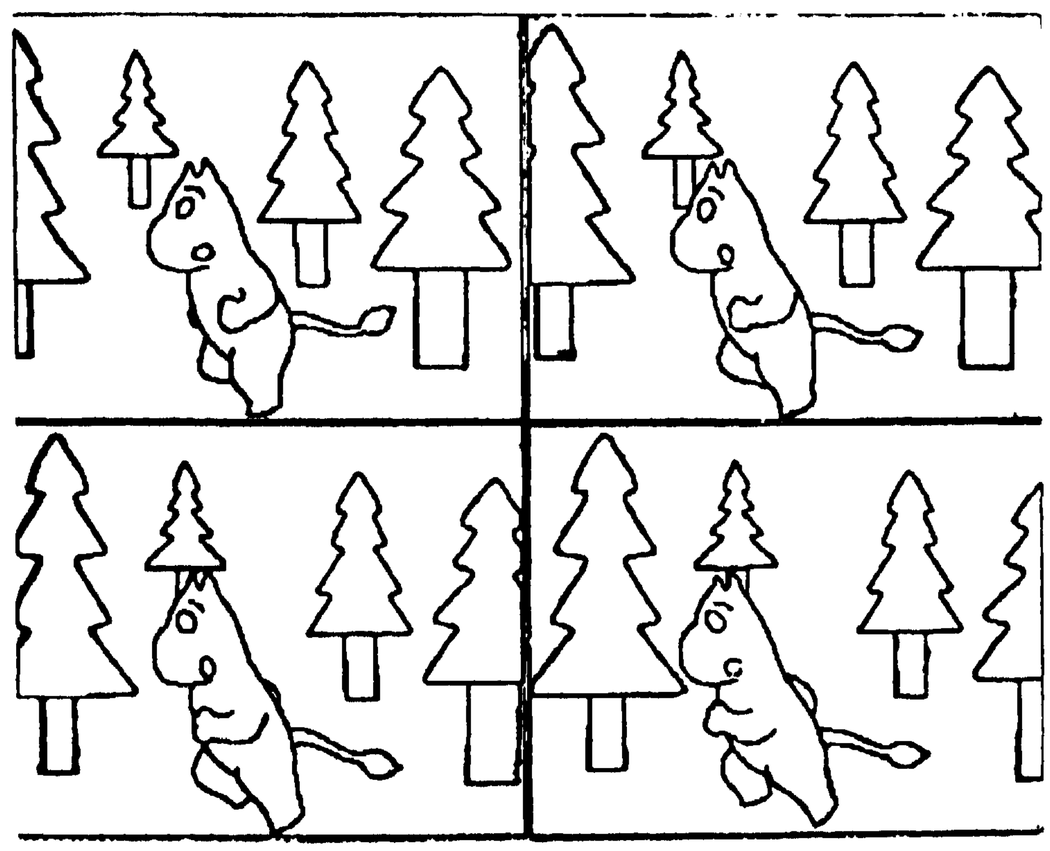

Fig.2 Sample Frames of Film 2.

Although the location of the animal changes little, it is perceived as it runs leftwards, because the objects in the background move to rightwards.

If a computer observes Film 1 from its first frame, where the animal is separated from the other objects, it can easily creat a model of the scene in which the segmentation of each constituent is established. Then, the successive frames will be analyzed by following moving constituents with the aid of the scene model. However, we try to analyze a more complex case; a frame in which occlusion has already occured, for example the 65th frame, is selected as the first input picture to the computer, and the successive frames are then analyzed without the already segmented model of the scene.

A TV camera is used as an input device of the system, and a digitized (200 by 200 4bit) image of each frame is converted into a binary picture by thresholding. Applying a simple thinning operator, we track every arc in the picture, and arrange the line image into lists Of arcs; an arc is described in terms of end points, connected arcs, and chain coded pixels on it. Illustrated in Fig.3 is a graphical representation of the arc list of the 65th frame of Film 1.

2.2 SEGMENTATION OF SCENE BY MOTION ANALYSIS

Our system is a lower level motion analyzer which segments scenes into their constituents by examining their motion patterns, and interprets them into moving, stationary, or partly occluded objects. Movement patterns of short segments of a moving object are also analyzed in order to subdivide the object into meaningful moving parts such as hands or legs.

Most motion analyzers extract movements of the objects in consecutive frames, but they do not analyze how different parts of a moving object show different motion patterns. Our system is characterized by extraction of motion patterns of sufficiently short segments, and also by tests of similarities of the segment movements. The analysis is divided into the following phases.

(1) Inter frame comparison of segments

At first, we detect regions in the scene and establish their correspondence to those of the next frame. Then, we divide all arcs into sufficiently short segments, and follow them in the line image sequence to measure how they are moving. A flexible template matching method has been developed to find correspondence between the segments in the consecutive frames. The movement patterns of the segments are examined in the next three phases.

(2) Separation of non-stationary regions from the background

The objects in the backgroud may also move in the image because of the camera movements, therefore we need to know which objects are really moving. Detecting the background movement as that of the majority of the segments in the scene, we classify the regions in the scene into stationary and non-stationary ones.

(3) Labeling non-stationary regions
The movements of the segments in the non-stationary regions are examined to classify them into partly occluded objects (for example, Region ABCD in Fig.3), moving objects, or false objects that are areas surrounded by moving objects and static objects (Region EFGHIJE in Fig.3). The results are used to creat and update a scene model. This labeling is not always correct, and the analysis is backtracked when the analysis of the later frames finds the wrong labeling in the scene model.

(4) Grouping of segments in a moving object
Finally, the similarities of the segment movements in each moving object are analyzed in order to divide the object into meaningful parts.

We have implemented the system on a mincomputer HP2108A with 256 kbyte buffer memory. The program is written in FLISP, a modified version of INTER LISP, which can control lower level programs written in FORTRAN.

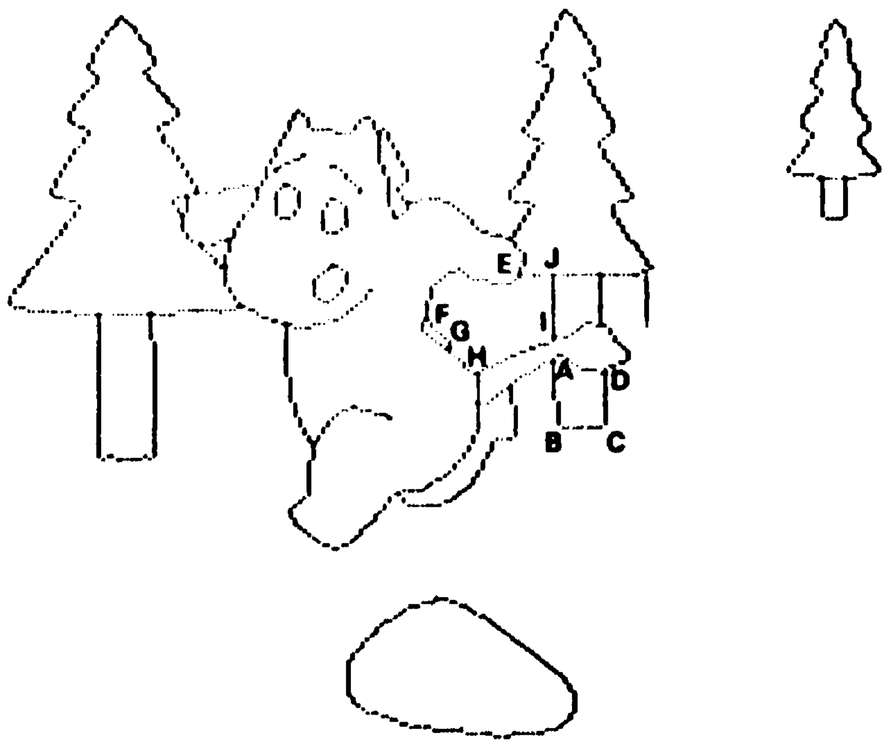

Fig.3 Graphical Representation of Arc Lists of the 65th Frame of Film 1.

3. INTERFRAME COMPARISON OF SEGMENTS

3.1 CORRESPONDENCE OF REGIONS

As mentioned in the previous section, our motion analyzer follows the movements of short segments in the sequence of line images with the aim of obtaining an interpretable goal partition of the dynamic scene. At first, the system examines correspondence of regions in the consecutive frames, and then it analyzes that of each short segment in them.

We can easily divide the input scene into regions, and obtain a list of regions for each frame, in which a region is described in terms of a location of its centroid, its size (perimeter), and a list of arcs (its boundary and internal edges). Now, we examine correspondence of regions in the sequence of frames by a simple template matching method, because changes of the line images between two consecutive frames are small.

Let *R* be a region in the current frame. At first, we search the region list of the next frame for a small number of regions, one of which possibly corresponds to *R,* such that both locations of their centroids and their perimeters are almost same as those of *R.* Then, the boundary of *R* is used as a template, and we find the best matched one of the selected regions by the following method.

At first, a distance map of the template, an array of numbers representing distance to the nearest point on the template, is created in order to easily compute a distance from the template to a region boundary by simply summing distance values in the map at every point on the boundary and then normalizing by the boundary length [9]. By a hill climbing method, we search for the best matched location of each selected region boundary to the template, and a region having the minimum distance value is selected. If the distance value is less than a threshold, we consider it as corresponding to *R.* Eliminating the detected pair from the region lists, we iteratively apply the method to find correspondence of all regions. The results are successful, unless changes in the structure of the line image such as appearance of a new region do not occur between two frames. The unmatched regions in this case are also recorded for higher level motion analysis.

3.2 TRACKING OF SEGMENTS IN CONSECUTIVE FRAMES

Let us consider how we can find correspondence of short segments in two regions whose correspondence has been established. Since the line image of the animal consists of curved segments, we cannot find useful singular points in it, such as true vertices in a polygonal world [61, by which we can easily establish their true correspondence between two frames. Although T joints give us useful information about segmentation between objects, two T joints in different frames not always correspond each other, because they belong to a category of *false vertices* in the polygon world.

Another difficulty for examining the correspondence of the segments is that the shape of the moving object changes from frame to frame. The body of the animal moves and rotates in the three dimensional world, and its moving parts such as its hands and legs independently rotate about different axes. Therefore, the template matching method, which assumes shape rigidness, is not adequate for examining correspondence of each portion of the object.

A flexible template matching method called as *rubber mask* technique [10] was developed for matching of a distorted pattern to its template. The method, however, is not applicable to our problem because it assumes a priori knowledge about the structures of patterns which are built in the matching program.

Therefore, we have developed a new flexible template matching method for finding correspondence of each

short segment in a line pattern to that in a partly distorted one. Consider a problem to match each part of Pattern 1 shown in Fig.4 (a) to Pattern 2 in Fig.4 (b). Because of the shape distortion, we cannot establish a complete or almost complete matching of the two patterns. However, we can establish a good match of a considerable long arc of Pattern 1 to a part of Pattern 2 as shown in Fig.4 (c). Also we can match the other arcs by shifting the template (Fig.4(d),(e),(f)), Thus, we can consider points A,B,C,D, which belongs to the matched portions in the successive partial matching process, as corresponding to A', B', C, and D', respectively.

Our method utilizes this matching process. Let *R* and *R'* be two regions which consist of sets of arcs *{aJ}* and {a/,} respectively. At first, we search *{ai)* and *{a/}* for the best matched pair of considerably long arcs *ak* and *am'* by a similar method as that for matching regions. Next, *ak* is divided into segments // , l2 . . . .*In* shorter than a predetermined threshold value.

If one cannot match a_k precisely to a_m\ we shift each segment by a small amount to obtain a better matching to a_m and also its connected arcs as shown in Fig.5. As a result, a point which is a common terminal point of two segments in a_{kf} for example point 2 in Fig.5, is mapped on two different points in a_m\ Therefore, the correspondence of a segment is described with the transition of a representee point, a point located at near its center. After this type of matching process is accomplished for the selected arc, then its connected arcs are also precisely matched by the same procedure. Thus, we get a correspondence table of *R* to /?' on the segments. We iterate the above-mentioned procedure to find correspondence of the successive frames, and representative points of segements in the first input frame are tracked by interpolation of those in the later frames. Results of tracking of segments in a moving region and a partly occluded objects from the 65th frame to the 70th frame in Film 1 are illustrated in Fig.6.

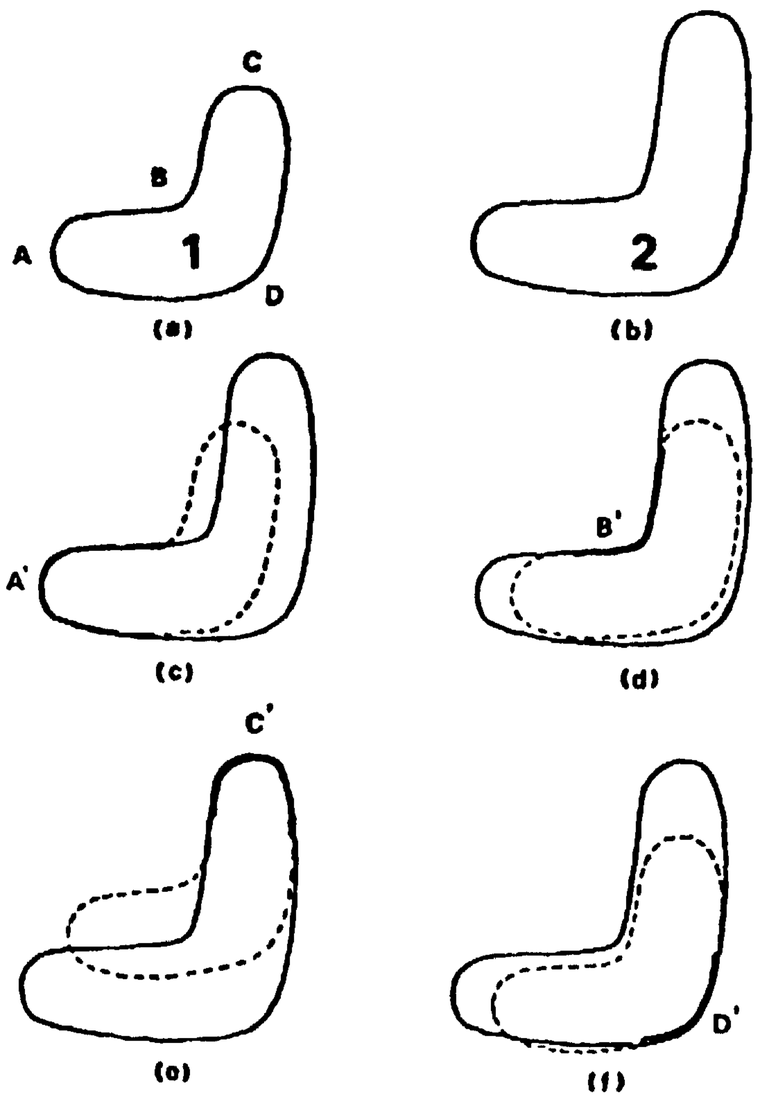

Fig.4 Flexible Template Matching.

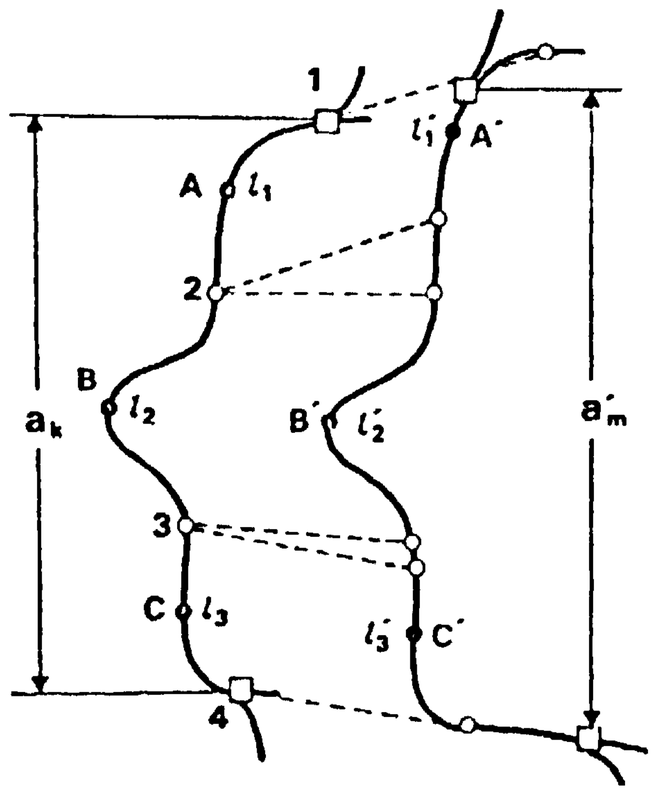

Fig.5 Correspondence of Segments.

4. SEPARATION OF MOVING REGIONS FROM BACKGROUND

4.1 DETECTION OF BACKGROUND MOVEMENT

Stationary objects in the background may move in the image because of camera movements such as panning, tilting, and zooming, therefore, the system needs to detect how the background is moving in consecutive images. We consider that there are many more segments in the background than in moving objects, and they show almost a similar movement pattern; a horizontal or vertical movement by panning or tilting, and a radial movement by zooming.

Therefore, histograms of the segment movements will give us valuable information about the background movement. Fig.7 illustrates two histograms that frequencies of segment movement

Arc a_x is matched to Arc a_k\ a* is divided into segments *h , h* and *h* J and the best matched location of each segment to a_m' and its connected arcs is detected by a hill climbing method. As the result, correspondence of A, B, C, to A', B', C is established.
vectors in Film 1 and Film 2 are mapped on a X-Y plane. The sharp peak at (0,0) in Fig.7 (a) shows that the background of Film 1 is still, and the peaks of Fig.4 (b) suggest that Film 2 Was taken while the camera was panning to track the moving object.

Subtracting the background movement from the movement vectors of all segments, we separate non-stationary regions, as those ■ containing moving segments, from stationary ones.

4.2 LABELING OF NONSTATIONARY RE6I0NS

The non-stationary regions are not always parts of moving objects. Partly occluded regions of stationary objects by moving objects and regions surrounded by moving objects and stationary objects are also registered as non-stationary by the above-mentioned separation process.

Therefore, we creat a scene model after analyzing several consecutive frames. The model is a collection of descriptions of the regions on their movements, and we label a non-stationary region as moving if most of their segments are moving, and as partly occluded if a considerable long sequence of segments is not moving (a region shown in Fig.6 (b)). Next, successive frames are sequentially analyzed, and labels of corresponding regions are examined. If the structure of the line image changes between two frames, for example a new region appears, the system marks the frame in the model for higher level analysis. The system, however, manages a simple case that a partly hidden region is merged into the empty background as Region EFGHIJE in Fig.3 which disappears at the 69th frame. It is considered as a false region, and the analyzer backtracks to correct the wrong label.

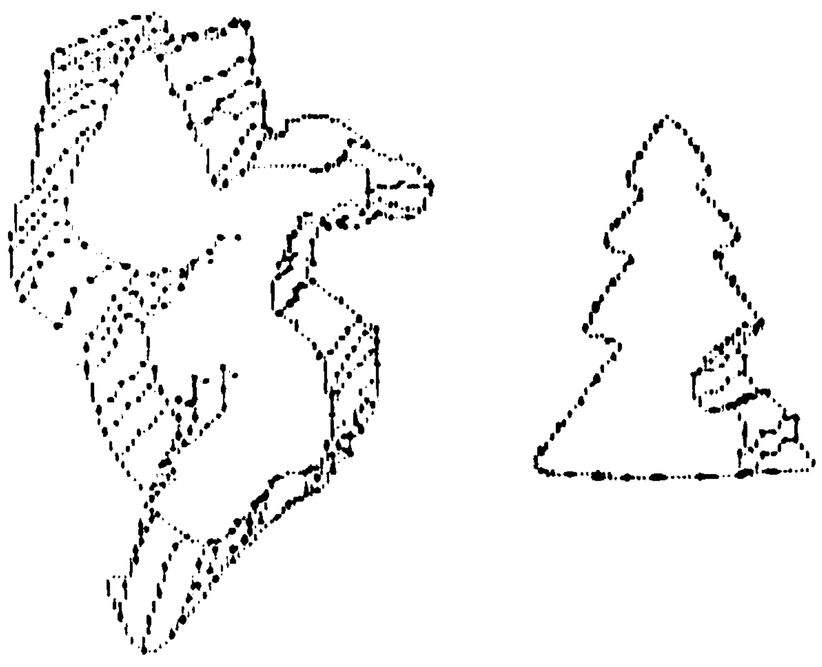

Fig.6 Tracking of Segments.

5. GROUPING OF SEGMENTS IN A MOVMG OBJECT

The final process is to segment a moving region into meaningful parts showing similar movements. Since the movement vectors of all segments in each moving region have been analyzed, we can divide them into groups by a similarity test of their displacements. At first, we subtract a displacement vector of the centroid of the moving region from the movement vector of every segment in it. Fig.8 shows an example of the relative movement vectors displayed on the figure of the moving region. One can find a strong movement similarity for each group of segments such as its leg, body, and hand, therefore its segmentation is easy. We iterate comparing of each two adjacent vectors and merging them into a group

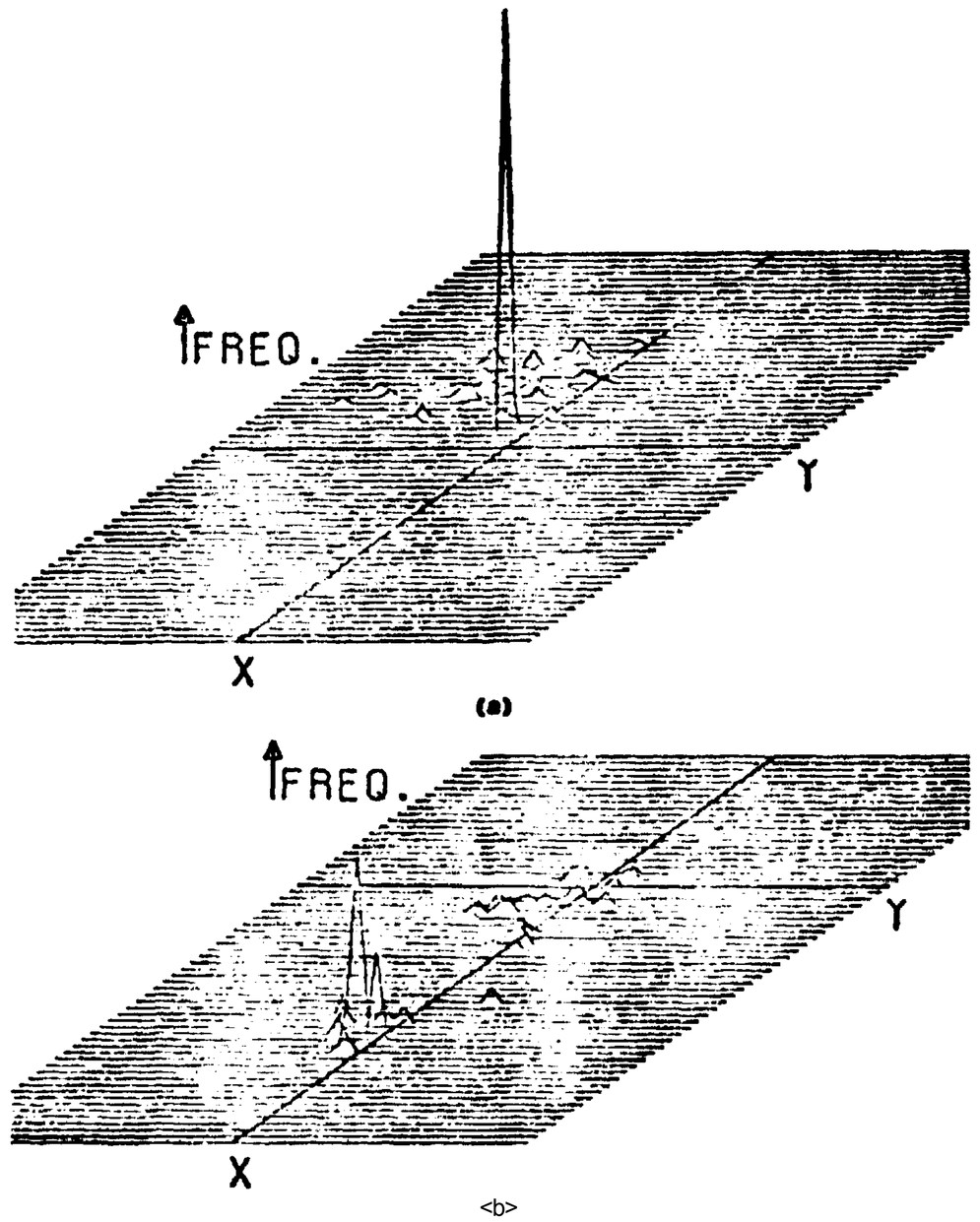

Fig.7 Detection of Background Movement.

A sharp peak in (a) shows the background Is still, and peaks on X axis in (b) indicate that the camera was panning when the film was taken.

if the difference of two vectors is smaller than a threshold. Fig.8 (c) shows the result of segmentation. Next, each set of segments between two groups is divided into two parts by a test of the movement similarity. Thus, segmentation of the moving object into its hand, leg, body, and head is accomplished.

6. DISCUSSION

We have developed a motion analyzer which separates non-stationary regions from stationary ones and subdivides the moving region into meaningful components on the basis of segment movements. Usefulness of a flexible template matching method for establishing correspondence of segments in consecutive frames is shown. Similarity tests of segment movements are also useful to detect the background movement and to segment a moving region into its moving components.

However, the scene model used is very simple, and the acquired knowledge about the properties of the regions by analyzing the previous frames such that each region has been occluding (or occluded by) what regions or not, region is not used to analyze a new coming frame. We could easily implement this

function, an essential function for dynamic scene analysis, to our system, and we would be able to save much computing time.

Also many important problems such as (1) analysis of the structural change of the line image, (2) semantic interpretation of moving and stationary regions, and (3) understanding meaning of the movements, are left for future research.

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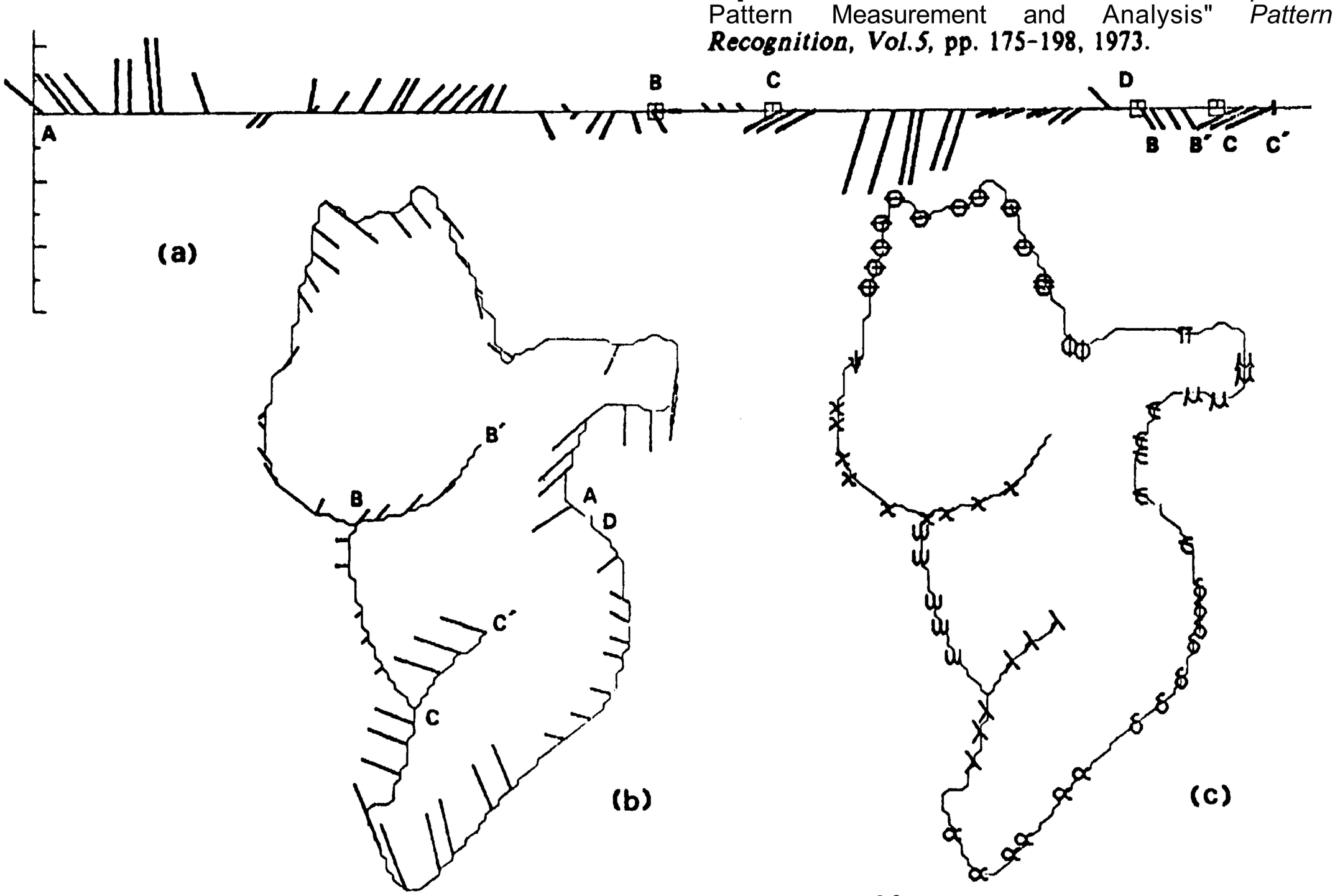

Fig.8 Grouping of Segments by Similarity of Segments Movements.
Segment movement vectors of a moving region from the 65th frame to the 70th frame relative to the centroid of the region are displayed (a) along the arcs and (b) on the image at the 65th frame. The segmentation result is shown in (c).

AN APPLICATION OF DECISION ANALYSIS TO STRATEGY-MAKING IN GAME PLAYING

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This paper presents a game playing model of Score-Four that is a kind of alignment game similar to three dimensional tic-tac-toe. The present model aims at winning a game most efficiently. The pricipal proposal is an adoption of Decision Analysis, a wide-spread method of systems analysis, instead of Minimax Procedure. This paper includes a static evaluation on the state of game, a brief illustration of Decision Analysis, a method of strategy-making and an outline of a game playing machine. Based on the results from the experiments conducted with human players, we assert that Decision Analysis is a good method to make strategies which enable us to take advantage of the opponent's mistakes and it is shown that the risk caused by abandonment of the conventional assumption that the opponent selects the best move is averted by the introduction of a learning system.

1. INTRODUCTION

There are many papers as for game playing model which satisfies the following conditions.

1. Play starts from a situation which is not advantageous to either player.
2. The interest of game playing is just "to win a game" and there is no more.

If a game is played under the above conditions, it would be valid that a player adopts the assumption that the opponent selects the best of all legal moves in every situation, for he sometimes loses a game by making little of his opponent's skill. In this sense Minimax Procedure [1] on the basis *of* the above assumption is adequate for strategy-making when we need not dare to run a risk. However games are not always played under such conditions. For example, there are sometimes occasions when the interest of game playing is "to win a game more efficiently" rather than "to win a game". More efficient winning means winning with fewer moves in some games or with capturing more pieces of the opponent in other games, generally speaking, overwhelming one. In this case it becomes important for a player to make more efficient moves, which enable him to take advantage of his opponent's mistakes. In other words, the conventional assumption is too passive for winning a game efficiently. Similarly efficient moves should be played in occasions when a heavy handicap is imposed.

Decision Analysis *[2]* is effective for strategy-making in a game playing model where we are aiming at an efficient winning. In this method we can take into account the probabilities of its opponent's mistakes.

In this study, it is assumed that the opponent plays a move of the best three among all the possible moves even though he is an unskillful player. Then the key point of this method is the determination of the judgemental probabilities assigned to these three moves. We introduce an index representing the opponent's skill. It should be noted that there may be a risk caused by underestimation of the oppponent's skill or inefficiency by overestimation. This problem, however, is resolved by introducing a learning system which improves the initial value of the index step by step by evaluating the opponent's moves.

We are applying the above method to strategy-making in Score-Four game and Score-Four Playing Machine, which is a system playing with a human player, is constructed.

2. DESCRIPTION OF SCORE-FOUR GAME

Score-Four is an alignment game played by two persons; one uses black balls (simply called Blacks) and the other white balls (called Whites) as their pieces. The game is played on a board with sixteen sticks which penetrate the balls through their small hole. (See Fig.l)

rSince each stick is capable of accepting four balls, the board has 64 points on which players put them. Each point is denoted by a pair of number, (m, n), where m and n mean a stick number and a horizontal plane number respectively, and 1 < m < 16, 1 < n < 4.

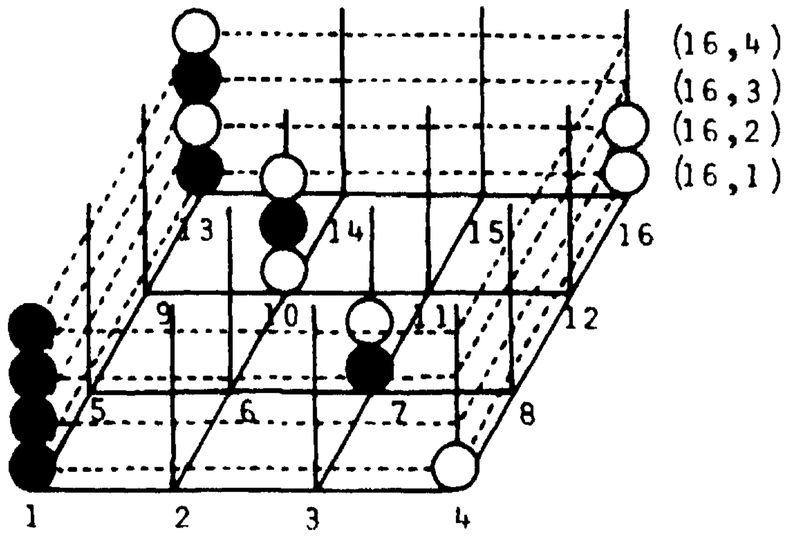


Fig.1 Board of Score-Four

Play starts with the first move of the player who has Blacks (called Player Black) and then each plays a move by turns. Players, however, can not put their balls on arbitrary points, that is, they are allowed to make a move on (m, n) only if n is eqaulto 1 or (m, n-l) is occupied. Such a point is called legal. In Fig.l, for example, (l6, 3) is a legal point and (l6, 4) is an illegal one. The game is won when a player forms a string of his four balls in any line, either horizontally, vertically or diagonally. If it is not won within *64* moves, it ends in a draw.

Now, we present some important properties of the game, which will help us to look for factors to evaluate a board situation.

1. The game is played on a three-dimensional board.
2 The game ends within *64* moves.
3 The number of legal moves in a board situation is equal to or smaller than l6.
4 The number of lines in which it is possible to form a string of four balls is 76.

3. METHOD OF EVALUATING BOARD SITUATIONc

A situation of the board may be determined with the consideration on all the possible states of 76 lines. Therefore we adopt them as the fundamental factors to evaluate a board situation. Each line is in one of the following eight types of states. Let j (j=l, ..., 8) be an index for evaluating a line in j-th state.

STATE I (Four) : There is a string of four Blacks (Whites). We fix the index, oti = 150.

TATE II (Active-Three) : Three points .-ire- occupied by Blacks (Whites) and the remainer is unoccupied and legal. Tf player Black (White) makes the next move and he can win a game by forming "Four", then ot2= 70, otherwise (X?=i(). (Gee Fig.2, a)

STATE III (Sleeping-Three) : Blacks (Whites) occupy three points in the line and the remainer is unoccupied and illegal. a_3 = l8. (Fig.?, b)

STATE IV (Active-Two) : There are two points occupied by Blacks (Whites) and two vacant and legal points, oiu = *U*. (Fig.2, c)

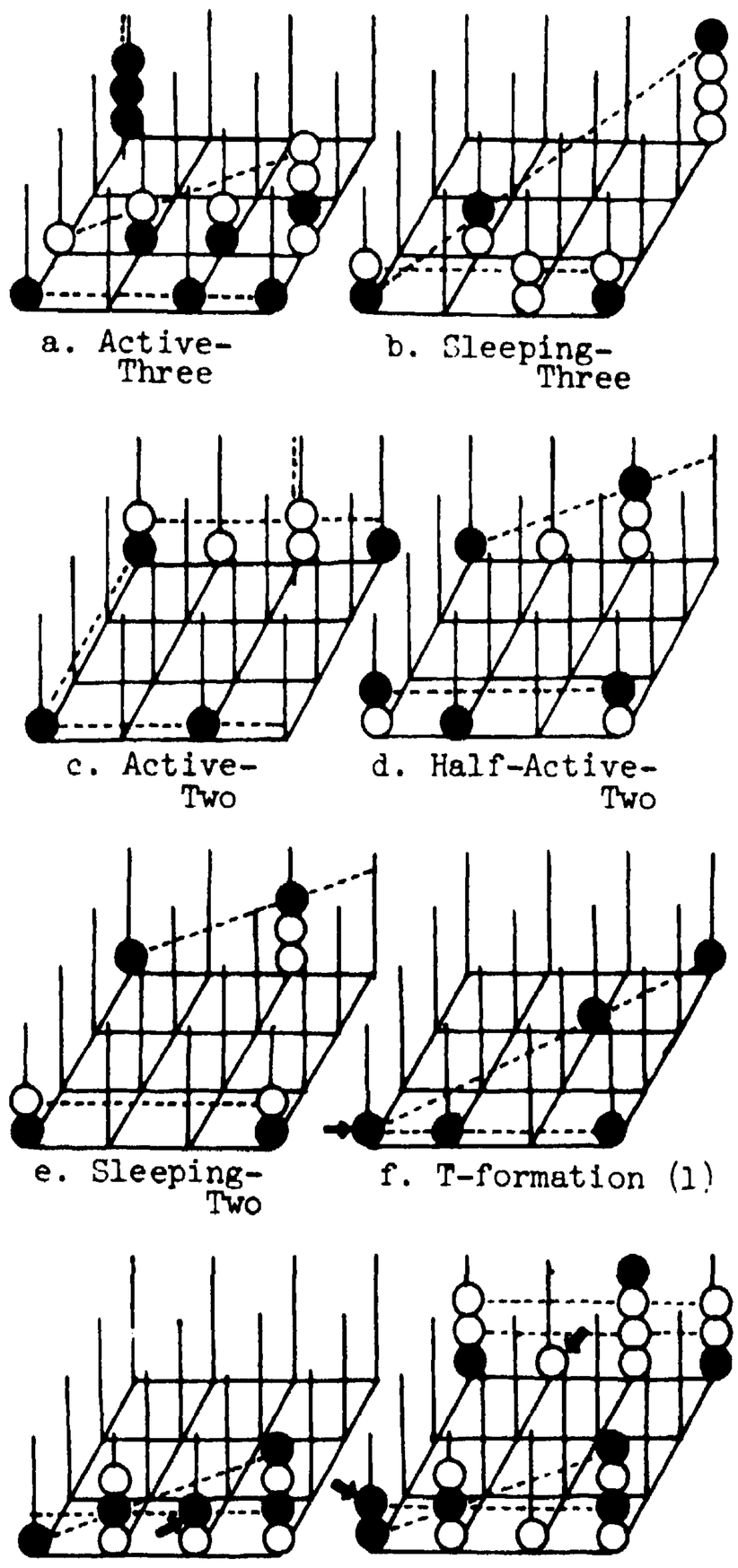


Fig.2 Factors to Evaluate a Board Situation

STATE V (Half-Active-Two) : There are two Blacks (Whites) and two vacant points; one is legal and the other is illegal. At his next turn, Player Black (White) can form "Sleeping-Three". $\alpha_5 = 5$. (Fig.2, d)
STATE VI (Sleeping-Two) : There are two Blacks (Whites) and two unoccupied and illegal points. Player Black (White) can not form "Active-Three" nor "Sleeping-Three" at his next turn. $\alpha_6 = 8$. (Fig.2, e)
STATE VII : There is only a Black (White) and the others are unoccupied. $\alpha_7 = 1$.
STATE VIII : Both Blacks and Whites exist or there is no ball in the line. $\alpha_8 = 0$.

Now we show the two important patterns on which games are won.

1. One forms two or more "Active-Three" with a move. He can surely win the game at his next move. This pattern is called "T-formation". (See Fig.2, f, g).
2. One player forms "Active-Three" where the only one vacant point is just under the vacant of his "Sleeping-Three". He can win the game at his next move. We call it "V-formation" which is shown in Fig.2, h.

So, as an additional factor, we consider whether or not there exists T- or V-formation and let $\alpha_9 = 50$.
Let us now show how to evaluate each factor as stated above. Let u_i $(i = 1,2, \ldots, 76)$ and v be the evaluations of i-th line and T- or V-formation, respectively. Then,

$$u_j = (-1)^k \alpha_j \quad : \text{if i-th line belongs to STATE j.} \quad (i = 1,\cdots,76)\ (j = 1,\cdots,8) \tag{1}$$

$$v = \begin{cases} (-1)^k \alpha_9 & : \text{if there exists T- or V-formations of one side.} \\ 0 & : \text{otherwise.} \end{cases} \tag{2}$$

where

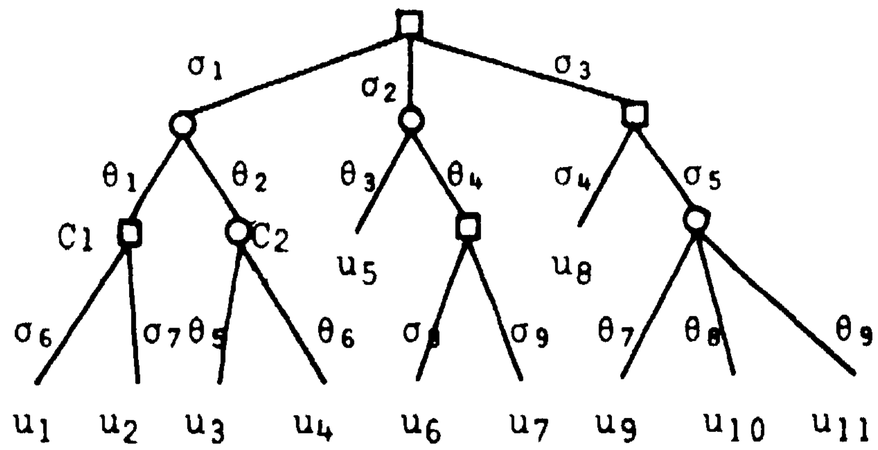
$$k = \begin{cases} 0 & : \text{if the factor is evaluated for Score-Four Playing System} \\ 1 & : \text{otherwise.} \end{cases}$$

Then, static evaluation, U, of a board situation is defined as the sum of u_i $(i = 1,\cdots,76)$ and v as :

$$U(S) = \sum_{i=1}^{76} u_i + v \ . \tag{3}$$

4. STRATEGY-MAKING BY DECISION ANALYSIS

First, we make a brief explanation of Decision Analysis. When one intends to make his decision about a certain problem by using Decision Analysis, he must generate the decision tree as shown in Fig.3. It represents a chronological arrangement of choices controlled by him and chance. The tree graph is composed of chance points, strategies selected by him, events depen dent on chance and utilities. In the above, it is only at decision points that decision maker can decide which path he goes to. The main procedures of Decision Analysis are "folding back" at decision points and "averaging out" at chance points. In Fig.3, folding back at C1 is the procedure to assign the maximun of U1 and u2 to C1 and averaging out at C2 means to assign the expected value of u3 and u4 to C2. After he accomplishes the procedures at every points, he only has to select the strategy leading to the point where the expected utility is the largest.



σ_i: strategy : decision point
θ_j: event
u_k: utility : chance point

Fig.3 Decision Tree

In game playing a player can not predict the opponent's next move precisely. He can consider at best the probabilities in terms of judgemental probability. Therefore we may take the opponent's next move as an event dependent on chance.
Now let us show a way to calculate the Judgemental probabilities, Pi, that the opponent plays the i-th best move, mi. Suppose there are n legal moves at his turn. Then, first, the judgemental probabilities must satisfy the following equation :

$$\sum_{i=1}^{n} P_i = 1 \ . \tag{4}$$

It is a natural assumption that the Judgemental probabilities depend on the opponent's skill, because skillfil player is likely to play the best move at a high probability and on the other

hand beginner frequently plays a worse move. Let by f_i be denoted an index for evaluating i-th best move where $f_1 \geqq f_2 \geqq \cdots \geqq f_n$. Then the degree of the opponent's skill may be roughly represented as follows;

$$\bar{f} = \sum_{i=1}^{n} P_i f_i \qquad (5)$$

where $\bar{f}$ means the expected value of the evaluation of the opponent's next move.
Furthermore, the concept of entropy is utilized to estimate the judgemental probabilities. Entropy in information theory [3] implies a degree of "uncertainty" or "randomness" of events. If we choose P_i $(i = 1, \cdots, n)$ so as to maxmize the entropy, they are the most reasonable judgemental probabilities. It is because the maximization of uncertainty implies the safest or most temperate estimation.
Entropy, H, is defined as:

$$H = -\sum_{i=1}^{n} P_i \log_2 P_i \quad . \qquad (6)$$

By maximizing H subject to Eqs. (4) and (5), we obtain:

$$P_i/P_{i+2} = (P_i/P_{i+1})^{K_i} \qquad (i = 1, \cdots, n-2) \qquad (7)$$

where

$$K_i = \frac{f_i - f_{i+2}}{f_i - f_{i+1}}$$

Here, let us assume that the opponent plays only one of the best three moves m_1, m_2 and m_3. Then, from Eqs. (4), (5) and (7) we readily obtain the following equation:

$$(f_1 - \bar{f}) + (f_2 - \bar{f})x + (f_3 - \bar{f})x^K = 0 \qquad (8)$$

where $x = P_2/P_1$ and $K = (f_1 - f_3)/(f_1 - f_2)$.

If Eq.(8) has zero or positive real solution, judgemental probabilities are expressed as follows. (See APPENDIX I)

$$P_1 = \frac{1}{1 + x + x^K}$$

$$P_2 = \frac{x}{1 + x + x^K} = P_1 x \qquad (9)$$

$$P_3 = \frac{x^K}{1 + x + x^K} = P_1 x^K$$

Since it is not guaranteed that Eq.(8) has zero or a positive real solution, we show ways determine f_1, f_2, f_3 and $\bar{f}$ and examine the solvability. First, consider the case where $K = 2$.
In this case one may find that f_1, f_2 and f_3 are an arithmetical progression and that P_1, P_2 and P_3 are a geometrical one. Moreover, except for the case where $\bar{f} = f_3$, Eq.(8) comes to be a quadratic one which has two real solutions - one of them is either positive or zero and the other is negative - because we are assuming that the opponent plays one of the best three moves, that is,

$$f_3 \leqq \bar{f} \leqq f_1 \quad . \qquad (10)$$

Therefore, if $\bar{f}$ takes on any value between zero and one, it is estimated that $f_1 = 1.0$, $f_2 = 0.5$ and $f_3 = 0$. Then in the case where $\bar{f} = f_3 = 0$, we obtain that $P_1 = P_2 = 0$ and $P_3 = 1$ from Eqs.(4), (5) and (7).
However it seems to be more natural than the above to consider that evaluation, f_i, for i-th move, m_i, is intimately related to the board situation, S, or to its evaluation, U(S), after m_i is played. This idea is appreciated by recalling that the facts that we sometimes find both the extreme cases where m_1 and m_2 have little differnt evaluations and where a player loses because he has played m_2 instead of m_1.
Let S_i be a board situation after a move, m_i, is played. Then, we define f_i by using $U(S_i)$-s given in Eq.(3) as follows;

$$f_i = \frac{U(S_i) - U(S_n)}{U(S_1) - U(S_n)} \qquad (11)$$

where S_1 and S_n mean the board situations after the best move and the worst one are played, respectively.
In general, it is impossible to solve Eq.(8) analytically. But if $\bar{f}$ takes any value between f_3 and 1, it is easily solved by using a computer. (See APPENDIX II) On the occasion when $\bar{f} < f_3$, Eq.(8) does not have any positive solution. It is, however, so risky to make little of the opponent's skill that we consider as if $\bar{f} = f_3$ from the view point of safety playing.
Now it is necessary to consider how to estimate $\bar{f}$. Since it is given without any reliable foundation at the beginning of games, it should be improved during the game. In this study we adopt the next equation for this purpose. Let f^k and $\bar{f}^k$ be the evaluation of the move, m^k, played by the opponent at his k-th turn and the estimation of $\bar{f}$ at the moment just after m^k is played, respectively.

$$\bar{f}^k = (1 - \beta)\,\bar{f}^{k-1} + \beta f^k \quad (k = 1, \ldots, 32) \qquad (12)$$

where β is a constant parameter which takes on a value between zero and one.
The above is the major algorithm to be installed by SFPM standing for Score-Four Playing Machine. In SFPM, the depth of lookahead is considered to be only two steps but it is almost enough on usual occasions, and since the static evaluation function takes into account T- and V-formations which guarantee a winning several moves ahead, the actual depth corresponds to four steps or more in the critical moment. The further details on SFPM will be presented at oral presentation.

5. EXPERIMENTS : SFPM V.S. HUMAN PLAYERS

The experiments are conducted to investigate the advantages of the method presented above. Experimental results of game playing with human players are shown in Table 1. The number of the subjects is fifteen and each plays several games under different conditions. Average nunber (A.N.) of moves required for SFPM's winning implies the index of efficiency of winning. As for conditions, $\overline{f}^0$ is the initial estimation of the opponent's skill. The conditions that $\overline{f}^0 = 1.0$ and $\overline{f}^0 = 0.5$ mean the overestimation and underestimation respectively, because $\overline{f}^k$ of every subject took a value between 0.65 and 0.93 at the end of a game.
Fig.4 shows a typical example of the fluctuations of $\overline{f}^k$ observed during a game.

Table 1. Results of Experiments.

Experiment Number	Conditions β	Conditions $\overline{f}^0$	Results of Games	A.N.
I	0	1.0	7 wins and 1 defeat	43
II	0	0.8	5 wins and 3 defeats	28
III	0	0.5	4 wins and 4 defeats	35
IV	0.05	1.0	6 wins and 2 defeats	39
V	0.05	0.8	5 wins and 3 defeats	29
VI	0.05	0.5	6 wins and 2 defeats	26

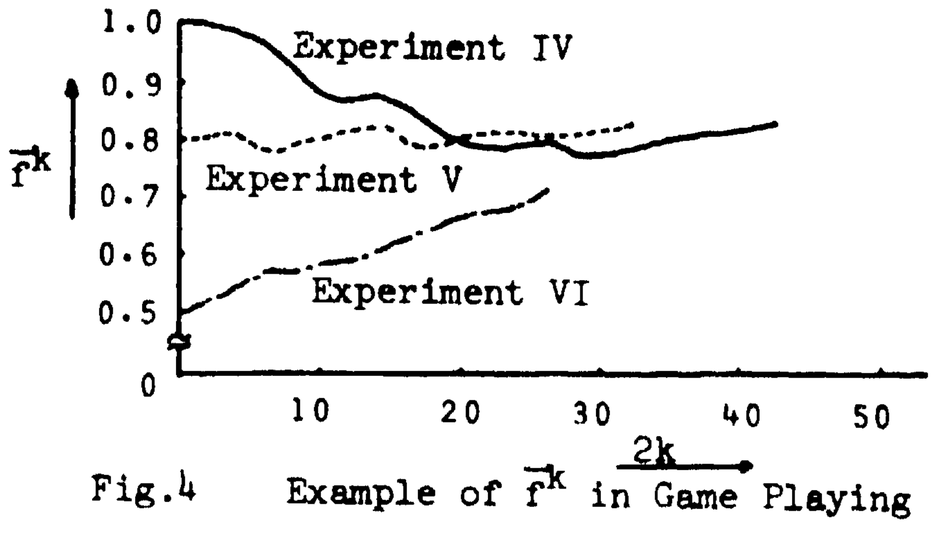


Fig.4 Example of $\overline{f}^k$ in Game Playing

Human player in this example belongs to middle class and he lost in the three experiments shown in Fig.4, but he won in Experiment III at the 34th move.
Next it is shown how SFPM plays a move in accordance with $\overline{f}^k$. When $\overline{f}^k$ is high, that is, SFPM regards its opponent as a skillful player, it inclines to form "Sleeping-Two" and "Sleeping-Three" rather than "Active-Two", "Half-Active-Two" and "Active-Three". This tendency is usually found in games played by skillful players. The tactics are adequate to game playing with skillful players for the following reasons.

1. Skillful players seldom miss blocking their opponent's "Active-Three".
2. To form "Sleepin-Two" or "Sleeping-Three" makes the opponent disadvantageous gradually because they restrict the opponent's selection of moves.
3. "Sleeping-Three" is a necessary preliminary for T- and V-formations. (Refer to Fig.2)

The tactics are, however, not efficient to defeat a beginner or an unskillful player in the sense that many moves are required to win a game, because they are the protracting tactics. On the other hand, when $\overline{f}^k$ is small, SFPM inclines to form "Active-Two", "Half-Active-Two" and "Active-Three" rather than "Sleeping-Two" and "Sleeping-Three". These tactics are effective for game playing with unskillful players who sometimes miss blocking the opponent's "Active-Three". However they are too simple to win when the opponent is skillful.
We can say from the experimental results that the figures in Experiment IV, V and VI are much improved in comparison with Experiments I, II and III. The strategy-making in Experiment I is the same as the one by Minmax Procedure.
It should be noticed that, in order that the use of Decision Analysis works well, it is necessary that the opponent's skill is known rather precisely.

6. CONCLUSIONS

In this paper we have presented a game-playing-machine which employs Decision Analysis as a substitutional method for Minmax Procedure. A game-playing -machine controlled by Minmax Procedure can not cope with the *game* playing in which efficiency of winning is make much of, while it works very well if it aims at only winning, in more strict words, minimizing the risk of losing. Decision Analysis is a good method to decide strategies which enable a game playing machine to take advantage of its opponent's mistakes -not playing the best move- and to win a game efficiently, while the good efficiency is obtained at the expense of increase in the risk. However, such a risk is capable of being averted to passable extent by estimating the opponent's skill correctly and assuming that he plays a move of the best three in any board situation. Learning system yields the high rate of winning and the good efficiency even though the opponent's skill is misestimsted at the beginning of a game.

Besides, we may conclude that Decision Analysis is also useful for many other games which do not satisfy the conditions stated in INTRODUCTION. Finally we suggest that the opponent's move selection is usually influenced by not only his skill but also his various biases; some players may incline to make such moves that are very offensive or very defensive *[4].* If we take the bias into consideration in order to determine the Judgemental probabilities, Decision Analysis must be a more useful method of strategy-making in game playing.

ACKNOWLEDGEMENTS

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APPENDIX I

Let us transform Eq.(7), then we obtain:

$$P_3 = P_2^K P_1^{1-K} .$$

Since $x = P_2/P_1$, we can re-write it as:

$$P_3 = (P_1 x)^K P_1^{1-K} = P_1 x^K .$$

Therefore

$$P_1 + P_2 + P_3 = P_1(1 + x + x^K) = 1 ,$$

which directly leads to Eq.(9).

APPENDIX II

Let us denote Eq.(8) by $F(x) = 0$.

1. If $f_3 < \bar{f} \leqq f_1$ and $f_3 < f_2 < f_1 \equiv 1$, then

$$F(0) = f_1 - \bar{f} \geqq 0$$

and

$$\frac{d^2F(x)}{dx^2} = K(K-1)(f_3 - \bar{f})x^{K-2} < 0 \quad (x > 0).$$

Therefore Eq.(8) has only a real solution within the interval, $[0,\infty)$ and we can obtain the judgemental probabilities from Eq.(9).

2. If $\bar{f} = f_3$ and $f_3 < f_2 < f_1 \equiv 1$, then we obtain $P_1 = P_2 = 0$, and $P_3 = 1$ from Eqs.(4), (5) and (7).

3. If $f_3 \leqq \bar{f} \leqq f_1 \equiv 1$, and $f_i = f_{i+1}$ $(i = 1,2)$, then we can calculate the judgemental probabilities from Eqs.(4) and (5).

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DETECTION OF THE MOVEMENTS OF MEN FOR AUTONOMOUS VEHICLES

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This paper describes a method for detecting the movemens of men waking on a passage using two consecutive TV image. The method consists of three steps: (1) finding a passage region and regions of objects in a TV images, (2) locating men in the region map, and (3) detecting the movements of men using their location in tow consecutive region maps. High speed processing is to be achived by employing a special hardware for image processing.

1. INTRODUCTION

This paper describs a method for detecting the movements of men walking on a passage using two consecutive TV images. Our final goal is to develop an autonomous vehicle with a TV camera, such as the one in a hospital for guiding the blind . Here, we deal with a simplified case where a TV camera is fixed and only men are on a passage.

There have been some works for detecting moving objects using cross-correlation [1]. But they are not effective for our purpose, because the size and the orientation of moving objects may change to a great extent and the numbers of objects are not always equal between the images.

The method in this paper finds the movements of men by locating them in each image. It consists of three steps as follow: (1) finding a passage region, (2) locating men, and (3) detecting the movements of men.

In order to catch up with the movements of men the processing for finding a path should be done very fast, say every 0.7 sec. We used a special hardware for the high speed processing.

2. FINDING A PASSAGE REGION

A passage is assumed to be illuminated sufficlentry by many lamps on the ceiling and color of the surface of a passage is light enough. Under these conditions, vertical surfaces are much daker than horizontal ones, up to a certain height. The mean of brightness of men is smaller than that of the passage. However, some parts of men's cloths may be a little brighter than the passage due to wrinkles. In this case, the variance of brightness of the parts is expected to be lager than that of the passage. Therefor, we use the mean and the variance of brightness of TV image to find a passage region.

Let I(i,j) denote the light intensity of the pixel at (i,j) in a image. We use the following measures for the mean M(i,j) and the variance D(i,j) at the pixel at (i,j);

$$M(i,j)=\sum_{(k,l)=(1,1)}^{(3,3)} I(i,j) \qquad 2 \leq i,j \leq 255$$

$$D(i,j)=\left|\sum_{k=1}^{3}[I(i,1)-I(i,3)]\right| + \left|\sum_{l=1}^{3}[I(1,j)-I(3,j)]\right|$$

Each pixel is classify into a passage region or the other region by the following procedures.

(1) If M(i,j)>01, then it is classified into a passage region.

(2) If M(i,j)<02, then it is classified into the other region.

(3) If 01>M(i,j)>02 and D(i,j)<03, then it is classified into a passage region.

(A) Otherwise, the pixel is classified into the other region.

01, 02 and 03 are fixed based on the first TV image.

Here, we call the other regions the object regions on the passage. The small object regions are merged with a passage region. Since the width of the passage and the direction of the TV camera are known in advance, some erroneous parts such as wall regions, can be eliminated.

Fig.I shows an example of a TV image and a passage region.

3. LOCATING MEN

We use the shapes of men and their size in order to find men in the object regions. We define an X-Y coordinate on a plane parallel to the passage plane of which the origin is at the location of TV camera and of which the Y axis coincides with the direction of the passage. Since the range information about points on passages can be obtained from the declination of the TV camera and its height, a passage region in a TV image can be transformed to the plane as shown in Fig.2. The area surrounded with broken lines in Fig.2 represents the maximum of a passage region and we call the area a region map.

The shapes of men on a region map can be clasified into four types as shown in Fig,3 according to the position of feet. The type (d) represents the situation that one man overlaps another.

We shall explain the method for locating men on a region map using an example as shown in Fig.4. First, the region map is scanned from the bottom to the top to find the bottom point PI. Next, the curve is searched for a pair of P2 and P3 such that the width W of the curve is greater than the threshold 94 (0.3m) for the first time. If a pair of points P2(X2,Y2) and P3(X3,Y2) satisfies the condition, the man is located at the point P4((X2+X3)/2,Y1). Third, the detected man region is deleted from the region map. The lower part of the curve is deleted from the region map. The upper part of the curve is covered with a mask like a horn as shown in Fig.5(a). If the width W of the protruded part under the mask is greater than the thresshold 05 (O.Ira), we determine that another man is also included inside the curve. Then, the shape of the mask is changed into that of Fig.(5), so that another man may be easily found later. This process repeats until no man is found.

4. DETECTING THE MOVEMENTS OF MEN

The movements of men are obtained by finding the correspondence of the positions of 'men between two consecutive region maps. Suppose that the position of the k-th man in the first and in the second region maps are (X_{1k}, Y_{1k}) and (X_{2k}, Y_{2k}), respectively, the distance between them is less than $V \cdot \Delta t$, where V is the maximam speed of men (assumed 1m/sec) and Δt is time interval (0.7sec). If the candidate position is only one under this condition, the correspondence is immediately determined. If there are n positions with more than one candidate, the correspondence of them is determined as follows.

Assuming that men are apt to move along the Y axis than the X axis. Now, we define a weighted distance for the k-th man as follows.

$$E_k = \sqrt{w \cdot (X_{1k} - X_{2k})^2 + (Y_{1k} - Y_{2k})^2} \qquad w > 1$$

We determine the correspondence such that the following evaluation function may be minimized:

$$E = \sum_{k=1}^{n} E_k$$

Now, we consider the case where men come into or out of the region map and occlusion. A region map is divided into three zones (A,B and C zones) as shown in Fig.6. It is assumed that men always come into or go out of the region map through A or C zone.

First, the correspondence is found between men in B zone on the first map and those in the whole area on the second map. In this

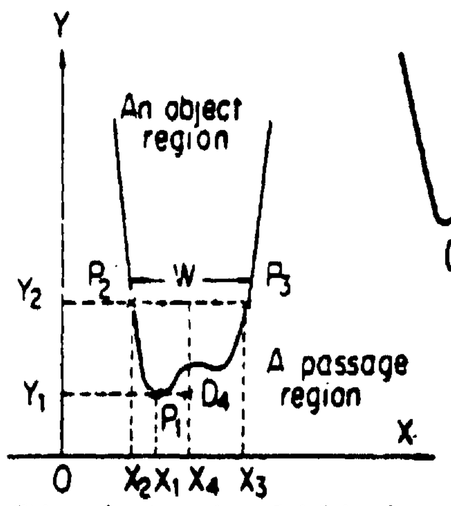


Fig-4 A simplified example of an object region

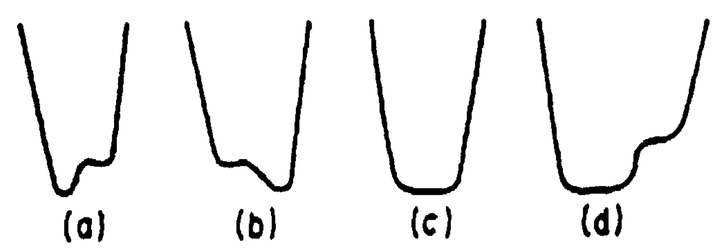
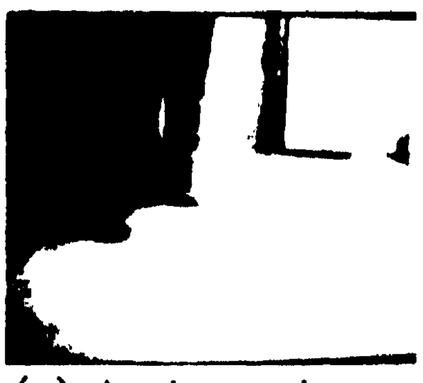


Fig-3 The shapes of men on a region map

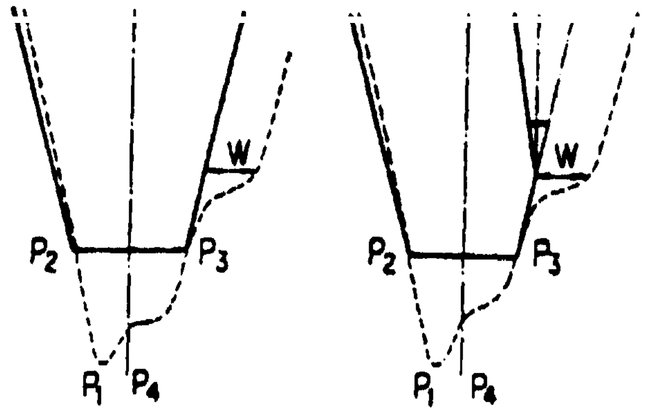


(a) An input image

(b) A passage region of the image(a)

Fig-1 An example of finding a passage region

Fig-2 The region map of the image of Fig-1



(a) An original mask (b) A modified mask

Fig-5 Example of maska on a region map

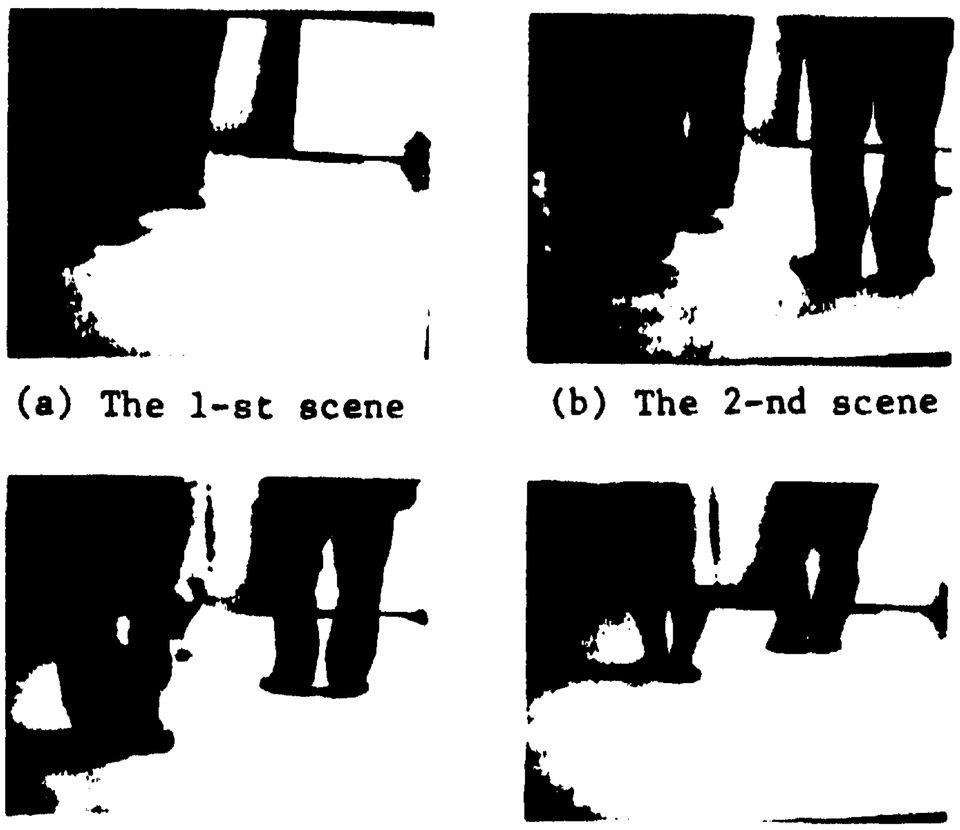
procedure some corresponding pairs are found. The remaning men in both maps are dealt with in the following way,

CASE 1 : there is no man in A and C zones on the first map.

In this case, men on the first map can not go out of the map. The remaining men on the first map are determined that they are behind some one on the second map. Conversely, the remaining men on the second map are determined to behind some one on the first map. The remaining men in A and C zones on thsecond map are determined that they have entered the map from the outside area.

CASE 2 :ther are some men in A or C zone on the first map.

The correspondence is found between men in A and C zones on the first map and the remaing men on the second map. If there still remain some men without correspondence, they are dealt with in the similar way as in CASE 1, except that the remaining men in A and c zones on the first map are determined that they have gone out of the map.



(a) The 1-st scene (b) The 2-nd scene

(c) The 3-rd scene (d) The 4-th scene

Fig-7 Examples of four consecutive scenes

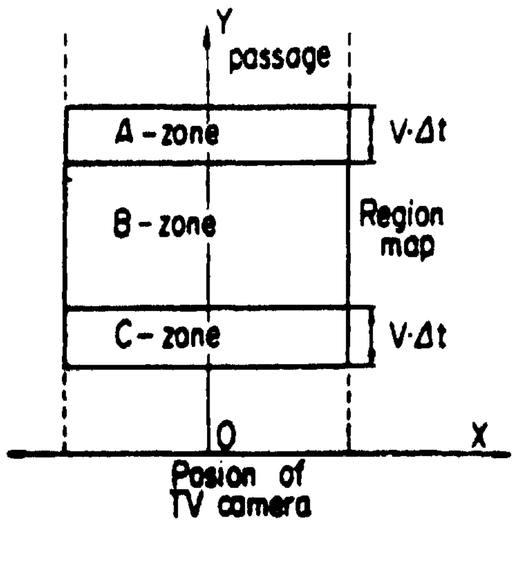


Fig-6 Three zones on a region map

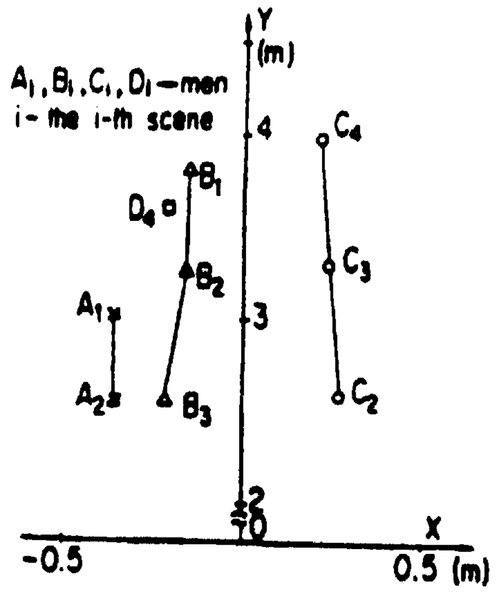


Fig-8 THe locations of men of four scenes in Fig-7

5. EXPERIMETAL RESULTS

We examine the metod in many cases. The four consecutive scenes as shown in Fig.7 are examples of input images. The men in these images are located on the map and the movements are detected as shown in Fig.8.

6. DISCUSSIONS

We used the Parallel Patten Processor (PPP) *[1]* for high speed processing. The PPP has several basic image procssing function in hardware, memories for pictur data and a microprogrammed processor. We estimated the time needed for finding the region of a passage. The time was 580 msec as shown in Table 1. The total time for the processings includeding the location of men and the detection of the movement is larger than the time interval (0.7sec) at present. But the improvements of the hardware and the program will make the total time less than 0.7 sec.

In order to realize autonomous vehicles, we must consider the following problems: (1) a TV camera moves on a passage, (2) a passage is hook-shaped one, and (3) there are some objects on a passage, besides men.

OPERATION	NUMBER OF INSTRUCTIONS	EXECUTION TIME	FREQUENCY IN USE	CONSUMED TIME
MASK	3 step/pixel	65 msec/Image	0.4	26 msec
MEAN OF BRIGHTNESS	5 or 6	130	0.36	47
VARIANCE OF BRIGHTNESS	12	195	0.24	47
2D-CONVOLUTION	by hardware	65	3	195
REGION LABELING	by hardware	200	1	200
DATA CONVERSION	by hardware	65	1	65

An instruction of the microprogram needs 250 nsec.
The memory cycle is 1 μsec/pixel.
An image has 256x256 pixels.

Table-1 The detail of consumed time

ACKNOWLEGEMENT

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PARALLEL-SERIAL PRODUCTION SYSTEMS*

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This paper describes several extensions to standard Production System (PS) languages that appear to make them more conveniently usable for a wider variety of perceptual and cognitive systems. The extensions are described (giving parallel productions, multiple memories, and productions that are implied by productions), and a programming language ((PSj^M^{11}) is presented (in Uhr, 1978) that incorporates them. Sketches are given indicating how several different kinds of cognitive and perceptual systems might be coded in this extended language, and suggestions are made as to additional extensions that might further augment the power and convenience of such a language.

1. INTRODUCTION

This paper describes a Parallel-Serial Multi-Memory Production System language, (PS)'~M^n, that handles I) parallel sets of productions, *2)* more than one working memory in which to look for the conditions, of productions, and fire the consequences of successful productions, and 3) productions that are fired by productions. These extensions, would appear to be convenient for a variety of systems, where parallel processes and dispersed memories are needed. The following such systems are briefly described

A) Several "Knowledge Sources," all working, in parallel with separate working memories, but communicating through a common single "Blackboard" memory.
h) Systems. Tor parallel eompatability relaxation, where a number of nodes are examined in parallel, for contextual information that might *nerve* to disambiguate them.
C) Discrimination nets (e.g. for "concept formation" and "KPAM"), where a sorting tree is used to find the appropriate name.
D) Parallel-serial perceptual systems, where sensed information is successively transformed, by layers of parallel feature-detectors and characterises;, into successively more abstract memory representations.

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E) Parallel search for solution paths in problem-solving.

See Uhr, 1978, for programs (in EASEy/Snobol*) for (PS)2M^n and for a traditional (serial, single-memory) Production System, along with a short Primer description of the language.

1.1 Parallel-Serial Production Systems With Many Working Memories

It is often necessary (as in systems for perception, memory search and heuristic problem-solving) to apply a whole set of trans.formations, or productions., to a Working Memory store in parallel. Systems with several knowledge sources frequently use parallel processes and several memories. In multi-layered or hierarchical perceptual systems, the conditions of productions must be looked for in one WMj and the consequent acts effected on another WMi. Therefore a whole set of WM, WM_{lt}...WM_N are' needed. Each production will look at a specified WMJ; (or several WM) and, if fired (because all its conditions have been satisfied by a match with elements in that WM^), effect its consequent acts (e.g. insertions, deletions., arithmetic operations, generations of productions, deletions, arithmetic operations, generations of productions, input-output) on the specified WMj.

* See Uhr, 197*m; Oriswold et al., 1968.

This paper describes extensions to current Production Systems that handle such processes, without the often cumbersome code otherwise needed, but also in a well-structured and simple way.

1.2 Traditional Production Systems

A Production System (PS) (Newell and McDermott, 1975; Rychener, 1976; Waterman, 1975) consists of an ordered set of Productions (P),P1,...PM, each with a set of Conditions (C) and a set of consequent Acts (A), plus one Working Memory (WM). E.g.:

```
P I:  RED BLUE "* GREEN DELETE (RED) DELETE (BLUE)
P2:   BROUN YELLOW ■* DIRT
P3:   GREEN-DIRT = POOR-GRASS (STOP)
WM:   RED BLUE YELLOW BROWN
```

Each Condition specifies a set of elements. An element specifies a string (or list structure) of sub-elements to be matched with strings found in WM. The match usually demands that the first sub-elements match, and that each subsequent sub-element *in* C^ match a subsequent (but not necessarily the next) sub-element in WM. Variables are usually bound by whatever they find in the first match where they occur (rather than have the system try all possibilities). Acts specify insertions or deletions in Working Memory, the generation of new Productions, or any of several primitive Acts, like OUTPUT, or STOP. A Production "fires" its Acts if all its Conditions are satisfied. Usually the system moves from the top Production down, until one Production fires, when it Jumps back to the top, to repeat the process. Some systems use different flows, e.g. continuing on to the next production whether the prior one fired or not (note that this does not mean that Productions are applied in parallel, for each fired Production immediately effects its Acts, and therefore modifies WM). Some systems find all Productions that succeed, and then use one of a variety of criteria for choosing and firing one Production, e.g. the one that matclies the most recently added element in WM (Newell and McDermott, 1975).

1.3 Parallel-Serial Multi-Memory Production Systems

Living cognitive systems effect sets of parallel transformations, and use a number of temporary buffer Working Memories. Such parallel-serial multi-layered architectures seem similarly desirable for computer-programmed systems since (once they run on the parallel-serial computers, see e.g. Duff, 1976, Lipovski, 1977, that current technology is on the verge of making feasible) they offer great economy and power.

(PS) M extends traditional Production Systems so that they can conveniently handle parallel processes applied to more than one Memory. The key extensions include the following.

A) Any number of Memories c.*tn be specified and used, with sets of Productions looking at and firing into each.
B) Each Production can look at several Memories, and fire into several Memories, if desired.
C) Sets of Productions can be applied in either a Parallel or a Serial mode, as specified, and the mode can be changed during a run.
D) A Production can fire one or more Productions to be applied, as specified.
E) After a Production succeeds in firing, the system can either attempt to fire the next Production, or go back to attempt to fire the first Production, as specified.

These extensions allow for relatively convenient coding of a variety of perceptual and cognitive systems, some examples of which are described below.

I.U Some of the Uses of Multiple Memories, and of Parallel and Dynamically Implied Productions

A single Memory can always be set up to do anything that multiple memories can do (since standard Production Systems are based on Post Productions they are universal computers, and anything can be programmed in them)-but often at a heavy price. Essentially, the system can no longer use the Memories' names and attendant pointers to directly access sub-sets of information in the relevant Memories. Rather, elements in the single Memory must be given appropriate name-like tags, and the system must use the relatively slow Production-matching routines to search for the appropriately ta^r.ed elements. All the elements in a particular Memory could be grouped together, so that only one tag, was needed. But that means, the system must work with and try to match a large and cumbersome list of lists - and that can be a slow and costly process. Alternately, each element can be separate, but each with the same Memory tag. But that means the search for the appropriate tag must be turned into a loop, iterating through the entire Memory.

The original development of Production Systems was directed toward work with a *wry* small

"Working Memory" for scratch-pad-like intermediate renuJ.tr., one that models the human "short-term memory" that is capable of handling some small number like '(items. For such uses there is no need to add more Memories or other structures. But for a general-purpose programming language multiple Memories serve a number of purposes.

Without a parallel capability of the sort provided in (PS)^M^n, a program must make several extra passes through a set of transforms to simulate parallel processes.. The first pass would not actually change the Memory; rather, it would output its set of acts each specially tagged as a temporary output. Then the program would have to keep applying a set of Productions that looked for all these tags, use the output information from the tagged elements to modify Memory, and erase all these tagged temporary eicrnents.

The dynamic implication of trans.forms gives the programmer powerful control capabilities for structuring the flow of processes. Without this feature a program must use a production that adds an element to Memory that only one other Production- the one to be fired next -will succeed in matching. This means the system must make an extra cycle through its. productions to find that next production, in addition to adding, and deleting the identifying element. Dynamic Productions make this process direct and simple.

The present system can use dynamically implied productions, but it cannot generate them. For it can insert newly generated productions only into its main list of Productions (as is done by standard Production Systems). But it also needs the ability to insert a Production's name into the list of Consequences of another Production, and to choose that Production correctly. This needs a capability of modifying a Production, and not simply creating one, and of accessing and conveniently storing histories of the names of Productions fired. Such an extension is discussed below, as part of a more general ability to create, modify, and erase both Productions and Memories - that is, to treat productions and memories in exactly the same way.

2. EXAMPLES OF SYSTEMS THAT COULD FRUITFULLY USE (PS)^{2}M^n

2.1 Parallel Sets of "Knowledge Sources" a: Parallel Communicating Production Systems

An attractive structure for cognitive and perceptual systems is one that uses a set of independent "Knowledge Sources" (e.g. Reddy, 1973, Lowerre, 1976), or "demons" (e.g. Lenat, 1977). Each works at the same time, independently of the others, and therefore could be executed in parallel by one processor in a suitable network of minicomputers, or parallel processors. All communicate with one another by passing information into and out of a common "blackboard" memory. Such systems cannot be conveniently coded in a standard Production System language like PSG or PAS-2, because the knowledge sources act in parallel, and often contain parallel processes.

Such a system can quite straightforwardly be handled by (PS)^{2}M^n, as follows: Each knowledge Source is executed in turn, since each works with its own local memory. Then, after all have completed their processes, a set of parallel production transfers their (present, intermediate) results to the common Blackboard Memory. Then a second set of parallel productions transfers selected information from the common Memory to the individual Knowledge Sources' memories.

The parallel capabilities of (PS)^{c}M^n make the transfer of information into and out of the common Memory very convenient, since there is now no danger of unwanted interactions between Knowledge Sources. And now each Knowledge Source can itself contain a mixture of parallel and serial flows of productions. Ajid each can contain one (or more) separate memories, whereas in a standard PS each subset of memories, would have to be protected (in a very cumbersome way) from all Knowledge Sources that did not have access to it.

Most large Production-oriented programs of this sort appear to be Production Systems in spirit, but without being coded in an actual Production System language. The extensions handled by (PS)2M^n would appear to move in the direction of a language that might be suitable for convenient coding and running of such large production Production Systems..

2.2 Compatibility Pairs

A production for relaxation using pairs of compatibility labels (e.g. Zucker, 1977; Davis and Rosenfeld, 1978; Tennenbaum and Barrow, 1976)

need only bo a 2-tuple, designating the label to be looked at and the context label. When both are found the label is fired into an output Memory, But each label must be searched for in it:; designated memory, and many such productions must be applied in parallel. And to iterate} to more distant contexts each must imply the next production to apply. The present system will handle deterministic constraints, if it raises a flap; with each success, tests and lowers the flap; after each iteration, and then stop:; iterating after one pass without raising the flag (meaning that nothing new has been accomplished), Extensions to be discussed below will handle probabilistic constraints and dynamic stopping rules, and also situations that mix compatibility pairs with other types *oV* transforms.

2.3 A I'roduction System that Uses Compatability I'airs to Choose Among Productions

Zuekcr, 1977, has suggested that compatibility pair relaxation techniques might fruitfully be used to choose the single judged-best Production to fire next, when a serial Production System finds that more than one Production might Tire. (This is the case in those standard Production Systems that, instead of firing the first Production that succeeds, get all I'roductions that succeed, and then use some criterion to choose among them.)

(Pr>)'-M^n allows such a system to be coded entirely as a parallel-serial Production System, as follows:

List all the Productions to be chosen among as a parallel set on the MASTER list (the main list of productions - see Uhr, 1978). Each Production implies all of its compatibility labels as dynamically implied Productions on its set of ACTS. Thus all Productions that succeed fire their compatibility labels onto the set of (parallel) productions that will fire next, after this parallel set has been completed. Then this parallel set of compatibility labels will be applied. This procedure continues, as in the proceeding section, until either a single production remains or no more relaxation can be done. Thus the separate relaxation phase is absorbed into and handled by the (PS)^M^n Production System.

2j+ Discrimination Nets% Concept Formation, KPAM

The program uses a tree of Productions, each making one test. The Master list starts with a Production that tests for the first node of the discrimination net (really a tree), followed by all Productions on its negative path. If it succeeds it implies the Production on its positive path to be immediately executed in the serial mode followed by all Productions on that node's negative path. Thus the fra/^ient of a discrimination tree shown in Figure 1 needs, the l'roductions shown in Table 1 (a number refers to the test for that node):

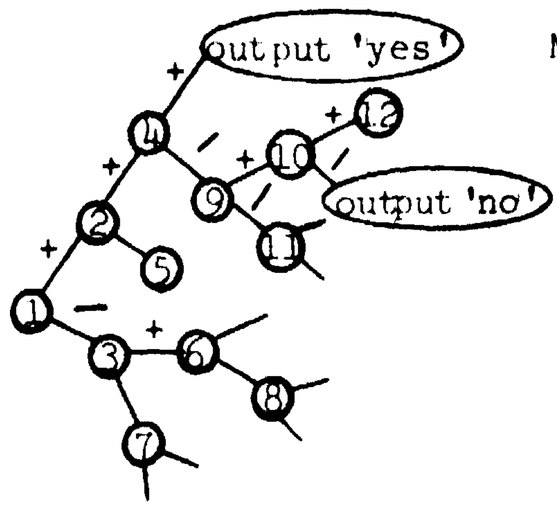

Figure 1

MASTER = 1,3,7...
1 = 2,5,...
3 = 6,8,...
4 = output 'yes', 9
9 = 10,11...
10 = 12, output, 'no'

Table 1

Note that the only Productions on the MASTER list are the first and the successive '-' (failure) branches from it. All other Productions are implied by Productions that fire.

This program uses a true discrimination tree, where each Production tests only the single next node. This is in sharp contrast to the EPAM program (Waterman, 1975) coded in PAS-? (which uses a separate template for each entire path in the tree, and has no ability to dynamically imply transforms).

2.5 Layered Perceptual Systems (e.g. Cones, Pyramids, Hierarchical Relaxation)

The use of a sequence of several memories between pairs of which are sandwiched sets of parallel productions can be quite straightforwardly coded as a parallel-serial production system. Productions need only be stored as parallel sets, their INput MEMory and OUTput MEMory specified for each such set, with the OUTput MEMory for one set the INput MEMory for the corresponding subsequent set.

Dynamically implied transforms can be handled as productions that are implied as consequent acts of successful productions. Iterations through relaxation can be handled by using the same INput MEMory and OUTput MEMory for several cycles. These would be especially attractive for parallel-serial layered perceptual systems such as the cones and pyrami dc being, developed by Hanson and Riseman, 197^; Tanimoto, 1976;

Uhr, 1972, 197^, and others.

Such systems would benefit greatly from several extensions (that are projected for future productions systems). These include a) weights, thresholds, and probabilistic productions, b) a convenient way to iterate through a whole array of memory locations (as in the 2-dimensional retinal mosaic), applying the same set of parallel productions in parallel to each cell in the array, and c) techniques for choosing among alternative implications (as in naming and describing), and for deciding when to choose (as in deciding when to stop relaxing).

2.6 Heuristic Problem-Solving

A heuristic problem-solver could take advantages of several levels of parallel processes, given a suitable language. Typically, a whole set of heuristic evaluation functions is to be applied in parallel to a node that might be a candidate for further search. And a whole set of such candidate nodes might conveniently be evaluated in this way, in parallel.

A (PS)^M^n program with the following structure can handle such a system:

The set of heuristics is coded as a parallel set of Productions.

For a heuristically guided search for a path from a set of (livens to a Goal (or from Goal to Givens), the Givens (or the Goal) are input as elements in the first WM, The Rules of Inference (sometimes called legal moves, transformations, etc.) are coded as a parallel set of productions and put on the MASTER list. They are applied, giving the buds (which are put into a second WM) from the presently achieved expressions, deleting elements in the first WM, and firing set of heuristics (coded as a second parallel set of productions). The heuristics now look at these budded expressions, and accumulate the evaluation of each. They are followed by a serial set of productions that chooses and puts into the first WM the most highly valued expression(s), and deletes all expressions in the second WM. The Rules of Inference are again applied, and this process continues.

I have ignored a number of important details, but almost certainly several more Working Memories will be preferable - e.g. to store the pointers back from buds to their fathers *for* later use in getting the solution-path, and to get that path.

3. SOME ADDITIONAL EXTENSIONS THAT WOULD SEEM TO BE USEFUL

There are several further extensions that would appear to make for substantial further improvements in the ease of coding of cognitive and perceptual systems, and the resulting transparency and clarity of structure *of* the resulting systems. These include the following:

A) Probabilistic transforms would allow for the emerging of multiple implications, from perceptual characterizers or problem-solving heuristics. This entails rather simple extensions: l) Associated with each element of a condition will be a number (that can be interpreted as a weight, probability, fuzzy value, or whatever the programmer desires), associated with each production will be a treshold, and associated with each implied act will be a weight. When the combined weights of successful conditions exceeds the Production's threshhold, the Production will be considered to succeed, and fire its implications with their assigned weights. 2) Several implications of the same thing will have their weights merged. 3) When this is specified in the program, then the system will choose among alternative implications from among some mutually exclusive set that the programmer has specified.

B) A set of Production.", should be able to iterate conveniently throug.li an array of memories. This would allow for very convenient and straightforward coding of perception systems, e.g. pyramids and cones, and relaxation labelling, where sets of transforms (coded as Productions) could be applied to the different cells, or regions, of the retinal image, or ■ internal abstracted images.

C) A system should have a more general set of capabilities for creating and erasing lists (whether Productions or Memories), and adding and deleting information to and from these lists. This would allow for the convenient building, and modifying, or complex list structures and graphs of information. If done with as much generality as possible, it should also make Productions and Memories, and their manipulations, quite similar.

k. DISCUSSION

Today's production systems have a heritage much older than Post's productions, and much broader than problem-selving. For Post productions are probably the single Turing machine-equivalent formulation that most directly embodies that elusive (and possibly imaginary) entity,

"intuitive thinking." The rules of inference of Euclid's geometry, and of Aristotle's syllogism, are very similar to productions. Consider the linguist's rewrite rules and transformations, the physicist's Feynam diagrams, the psychologist's S-R mappings, the "if. a,b,c, then d,e,f" lines of reasoning of detective, diagnostician or trouble-shooter.

So an embodiment of thinking in terms of productions would seem especially desirable. We could use it conveniently; we could understand it; and it might well be appropriate, and powerful. But the particular production system chosen should be sufficiently flexible and powerful for convenient programming.

The three major extensions to Production Systems incorporated into (?S)^M^{n} - I) the ability to apply productions in parallel, when desired, 2) the partitioning of information into several working memories, and 3) the firing of productions to be applied next by productions that are fired - often appear to go together, and to complement and enhance one another. But one might prefer to use only one, or two, of these extensions, for the following reasons:

1) If it is known that all programmers who will use the production system language will code all their programs using only serial productions, then the parallel capability is not needed. But many cognitive processes, especially in perception and associative memory search but also in heuristic deductive problem-solving, appear to have important parallel components. And although yesterday's computers are serial, today's are beginning to be parallel, and tomorrow's will become increasingly parallel.

2) From a certain esthetic perspective as to the meaning of "simplicity" the single Working Memory seems simpler than several Working Memories, But if a program uses several memory stores it seems less simple to throw them all together into one, and then do a lot of otherwise unnecessary searching and matching to find the one that is needed.

3) Productions that fire productions to be applied may well violate the simple modular structure of standard production languages, with their top-down flow through the stack of production."). But they may more closely reflect the actual operative structure and flow of the program, in the sense of the productions that actually will fire. Without this capability a program becomes cluttered up with cumbersome and time-consuming devices that make use of the addition and deletion of special data symbols to direct the program's flow.

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A SYSTEM FOR FUZZY REASONING

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This paper describes an implementation of a system for fuzzy reasoning which facilitates the execution of approximate reasoning from the specified propositions and gives the result in both fuzzy-set and linguistic forms. The description of the Approximate Reasoning System contains the Universe of Discourse Block which defines several universes of discourse; the Primary Term Block which defines several primary terms; the Proposition Block which states propositions using primary terms, linguistic hedges and IF ... THEN ...; and the Approximate Reasoning Block which executes approximate reasoning and linguistic approximation. The Approximate Reasoning System is implemented using the FSTDS System for fuzzy-set manipulation and is running on a FACOM 230-45S computer.

1. INTRODUCTION

Much human reasoning is fuzzy rather than precise in nature. An example of such reasoning may be "If x is *smalt* and x and y are *approximately equal,* then y is *more or less small".* The fuzziness in the words: *small, approximately equal* etc. may be defined by fuzzy sets and fuzzy relations[I). Reasoning with fuzzy concepts has been formulated by Zadeh[2] who calls it approximate reasoning.

In this paper, we describe a system for fuzzy reasoning, called an Approximate Reasoning System, which is based on Zadeh's formulation of fuzzy reasoning. This system facilitates the definitions of universes of discourse and primary terms, the description of fuzzy propositions, and the execution of approximate reasoning using the specified fuzzy propositions. The result of approximate reasoning is given in both fuzzy-set and linguistic forms.

2. APPROXIMATE REASONING AND LINGUISTIC HEDGES

Zadeh's formulation of approximate reasoning is defined as the compositional rule of inference which is expressed in symbols[2] as

P^: x is A.
?2: x anc* y are R (1)

P3: y is AoR,

where x and y are object names, A is a fuzzy set in U, R is a fuzzy relation in UxV, and AoR is the composition of A and R, i.e., is a fuzzy set in V. If P2 is a conditional proposition such as

P_2: If x is P then y is Q (2)

where x and y are object names and P and Q are fuzzy sets in U and V, respectively, then it is translated into the fuzzy relation R of x and y using the arithmetic rule for conditional propositIons[2],

R (^P x V) * (U x Q) (3)

where x, ^ and • stand for the Cartesian product, the complement and the bounded sum, respectively.

[Example 1] Let U be a universe of discourse expressed by

U {1, 2, 3, 4}.

If we have the fuzzy set *small* in U as

small - {1/1, 0.6/2, 0.2/3}

and the fuzzy relation *approximately equal* in UxU as

approximately equal [a] {1/<1,1>,
I/<2,2>, I/<3,3>, I/<4,4>,
0.5/<I,2>, 0.5/<2,3>, 0.5/<3,4>},

then from the premise propositions:

P_1: x is *small*.
P_2: x and y are *approximately equal*.

we can infer by approximate reasoning the consequence:

y = *small* o *approximately equal*
= {1/1, 0.6/2, 0.5/3, 0.2/4}.

A linguistic hedge such as *very*, *more or less*, *much* and *slightly* can be viewed as an operator which operates on the operand fuzzy set. For example, several hedges are defined by Zadeh[3] and Lakoff[4].

The effects of some linguistic hedges are shown in Fig.1 in the case where a fuzzy set is *tall*[4].

We can obtain a fuzzy set as the consequence of approximate reasoning. If the consequence remains in fuzzy-set form, it is difficult for us to understand its meaning, as was the case in Example 1. So the consequence would be better given "*more or less small*" rather than a fuzzy set {1/1, 0.6/2, 0.5/3, 0.2/4}. Thus representing a fuzzy set approximately in a linguistic form by some appropriate hedges and fuzzy sets already defined is called linguistic approximation.

3. APPROXIMATE REASONING SYSTEM

The Approximate Reasoning System (AR System for short) facilitates the execution of approximate reasoning from the specified propositions and outputs the consequence in a linguistic form by linguistic approximation.

We shall illustrate the facilities of the Approximate Reasoning System using a simple example.

[Example 2] If we have a description in the AR System as in Fig.2, then we obtain the output as in Fig.3.

The UNIVERSE OF DISCOURSE BLOCK defines a universe of discourse U and the PRIMARY TERM BLOCK defines fuzzy sets SMALL, MIDDLE and LARGE on U. In the PROPOSITION BLOCK, we describe the propositions P1 and P2. In the AR BLOCK (APPROXIMATE REASONING BLOCK), PARA sets parameters (the threshold value of the evaluation function and the depth of nested hedges) for linguistic approximation and AR executes

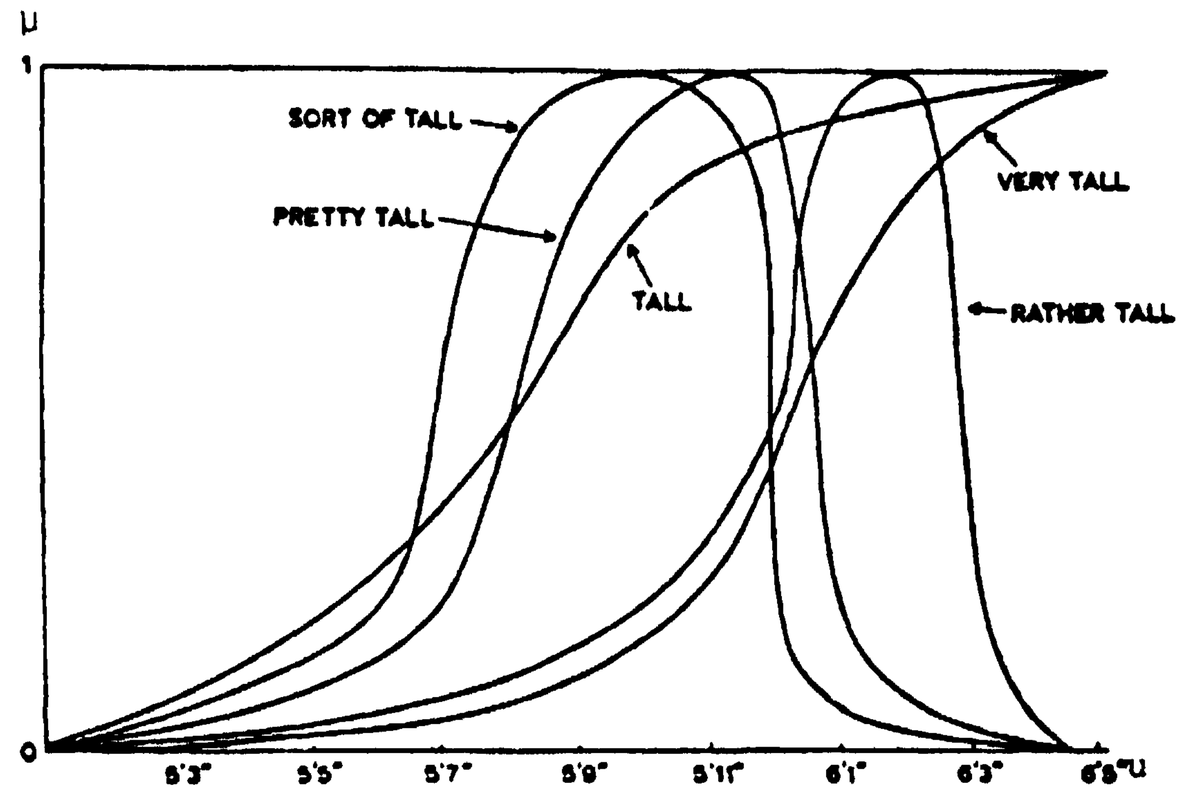

Fig.1. The effect of hedges *very*, *sort of*, *rather* and *pretty* (Lakoff[4]).

```
******* UNIVERSE OF DISCOURSE BLOCK *********
    U=(1, 2, 3, 4, 5);
******* PRIMARY TERM BLOCK ******************
/U/ SMALL=(1/1, 0.8/2, 0.5/3, 0.2/4);
/U/ MIDDLE=(0.2/1, 0.5/2, 1/3, 0.5/4, 0.2/5);
/U/ LARGE=(0.2/2, 0.5/3, 0.8/4, 1/5);
******* PROPOSITION BLOCK *********************
P1: X IS LARGE;
P2: IF X IS VERY LARGE THEN Y IS NOT LARGE;
******* AR BLOCK *******************************
    PARA(C=2,T=13);
    AR(P1,P2/SMALL MIDDLE LARGE);
******* END OF APPROXIMATE REASONING ********
```

Fig.2. A description in the Approximate Reasoning System.

```
..... OBTAINED SUFFICIENT LINGUISTIC APPROXIMATION

* LINGUISTIC APPROXIMATION... MINUS MORE OR LESS SMALL

* PRIMARY TERM... SMALL

* FUZZY SET WHICH IS PRIMARY TERM...
    FSET(1/1, 0.8/2, 0.5/3, 0.2/4);

* FUZZY SET GENERATED BY COMPOSITIONAL RULE OF INFERENCE...
    FSET(1/1, 0.96/2, 0.8/3, 0.56/4, 0.5/5);

* FUZZY SET MODIFIED BY SOME HEDGES...
    FSET(1/1, 0.9197/2, 0.771/3, 0.5468/4);

* EVALUATION FUNCTION VALUE... 0.1165

* THRESHOLD VALUE... 0.130
```

Fig.3. A result of the Approximate Reasoning System.

approximate reasoning from the propositions PI and P2, and approximates the consequence linguistically by the primary terms SMALL, MIDDLE and LARGE.

As shown in Example 2, a description in the AR System contains four blocks, namely, the Universe of Discourse Block, Primary Term Block, Proposition Block and Approximate Reasoning (AR) Block. We have no more detailed explanation of their blocks on account of limited space.

4. IMPLEMENTATION OF THE AR SYSTEM

The Approximate Reasoning System is implemented using the FSTDS System (Fuzzy-Set-Theoretic Data Structure System)[5] which enables a user to write a program in FSTDSL/FORTRAN using 52 fuzzy-set operators on fuzzy sets and fuzzy relations.

The AR System passes to the FSTDS System the sets and fuzzy sets defined in the Universe of Discourse Block and Primary Term Block. A composite term is translated into an expression in FSTDSL, that is, hedges are replaced by the corresponding operators in FSTDSL and connectives are translated into prefix operators. A conditional proposition IF ... THEN ... is translated by (3).

For the AR statement, the AR System passes the statement:

```
%CONSEQUENCE = IMAGE(P2, PI);
```

to the FSTDS System. Note that AoR in (2) reduces to the image of A under R since A is a unary fuzzy relation.

As for the linguistic approximation, we can not use the really best linguistic approximation, since it generates too many composite terms. Therefore we use the following strategy.

First, we apply each hedge to given m primary terms and compare its result with the consequence fuzzy set B. If we obtain a sufficient approximation, that is, the value of evaluation function is less than or equal to the threshold value, then it is accepted as the linguistic approximation of B. Otherwise we choose one composite term of the best approximation in the first step of linguistic approximation and apply each hedge again to it. If we cannot still obtain a good one, the same is repeated n times. If a sufficient approximation has not been obtained yet after n repetitions, the best approximation by this time would be considered as a linguistic approximation of B. There is, however, no guarantee for the really best approximation.

For the evaluation function, there might be several definitions. We have adopted the evaluation function such as

$$f(B,B') = \frac{\sum |\mu_B(u) - \mu_{B'}(u)|}{\#(U)} \qquad (4)$$

where B is the fuzzy set obtained by approximate reasoning, B' the fuzzy set modified by hedges in linguistic approximation and U a universe of discourse of B and B' and //(U) denotes the number of elements in U, x| the absolute value of real number x and I the ordinary sum over U.

5. CONCLUSION

We have described an Approximate Reasoning System which facilitates the definition of universes of discourse and primary terms, the description of propositions and execution of approximate reasoning and linguistic approximation. In the implementation of the AR System, the translation of the description in the AR System to FSTDSL is programmed in PL/I and the construction and manipulation of fuzzy sets and fuzzy relations are programmed in FSTDSL/F0RTRAN[5], and it is currently running on a FACOM 230-45S computer. The current AR System is an interpreter version.

As a basis of question/answering system and intelligent access to database systems, fuzzy reasoning plays so important role in the interface between such systems and users that we expect the AR System will find various other applications.

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A Knowledge-based Interactive Robot-vision System

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A robot-vision project is reported which incorporates several existing AI methods and some new results. The ambition of the project is a system which can economically complete various intelligent tasks within the scope of mini- and microcomputers. The tuned composition of the applied methods provides a new and powerful approach to RandD, engineering and workshop-operation.

1. INTRODUCTION

This paper reports on a robot-vision lab for RandD and for experimentation of specialized industrial applications. The system combines many well-known methods of recognition with some own ones /a fast template method, a quasi-parallel edge-finder etc./ but this combination provides a sophisticated goal-oriented approach for real-life problem solving.

2. PICTURE PROCESSING, RECOGNITION

The system is based on man-machine communication; the goal is the recognition of 3D industrial objects whose number is limited to 10-20 for each task. The objects are taught either by building a geometric model or by a computer-aided transformation of the real situations viewed during the learning period to create a standard model description similar to the artificial one. The camera input /Fig. 1/ is processed in overlapping pixels by a simplified version of the Hueckel-operator using only two linear templates. An estimator of the fit coordinates a weight-attribute to the stroke. These weights and some fuzzy-like parameters which are attributed to the higher picture-hierarchy are relevant elements of the heuristic search. The hairy stroke-picture /Fig. 2/ is used both by the brute-force shape estimators which provide a first guess and, by the further picture processing.Nodes

Fig.1. Digitized input /negative picture/

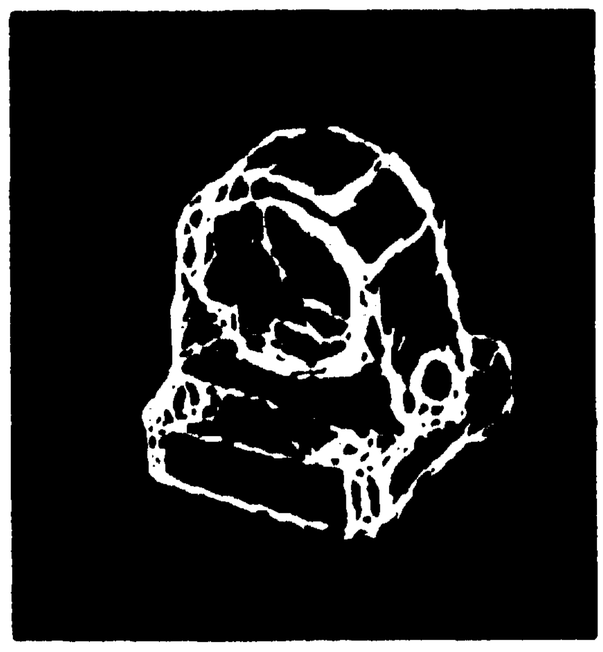

Fig.2. The strokes found in the picture

of the contour are supposed where the slope-variances of the strokes attain local maxima /Fig- 3/. Streaks along the contour lines are detected by a quasi-

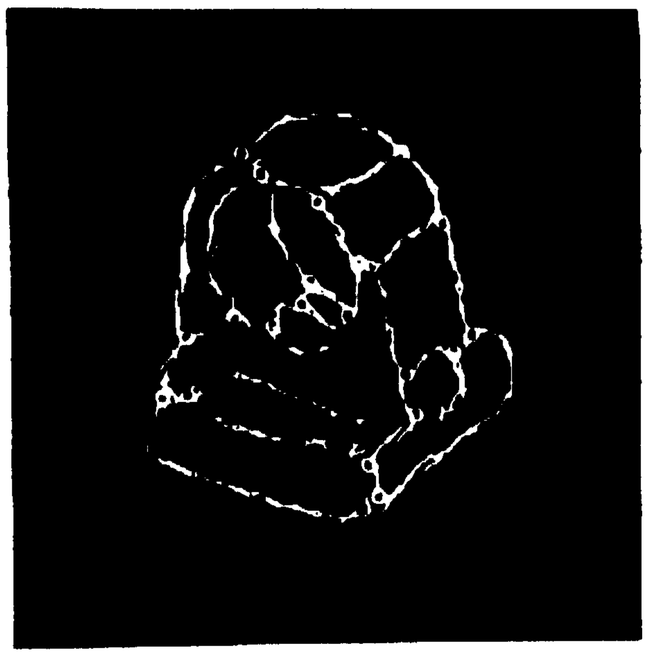

Fig.3. The streaks of strokes with the nodes found

parallel minimum-cost algorithm operating in parallel between every supposed node-pair connected by paths.

This a]gorithm is based on a mathematical model of the expected streaks. The requirements with the paths are expressed by four graph-theoretic criteria which mean that every contour-line should be optimally approximated by a streak and each of them by only one streak. A potential-field growing algorithm has been developed in order to find the streaks and it can be proved that the streaks provided by this algorithm satisfy the criteria of the mathematical model, of the streaks. The streaks found using this algorithm are displayed on Fig. 3.

The next preprocessing algorithm merges the streaks either into line segments by uniting the approximately identically directed consecutive strokes or into arcs by comparing the slope differences. This interpretation is generally weak. due to the uncertainty of the whole process; thus a probability value is assigned to each possible interpretation, considering that each streak may have various interpretations /Fig. 4/. This value serves for the ordering of hypotheses in the linguistic recognition.

Matching the processed picture with the model and the whole knowledge base, decision on the ambiguities due to multi-

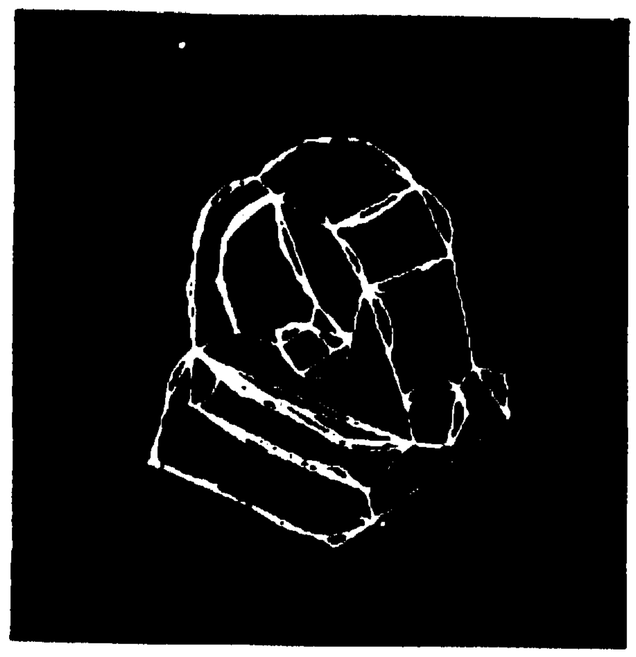

Fig. 4. All possible interpretations of the streaks

ple or failing edges and areas are solved by linguistic methods. Three accelerating heuristic tools are applied in directing the search on the problem-graph: a priori information, the weights with the calculated fuzzy-like estimation attributes of the picture hierarchy and the distance measures between pictures and models. The estimation attributes are calculated from the weights of the strokes, considering in each stage /node, streak, edge, picture part/ the reliability of the fit, decomposition and concatenation. Several distance measures are distinguished: brute-force characteristics with their special task-oriented combinations, distances similar to those used by Fu / 3 /, distances obtained from statistics of learning, special measures preprogrammed by the operator with the help of his personal experience.

The process of recognition includes the determination of orientation, namely the calculation of the transformation matrix which transforms the position of the model to the real position of the object.

Modelling is used not only in the ways initiated by Roberts and later Baumgart and others but as a general tool for man-machine communication during i/ the system design, ii/ the task learning and iii/ the robot operation. Each level is different in intelligence; none of the levels can disturb its superior one but each has a systematic downward compatible interactive apparatus based on a graphic display. The graphics is 3D-2D oriented: the internal representation and manipulations refer mostly to the 3D model /Fig. 5/, the different 2D pic-

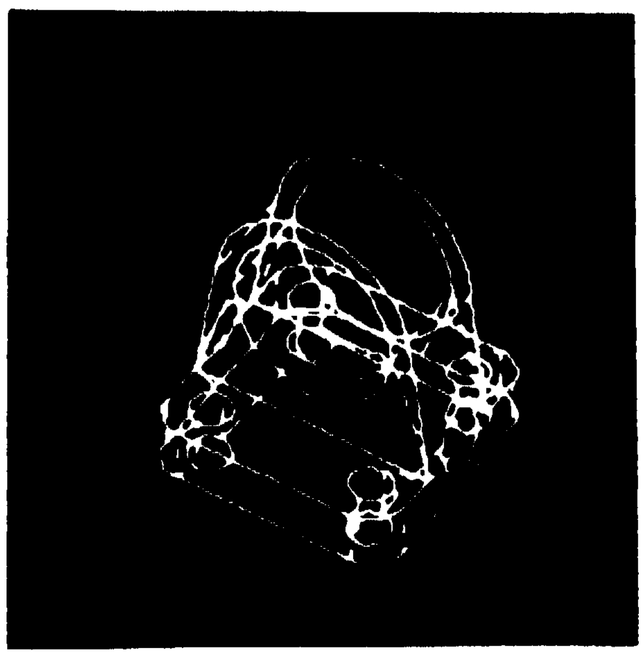

Fig. 5. 3D wire-frame model of the object

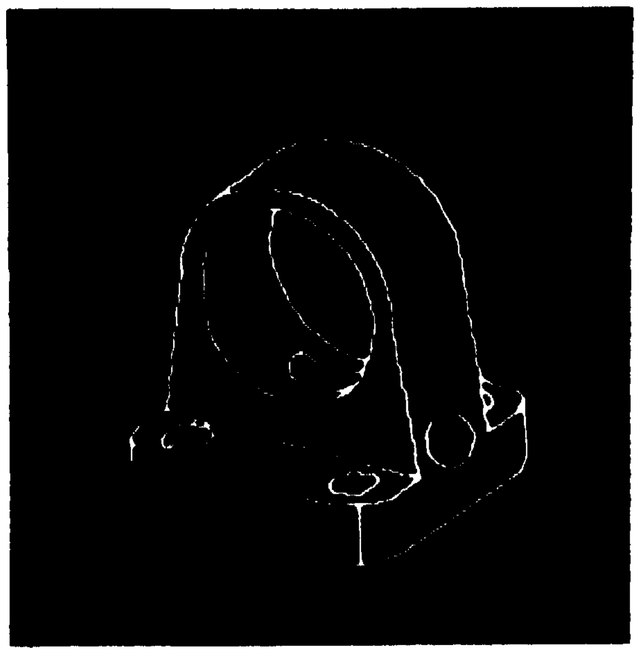

Fig. 6. A hidden line projection of the perfect model

tures to be matched with the scene are derived from that using a fast hidden line elimination algorithm. This means that all usual 3D operations are implemented /rotation, distortion, unification etc./, adapted specially to our requirements, i. e. real time, low storage capacity.

3. EXPERIMENTAL RESULTS

Robot control and hardware are usual not to be detailed here. The system uses a 16 bit 40 kB mini with a 2,us cycle-time /VIDE0T0N R-10 licence after the French CII-Mitra-15/, mini'disc, magtape, graphic display.

The whole recognition procedure needs about 30-50 seconds to recognize an object shown e. g. in Fig. 1. The running times of the particular algorithms are the following. The hidden line algorithm is extremely fast, it provided e. g. Fig. 6 within 2 seconds. The edge-finding operator needs about 4 seconds for processing a TV picture input. The algorithm which assembles the strokes into streaks requires 10-15 seconds. The grammatical searching procedure of finding the possible faces and the possible object drawings in the streaks' interpretations takes 5-8 seconds. The other on-line algorithms take less than 1 or 2 seconds altogether.

Experiments have proved that the indicated heuristic search results in a time requirement depending statistically linearly on the object' complexity, number of objects, number of ambiguities /edges, interpretations, shadows, partial observations/. A successful guess /e.g. a brute-force estimator/ can cut short occasionally all further trials. In unfortunate cases the interaction of the operator is also possible.

4. APPLICATIONS

The system is primarily assembly-oriented. Other applications of our results that already work are being realized recently: a recognition system in a bus-body factory identifying the metal sheets for controlling a painter robot and a man-machine system in neuro-biological research which should detect neuronal nets in microscope-sections.

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A DOMAIN-INDEPENDENT PRODUCTION-RULE SYSTEM FOR CONSULTATION PROGRAMS

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EMYCIN IS a programming system for writing knowledge-based consultation programs with a production-rule representation of knowledge. The major components of the system, including an explanation program and knowledge acquisition routines, are briefly described. EMYCIN hns been used to build consultation systems *m* several areas of medicine, as well as an engineering domain. These experiences lead to some general conclusions regarding the potential applicability of EMYCIN to new domains.

1 Introduction

The focus of mucn curront work in artificial intelligence is the development of computer programs that aid scientists with complex reasoning tasks. Recent work has suggested that one key to the creation of intelligent systems Is tho incorporation of large amounts of task-spocIfIc knowledge. However, building such "knowledge-based" programs from scratch can be a very time-consuming task. We have found that tho basic framework of the MYCIN program [9] could bo generalized sufficiently to make possible the substitution of knowledge bases from other domains. Tho result of this generalization is EMYCIN*, a system for doveloping rule-based consultation programs. Tho aim of this work Is to moke knowledge-based systems technology more accessible to Investigators in many fields.

2 Description of EMYCIN

E MYCIN Is used to construct a *consultation program,* by which we mean a program which offers its user advice on some problem within Its domain of expertise, much as a human consultant does. The program elicits Information relevant to the case by asking tho user questions during tho course of tho consultation. The program then applies Its knowledge to tho facts of the case and informs the user of Its conclusions. Tho user is free to ask the program questions about Its reasoning in order to hotter understand or validate tho advice given.

2.1 Knowledge Organization

Knowledge In EMYCIN is represented In terms of production rules operating on associative (attrIbute-object-vnlue) triples. To represent the uncertainty of data or competing hypotheses, attached to each triple Is a *certainty factor* (CD, a number between -1 and 1 Indicating tho strength of the belief in that fact [8].

Reasoning Is performed using domain knowledge encoded as *production rules.* Each rule has a *premise,* which is a conjunction of predicates over triples in the knowledge base. If tho premise is true, tho conclusion in tho *action* part of the rule Is drawn. If the premise Is known with less than certainty, tho strength of the conclusion Is modified accordingly (see [8]). FIguro 1 shows a typical rule from the domain of structural analysis (described In Section 3).

Rule 68

If: 1) The material composing the sub-structure 1s one of tho metals,
2) The analysis error (in percent) that 1s tolerable Is less than *b,*
3) Tho non-dimensional stress of the sub-structure is greater than .5, and
4) The number of cycles the loading 1s to be applied is greater than 16000

Then: It 1s definite (1.8) that fatigue is one of the stress behaviour phenomena in the sub-structure

```
PREMISE: (SAND
                (SAME CNTXT COMPOSITION (USTOF METALS))
                (LFSSP* (VAL1 CNTXT FRROR) 5)
                (GREAURP* (VAII CNIXI ND-STRESS) .5)
                (GREATERP* (VAII CNIXT CYCLES) 10000))
ACTION: (CONCLUDE CNTX1 SS-SIRESS FATIGUE IALLY 1.8)
```

Figure 1
English and internal Lisp forms of a SACON rule.

2.2 Application of Rules -- the Rule Interpreter

He control structure is a goal-directed backward-chainIng of rules. At any given time, EMYCIN is working toward establishing the value of some attribute. To this end, the system retrieves tho (precompiled) list of rules whose conclusions bear on this goal. The rule in figure 1, for example, would be retrieved in the attempt to determine the stress of a substructure. If, in the course of evaluating the premise of one of these rules, some other piece of Information is needed which Is not yet known, EMYCIN sets up a subgoai to find out that information; this In turn causes other rules to be tried. Questions are asked during the consultation when the rules fail to deduce the

* "Essential MYCIN", I.e. MYCIN stripped of its domain knowledge. This work was supported in part by the NSP grant MCS *77-027)2* and tho Advanced Research Projects Agency, contract MDA 903-77-C-0322.

necessary Information. If the user cannot supply the requested Information, it remains unknown, and rules that require It will simply fail. Thus, the rules unwind to produce a succession of goals and It Is the attempt to achieve each goal that drives the consultation (EMYCIN also permits a limited use of *antecedent rules,* triggered when the program receives new data or makes a conclusion).

2.3 Usefulness of the rule representation

As has been described in earlier reports of the MYCIN program [4], many of the system's Important features are facilitated by the use of rules as the primary representation of knowledge. Since each rule is intended to be a single "chunk" of Information, the knowledge base is inherently modular, making it relatively easy to update. Individual rules can be added, deleted or modified without drastically affecting the overall performance of the system. The rules ore a convenient unit for explanation purposes. The system's ability to "read" its own rules is *used* extensively by the explanation program (below) and other routines which assist the user in manipulating the rule base.

2.4 Explanation Capability

EMYCIN's *explanation program* allows the user to Interrogate the system's knowledge, either to find out about inferences made In the particular case at hand or to examine the static knowledge base in general. During the consultation, In response to certain user commands, EMYCIN can offer explanations of the current, past and likely future lines of reasoning *(WHY* a question was asked, or *HOW* a conclusion is reached). A more general form of explanation Is available via the *QA Module,* which Is automatically invoked after the consultation has ended, and con also be entered during the consultation to answer questions outside the scope of the special WHY/HOW commands. The QA Module accepts simple English-longunqe questions dealing with any conclusion drawn during the consultation, or about the domain in general. The questions are parsed by pattern matching and keyword lookup, using a dictionary which is automatically constructed from the phrases used in defining the various objects and attributes of the domain. The QA module has boon described in great detail elsewhere *[7].*

The explanation program Is also a helpful high-level debugging aid for the system developer. Without having to resort to Lisp-level manipulations, she can examine any inferences that were made, find out why others failed, and thereby correct *errors or* omissions in the knowledge base.

2.5 Knowledge Acquisition

A substantial part of the initial effort Involved In creating an EMYCIN system Is spent in the acquisition phase, viz. constructing tho knowledge base of the rules and tho object-attribute structures upon which they operate. Thus we have devoted much effort to providing programmatic assistance for this task.

(MYCIN supplies a high-level database editor for the data structures in the system. The data must be entered In Its Lisp format (understanding English rules Is far too difficult, especially In a new domain where the vocabulary hasn't even boon identified and organized for the program's use), but the editor handles all the bookkeeping involved In managing the rule base and performs various checks to catch a number of common user errors.

To partially bridge the gap between precise Lisp Input and free-form English text, there is an intermediate "terse" rule format. This format is a simplified Algol-like language which uses the attributes and their values as operands; the operators correspond to EMYCIN predicates. E.g. SACON's Rule 68 shown in Figure 1 above could be written Instead as:

```
If  Composition = (LISTOF METALS) and
    Error < 5 and
    Nd-stress > .5 and
    Cycles > 10000
Then   Ss-stress = fatigue
```

Figure 2. Stylized English format for rule input.

The terse rule format Is also available on output, for users who prefer It to the more verbose English translations.

As each rule is entered, it is checked for syntactic validity, to catch spelling errors and other simple errors. Other data structures *are* also updated, such as the one telling the rule Interpreter which rules conclude about which attributes.

2.6 Other support features

EMYCIN has facilities for maintaining a library of sample cases. These can be used for testing a complete system *or* for debugging a growing one. When a library consultation is rerun, the system's questions are answered by supplying the response, if any, given when the case was first *run.* Many such cases may be automatically rerun In background mode, with the system comparing the "results" with those of earlier runs. This makes It easy to check the performance of a new set of rules on "standard" cases.

EMYCIN's existing human-engineering features relieve the system builder of many of the tedious cosmetic concerns of producing a human-useable program. Most of these center around the consultation Interaction where the system requests data from the user; they Include a terminal Input facility with such features as spelling correction and Tenox-style completion on altmode from a list of possible answers, and a simple help facility.

3 Applications

Several consultation systems have been written In EMYCIN. The MYCIN program (which could be viewed as the original implementation of EMYCIN) provides advice on tho diagnosis of and therapy for patients with Infectious diseases. There are currently some 460 rules in the MYCIN rule set, making conclusions about 86 of the 236 attributes (the remaining attributes are simply input data). Results of formal evaluations of MYCIN'S competence In tho domains of bacteremia (bacterial Infections In the blood) and meningitis Indicate that MYCIN'S performance In these areas has begun to approach that of medical specialists [10].

The PUFF system [6] performs interpretation of measurements from the pulmonary function laboratory. The data front over 100 cases wore used to create some 60 production rulos diagnosing the presence of pulmonary disease. These rules are used to create a complete report including the Input measurements, historical information, and the measurement interpretation.

The HEADMED program [6] is an application of EMYCIN

to clinical psyehopharmacology. The system diagnoses a range of psychiatric disorders and can recommend drug treatment if Indicated. The system contains 276 rules at present, one of which Is shown In Figure 3.

If: 1) The diagnosis for which therapy is being recommended is major-depressive-disorder,
?) The intensity of this patient's psychiatric disturbance is one of: moderate, mild,
3) Tho current mental state of the patient 1s psychotic, and
1) There is no recent prior episode of psychiatric disturbance
Then: There is strongly suggestive evidence (.8) that the class or category of treatments 1s antipsychotic

Figure 3. A sample HEADMCD rule.

As a stronger test of domain independence, EMYCIN wns applied to the completely non-medical domain of structural analysis. SACON (Structural Analysis Consultation) *[?]* provides advice to a structural engineer regarding tho use of a large structural analysis program called MARC. The MARC program uses finite-element analysis techniques to simulate the mechanical behavior of objects. The goal of the SACON program is to recommend on analysis strategy to guide the MARC user in the choice of specific input data, numerical methods and material properties, The system contains some 160 rules and 50 attributes, half of which are concluded by the rules.

4 Range of Applicability -- Limitations

Although we do not have a precise characterisation of domains which are most suitable for an EMYCIN application, our experience provides some general guidelines. Wo found that many of the simpler systems did not even make use of the inexact Inference mechanism provided by CFs. It is possible that more efficient representations exist for the precise knowledge existing in such domains. However, it still seems appropriate to build a reasoning program from (MYCIN as a first test of the inference rules written by an expert. While many of the system's complicated features, such as certainty factors, may go unused in the simpler systems, those features do not substantially burden a program which does not use their extra generality.

It is not always easy to actually formulate the domain knowledge Into production rules, even in the domains that have been successfully implemented so far. Our desire to keep the rule format simple is occasionally at odds with the need to encode the many aspects of scientific decision-making. For example, the process of therapy selection in MYCIN proved more amenable to a generate and test algorithm [3]. The backward-chaining of rules by the deductive system Is also often a stumbling block for experts who are new to the system; however, they soon learn to structure their knowledge appropriately. In fact, some experts have felt that encoding their knowledge Into rules has helped them formalize their own view of the domain, loading to greater consistency in their decisions.

The representation of facts as associative triples with Cf's may not be natural or adequate for many domains. However, the triples have proved a flexible enough data structure in our investigations thus far. The specific control structure In I MYCIN, viz., goal-directed backward chaining of rules, might be considered much more restrictive.

Certainly other control structures and representations ore possible. We recognize that *i* MYCIN is not as general as some other efforts, e.g. KRL [1], nor Is It Intended to be: there may weil be advantages in restricting the user's options. At least during the initial formulation of the knowledge of a domain, the simple framework of a single, easily understood control structure allows the expert to focus on the knowledge In the rules themselves, and not get sidetracked by a bewildering array of control choices.

5 Conclusion

Currently the system builder still requires a fair knowledge of Lisp and the workings of EMYCIN Itself. Our work alms at improving the facilities for acquiring and debugging rules, as these are the most time-consuming portion of creating a new consultation system. Our aim Is to have a truly convenient "workshop" for knowledge-based system exploration, In which a knowledge engineer can relatively guickly create a functional consultation program in a new domain, try out a new set of rules, of simply discover whether a rule-based system Is reasonable for the task.

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VISUAL, ANALOG REPRESENTATIONS FOR NATURAL LANGUAGES UNDERSTANDING

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In order lor a natural language system to truly "know what it is talking about," it must have a connection to the real-world correlates of language. Tor language describing physical objects and their relations in a scene, a visual analog representation of the scene can provide a useful target structure to be shared by a language understanding system and a computer vision system.

This paper discusses the generation of visual analog representations from input English sentences. It also describes the operation of a LISP program which generates such a representaIion from simple Knglish sentences describing a scene. A sequence of sentences can result in a fairly elaborate model. The program can then answer questions about relationships between the objects, even though the relationships in question may not have been explicit in the original scene description. Results suggest that the direct testing of visual analog representations may be an important way to bypass long chains of reasoning and to thus avoid (he combinaliona1 problems inherent in such reasoning methods.

I. UNDERSTANDING LANGUAGE ABOUT THE PHYSICAL WORLD

Suppose that we are given a sentence such as (1):

(1) A dog bit a mailman.

How do we understand such a sentence? What inferences do we make and what inferences can we make? To help answer these questions, suppose that we are asked:

(2) Where on his body did the dog probably bite the mailman?

We suggest that most people would answer (2) with: "on the leg," and that as a first guess, such an answer could plausibly be part of a BITING script or default slots of a frame for BITING. However, suppose that we insert one or more of the following sentences after (1) before asking (2):

(3a,b) The dog was a {doberman. / dachshund.

(3c,d,e) The man was {sitting. / lying down. / 3 feet tall.

(3f,g) The dog was {standing on its hind legs. / sitting.

In these cases the answer to (?) could be quite different parts of the body ("arm" becomes most likely if bitten by a doberman) or one could be much more definite about the answer ("leg" becomes overwhelmingly likely *if* one is bitten by a dachshund while standing up).

How could we successfully model *in* a program the understanding process a person goes through in this example? We suggest that the simplest and most natural way to model this understanding is to build up a visual analog knowledge base (representing "person," "dog," etc. as 3-D spatial entities) and to write programs which can manipulate and integrate these visual analog representations. *For* the example given (1) - (3), figure 1 illustrates some of the information that would have to be included. As another example, suppose we were given the following set of sentences:

(4) A goldfish is in a goldfish bowl.
(5) The goldfish bowl is on a stand,
(b) The shelf is *on* a desk.
(7) The desk is in a room.

Now suppose that we are asked:

(8) Is the goldfish in the room? or
(9) Is the goldfish on the desk?

The answer to (8) should of course be "yes" and the answer to (9) should be something like "Not directly on, but on is still an appropriate description." How could we mechanize the answering of such questions?

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We suggest that these questions can be easily answered if we use (4) - (7) to build an integrated visual analog structure which represents (4) - (7). Then given procedural definitions of prepositions like in and on, with the "oubject" and "object"* that the prepositions relate viewed as arguments to the procedures, we can apply the procedures to the structure directly to answer the questions. Boggess [2] has written a program, described later in this paper, which works exactly in this manner. Given (4) - (7), the program constructs an analog model like that shown in figure 2.

In constructing the model, the program uses properties of the subject and object to decide what the preposition means in each given case. For example, on would be interpreted quite differently in "the shelf on the wall," and "the shadow on the wall." "The shelf" is assumed to touch the wall, be supported by it, and to have a preferred orientation and position (height) with respect to the wall, whereas none of these are true of "shadow." The differences in treatment are the result of noting in the lexicon that "shelf" is an ordinary physical object (requiring support) with preferred orientation--its free surface should be horizontal--whereas a "shadow" is 2-D and weightless and thus does not require support. Each object has default dimensions as well as weight, and these dimensions (actually a rectangular parallelepiped which encloses the object) can be used to construct

(iiven the phrase "the cat on the mat," or the sentence, "The cat is on the mat, we call cat the subject and mat the object.

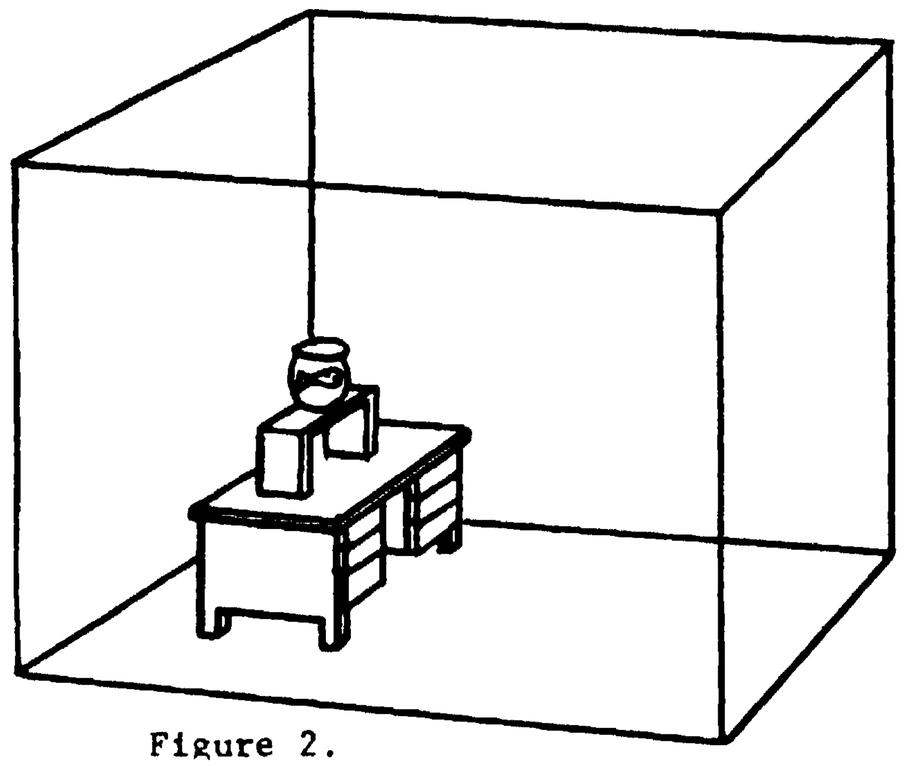


Figure 2.

the visual analog model.

To illustrate the interpretation of this model, consider the preposition in. If in's object is a 3-D enclosure, then all we need to do to see whether the subject is in the object is to check whether the coordinates of all the corners of the subject are within the intervals of the coordinates of the corners of the object. The answer can be found with one set of tests, regardless of how many chained statements were required to relate the subject and object in the scene description. Thus, given a model like figure 2, it is very easy to answer (8) because all the dimensions of "goldfish" are within the dimensions of "room."

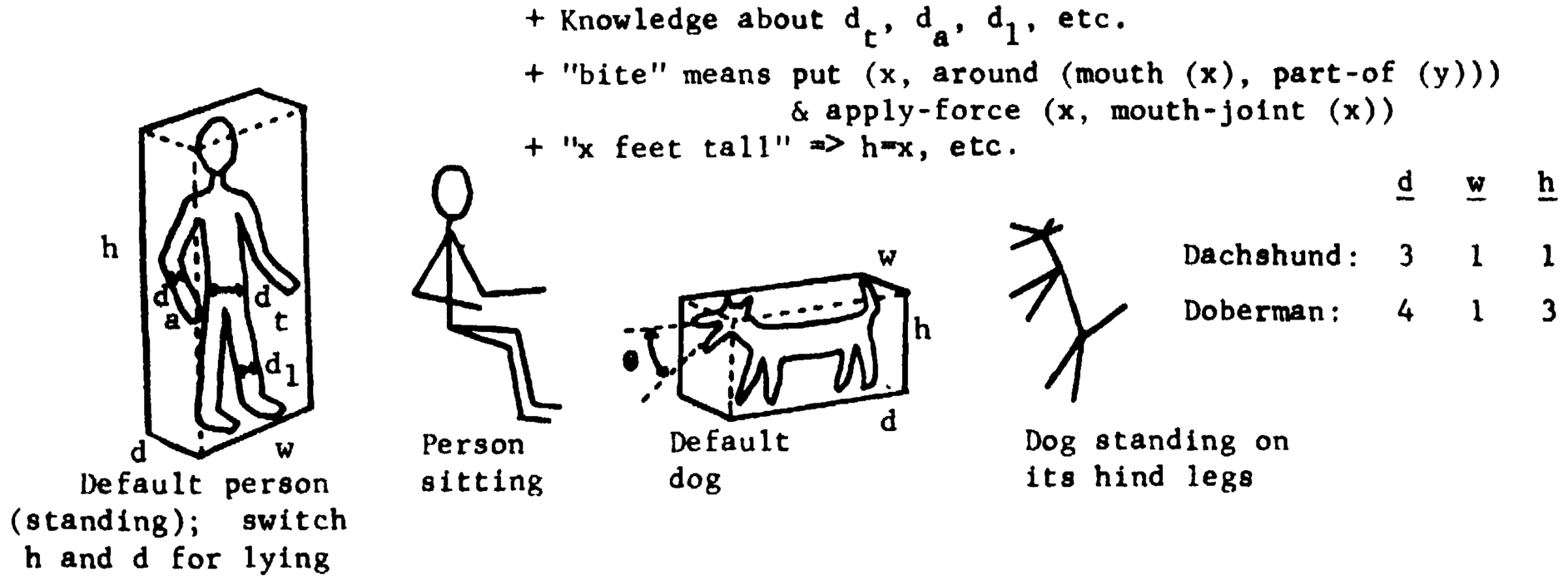


Figure 1. Some of the information needed to understand (1) - (3).

2. USING DEDUCTIVE RULES ON A DATA BASE OF ASSERTIONS,

Starting with Black [I], there have been programs which dealt with similar questions. Most of these programs have "understood" sentences like (4) - (7) by adding something equivalent to an assertion of the form (ON GOLDFISH-BOWL1 STANDI) to a data base. Answering questions about the scene described has then Involved applying deductions rules such as:

(10) (ON ?A ?B) AND (ON ?B ?C) ->(ON ?A ?C)

to verify that a given relationship does or does not hold between two given objects. In general, the set of assertions in the data base will define a network, i.e. any two Items In the data base may be connected by an arbitrary number of deductive chains or direct assertions. For example, a chair can at the same time be at a desk, under the desk and touching the desk. There are at least two serious difficulties with using a method like deductive chaining to understand the spatial domain, represented as a data base of assertions:

A. If there are many rules and many objects, the search for a deductive chain which can prove or disprove a given relation between two objects can Involve combinational explosion. Often there will be Insufficient Information to decide whether a relationship holds between two objects; In such a case, all relevant paths between the objects will have to be explored before a system can decide that the problem cannot be decided.

B. Even more serious is the difficulty In formulating deduction rules properly to begin with. For example, rule (10) allows us to deduce correctly that a leaf is on a tree if the leaf is on a branch and the branch is on a tree, but it is not correct to deduce that a cow has wings If we know that a wing Is on a fly and the fly Is on a cow.'

One obvious solution to this difficulty has been to create a number of definitions for 0N--0N1, ON2, 0N3, and so on, where ONI might mean "Is a part of" as In "the wing on a fly," 0N2 might mean "above, touching and supported by" as In "the pencil on the desk," etc. Deduction rules can then be formulated with greater precision, but we have added an additional problem: when on Is asserted to hold between two objects or used In a question a program must now decide whether ONI, 0N2, 0N3, or ONn Is Intended. More rules delimiting the classes of objects which can be related by each meaning of on must then be formulated and somehow utilized to decide which meanIng(s) are appropriate.

But even a large number of such rules cannot easily substitute for the visual analog model. Suppose that (4)-(6) were followed by

(11) The desk Is In a box.

In this case the goldfish may or may not be Inside the box, depending on the dimensions of the box, desk, and stand (see figure 3). But how could a deduction-rule-based system give a different answer to these two cases, unless it implicitly coded metric Information? And If it coded metric information, why bother with the potentially long deductive chains?

3. OPERATION OF A PROGRAM FOR UNDERSTANDING SIMPLE LANGUAGE ABOUT SPACE.

A MACLISP program has been written by Boggess [2] which can build a spatial model of sentences involving in and on relations, and answer questions about its model. Input to the program consists of normal English sentences, which are parsed with the aid of a LINGOL f 9) preprocessor. LINGOL is an MIT-originated program package which accepts grammatical rules of the type S->NP+WP and produces LISP programs which can then parse input sentences according to the rules of the specified grammar. For this implementation, LINGOL was used to single out prepositions and their semantic subject and object. For example, in the sentence, "On the bed was a box," the LINGOL portion passes the preposition on, the semantic object the-bed and the semantic subject the-box to the rest of the program. Let's follow and extended example.

Input: A glass is in a box.

Resulting model: figure 4.

Figure 3.

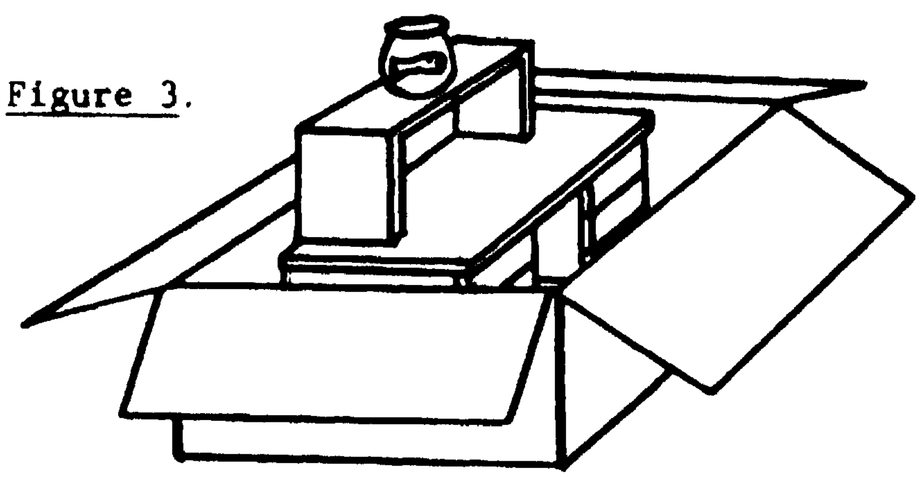
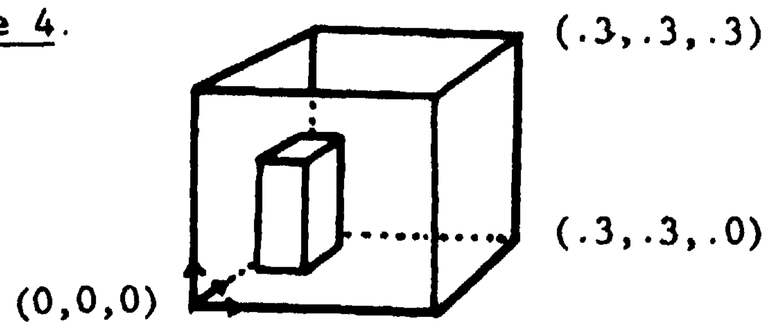


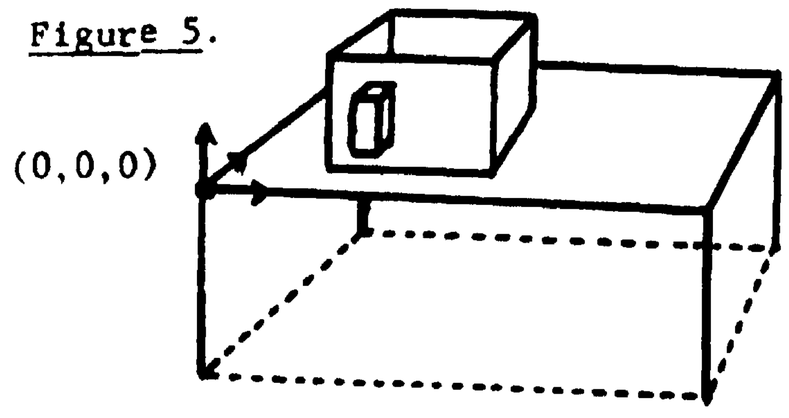
Figure 4.



Comments: The glass has weight, so it ends up not only in the box, but at the bottom of it.

Input: The box is on a table.
Resulting model: figure 5.

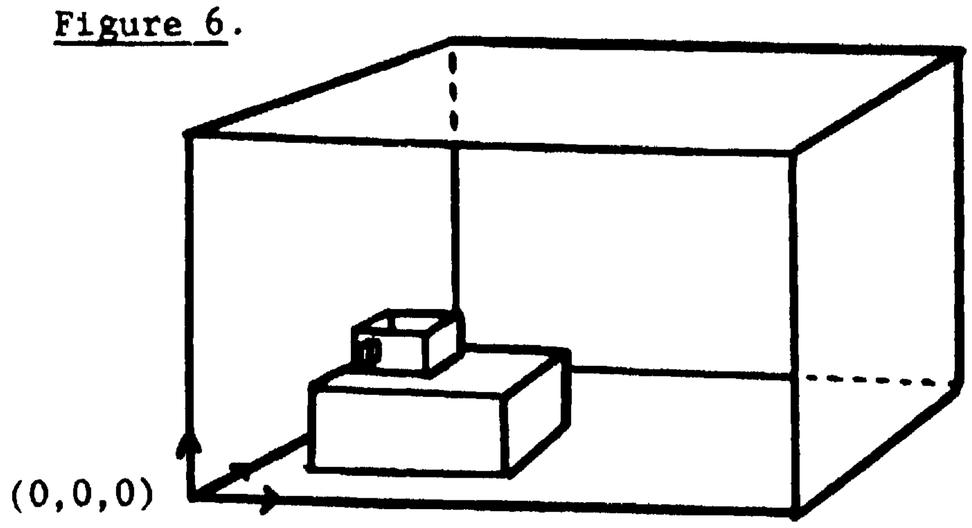
Figure 5.



Comments: There is only one individual box known to the system, so the "the box" can be interpreted with no difficulty. Notice that the surface of the table is taken as the basic plane for the discussion so far, rather than putting the origin at, say, a point at the bottom of the table.

Inputs: The table is on a floor.
The floor is in a room.
Resulting model: figure 6.

Figure 6.



Comments: "A floor" sounds strange, but the system doesn't know for the present that tables are almost always on floors, so mentioning a particular table does not allow It to presuppose a particular floor that it could reference as the floor. As is probably becoming obvious, the model does not choose locations randomly. Rather, it tends toward a particular corner. This choice was made in hopes of avoiding the "findspace" problem [11] when several objects must be located on one surface.

The current model doesn't know that a floor is part of a room. Naturally, a default-sized floor exactly fits a default-sized room, but the model has to know that a floor belongs at "ground level" or it would try to put the floor at a more or less arbitrary level in the room. While this particular sentence sounds unusual, it is natural to speak, say, of "the floor in Jonathan's room."

Suppose after all this the user types: Is the box on the table? The response from the system is YES.
To the input: Is the box on the floor? The system responds NO.
Is the box in the room? YES
Is the glass on the table? NOT DIRECTLY, BUT ON IS STILL AN ACCEPTABLE DESCRIPTION.

The program answers these questions by directly interrogating the three-dimensional model, not by knowing that, say, if A is on B and B is in C then A is probably in C. At no time did we say that the box was in the room. But thanks to the sizes of boxes and tables and the locations of floors relative to the rest of a room, there is no question but that the box must be in the room in the most rigorous sense of the word.

It is also possible to handle situations which would be difficult for systems based on chained inference rules. For example, this program can distinguish between a glass on a tall object in a box and a glass on a small object in the box. If the tall object were large enough that the glass was exterior to the box, then this sort of model could reasonably balk at calling the glass ijn the box--or at least hedge, as a person might. A system built on the sort of inference rules mentioned above could have trouble distinguishing between these cases.

3.1 Use of Other Knowledge

If the preceding dialog were continued with "The room is in a house," the room would be placed within the volume of the house several feet off the ground, since rooms are weightless. While this seems odd (and could obviously be "fixed'') it is reasonable given that houses can have more than one story. In contrast, given "The

house is in a field," the model puts the house on the ground, even though houses have no weight either, as far as the model is concerned. This is because a field is a 2-D object, and the in relation implies contiguity under those circumstances.

Given "A shelf is on a wall," the model uses(l) Knowledge about the free surface of a wall, (2) Knowledge that a shelf's free surface is horizontal, and (3) Knowledge about typical heights of shelves to place the shelf appropriately. The free-surface of a ceiling is downward, so after "A light is on a ceiling," the light ends up on the correct side of the ceiling surface.

4. PROGRAM IMPLEMENTATION-REPRESENTATION OF PREPOSITIONS AND OBJECTS

The examples given in the preceding section were from a session with a small program, written in MACLISP and run on the DEC-10 system at the Coordinated Science Lab. The program consists of about 45 functions, most of them fairly short. Data for the implementation consisted of twenty-two "definitions" of objects and the definitions of the prepositions themselves. Input to the program consists of English sentences—either statements or questions. Statements are expected to be either "naming" statements (Tweety is a " or "Volume-1 is a book") or locative statements ("A book is on a table," "In the room is a bed"). Output is either a set of coordinates for each object in the "mental model" or a response to the question.

4.1 Object Definitions

Some sample definitions of visually perceptible objects follow (units of measurement are meters and kilograms):

```
(TABLE PROTOTYPE
   (INSTANCE-OF FURNITURE)
   (TYPICAL-SHAPE ((HEIGHT 0.75)
                   (CROSS-SEC 1.2 0.9)))
   (FREE-SURFACE (((PLANE HORIZONTAL)
                   (FREE-DIRECTION /+Z)
                   (HEIGHT 0.75)
                   (DIMENSIONS 1/2 0.9))))
   (WEIGHT 25.0))

(BOX PROTOTYPE
   (TYPICAL-SHAPE ((HEIGHT 0.3)
                   (CROSS-SEC 0.3 0.3)))
   (FEATURES (CONTAINER OPEN-TOP))
   (WEIGHT 1.0))

(FLY PROTOTYPE
   (TYPICAL-SHAPE ((HEIGHT 3.0E-3)
                   (CROSS-SEC 3.0E-3 5.0E-3))))

(CEILING PROTOTYPE
   (TYPICAL-SHAPE ((CROSS-SEC 3.6 4.)))
   (FREE-SURFACE (((PLANE HORIZONTAL)
                   (FREE-DIRECTION /-Z)
                   (DIMENSIONS 3/6 4.0))))
   (FEATURES ((TYPICAL-HEIGHT 2.5))))

(SHELF PROTOTYPE
   (INSTANCE-OF FURNITURE)
   (FEATURES ((TYPICAL-HEIGHT 1.0)))
   (WEIGHT 1.5)
   (TYPICAL-SHAPE ((HEIGHT 0.025)
                   (CROSS-SEC 0.2 1.2)))
   (FREE-SURFACE (((PLANE HORIZONTAL)
                   (HEIGHT 0.025)
                   (DIMENSIONS 0.2 1.2)
                   (FREE-DIRECTION /+Z)))))
```

At initialization, the components of the typical-shapes are used to create a simple "mental picture" of the object, in the form of coordinates of an enclosing right parallelepiped. This permanent mental picture is kept under a "local coordinates" property, with the bottom right front taken as local origin.

The definitions specifically single out planar free surfaces on a free-surface list, since it is impossible to judge from the representation whether a planar surface is a characteristic of the object itself.

Also included in the definitions is an indication of whether the object is essentially hollow as opposed to essentially "solid" throughout. The surfaces of the latter are the boundaries of matter; the surfaces of the former enclose space. The feature CONTAINER is used to indicate an object whose interior is canonically empty. Another feature applied to CONTAINERS only and is used to indicate whether they are OPEN-TOPped or not.

TYPICAL-HEIGHT as part of a feature list indicates that an object normally would be found at a given height above the default ground-level (either the floor or the actual ground). Otherwise a clock placed randomly on a wall might end up very close to the floor. After using the program for a while, it became obvious that we needed to have such default heights for a number of items--clocks, windows, shelves, counters, cabinets, and so forth.

4.2 Preposition Definitions

Each preposition is defined as a LISP function with the subject and object as arguments. The LISP functions are based on the results of an extensive analysis of about 20 spatial locative prepositions (see [2]). In this analysis, a number of primitives were identified, such as CONTIGUOUS, SUPPORTed, INTERIOR (2-D and 3-D), CROSS-SECTION (of objects), PROJECTION (of CROSS-SECTIONs), TRAJECTORY, UP/DOWN, HORIZONTAL,

VERTICAL, and various coordinate systems. These primitives constitute a major result of this research. They will allow us to express neatly the meanings of the approximately 20 locative prepositions analyzed but not yet programmed, and seem on preliminary analysis to be an adequate set for the spatial use of most of the rest of the prepositions as well (prepositions form a closed set).

Each preposition seems to have a default interpretation if its subject and object are unknown, as in "the thingamajig on the whatchamacallit." The default interpretation represents a "pure" case of the prepositional relation--however the preposition can be used to describe a range of physical situations which vary from the "pure" instance by having one or more components of the default case missing or modified. For example, the pure case of above is that in which the SUBJECT is INTERIOR (3-D) but not CONTIGUOUS to the bottom of a volume defined by projecting the HORIZONTAL CROSS-SECTION of the OBJECT upward VERTICALly in space for a distance of on the order of 3 times the object's diameter. However, above can also be used to describe a variety of "impure" relationships in a scene, including cases where the subject is merely at a higher level than the object (as in "there are clouds above us") and cases where the 2-D projected image of the SUBJECT is INTERIOR (2-D) to the region defined by projecting the HORIZONTAL extreme of the 2-D projection of the OBJECT upward VERTICALLY (as in "the moon above Miami").

To give a better idea of what each prepositional definition is like, let us look at what the functions for on and in do. On is faced with two decisions: it must decide which surface of the object the subject is continguous to, and it must decide which side of the subject is contiguous to the object.

If the subject does not behave normally with respect to gravity (shadows, visual patterns, thin films of liquids and many insects exhibit gravity-defying behavior) then any available surface of the object will do.

If the subject is under gravitational constraints, then the routine looks for one of four possibilities: in order of preference, 1) a horizontal plane in the object, 2) if the object is three-dimensional and is not an open-topped container, then the top of the object 3) failing either of these, then any planar free-surface, and finally 4) any available surface. In any of these cases, the object requires support and by supposition the semantic object furnishes it.

Having found the surface of the object, on looks for a probable surface of the subject. A check is made to see if the subject has a marked free-surface (actually a back-handed way to see if the subject has a preferred orientation). rf it has, the preferred orientation is presumed to be the canonical one, and on passes to a function called CONTIC, not a surface of the subject but the entire subject, thereby instructing CONTIC to translate the subject in whatever direction necessary to bring it into contact with the object-surface indicated. On the other hand, if the subject has no preferred orientation, on selects the canonical bottom of the subject.

The definition of the preposition in has to decide if it is dealing with a container, whether the container is open-topped, and whether the subject behaves normally with respect to gravitational constraints. It then calls one of the INTERIOR functions and, sometimes, CONTTG (when the subject is assumed to be in the bottom of a container, for instance). At present, the system has 2- and 3- dimensional interior functions, which restrict the location of their subject with respect to a plane of their object or the volume delineated by the object, respectively.

5. ASSESSMENT OF THE PROGRAM.

5.1 Inferencing Problems

One of the nice features of this "analog model" is that it holds out hope for doing inferencing and deduction by direct reference to the model, under optimum conditions, and by reference to the model plus the location restrictions under other circumstances; the construction of chains of rules can be avoided.

Two cautions are in order, however. In interpreting a description (building the model in the first place), it suffices to place objects in simplest possible relationships. If a description mentions a book on a desk, we probably visualize the book as being directly on the desk.

The reverse process--judging from a mental model whether a particular preposition is an appropriate description of the relation between two objects—is not always so simple. In deciding whether "above" is an acceptable description, for instance, there is little question when one object is directly above the other, but clearly the word is acceptable even when the direct case is not applicable, and deciding these more marginal cases often leads to a lot of hedging, even from native speakers.

The second caution is best put by describing a session with the implementation: as it happened, the particular mental model produced after "a shelf is on a wall" and "a fly is on the wall" was the equivalent of figure 7.

Now suppose we were to ask if the fly is under the shelf. The program will say "yes". The correct answer, of course, if "I don't know," since on the basis of the description the fly might be under the shelf, but it might be elsewhere too. Clearly, then, the simple expedient of directly consulting the constructed model is

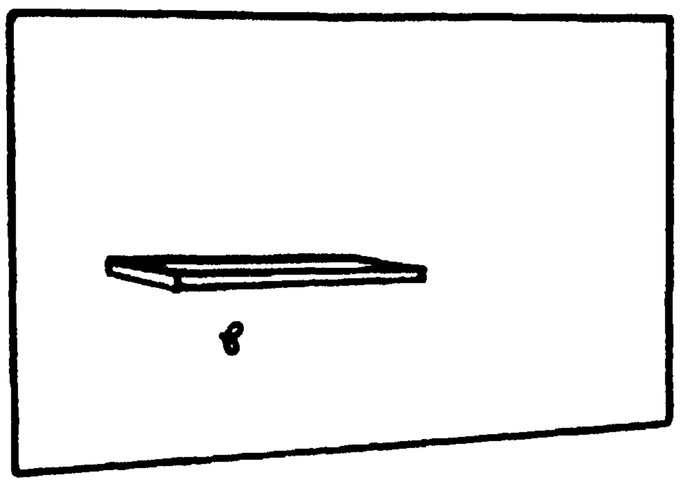


Figure 7.

a little too simple. The more freedom a model allows in choosing the location of an object, the more incidental any relations between various objects may be. In the end what we know are the location restrictions and it is based on them that we need to make judgments.

5.2 Regularities

For all the hedges and caveats of the preceding paragraphs, it was evident from the implementation that paying attention to a very small set of attributes of objects yields an astonishing amount of descriptive power. The attributes included a very rudimentary surface description, the concept of a free-surface with associated free-direction, the essential "emptiness" of containers, some notion of gravity, of contiguity, of the interior relation in two or three dimensions, of partial axes of symmetry, some awareness of scale, and a coordinate system with marked vertical direction. Clearly, these concepts do not handle all cases of descriptions using place locatives. It might even be said that they do not handle some of the most common cases (we will come back to this in a moment). But they do handle the most typical cases--the regular uses of in, on, and the other prepositions—the uses we are most likely to think of as standard. In so doing, they capture much of the descriptive power of the prepositions.

Why then could it be said that they do not handle some of the most common cases? It is well known that the most frequently occurring verbs in English are also the most irregular. Something of the same sort seems to apply to uses of the prepositions with common objects. Tables, for instance, have a tendency to be treated as if they were essentially the table top--"under the table" for most objects means under the table top but definitely not under the legs. Rugs are an exception, of course, as are floors, and there are undoubtedly other exceptions to the mini-rule of treating the table as top only.

5.3 Is on Transitive?

As another example ot the irregularity of tables, consider a scene like that in figure 8, which can be described by (12a - h):

(12a) Volume 8 is on volume 7
(12b) Volume 7 is on volume 6
:
(12i) Volume 2 is on volume 1.
(12j) Volume 1 is on the table.

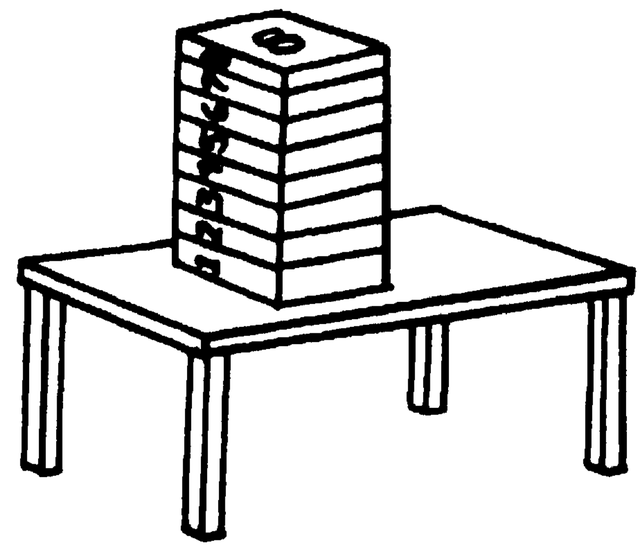


Figure 8.

Since all volumes, 1-8 can be said to be 'on the desk" we would like some kind of transitive rule to apply, but it would not be proper (or at least it would be very odd) to say that "Volume 8 is on volume 2." The hidden regularity here is that tables (and other furniture: desks, shelves, counters, etc.) have on relations with everything they support, directly or indirectly. Most other objects do not have on relations with everything they support, so that, for example the top book on a stack of books on the ground is not normally said to be "on the ground."

Fortunately, even the most common objects (including tables) appear to be regular most of the time, with most of the prepositions. It is interesting that some of the irregularities fall into classes, like classes of irregular verbs (sing, sang, sung; drink, drank, drunk; sink, sank, sunk). For example, "the people on the bus" are actually in the bus--they aren't on the bus in the same sense that "the people on the car" would be on the car. On has the same interpretation in "on the plane," "on the subway,"or "on the boat"--indeed for anything that can be boarded or alternatively that one can stand up in. So at least potentially there may be classes of irregular objects.

After all is said and done, though, it is still the case that the system seems to work, and work well, for the great majority of regular objects, and even for the irregular ones most of the time. It seems clear that basic understanding of the use of the prepositions is ours if only we pay attention to a small set of perceptually salient characteristics of the objects related.

6. PROBLEMS REMAINING

Clearly there will be surprises in programming the rest of the prepositions, and we have only begun to scratch the surface of the problems in implementing programs to deal with sentences like (l)-(3) (the "dog bites mailman" example). However, we are already aware of some problems and exceptions to the general picture presented in this paper.

One major problem was alluded to in the example in section 5 of the fly which was (arbitrarily) placed under a shelf in the mental model and could thereafter not be differentiated from a fly specifically asserted to be under the shelf. What seems to be needed is some way of keeping track of the range of possible positions available to objects described; we have debated several schemes (e.g. a probability distribution for position, a tag on objects explicitly negating accidental relationships between objects, deferring the creation of a mental model until a question is raised, etc.) but are still undecided about the best way to proceed.

Another difficulty (initially pointed out to us by Phil Johnson-Laird) is that the preposition at seems to have the function of specifying a canonical relation between subject and object. Thus "the chair is at the desk" describes a specific relationship—if the chair is upside down or facing away from the desk, it can no longer be naturally said to be at the desk. Similarly at picks out canonical relations in "I stood at the window," "John was at the door," "I am at my desk,"etc. At seems to require special scenarios for each object, and is otherwise regular only in that most scenarios require proximity of subject and object.

Many prepositions require that the positions of the speaker and/or listener with respect to the subject and object be known. For example, I could say to a listener in Japan that "Urbana is near Chicago," (it is about 130 miles away) but I would not say this to a listener 10 miles from Urbana (see f5]).

Most difficult (and most exciting) of the problems we are aware of are the transfers of meanings from the spatial domain to abstract domains. A representation of physical objects, events, and their relations should be able to be used in constructing effective representations for abstract phenomena. An important part" of understanding the abstract use of prepositions involves identifying the "covert categories" [14] to which words belong. As an example, consider the phrases below:

get { into a car / into trouble / into mischief } be { in a car / in trouble / in mischief* }

get { out of a car / out of trouble / out of mischief* }

We suggest that both trouble and car belong to a covert category which could be called "spatial enclosures," but that mischief does not belong to this category, even though its meaning is closer to trouble's than is car's meaning. This example seems to us to be similar to the mass/count distinction in English--words like house, person, and book are count nouns (we can say"a house" or "two houses") whereas sand, butter, and water are mass nouns (we cannot say "a sand" OR "two sands," but must add a measure phrase, e.g. "a ton of sand," or "a lot of sand") Mass nouns with common measures associated with them can sometimes be used as count nouns, as in "Waiter, bring me two waters," and some nouns, like paper, seem to fit equally well in either category. (Such categories are extensively discussed in [12] and [14]. For those interested in this topic, Jackendoff [7] is a fascinating source of ideas; also see Waltz [13] and Pylyshyn [10].)

7. RELATED WORK

This research has been influenced by a number of other pieces of work; three items stand our particularly: a thesis by N. Goguen [6], a report by G. S. Cooper [4], and a paper by H.H. Clark [3]. Cooper's work developed a set of primitives and paper definitions for a number of prepositions. While the primitives proved to be inadequate when we began programming, this paper was an inspiration for the overall approach. Goguen wrote a program in many ways similar to this, but did not address the problems of multiple interpretations of prepositions. Clark's paper provided valuable insights into the coordinate systems underlying spatial language, and into the types of mental models people create from scene descriptions.

D. V. McDermott's TOPLE [8] dealt with some very interesting aspects of building a "mental model" of a scene from natural language. For example, given the sentence:

(13) The banana is under the table,by the ball,

there are two interpretations: (I) the ball can be under the table, or (2) the ball can be near the table, but not under it. If we were given

(14) The banana is under the table, by the floor lamp.

then the interpretation where the floor lamp is near but not under the table becomes more likely, based on the typical size of a floor lamp. McDermott's program is able to use size to make this type of distinction. However, the "mental model" in this work is a data base of assertions, e.g.

(UNDER TABLE1 BANANA1).

Winograd's SHRDLU [15] is probably the most closely related program, though its tasks were rather different--its "mental model" was known completely to the language understander,not constructed by descriptive natural language input.

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A Method for Automatically Analyzing Programs

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ABSTRACT - This paper presents a method for automatically analyzing programs and discusses why it is a useful way to look at programs. The method is based on the idea that there are only a few basic ways in which the logical structure Of programs is built up. An experiment is presented which shows that this accounts for the structure of a large class Of programs. The paper discusses how the method can be used to automatically analyze the structure of a program, and how the resulting analysis can be used to guide a proof of correctness for the program. An automatic system is described which performs this type of analysis. The paper discusses the relationship between the structure building methods presented and programming language constructs.

1- Introduction

This paper presents a method (described fully in [21]) for analyzing programs. This analysis of a progarm results in a "plan" for the program which represents the underlying logical structure of the program. The analysis method is based on the observation that programs are built up in a small number of stereotyped ways referred to as plan building methods (PBMs).

An important application of PBMs is that they can be used to analyze a loop in a way which makes it easier to understand what the loop does and why. Section 2 shows why this is a more useful analysis than one based on basic structured programming constructs. Section 3 describes the PBMs in detail. Section 4 discusses how an analysis of a loop in terms of the PBMs can be used to guide a proof of correctness for the loop. II also shows why the resulting proof is more useful than a proof based on a single loop invariant.

An experiment is discussed in Section 5 which shows that the PBMs can be used to analyze a large class of programs. The experiment also shows that the pieces which result from the analysis are largely simple and easy to understand. A system (described in Section 6) has been implemented which performs PBM analysis automatically. Section 7 discusses the relationship between the PBMs and current programming language constructs.

2. Desiderata For an Analysis Method

An analysis method views a program as built up out of parts, and makes it possible to understand the relationship between the operation of the program as a whole and the operation of its parts. From the point of view of gaining an understanding of a program, the parts are subproblems. Once the parts have been understood, their understandings can be combined in order to obtain an understanding of the whole.

There are several criteria which can be used to evaluate the usefulness of an analysis method. First, given a program, it should be straightforward to identify the parts. Second, the parts should be easier to understand than the whole. Third, the process of developing an understanding of the whole based on understandings of its parts should be as easy as possible.

The development which is most similar to PBMs has been the development of structured programming constructs. Consider the loop program in Figure 1. A naive approach to looking at how this program is logically built up is based on the idea that it is constructed on a line by line basis. Given this approach, it is easy to analyze the program in order to break it up into its component parts (the six lines of the program). Further, the parts are indeed much easier to understand than the program as a whole. However, the problem with this approach is that it is not at all easy to discover what the program does once the parts are understood, because the interactions of the lines with each other are complex.

```
      I ← 1;
      Z ← 0;
LOOP: IF NOT(A(I)>0) THEN GOTO SKIP;
      Z ← Z+A(I);
SKIP: I ← I+1;
      IF I≤N THEN GOTO LOOP;
```

Figure 1: An example program.

The basic structured programming constructs (composition, if-then-else, and do-while) suggest a much better analysis method. They indicate that the program should be viewed logically as being built up hierarchically using these structured programming constructs. Figure 2 depicts the program in Figure 1 analyzed in terms of these three basic structured programming constructs. The program is analyzed as being a composition of "Z-0" with an extended form of do-while which consists of counting from 1 to N in I and a body which is an if-then-else consisting of a predicate "A(I)>0" and a then clause "Z-Z+A(I)".

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```
Z = 0;
DO I=1 TO N;
   IF A(I)>0
      THEN Z = Z+A(I);
END;
```

Figure 2: The example program in structured form.

When it is possible without transforming a program, this is *an* easy analysis to perform. This is true whether or not the program is written in a syntactically structured way. It is possible to write a program which cannot be analyzed in terms of the basic structured programming constructs, unless it is first transformed to change the topology of its control flow. (An example of this is a program which contains a loop with more than one entry point). However, a large number of programs can be directly analyzed in this way. In any case, the parts are easy to understand once they *are* isolated.

Let us now look at the structured programming oriented approach in the light of how easy it is to develop an understanding of the result based on understandings of its parts. First consider if-then-else. If the parts are understood, then it is easy to get *an* understanding of the whole. Namely, in a given situation an if-then-else either acts like the then clause, or like the else clause, depending on the value of the predicate. In Figure 2 the if-then-else adds A(I) to Z if A(I)>0. Composition is also an easy operation to understand. In general, these two structured programming constructs, which describe non-looping programs, meet the criteria set forth above very well.

In contrast, consider the construct do-while in the light of how easy it is to develop an understanding of the resulting program based on understandings of its parts. The body of the loop in Figure 2 can be understood as a conditional which adds A(I) to Z *if* A(I)>0. Unfortunately, it is not easy to go from this to *an* understanding that the loop adds the sum of the positive members of the first N elements of A to the initial value of Z. It is easy to conclude this if an appropriate loop invariant can be found. However, in general, it is not easy to find such *an* invariant.

Another problem with the analysis in the figure is that the close relationship between the statements "Z«B^{H} and "Z-Z+AU)" is not made clear. In order to analyze a *program* in such a way that things which are intimately related are closely linked together, these two statements should be put together in a single locality distinct from the rest of the loop. Having the statements spread through the loop makes it harder to understand that the program as a whole computes the sum of the positive members of the first N elements of A.

The difficulties with do-while stem from the way it looks at a loop. The body of the loop is first *ana\lyzed* like *any* other straight-line program. This understanding of the body is then bootstrapped up to an understanding of the loop as a whole. The problem is that this bootstrapping process is far from automatic. The PBMs for loops take a different approach. They are based on the idea that the body of a loop should not be analyzed in the same way as a straight-line program. Instead, they break the loop up in order to analyze it as built up out of stereotyped loop fragments. (The lines "Z»0" *and* "Z-Z+AU)" *are* an example of such a fragment.)

The PBMs for loops break the loop in Figure *2 up* into four fragments as shown in Figure 3. The first fragment (A) counts

```
 A          B                C          D
I=1;    IF I>N THEN                    Z = 0;
I=I+1;     GOTO EXIT;  IF A(I)>0 THEN  Z = Z+A(I);
```

Figure 3: The example program analyzed by PBMs.

up by one from one. It enumerates the sequence of integers (1,2,...). The second fragment (B) tests the sequence of integers produced by A and stops the loop when an integer greater than N is found. This has the effect of truncating the sequence of integers to the sequence {1,2,... N). The third fragment (C) operates on the truncated sequence of integers. It restricts the sequence by selecting only those integers which correspond to positive elements of the vector A. The last fragment (D) computes the sum of the elements of A corresponding to the integers in the restricted sequence produced by C. In the loop as a whole, the four fragments are cascaded together so that the loop computes the sum of the positive members of the first N elements of A.

The key feature of the analysis above is that it breaks the loop apart along a different dimension from the one used by an analysis in terms of do-while. There *are* two principle advantages to looking at a loop in this new way. First, the loop is broken up into pieces which correspond to easily understood stereotyped fragments of looping behavior. Second, the way the pieces *arc* combined is logically equivalent to composition, which makes it easy to understand.

In order to make the idea that the fragments of the loop are composed together precise, the notion of a temporal sequence of values has been developed jointly by Howard Shrobe [19] and the author [21]. Given a program, such as a loop, which is repetitively executed, it can be useful to talk about the sequence of slates in which some part of the program is executed, and about the sequences of values available in those states. For example, consider the statement ^{M}Z-Z*A(ir in the loop in Figure 2. This statement is executed in a sequence of states. There are sequences of values of I, and Z which are available in those states. These sequences are referred to as temporal sequences of values. The insight is the realization that logically, a temporal sequence of values can be treated in the same way as any aggregate data object. The concept of lazy evaluation [5, 8] uses the same insight going in the other direction. If an aggregate data object (such as a sequence of numbers) is desired, then it can be created temporally, rather than all at once, so that each piece of it is not actually created until it is needed.

Looking back at Figure 3, fragment A produces a temporal sequence of values of I. The elements of this sequence are tested by fragment C. Logically, the key relationship is that A creates data used by C. A is composed with C by passing this data from A to C. Viewed abstractly, it makes no difference whether this data is put into a vector which is passed all at once to C, or, as in the example, A and C are intermingled so that C can use each individual value created by A as soon as it is produced. Intermingling A and C is just *an* efficient way of implementing the data flow from A to C.

The key property of composition which makes it an easy process to understand is that the only interaction between two things which are composed together is that one passes data to the other. They have no other effect on each other. The loop fragments above have this key property. Fragment A will produce a sequence of values of I counting up from 'me no

matter what is happening in the rest of the loop. Fragment B tests the values of I it sees no matter what else is going on in the loop. As a result, each of the fragments can be understood completely in isolation from whatever loop they are being used in. (Fragment B presents a problem because it controls the number of times the other fragments are executed. In order to maintain the independence of the fragments in the face of this interaction, the descriptions of the fragments are prohibited from making any statements about the absolute number of elements in any temporal sequence of values. As a result, from the point of view of the descriptions, the fragments do not interact because their interaction cannot affect anything in the descriptions.)

3. The Plan Building Methods

This section describes the ten PBMs which have been developed. Figure 4 shows how the PBMs are related. They are divided into two main groups. One group can be used to analyze straight-line (non-looping) programs while the other group is used to analyze recursive programs and loops.

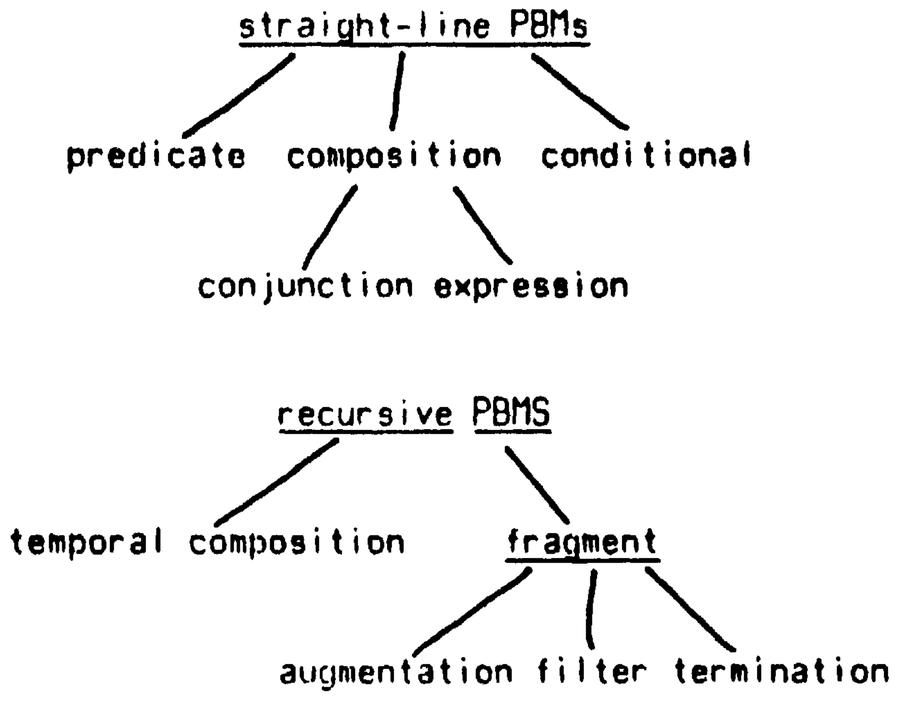

Figure 4: A taxonomy of the PBMs.

There are three basic straight-line PBMs: predicate, composition, and conditional. In addition, two special cases of composition are recognized: conjunction and expression. Figure 5 shows examples of segments of code which would be analyzed in terms of straight-line PBMs.

```
          predicate
IF X<Y THEN GOTO L1;
   ELSE IF Z<Y THEN GOTO L2;
        ELSE GOTO L3;

   conditional          composition
IF X<0 THEN X=-X;    Z=FIRST(SORT(A));

   conjunction          expression
Z=COS(X); W=SIN(X);    Z=SIN(COS(X));
```

Figure 5: Examples of straight-line PBMs.

The PBM predicate is used to build up complex tests out of simpler ones. In the example, two two-way branching tests are combined into a three-way branching test. The PBM conditional combines a test with some actions in order to construct a conditional expression. It is exactly analogous to the structured programming construct if-then-else.

The PBM composition is used to construct arbitrary non-branching sections of straight-line code. Two special cases of composition are recognized because they have particularly useful logical properties. The PBM conjunction combines segments in such a way that there is no data flow between the segments. This means that the pieces are totally independent and can be understood completely in isolation from each other. It is particularly easy to understand what a conjunction does, because the specifications for the conjunction as a whole are simply the conjunction of the specifications for the segments which have been combined.

With the PBM expression, as with composition in general, there is data flow carrying the outputs of segments to the inputs of other segments. The PBM expression is more restricted than general composition in that the segments combined are required to have "substitutable" specifications. A specification is said to be substitutable if each output is described by a single assertion of the form "output-expression-involving-the-inputs". For example the segment "COS" is described by the assertion ^{H}output"cos(input)". It is easy to understand what an expression does, because substitution can be used in order to develop simple specifications for the expression as a whole.

In contrast to an expression, a general composition can combine segments with non-substitutable specifications. This makes it cumbersome to develop a description of what the result does. For example, in the composition in Figure 5, SORT might well be described as producing an output which contains the same elements as the input, and in which the elements appear in increasing order. This being the case, simple substitution will not suffice to conclude that the composition as a whole computes the minimum element in the input. Some actual deduction is required.

It is very easy to analyze a straight-line segment of a program in terms of the straight-line PBMs because it is not possible to confuse an instance of one with an instance of another. This is due to the fact that there *are* only three basic PBMs (predicate, composition, and conditional) and the fact that they are completely different from each other. It should be noted that it is possible to write a straight-line program which is unstructured in that it cannot be analyzed in terms of these PBMs, or in terms of structured programming constructs, without first transforming the code.

The four PBMs which build up recursive structures embody the idea that recursive structures are built up by composing together stereotyped fragments of recursive behavior in a way which is exactly analogous to the way non-branching straight-line segments of code are built up by composing simple segments together. For simplicity, the discussion below describes the recursive PBMs solely in terms of loops. The discussion in [21] shows how they apply to arbitrary singly self-recursive programs. Three of the recursive PBMs (augmentation, filter, and termination) construct loop fragments. The fourth one (temporal composition) combines fragments together.

The PBM augmentation combines an initialization which is executed once with a body which is executed repetitively in order to create a loop fragment. The resulting fragment takes in temporal sequences of values and produces temporal sequences of values. The name "augmentation" is derived from the fact that *an* augmentation can be added into a loop in order

to augment its activities without affecting anything else the loop does.

```
                count                sum
init:           I=1;                 Z=0;
body:           I=I+1;               Z=Z+X;

                 max                 feedback free
init:   Z=very-small;
body:   IF X>Z THEN Z=X;             Z=2*X;
```

Figure 6: Example augmentations.

Figure 6 shows four different augmentations. Consider the second one "Z=0; Z=Z+X;" which computes a sum. The variable X is underlined in order to indicate that it stands for the place where the fragment receives a temporal sequence of values. It creates a corresponding sequence of partial sums in the variable Z. The behavior of an augmentation can be straightforwardly described in terms of a recurrence relation derived from the initialization and the body. For the summation fragment this recurrence relation is "$Z_1=0 \wedge Z_{i+1}=Z_i+X_i$". In situations where the recurrence relation has a simple solution, better specifications can be derived (such as "$Z_i=\sum_{j=1,i-1} X_j$" for the summation augmentation). A large number of the augmentations seen in programs correspond to simple actions such as counting, summing, or calculating a maximum. The count augmentation is interesting in that it does not take any temporal sequence of values as an input but rather simply generates a sequence of values. The feedback free augmentation is particularly easy to understand because is recurrence relation ("$Z_i=2*X_i$") does not refer to prior values of Z and therefore is trivially solvable.

```
IF X<0 THEN ...;
       ELSE ...;
```

Figure 7: An example filter.

The PBM filter constructs a loop fragment from a test which is repeatedly executed. The fragment takes in a temporal sequence of values and restricts the sequence by filtering out some of the values. In a loop, this action is realized by creating a restricted execution environment which is only executed on some of the iterations of the loop. The filter in the example takes in a sequence of values of X and creates two outputs: the sequence of negative values of X and the sequence of non-negative values of X.

```
IF I>N THEN GOTO EXIT;
```

Figure 8: An example termination.

Like a filter, a termination creates a fragment out of a test which is repetitively executed. Also like a filter, it takes in a temporal sequence of of values and outputs a restricted sequence of values. The restricted sequence corresponds to the initial portion of the input up to the first value which satisfies the test. However, unlike a filter, a termination has the far reaching effect that it causes the loop as whole to terminate.

The PBM temporal composition builds complex loops by combining loop fragments together. The process of combining the fragments is logically equivalent to composition. This makes it easy to understand what the resulting loop does. Figure 9 shows an example of this. The four fragments in the figure are composed together in order to yield the loop shown (which is the same as the one in Figure 1). Logically this is just a composition of D(C(B(A()))) and therefore it is clear that the

```
                    Z=D(C(B(A())))      where

 A is          B is          C is              D is
I=1;    IF I>N THEN                          Z = 0;
I=I+1;    GOTO EXIT;    IF A(I)>0 THEN     Z = Z+A(I);
```

the loop which results from the temporal composition

```
        I = 1;
        Z = 0;
LOOP:   IF NOT(A(I)>0) THEN Z = Z+A(I);
        I = I+1;
        IF I≤N THEN GOTO LOOP;
```

Figure 9: An example temporal composition.

result computes the sum of the positive members of the first N elements of the array A since the augmentation A counts up by 1 from 1, the termination B truncates this sequence at N, the filter C selects the elements of the sequence which correspond to positive members of A, and the augmentation 0 computes a sum of these elements.

The process by which the fragments are actually combined in order to produce the resulting loop is somewhat complicated. This process is designed so that the validity of the simple logical analysis in terms of composition will be preserved. The fragments are taken apart, and their pieces *are* reassembled into the resulting loop. The initializations of the fragments are placed before the resulting loop. The bodies *are* placed inside the loop. Their arrangement in the loop is dictated by the data flow communicating temporal sequences of values between the fragments The Key idea is that if the body of one fragment uses a temporal sequence created by the body of another fragment, then the first body should be placed after the second one in the resulting loop. The action of a filter is produced by placing the bodies which receive its outputs within the scope of a conditional predicated on the filter's test.

It turns out to be straightforward to analyze a loop in order to break it apart into fragments combined by temporal composition. The analysis process is based on locating sections of the loop which do not affect any other parts of the loop. One section affects another if it either has data flow to it, or if it controls when it will be executed. Once such a section is located, it is removed as a fragment and the analysis continues. This process is sufficient to locale augmentations and filters. Consider the resulting loop in Figure 9. If it were being analyzed, the first fragment to be located would be D. This would be done by noticing that the line "Z=Z+AOT does not have data flow to any other part of the loop. Once this line is removed the filter C is no longer controlling the execution of anything, so it too can be isolated and removed.

Terminations are somewhat more complex because they perforce affect everything else in the loop since they determine when the loop will terminate. To allow them to be located and removed, the definition of not affect is weakened in order to allow this particular kind of effect. In order to maintain the logical structure based on composition, the descriptions of the fragments have to be prohibited from mentioning anything which a termination can affect (namely the absolute number of timet anything will be executed).

4. Using PBM Analysis to Guide Verification

The most fundamental impact of the PBMs on verification is that they break up a program into a useful hierarchy of segments within segments. This structure can be used as the underlying structure of a proof of correctness, by determining specifications for each segment and then verifying these specifications. With each subproof, the method which is used to generate a proof can benefit from the fact that it only has to work on the single subproof which has been singled out by the PBMs, rather than on the program as a whole.

The impact of the PBMs on the structure of a correctness proof is greatest with *regard* to loops. They lead to a proof which is fundamentally different in form from the standard approach of using a single loop invariant. Consider the program in Figure 10 and how it would be verified by using a single loop invariant as originally introduced by Floyd [4] and Hoare [9]. Assertions *are* passed over the body of the loop in order to develop a statement of what the body does. Then an appropriate loop invariant is developed. Finally, the statement of what the body does is used to prove the invariance of the loop invariant, and the loop invariant is used to verify the specifications of the loop.

```
X = 0;
Y = 0;
L = 11;
DO K=1,10;
   IF C(K)>0 THEN DO;
      X = X+A(K);
      Y = Y+A(K)*A(L);
   END;
   L = L+1;
END;
```

the program is claimed to compute

$X=\sum_{(1\le i\le 10 \mid C(i)>0)} A(i)$ ∧
$Y=\sum_{(1\le i\le 10 \mid C(i)>0)} A(i)*A(i+10)$

assertion summarizing the actions of the body

$(C(K')>0 \rightarrow (X=X'+A(K') \wedge Y=Y'+A(K')*A(L'))) \wedge$
$L=L'+1 \wedge (C(K')\le 0 \rightarrow (X=X' \wedge Y=Y')) \wedge K=K'+1$

a loop invariant

$0\le K\le 11 \wedge X=\sum_{(1\le i\le 10 \mid C(i)>0)} A(i) \wedge$
$L=K+10 \wedge Y=\sum_{(1\le i\le 10 \mid C(i)>0)} A(i)*A(i+10)$

Figure 10: Steps in a proof using a single invariant.

One of the most difficult steps in a proof of this form is the determination of an appropriate loop invariant. Considerable research has been done on ways to automatically develop invariants. Much of this work centers around heuristic methods which can be used to guide a search for an invariant [6, 12, 22J. Some of it is oriented toward directly deriving invariants for specific classes of loops [2, 3, 14]. The work of Basu and Misra is particularly interesting. They analyze the mathematical properties of a loop in order to directly derive an appropriate loop invariant for certain classes of loops.

Figure 11 shows how the program in Figure 18 would be analyzed by PBMs, and how this leads to a proof of correctness. The program is divided into six parts: an augmentation which enumerates integers in K, a termination which truncates this to the sequence of integers from 1 to 18 in K, an augmentation which enumerates the integers from 11 to 20 in L, a filter which restricts these temporal sequences of values by selecting only those elements which correspond to positive values of C(K), an augmentation which computes the sum of the indicated elements of A, and an augmentation which computes the sum of the products of the indicated elements of A. This decomposition leads to a style of proof based on composition which is v*ery* different from the proof in Figure 10. First several lemmas are proved. Each lemma summarizes the actions of one of the parts of the program. Second, the lemmas are combined by composition in order to yield the desired result.

loop fragment	values it produces
K = 1;	$1\le i$
K = K+1;	$K_i=i$
IF K>10	$1\le i\le 10$
THEN GOTO EXIT:	$K_i=i$
L = 11;	$1\le i\le 10$
L = L+1;	$L_i=i+10$
IF C(K)>0 THEN	restricts K_i and L_i
X = 0;	$1\le i\le 10$
X = X+A(K);	$X_i=\sum_{(1\le j\le i \mid C(j)>0)} A(j)$
Y = 0;	$1\le i\le 10$
Y = Y+A(K)*A(L);	$Y_i=\sum_{(1\le j\le i \mid C(j)>0)} A(j)*A(j+10)$

Figure 11: Steps in a proof based on PBM analysis.

The problem of finding the loop invariant is dealt with by breaking it up into pieces. No invariant is needed in order to verify the program as a whole. Rather, each of the proofs of the lemmas requires an invariant. However, each of these proofs is so simple that it is easy to determine what the invariant should be by the methods of Basu and Misra, if not by simple recognition. It should be noted that not all programs can be decomposed by PBMs as nicely as the one in the example. There is no limit to the complexity of the pieces which result. Therefore, it may be very difficult to determine the invariant needed to prove one of the lemmas needed. Even in this situation, the PBM analysis is useful because it determines the parts of the invariant as a whole which are easy and separates them from the parts which *are* difficult. PBM analysis is not a uniform procedure which will determine the invariant for any loop; rather, it simplifies the problems involved with finding most of the invariant for most loops.

The fundamental difference between the form of the proof engendered by PBM analysis and the form of the proof resulting from the single invariant method becomes apparent when the proof is used for something other than giving a yes/no answer to the question of whether or not the program is correct. For example, suppose that the program were incorrect and that therefore the proof failed. The PBM proof is broken up into a sequence of steps which *are* directly linked to parts Of the program. If the failure of the proof can be localized to one of the steps of the proof, then the bug in the program can be localized to the corresponding part of the program. The failure of a proof based on a single loop invariant does not lend itself to this kind of analysis.

5. An Experiment

The straight-line PBMs are similar to basic structured programming constructs, and can be used to analyze any straight-line program that does not have spaghetti-like control flow. The loop PBMs are more novel, and it is not immediately clear how wide their range of applicability is. An experiment was performed in order to estimate what percentage of the loops which programmers actually write can be analyzed in terms of the PBMs without anything more than trivial transformations being done. 20% of the 220 programs in the IBM FORTRAN Scientific Subroutine Package (SSP) [10] were chosen at random and analyzed in terms of the PBMs by hand. The SSP was chosen as an object of study because it is a large group of clearly written programs which is an actual commercial product.

The 44 programs chosen contained 164 loops. It was possible to analyze all of the loops with the PBMs. They were analyzed as being built up by means of the PBM temporal composition out of 442 augmentations, 6 filters, and 186 terminations. Configurations which cannot be analyzed (such as a loop with more than one entry point) did not occur in these loops. The sole difficulty was that one loop had multiple level error exits which branched outside of the loop from inside *an* inner loop. In order to analyze the error exits in terms of the PBMs, they had to be looked at as being explicit exits from the inner loop and the outer loop. This may or may not be a good way to look at them.

Nearly 90% of the time, the pieces which resulted from PBM analysis were very simple. Of the 442 augmentations, 374 (85%) were either easy to understand because they did not have feedback to themselves, or easy to recognize as a product, a sum, a max, a min, or a count. Only 31 (7%) were really difficult to understand. The remainder were of intermediate complexity. All 6 filters were simple comparisons with zero and therefore easily understood.

Of the 186 terminations, 165 (89%) were v*ery* simple to understand because they were simple comparisons with a fixed number, *and* the input which they tested was a simple sequence of numbers, most often (1,2,3,...). Due to the fact that their tests and inputs were so simple, it was trivial to determine the exact number of states associated with their inputs, and hence exactly when the loops they were in would terminate. Most of the 21 terminations that were more complex, were additional terminations in loops which had at least one simple termination. As a result of this, 162 (99%) of the 164 loops contained at least one simple termination, and therefore can be trivially shown to terminate.

6. An Automatic Analysis System

The author has implemented a system (described fully in [21]) which automatically analyzes programs in terms of PBMs. The system operates in two phases. A translation phase reads in • program and converts it to a language independent internal form called a "surface plan". An analysis phase then *analaysis* the program by looking at its surface plan.

A surface plan makes the control flow and data flow explicit independent of the syntactic constructs of any particular language. It is essentially a graph with two kinds of arcs. The nodes of the graph correspond to primitive operations such as: plus, times, and less than. One type of arc specifies the flow of a data object from one node to another. The other type of arc specifies the flow of control from one node to another. Constructs which languages use to implement data flow (such as: variables, assignment, parameters, and nesting of expressions) are not present in a plan. All information about data flow is contained in the data flow arcs. Similarly, constructs which languages use to implement control flow (such as GOTOs and sequential placement of statements) are eliminated in favor of the control flow arcs.

A translator has been written which converts FORTRAN programs, like those in the IBM SSP, into surface plans. Charles Rich [17] has written a translator which converts LISP programs into surface plans. After this conversion, the analysis phase of the system works on LISP programs just as easily as on FORTRAN programs.

The translator works by running over the program like an evaluator, creating control flow arcs, data flow arcs, *and* nodes which comprise a surface plan as it goes. The translator has detailed knowledge of the constructs which implement data flow and control flow. It does not have any knowledge of what the primitive functions do except how many inputs and outputs they have.

Once a program has been translated into a surface plan, it is then analyzed in terms of PBMs. This is done in two main steps. The first step looks primarily at the control flow arcs and analyzes the straight-line sections of the program while merely identifying the loops in it. This is essentially an analysis in terms of basic structured programming constructs as discussed in Section 2. The analysis is done bottom up by locating minimal configurations which can be grouped together in accordance with a PBM. Whenever such a configuration is located, it is grouped together into a single node, and the analysis continues. This process terminates when the entire program is grouped into a single node.

The first step of analysis can be compared with the system of B. Baker [1]. Her system uses graph theoretic methods in order to analyze FORTRAN programs based on their control flow in terms of basic structured programming constructs. *Her* system then outputs the program in a structured form. GOTOs are used in situations where an analysis in terms of the structured programming constructs is not possible.

The second analysis step analyzes the loops discovered by the earlier steps according to the four PBMs temporal composition, augmentation, filter, and termination. This analysis is based primarily on data flow connectivity and proceeds as described in Section 3. For example, augmentations are located by finding minimal subsets of the body of a loop which do not have data flow to any other part of the loop. Once an augmentation is discovered, it is removed from the loop and the remaining loop is analyzed further.

7. PBMs and Programming Language Constructs

The PBMs which are used in the first step of analysis correspond to basic structured programming constructs. If the analysis system operated on programs written in a language which required the use of these basic structured programming constructs, the first step of analysis would not be necessary. On the other hand, the loop PBMs do not correspond to any existing structured programming constructs.

However, the loop PBMs do embody natural ideas, and many

programming constructs have features in common with them. For example, there are a variety of constructs which have the feature that they separate out an augmentation and a termination, which together enumerate a sequence of values, from the rest of the loop which does something with them. The most common example of this is the DO statement. It makes a clear syntactic distinction between the enumeration of a sequence of integers a*nd* their use. However, in most languages, the DO statement does not correspond semantically to an augmentation *and* a termination because the programmer is not prohibited from assigning to the DO variable in the body of the loop.

The MAPC function in LISP is similar to the DO statement except that it enumerates the elements of a list instead of a sequence of integers. GENERATORS in ALPHARD [18] and ITERATORS in CLU [13], extend this concept to the enumeration of elements of arbitrary data types. The MAPCAR function in LISP is interesting because as well as enumerating the elements in a list, it contains a standard augmentation "(SETQ X NIL) (SETQ X (APPEND X result))" which forms a list of the results.

The language APL [15] has several operators which operate directly on vectors in a fashion very similar to the way PBMs operate on temporal sequences of values created by loops. For example, the reduction operator is similar to augmentation in that it applies an operator such as plus or times to the elements of a vector in order to compute the sum or product of all the elements in the vector.

The Language developed by Kahn and MacQueen *[11]* makes it possible to construct coroutine processes operating on sequences of values which interact in the same way as augmentations and filters. The processes can be combined together into expressions which can be evaluated either sequentially, Or in parallel.

With either APL or the language of Kahn and MacQueen, in order to get the significant savings in time and space which result from implementing augmentations and filters by loops operating on temporal sequences of values the language would have to have a smart compiler. The compiler would have to know how to combine the pieces together into loops. The work which has been done on developing a compiler for APL (see for example, [7]) indicates that this is not an unreasonable goal.

8. Conclusion

The basic idea behind the analysis method presented here is that a typical loop can be looked at as a composition of stereotyped fragments of looping behavior. This point of view reflects the way many programmers analyze, understand, and reason about loops. The PBMs, and the idea of temporal sequences of values *are* important because they make if possible for an automatic system to analyze, understand, and reason about loops in this same straightforward way.

The PBMs were developed as part of a larger research project. The goal of this project is to develop a system (called the "Programmer's Apprentice") which can assist a person who is writing a program. Research on this system [16, 17, 19, 20, 21] is being carried out by a group consisting of Charles Rich, Howard Shrobe, and the author. The intent is that the apprentice system will cooperate with a programmer throughout all phases of work on a program and be able to communicate with him about it. The *programmer* will do the hard parts of design and implementation while the apprentice will act as a junior partner and critic, keeping track of details and assisting the programmer whenever possible. PBMs play an important role in the processes by which the apprentice develops an understanding of and reasons about a program.

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EXPERT: A SYSTEM FOR DEVELOPING CONSULTATION MODELS

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ABSTRACT

EXPERT Is a system for designing and building models for consultation. An EXPERT model consists of hypotheses (which can be structured Into causal and taxonomic networks); findings or observations; and decision rules for logically relating these components. A relatively simple language for describing models is employed. Logical and probabilistic rules are restricted to particular types which implicitly order the tasks performed by the control strategies: classification, question selection, and explanation. Explicit representations of decision rules are emphasized, as opposed to suboptimal scoring functions. This results in more easily predictable and correctable performance for a model. *The* system is currently being used to develop consultation models in domains such as rheumatology, ophthalmology, and endocrinology.

INTRODUCTION

The development of knowledge-based consultation programs that exhibit near-expert performance has progressed rapidly in recent years [1-1]. These efforts have focused on specific medical application areas and have relied on one or more experts to build a knowledge base. The hallmark of these consultation systems has been their reliance on large amounts of structured expert knowledge in the application domain [5]. In each system, the choice of knowledge representation has come first, and been a primary determinant of the type of reasoning procedures used. In contrast to traditional methods of automated diagnosis, little emphasis has been placed on the optimality of decision-making under general criteria (utility, information entropy, etc). Rather, these systems have attempted to develop representations based on simulations of the experts* conceptual structures and reasoning [6]. The various systems have been reviewed and contrasted in [7] and [8]. Szolovits and Pauker [8] point out that there is frequent and general use of categorical (explicit) decision rules In all the systems, although they all also use various kinds of heuristic scoring methods to capture the uncertainty associated with medical decisions. Unfortunately, these methods often have side effects of propagation that make the results of a consultation less clearly predictable. Despite the specific applications for which they were first developed, some of the systems, such as CASNET and MYCIN have been generalized to accept knowledge bases in other domains. After several years of developing the CASNET representation [9]$_t$ enough new ideas have emerged from our own experience and that of the other AIM (Artificial Intelligence in Medicine) investigators to lead us to develop a new and more general representation of knowledge for use in consultation systems.

The new consultation scheme EXPERT, consists of a general facility for developing and testing consultation models. It was designed without being tied to a specific application. EXPERT has been used to develop models in ophthalmology, endocrinology and rheumatology. Some of the major themes in the design of EXPERT include:

1) a relatively simple language and notation to represent expert knowledge. The representation is consistent with the traditional two-level view of a diagnostic problem: selecting appropriate hypotheses or conclusions by interpreting a set of findings or observations.

2) an emphasis on categorical reasoning instead of on suboptimal scoring functions. A form of probabilistic production rules is available, which can be compatible with statistically accurate classification when appropriate data is available.

3) descriptive knowledge as a partially-ordered conceptual network, a special type of a semantic net, which, as in the CASNET system, can be pre-compiled for the interpretation of individual cases, hence leading to efficient performance.

4)an emphasis on decision methods which tend to yield predictable and correctable results. This may in some cases require that the expert provide more explicit statements of correlations among findings and a greater number of decision rules. The representation and control strategy simplify the task of correcting erroneous conclusions. Since the interaction among rules and the associated classification strategies is consistently predictable, it is not difficult to trace the changes in program behavior that will result from modification of individual rules. A novel feature of EXPERT is that it automatically detects changes in the reasoning about cases stored in its data base that will arise from modification of the decision rules. This is an important tool for incrementally generating and testing an expert model.

The process of creating and running an EXPERT decision-making model is somewhat similar to writing and running a computer program. An editor is used to create a file which will contain statements describing a model. A model is translated into an efficient internal representation by the compiler program, XP. The model may then be executed, and cases may be entered for consultation, using the program EXPER1.

MODEL DESCRIPTION

An EXPERT consultation model consists of 3 sections:

a) hypotheses,
b) findings,
c) decision rules

Findings are the facts about a patient elicited during a consultation. In a medical domain, they are the history, symptoms, signs, and laboratory test results. Findings are reported in the form of true, false, numerical, or unavailable responses to questions from EXPERT. Hypotheses are the conclusions that may be inferred by the system. They include diagnostic and prognostic decision categories, therapy recommendations, and intermediate hypotheses about pathophysiological states, expected causes of illness, or typical aggregates of findings. A measure of uncertainty is usually associated with a hypothesis.

Within the 3 sections of the model, several subsections are possible. The representation used in building a model divides the sections as follows:

```
**HYPOTHESES
•TAXONOMY
[•CAUSAL AND INTERMEDIATE HYPOTHESES]
[•TREATMENTS]
••FINDINGS
••RULES
[•FF RULES]
•FH RULES
[•HH RULES]
```

Two asterisks indicate one of the three major sections. A single asterisk indicates a subsection, and brackets indicate optional statements.

HYPOTHESES

The major hypotheses are structured into a taxonomic classification scheme. Contained within the "TAX0N0MY subsection shown above are the possible diagnostic and prognostic conclusions and the useful set-subset relationships between general diagnostic categories and intermediate interpretations. As an example, we show part of a thyroid disease classification:

```
•TAXONOMY
EU      .Euthyroid (.75)
ThD     .Thyroid Dysfunction (.25)
HYPER   ..Hyperthyroidism (.05)
HYPO    ..Hypothyroidism (.20)
NOP     .No Pathology (.70)
GRAV    .Graves' Disease ( .25)
```

The mnemonics for each hypothesis become a shorthand for specifying its place in the production rules. The optional weight associated with some hypotheses indicates their frequency of occurrence relative to the higher level hypotheses in which they are included. The indentation indicates the set-subset relationship among hypotheses.

The optional subsection of "*CAUSAL AND INTERMEDIATE HYPOTHESES." is used to define hypotheses that may not belong in the taxonomy because they are not explicit categories of disease. However, these intermediate hypotheses can be valuable diagnostic summaries of important combinations of events. They can stand for pathophysiological states, such as "elevated thyroid uptake," or they may abstract many findings such as "ocular symptoms of Graves[1] disease." It is usually much simpler to reason with a small set of such hypotheses than with the much larger set of original findings. Hypotheses which appear in the taxonomy may reappear in this section indicating a causal or superset-subset relationship with the intermediate hypotheses.

Treatments are also described within

the general notational form of hypotheses. Their interpretation is somewhat different. They may stand as a taxonomy of therapies, or they may be organized into a hierarchy of treatment plans. The top level treatment hypothesis is the general treatment plan for a particular diagnostic category and lower level nodes are subsets of possible treatments. In this case, the weights indicate the prior frequency with which it is believed that a specific treatment will be successful, given that the treatment category is indicated for the patient. An example of a treatment category is:

•TREATMENTS
RXTHY Thyroid medication
RXUSP .Thyroid USP
RXU1 ..Thyroid USP, 1 gram daily
RXU2 ..Thyroid USP, 2 grams daily

FINDINGS

Findings are represented as attributes that can be present, absent, or undetermined in the patient, or as a numerical variable, which when measured adopts a value within a pre-specified range. In those cases where uncertainty is associated with an observation, the uncertainty must be described explicitly in terms of additional modifying findings. For example, the accuracy of a test result can be requested, and decision rules then written to logically modify inferences about the original test. Our experience has been that uncertainty about facts tends to be circumscribed by experts to a few important situations in each medical domain. Rather than impose a generalized heuristic for handling them, the EXPERT representation encourages the model builder to pay attention to the manner in which uncertainty in each important situation affects further inferences.

For purposes of acquiring information about a patient, four question types may be employed: a) multiple choice, b) checklist, c) numerical, and d) yes-no. The checklist question differs from a multiple choice question in that the choices are not mutually exclusive, and more than one may be true. The checklist question combines many questions that could be asked individually as single questions. Although some items in a checklist may be more important than others, placing them together serves to bring up for consideration related topics at the same time. There is a higher level of oontrol over the sequence of questioning by the system. It is possible to group several of the question types (checklist, numerical, etc.) together in the form of a questionnaire. When a member of the questionnaire is selected to be asked, all the questions must be asked in the order of the questionnaire. The questionnaire is particularly effective when used in conjunction with logical constraints among findings: the finding-to-finding, or FF, production rules.

Some questions may involve different degrees of risk or cost, which affect the general order in which they are usually sought in the course of a consultation. For example, history and symptom questions are almost always asked before a complicated laboratory test is requested. An optional cost declaration can be associated with a finding. It serves to order the acquisition cf findings, since the questioning strategy seeks information about the least costly findings first. Examples of the question types are shown below:

••FINDINGS
•BEGIN QUESTIONNAIRE
•NUMERICAL/MIN=1/MAX=100
AGE Age:
•MULTIPLE CHOICE

M Male
F Female
•MULTIPLE CHOICE
Pregnancy test:
PREGP positive
PREGN negative
•CHECKLIST
Symptoms Appeared/Intensified, Past Year:
RHP Rapid Heart, Palpitations
•END QUESTIONNAIRE

RULES

There are three types of rules for describing logical relationships among findings and hypotheses:

1) FF - finding to finding rules,
2) FH - finding to hypothesis rules,
3) HH - hypothesis to hypothesis rules.

The FF rules specify truth values of findings that can be directly deduced from an already established finding. They are processed in the fixed order specified by the model designer, and are crucial for establishing local control over the sequence of questions in a fashion consistent with medical practice. The format of FF rules is:

F(MNE1,TVAL) -> F(MNE2,TVAL)

where MNE1 and MNE2 are mnemonics for findings and TVAL *{T,F,U, or a number). If the left side of the rule is satisfied, the response to the right side of the rule is known, and question MNE2 will not be asked. A simple example of an FF rule is:

F(M,T) -> F(PREGP.F)

which would rule out seeking pregnancy tests for males. The FF rules are particularly useful when used with questionnaires. They can describe conditional branchings from sections of the questionnaire. This is most advantageous when questions are consecutively ordered from the general to the specific.

FH rules are logical combinations of findings which indicate confidence in the confirmation or denial of hypotheses. The general format for these rules is:

X1 & X2 & ...Xi->H(MNE,CF) -U< CF < = 1

Where: Xi = F(MNE.TVAL) or

= [n:F(MNE1,TVAL), F(MNE2,TVAL)...]

If the logical combination of findings on the left side of the rule is satisfied, the hypothesis, MNE, is assigned a confidence value, CF. The selector argument, n in [n:F(MNE1,...], indicates that if n of the listed findings are satisfied, the bracketed condition is evaluated as true. An example of an FH rule is:

F(RHP,T) & F(FFT,T) -> H(HYPER,.5)

which summarizes the inference:

IF: rapid heart palpitations are reported by the patient to have noticeably increased in the past year and a fine finger tremor is observed in the patient,

THEN: consider the hypothesis of hyperthyroidism with a confidence of 0.5.

Confidence measures are assigned on a scale of -1 to 1, with 1 being complete confirmation and -1 being complete denial, following the CASNET and MYCIN rationale and usage [2,9]. When in the course of a consultation several rules are applicable in inferring a hypothesis, they are compared and the single rule with the MAXIMUM absolute value of confidence in the hypothesis will prevail. The maximum is used as a fuzzy logic selector because of the disjunctive nature of the rules. Because no universal scoring function can adequately handle conjunctions of findings, we have taken the approach that requires the designer to explicitly specify separate rules for significant combinations of correlated findings. In return, the scheme guarantees predictability of weight interpretation for the model designer. This applies to the FH rules. After these rules are processed, inferences may be derived through the HH rules and the the taxonomic-causal network. These procedures are described below. The system also assigns a small bonus for hypotheses that have the greatest number of satisfied rules supporting them.

The HH rules allow the model builder to specify inferences among hypotheses and treatment selections that follow from other (diagnostic and prognostic) hypotheses. Since such higher level inferences may be sometimes modified by the presence or absence of a finding, the left hand side of HH rules may also contain assertions about findings. In addition, each HH rule must have a context defined in terras of a set of findings or hypotheses, which enables the application of efficient rule evaluation strategies over the compiled model. The context specifies a set of necessary conditions among the findings to enable evaluation of the HH rule. HH rules are evaluated in the order of specification in the model. Hypotheses are specified with a range of confidence which must be satisfied for the HH rule to be invoked. The HH rules are implemented in a table of the following form:

•HH RULES

•IF THERE ARE EYE AND THYROID DYSFUNCTIONS

F(EENO,FHF(HXTH,T)

•THEN CONSIDER GRAVES' DISEASE:

F(ETH0,T)&H(EYE,.5:1.) -> H(GRAV,.9)

•END

CONTROL STRATEGIES

In any consultation system, the principal control strategy problem is to structure and rank conclusions. In many general situations the control of sequential questioning is also desirable, whereas in more stylized and well-defined applications, a prespecified logical control of questioning may be possible. Question selection is usually closely related to the formulation of tentative hypotheses that best explain the patient's condition.

— Order of Evaluation —

When an assertion or result about a finding is made to the system, the rules in which this result appears are evaluated. The results are usually received in batches, as in the form of responses to a multiple choice or checklist question. The rules are evaluated in the following order to produce weights which rank the hypotheses.

1. FF rules are evaluated first. They take simple true, false, or unknown responses, and merely enlarge the set of new finding results. They are handled in the same way as results received directly in response to questions.

2. FH rules are evaluated next. Only those FH rules in which new results of findings appear need be evaluated. Fh rules have the property that when the left hand side of a rule is evaluated as true or false, it remains true or false for the

remainder of the consultation session, unless an erroneous response is received.

3. hh rules are evaluated last. The IF part of each hh rule table is evaluated at the same time as the FH rules. Only HH rules found in tables which have their IF part evaluated as true are considered. All such HH rules must be reevaluated sequentially. The premises and consequents of Hh rules may include hypotheses and associated intervals of confidence. Unlike findings which remain true or false, these intervals can change not only directly from finding results, but also indirectly from other rules (both Fh and HH) which affect the confidence measure of a hypothesis. Hh rules are evaluated in the order of their appearance in the model. There is no backwards chaining, because the order of evaluation is determined beforehand by the model builder. Self-referencing rules are therefore acceptable, because HH rules and tables are evaluated in sequence, by their order of appearance in the model file, it is important to order the HH rules carefully. An hH rule implying a hypothesis K1, which is later needed to establish another hypothesis H2, should appear in the model file before H2 is referenced in the left side of another KH rule. The confidence ranges used in the HH rules are those which have been directly set by other FH or HH rules. They are not the adjusted weights implied by the taxonomy.

JJ. The above procedures result in the assignment of those confidence measures, CF(i), which can be directly determined from the rules of evidence and hypothesis weight propagation: the FH and HH rules. When more than one rule is applicable, the maximum absolute value of confidence is used. Another procedure is invoked that is helpful both in question selection and as a simple heuristic to adjust weights slightly. Each hypothesis which has some positive evidence, in the form of a satisfied rule or a partially satisfied rule (with unknown truth value) is marked. The count of such rules which apply to each hypothesis is kept. This corresponds approximately to the number of positive indicators of a hypothesis.

5. A different set of weights is derived from the taxonomy and causal network structure. Forward weights are propagated from predecessor to successor and inverse weights are propagated from successor to predecessor. A taxonomy contains implied relationships between hypotheses that can be treated similarly to causal connections. The procedures used to generate weights are similar, but not identical, to those used in CASNET [9]. After all Fh and HH rules have been evaluated, the measures of confidence, CF(i), may be modified or propagated according to their the taxonomic or causal relationships. Because hypotheses which are related by causal or taxonomic connections can be topologically sorted, efficient algorithms can be used to compute the weights implied by this partially ordered network.

6. A final weight is derived from both the rule-based and taxonomic-causal net weights. It is taken as the maximum absolute value from all the indicated directions (with the appropriate sign). A small bonus (no greater than .33) may be awarded to the final weights. The bonus is given on the basis of the percentage and number of rules (derived directly from findings) that are covered by any single hypothesis. The largest bonus is given to the hypothesis which can potentially cover the most rules. The bonus effect is slight and has its greatest effect when only few results have been received, and not many high confidence rules are satisfied.

— Sequential Test Selection —

The question selection procedures are relatively exhaustive, but straightforward and efficient. Most of the tasks performed by the selection procedure are simple and follow directly from the inference procedures. Once a single finding is selected to be asked as a question, the explicit question structure, such as a multiple choice or checklist question is invoked. Rules are examined that have been evaluated as unknown and their effect on the most likely current hypotheses is considered. Question structures temporarily override the sequential question selection procedures; the system proceeds with the pre-specified questioning order, subject to the FF rules for branching. The general sequential test selection procedure may be specified as follows:

I. Consider those rules (FH or HH) such that:

a) They set confidence measures for marked hypotheses - they are related to current evidence.

b) The confidence of the rule is greater than the current confidence in H(J) - it provides useful additional information.

II. Select an unasked finding F(i), belonging to the set of rules found in part I. such that:

a) the cost is minimum;

b) the current weight W(H) is greatest - indicating that the finding pertains to the most likely hypothesis;

c) the potential CF(H) is greatest for F(i) - so that this finding F(i) is one that can yield greater confidence in H(j) than another F(k).

THE XP AMD EXPERT PROGRAMS

The system is written in FORTRAN and occupies about 70K on a DEC-20 computer. This results in relatively efficient processing and also provides the potential for implementation on a minicomputer. The program XP compiles a model for use by the EXPERT consultation program, and indicates any errors found in the model.

The consistency checking module considers the effect of modifications to a model. A data base of representative cases with known conclusions is stored, and after the model has been modified and compiled, the XP program proceeds sequentially through the cases, noting any changes in the reasoning for each stored case, as reflected in the confidence weight assignments to the major conclusions. This is a practical means of reviewing consistency in a model, short of more powerful theorem proving capabilities. It is a more empirical approach than that taken in TEIRESIAS [10], where a model of the relationships among rules and control strategy was developed to help the model builder write new rules for correcting a previously misdiagnosed case, without tracing the effect of rule changes on other cases.

The user communicates with EXPERT by responding to questions posed by the program or by using a simple command language. Commands may be issued on a sequential basis, so that the current ranking of conclusions may be determined. Explanatory information is also available, such as reasons for asking a question, or an analysis of why a hypothesis has a particular confidence weight.

RESULTS AND DISCUSSION

Several applications of the EXPERT system are in progress. Consultation models are being developed in endocrinology (thyroid diseases), ophthalmology, and rheumatology. A consultation system in rheumatic diseases appears to have strong potential for acceptance by the medical community. There is a shortage of rheumatologists in the United States, and keeping up-to-date on the interpretation of many new immunological tests can be difficult for non-specialist physicians. In collaboration with investigators at the University of Missouri wo have tested the EXPERT formalism by developing a prototype consultation system for rheumatic diseases. Initially, the set of problems considered has been confined to fewer than 10 important, yet complex diagnostic categories. The model is being expanded to cover additional problem areas.

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LEARNING PRODUCTION RULES FOR CONSULTATION SYSTEMS

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ABSTRACT

Production rules, with associated measures of probability or confidence, play an important role in contemporary consultation systems. Procedures have been developed which learn a set of probabilistic production rules from a training sample. We have experimented with these methods, by deriving a set of production rules from a medical data base.

Production rules, with associated measures of probability or confidence, play an important role in contemporary consultation systems [1,2]. A recent AI learning system has concentrated on extracting production rules from relatively noise-free data [3] whereas more traditional pattern recognition learning methods have to a large extent dealt with statistical approaches [4]. The major advantage of production rules (and a disadvantage of most statistical methods) is the readily understandable format of the production rule for the expert who is the source of knowledge and the user of consultation systems. A theme of the present work is to show that for some applications, probabilistic productions rules can be learned from a training sample. Moreover, the form of these production rules is similar to those used in a current large-scale consultation system [8]. Some of the procedures employed appear to be analogous to those an expert would use to generate rules from experimental data. A similar goal has motivated application of variable valued logic methods [9] to rule induction in pancreatic cancer.

The problem can be stated as: given a set of h binary features and samples for class C and its logical complement C, find a relatively small set of exhaustive and mutually exclusive production rules (of the type found in decision tables) and their associated probabilities. For simplicity, and to reduce dimensionality, binary features, and a single class and its complement are considered. The task of reducing the features to this form and feature extraction, has been considered separately [5].

A somewhat analogous problem has been previously investigated in the context of learning decision trees [6,7]. Our work has some similarities to version spaces [3], but we consider a set of production rules (not a single production rule) and the data may be very noisy, i.e. the same pattern often appears in both C and its complement. In our testing, the sample data was processed so that it appeared in the following form: For six features, there are 64 possible patterns, of which 39 occurred.

	PATTERN						PROB	FREQ
1)	1	2	3	4	5	6	1.0000	4
2)	1	2	3	4	5	-6	.5000	4
3)	1	2	3	4	-5	6	.8222	45
4)	1	2	3	4	-5	-6	.7104	38
5)	1	2	3	-4	5	6	.3333	3
6)	1	2	3	-4	5	-6	.0000	10
7)	1	2	3	-4	-5	6	.6874	32
8)	1	2	3	-4	-5	-6	.4374	16
9)	1	2	-3	4	5	6	.0000	0
			.					
64)	-1	-2	-3	-4	-5	-6	.0000	0

Table 1.

Each pattern has an associated PROB, the Probability of class C given the Pattern, and FREQ, the total frequency of the pattern (among the samples).

The solution consists of finding a smaller set of production rules (with don't care conditions on the variables in addition to yes/no) such that: the set of production rules is much smaller than the number of patterns, the frequency of occurrence for

each production rule is >k, and the classification accuracy is as close as possible to that in the original data base. This is desirable because : (a) the expert can only understand and accept a limited number of rules (b) the frequency of occurrence of any rule must be large enough to produce relatively accurate estimates of probability.

what follows is an example of a set of 7 production rules which was derived for the above 64 possible patterns. The data consists of historical information taken from 341 patients with bronchial asthma. The derived classification rate for the 341 patterns, which was used to aid in predicting which patients would benefit from therapy, was competitive with other statistical methods, such as the Layesian and the nearest neighbor methods.

	PATTERN						PROB	FREQ
1)	1	2	3	4	*	*	0.769	91.
2)	1	*	3	-4	*	6	0.606	66.
3)	1	*	3	-4	*	-6	0.315	54.
4)	*	*	-3	*	*	*	0.206	34.
5)	1	-2	3	4	*	6	0.645	31.
6)	1	-2	3	4	*	-6	0.375	32.
7)	-1	*	3	*	*	*	0.121	33.

OPTIMAL CLASSIFICATION RATE: 72.727 %
CURRENT CLASSIFICATION RATE: 71.261 %

Table 2. (* is a don't care)

In the order of increasing computation time, three procedures are described for deriving a set of production rules.

a) The features are ordered from highest to lowest in significance (this can be done in conjunction with the expert). A closeness threshold is given, for which rules with probabilities within the threshold can be combined (when logically compatible). The program proceeds to combine rules, beginning with the least significant feature (i.e. those patterns which differ only in the rightmost column). The procedure's criteria for combining patterns are similar to two important reasoning criteria used by experts: sensitivity and specificity. In this case we require a minimum frequency and a degree of closeness of probability for any pair of rules to be combined. however, the essential difference with the usual procedures for combining rules and replacing constants with variables, is that these rules have probability measures which must be taken into account. These measures change our interpretation of which rules may be combined. Ihis is a relatively simple procedure that gives quick ana often good results. For example, assume that the thresholds were set so that 2 rules could be combined either when they have probability measures within .1 of each other or when the frequency of one of them is less than .10 . In Table 1, patterns 1 and 2 could be combined because each has a small frequency. Patterns 3 and 4 could not be combined because both frequencies are above the threshold and the probability estimates differ by more than .1.

b) Without ordering the features as in (a), all possible orders (n!, where n is the number of features) are considered. This has in many instances yielded near-optimal results. Table 2 was generated using this procedure.

c) Using a search and branch ana bound technique, an optimal solution can be found for a set of n production rules. AI search techniques have recently been given more attention in pattern recognition theory [7].

These procedures can result in a set of production rules which are understandable to the expert, include dependencies, and are competitive in performance with other statistical procedures. The requirement that the number of features included in a rule be no larger than eight is consistent with the maximum size that an expert is likely to provide. The number of the samples must increase if rules containing more findings are required. Rules of this form are compatible and can be incorporated in models developed with a new consultation system [8]. The examples presented correspond to a form which was suggested by a physician who felt that it would be readily understandable by other physicians. We are currently working on another application of much greater complexity in developing a consultation system in rheumatology. While this learning approach is likely to work in only small applications, it should prove interesting to see whether limited sets of rules could be learned and used in relatively de-coupled subsections of the consultation system.

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AUTOMATIC PROGRAM DEBUGGING

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Abstract : This paper presents a system (PHENARETE) which understands and improves Incompletely defined LISP programs, such as those written by students beginning to program In LISP. Thes system takes, as Input, the program without any additional Information. In order to understand the program, the system meta-evaluates It, using a library of pragmatic rules, describing the construction and correction of general program constructs, and a set of specialists, describing the syntax and semantics of the standard LISP functions. The system can use Its understanding of the program to detect errors In it, to debug them and, eventually, to justify Its proposed modifications. This paper gives a brief survey of the working of the system, emphasizing some commented examples.

1.0 Introduction

Much effort Is spent on the development of tools to help programmers In constructing, debugging and verifying programs. From simple editors and trace-packages, the trend Is towards more and more sophisticated automatic programmers [3], automatic debuggers C7] automatic assistants [6], automatic verifiers [5] or even the construction of new - semantically more firmly based - programming languages (PASCAL, ALPHARD).

Most of these tools exhibit some weaknesses such as : they Impose too many constraints on the Intuitions of the programmer or they work only on a very limited subset of possible programs (cf [7]) or they work only on correct programs (cf [5]).

Our aim In the design of our program understanding system was three-fold :

- 1 - we wanted to have a system which makes explicit the knowledge Involved In constructing and debugging programs;
- 2 - we wanted our system not to verify the correctness of programs but their consistency and
- 3 - we wanted the system to provide hints for improving and correcting programs.

To this end we have built a program understanding system capable of automatically correcting and Improving programs. This system, PHENARETE, assists beginning programmers during the writing and debugging of their programs.
PHENARETE anlyses the text of the program and when it detects Inconsistencies or informalities, It constructs and proposes possible corrections or Improvements. These propositions constitute for the beginning programmer a crucial component of his apprenticeship : basing on examples the process of improving and correcting imperfect programs, and basing on models the process of inventing future programs.

2.0 Overview of the system

The system takes as input the draft version of a LISP program and delivers as result of its treatment one or more versions of the same program, corrected and improved. PHENARETE proceeds in several steps : first it effects a preliminary analysis of the text of the program to detect and correct surface errors. Surface errors are errors detectable by local anlysis : simple syntax errors such as misspellings or parenthesis errors and errors concerning the wrong number of arguments in function calls. During this first analysis PHENARETE collects information for the following steps. Every time it meets the name of a function it automatically activates a specialist, associated with this function, by the process of data driven function invocation. These specialists represent its knowledge about the use and the effects of the associated functions.

The result of the first analysis - a syntactically correct program - is then meta-evaluated to verify the programs well-formedness. We say that a program is well-formed if it doesn't contain evident infinite loops, doesn't have statements never executed and if it doesn't contradict the set of rules incorporated in PHENARETE. Every proposition our system delivers is a well-formed program.
When PHENARETE detects some informalities or inconsistencies, it annotates the corresponding part of the program and sends the code and the annotation to the repair-man, a module designed to eliminate errors. The system stops the analysis process when it doesn't find any more possible improvements.

3.0 Organisation of PHENARETE

The system is based on four main concepts :

-1- During the analysis of a program, PHENARETE constructs an internal representation of the program in the form of cognitive atoms. These may be considered as the nodes of a network-like representation of the program.
Each cognitive atom is composed of a set of facets which represent its different aspects, about which questions could be asked. The facets are filled in during the analysis process.
We distinguish between three classes of cognitive atoms, those concerning variables, those concerning labels and those concerning functions.

-2- A set of specialists, i.e. a set of procedural specifications of the syntax and the operational semantics of the standard LISP functions.
We distinguish between two different types of specialists :
- those describing the syntax and
- those describing the semantics

of the associated functions.

example : specialist CAR for the syntax

```
[CAR-1 (X) =>
        v (& atom (CAR X)
             & type (X) = LISTP)
        v (& S-expression (CAR X)
             & type (val (X)) = LISTP)
  else :
             modify X until CAR-1 (X) = T]
```

paraphrasing : CAR expects that its argument is - an atom and the type of the value of the argument is a list - a S-expression and the type of the value of that S-expression is a list (e.g. a function call) else CAR has to modify the argument until one of these two conditions is true

and the specialist CAR for the semantics

```
[CAR-N =>
  arg : (X (meta-eval X))
 test : (type (val (X)) = LISTP) ->
        (type (val (X)) = ?)
            -> hypothesize (X, type LISTP)
          T -> complain (X, type : LISTP)
action : if (exist (CAR X)) --> (CAR X)
      else (create (CAR, X)) --> (CAR X)]
```

or In paraphrasing : CAR-N has an argument named X, which must be evaluated. One must verify, If the type of value of the argument is a list, all is ok, else, if the type of value of the argument isn't Known, one has to create a hypothetical value of type LIST for X, else, one has to call the repair-man to change the text of the program in such a way that the value of X becomes a list. The value of CAR is if there exists already a CAR of X, this CAR, else one has to create a symbolic value for X, the CAR of which will be the desired value.

Note that the internal description constructed during the analysis of each user function is used to construct two new such specialists for each user function.
The specialists are the agents of the meta-evaluation and they represent the systems knowledge about the programming language used.

-3- An algorithm of meta-evaluation [2] which helps the system to understand each of the possible paths of the program. This algorithm includes modules to determine the symbolic values on which the evaluation is carried on.

-4- A set of pragmatic rules describing general program constructs and stereotyped methods to repair inconsistencies. These rules formalize and express explicitly the knowledge activated by every programmer when he is reading a program. Ue do not use rules concerning the task domain of the programs : our intention was to build a system which does not ask for any additional information. The system should work in any possible task domain, numeric as well as symbolic.

examples of pragmatic rules J

(1) rule of the dependence of a loop of the predicate ->
if no variable of the exit-test of a loop is modified inside the loop-body, then the loop is independent of the exit-test and its execution is non-terminating or the loop will never be executed.

A slight refinement of this rule is the following rule :

(2) rule of the structural well-formedness of loops ->
in a loop at least one of the variables used in the exit-test has to change its value inside the body of the loop, in such a way that its structure is simplified and converges towards the satisfaction of the exit-test.

In order to use this rule, we have implemented a small theorem prover which can prove the convergence by induction. For the proof of this rule, the theorem-prover takes the symbolic value of the variables at the entrance of the loop, and the modified symbolic values of the same variables after one meta-evaluation of the loop-body and tries to prove the convergence towards the stop test. Let us give one last example of a pragmatic rule :

(3) rule of the structure of recursive loops ->

in a recursive function, the recursive calls have to be inside of selection-clauses, and at least one of the clauses must not contain a recursive call.

Actually we have about a hundred rules incorporated in the system, dealing especially with iteration and recursion. For almost every rule ther exists a dual one indicating how to modify the program in such a way that the first one is satisfied.

4.0 A Commented Example

To use PHENARETE, the user has to give to the system only the text of the draft version of the program he wants to write, without any additional information like input/output assertions, commentary, plans etc. The system will try to understand what the user wanted to do, and, if necessary, modify the text of the programm.
To give some feeling of the working of the system, let us examine some examples in detail :
Our first example is a (very) erroneous version of the well known REVERSE function. Here is the actual input to the system :

```
? (P '(DE REV L1 L2 COND ULL L22 A1 T RVE A1 ONS
CRA A1 A2))
```

After having corrected the spelling errors, PHENARETE proceeds to a first analysis where she uses only her syntactic knowledge. The result of this first analysis is a syntactically correct LISP program (i.e. a program accepted by any smart LISP interpreter or compiler) :

SURFACE IMPROVEMENTS :

```
(DE REV (L1 L2)
   (COND
      ((NULL L2) L1)
      (T (REV L1 (CONS (CAR L1) L2)))))
```

These first improvements have eliminated all the syntactic errors. However, at least two semantic errors remain :
-1- in the recursive call of REV, the first argument L1 is not modified. This creates an infinit recursion (rule 1).
-2- even with a modification of L1 in the recursive call, the recursion won't stop since the stop-test has as argument L2, a list which grows longer and longer on succesive recursive calls (rule 2).

PHENARETE can not disambiguate this function - it does not know anything of the intentions of the programmer - so it gives two different propositions :

PROPOSITION 1 :

```
(DE REV (L1 L2)
   (COND
      ((NULL L2) L1)
      ((NULL L1) L2)
      (T (REV (CDR L1) (CONS (CAR L1) L2)))))

          AT LEAST YOUR FUNCTION SEEMS OK.
```

In this first proposition, PHENARETE supposed the stop-test given to be correct, but that the user omitted a second stop-test for the case where the second argument is not NULL at the initial call of REV.

PROPOSITION 2 :

```
(DE REV (L1 L2)
   (COND
      ((NULL L1) L2)
      (T (REV (CDR L1) (CONS (CAR L1) L2)))))

          AT LEAST YOUR FUNCTION SEEMS OK.
```

In this second proposition, PHENARETE supposed that the user inadvertently inverted the arguments of the stop-test, so she inverts the two arguments L1 and L2.

PHENARETE is assured that the two corrected versions of the initial draft-program (which are not identical) will stop and deliver a result when executed.

Presently we are working on some extensions to PHENARETE as to find automatically the intentions and the goals of given pieces of code. We would also like to adjoin to PHENARETE a module permitting an explanation to the user of the reasoning of the system. This would be a great help to the user.
The system is running on PDP-10, uses about 25k word memory, is implemented in VLISP [1,4], and is used by about 1000 students in our university.
A more detailed description may be found in [8].

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UNDERSTANDING COMPLEX SITUATIONS

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Natural language texts often *refer* to complex situations. Many of these situations involve relationships between people's goals. In order to build a program that understands texts, it is necessary to give the program knowledge about goal relationships and the situations to which they give rise. This knowledge constitutes a theory of planning about real world situations. We have incorporated this theory of planning into a program called PAM (Plan Applier Mechanism). As a result we now have a natural language processing system that can comprehend many complicated dramatic situations.

1. INTRODUCTION

A number of recent attempts have been made to address the problem of inference proliferation in natural language text understanding (for example, see Cullingford (1978) and Charniak (1978)). The thrust of this research has been to use knowledge to guide the inference process. By equipping an understander with knowledge of the particular situation referred to in the text, the understander makes those inferences which are the most plausible without generating many spurious or irrelevant ones.

The drawback of this approach is that a natural language understander cannot be expected to have familiarity with *every* situation it is going to encounter. A human reader can understand many natural language texts that contain some novel elements in them. To build a natural language understanding system that is capable of understanding such text, a more general inferential capability is needed.

1.1 PAM

PAM (Plan Applier Mechanism) is a program that uses knowledge about people's intentions to understand situations that do not necessarily conform to stereotypical sequences of events. PAM applies knowledge about plans and goals to find explanations for the events in a text. That is, PAM explains a character's actions by inferring the plan that the action is a part of, and inferring the goal that the plan is aimed at achieving. Once a character's motivation has been determined, PAM uses this inference to help interpret subsequent events.

1.2 A Problem

The intentional knowledge originally given to PAM is based on the plan representation scheme of Schank and Abelson (1977). This scheme includes a number of important goals that a character could use to achieve a goal. PAM organizes its knowledge about these entities so that it could infer a character's intentions while reading a story.

While this idea worked well for understanding simple stories, most interesting story situations do not conform to this notion of planning Real stories tend to be about dramatic situations in which some difficulty is presented for a character. Usually, this difficulty involves a situation in which numerous goals are present at once. These goals can interact in complicated ways, and knowledge about the nature of the goal relationships is needed to understand each character's behavior.

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We have been able to formalize some of the knowledge about goal relationships needed for story understanding. By supplying PAM with this knowledge, the program is now able to understand and answer questions about many complicated stories that are beyond its former capacity, as well as the capacity of other natural language processing systems.

The goal relationships that appear to play a central role in story situations are the following:

(1) Goal subsumption - A way of planning for recurring goals.
(2) Goal conflict - An inimicable relationship between simultaneous goals of the same character.
(3) Goal competition - An inimicable relationship between simultaneous goals of different characters.
(4) Goal concord - A mutually advantageous relationship between simultaneous goals of different characters.

Goal subsumption is discussed in detail in Wilensky (1978b), and will only be touched on here. Instead, we shall be concerned with goal conflict and competition. A more detailed analysis of these relationships, as well as an analysis of goal concord, is found in Wilensky (1970a).

2. GOAL SUBSUMPTION

Goal subsumption is a form of planning in which a character plans in anticipation of having a set of goals, rather than in reaction to each individual goal. For example, consider the following story:

(1) John got a job in another town. He asked Fred if he would sell him his car.

Instead of having a single goal, here John has a goal that is likely to recur repeatedly. Since having a job gives rise to the goal of being at work each day, it is possible to plan for these recurring goals at once rather than dealing with each one as it arises. John's plan to purchase a car makes it easier to achieve each of these goals since he would no longer have to obtain possession of a vehicle on each occasion.

Goal subsumption is composed of the following components:

(1) A set of anticipated goals.
(2) Plans for each goal, each plan sharing a common precondition.
(3) A state that meets this precondition and endures over a period of time during which the goals are expected to arise (called a goal subsumption state).

2.1 Goal Subsumption Situations

Goal subsumption is a useful concept in story understanding because there are a number of frequently occurring story situations based on it. The most important of these situations occurs when a functioning goal subsumption state is abruptly terminated, and is called Goal Subsumption Termination. The following is an example of a story PAM can process that involves such a situation.

PAM Example:

INPUT: JOHN AND MARY WERE HAPPILY MARRIED. THEN ONE DAY, JOHN WAS KILLED IN A CAR ACCIDENT. MARY HAD TO FIND A JOB.

Question:

INPUT: WHY DID MARY NEED EMPLOYMENT?

RESPONSE: JOHN DIED AND SO SHE NEEDED A SOURCE OF INCOME.

PAM infers that John's death terminates a subsumption state for Mary, and that she may seek to replace it. Since traditional marriage subsumes certain ecomonic goals that can also be subsumed by having a job, PAM infers that this is the reason behind Mary's goal. This explanation is accessed and given as the answer to the question above.

3. GOAL CONFLICT

Consider the following situations:

(2) John wanted to go bowling with his friends, but he had promised Mary he would take her out to dinner that evening.
(3) John wanted to live in San Francisco, but he also wanted to live near his relatives in Kansas.
(4) John wanted to go to the football game, but it was raining outside.

In each of these stories, a character has a number of goals that interfere with one another. Such a situation is called a goal conflict. To understand a story involving a goal conflict, a story understander must be capable of detecting the presence of the conflict, and of using knowledge about the types of situations to which goal conflict may give rise. For example, suppose story (2) were

continued as follows:

John decided to go bowling anyway. When he got home, Mary told John she was going to divorce him.

To understand that Mary wanted to divorce John because he had neglected her, a reader must infer that John didn't take her out to dinner. This inference is based on the fact that John's goal of taking Mary out was in conflict with another goal, and that this goal was pursued. When two goals are in conflict, and one of them is pursued, a reader can infer that the other has been abandoned. This knowledge about goal conflict is required to find an explanation for Mary's behavior.

3-1 Types of Goal Conflict

A classification of goal conflicts is needed to organize knowledge for both goal conflict detection as well as for understanding the situations to which goal conflicts give rise, lie have found the following taxonomy of goal conflicts to be useful:

Goal Conflict Classification

(1) Goal conflicts based on resource limitations.
(2) Goal conflicts based on mutually exclusive states.
(3) Goal conflicts based on generating preservation goals.

Each of these classes is now described.

3.1.1 Resource Limitations

Goal conflicts based on limited resources can come about in a number of ways, depending upon the nature of the resource involved. Two important categories of resource limitations are found to exist:
(a) Shortages based on time limitations
(b) Shortages based on consumable resource limitations.
Due to a conflict based on a shortage of the consumable resource paper, we cannot afford a description of that kind of conflict here. Me will discuss time limitations instead.

3.1.1.1 Time

Consider the following story:

(5) John wanted to watch the football game, but he had a paper due the next day. John watched the football gane. John failed Civics.

Story (5) is an instance of a goal conflict based on a shortage of time. In order for goals to conflict due to time resources, the plans for the goals must have some time restrictions on them; the amount of time available to the olanner must be less than that needed for the successful execution of the plans, and the planner must be incapable of carrying out the plans simultaneously. For example, John must synchronize his plan of watching the football game with the game's broadcast; he must initiate his plan of writing a paper sufficiently before its deadline, and he is probably incapable of executing both plans at once because they each demand his attention.

Thus a goal conflict based on a limitation of time resources really also involves a limitation of a functional object or of a person's abilities. However, the text of a story does not usually make all these limitations explicit. Instead, a reader must infer the conflict from hints in the text. Time-based goal conflicts are hinted at by one of the following occurences in the text of the story:
(1) A statement of a deadline.
(2) A statement of a limitation of a functional object.
(3) A statement of a limitation of a person's abilities.
(4) An explicit statement of a time shortage.

When one of these statements occurs in a story, the reader can infer that a time shortage exists. For example, story (5) above contains an explicit statement of a deadline. Thus the reader infers the goal conflict from the statement that John's paper' was due at a certain time.

This inference can be made in PAM with the following rule:

Rule TI:
If

a character has two or more goals,

and

the story specifies that the plan for one of the goals must be initiated, completed, or occurring at or before a particular point in time,

then

infer that a goal conflict based on a shortage of time exists among that character's goals.

Hints (2), (3) and (4) are applicable to the following stories, respectively:

(6) John wanted to simmer two dishes on his camp stove, but the stove had only one burner.

(7) John had to write a paper for a course, and read a book for an exam, but John was a very slow reader.

(3) John wanted to visit both Fred and Bill, but he didn't have enough time to see them both.

The rules needed to infer the conflict hinted at in each of these examples can be formulated similarly to rule Tl above.

When a reader sees one of these hints, the reader infers that a goal conflict is present. Of course, these are only hints, and the inference may be incorrect. For example, consider the following story:

(9) John wanted to chat with Nary, but his train left in two days.

Rule Tl says to infer that there is a goal conflict here, but this is probably not the case. Fortunately, most such situations are detectable with simple consistency checks. For example, in story (9), a consistency check would reveal that chatting usually takes much less time than is available, so that the presence of a conflict is unlikely. We shall not expand on consistency here because they are only of importance in unusual situations.

3.1.2. Mutually exclusive states

Goals often conflict because they require some states to exist that are inherently inconsistent. For example, consider the following stories:

(10) John wanted to marry Mary. He also wanted to marry Sue.

(11) John wanted to have a regular job. He also wanted to collect unemployment insurance.

Mutual exclusion is similar to Sacerdoti's' "double cross" conflict (Sacerdoti, 1977). A double cross occurs whenever "each of two conjunction purposes denies a precondition of the other". Mutual exclusion is somewhat different since it applies both to double cross situations and situations in which goal states are exclusive independent of particular plans. In addition, states can be either logically or socially exclusive. For example, being unemployed and having a job are logically impossible, while being married to two different people at once is exclusive only according to the conventions of one's society.

^•1-3. Causing a preservation goal

Consider the following stories:

(12) John wanted to go to the football game, but it was raining outside.

(13) John wanted to take the night off, but he thought his boss would fire him.

In both cases, the conflict arises because execution of a plan for a goal would cause a character to have the goal of preventing something from happening. Thus a goal conflict can occur when the plan for a goal causes a character to have a preservation goal. In order to detect these conflicts, a reader must examine the plans likely to be used for each character's goals, and determine if the execution of that plan will invoke a preservation goal for that character.

3•2• Goal Conflict Situations

Goal conflicts give rise to interesting story situations. For example, consider the following situations:

(14) John wanted to watch the football game, but he had a paper due the next day.
(a) That night, John watched the football game. John failed Civics.
(b) John called his teacher and asked if he could have an extension.
(c) John decided to record the football game on his Betamax.
(d) John's teacher informed him that the deadline for the paper had been postponed.

These stories are instances of the following types of goal conflict situations:

(1) Goal abandonment - The character opts for one goal, abandoning the others. This is the case in story (14a).
(2) Goal Conflict Resolution - The character can try to resolve the conflict, as in stories (14b) and (14c).
(3) Spontaneous Goal Conflict Resolution - The conflict may be resolved by some event not initiated by the planner. Such an event occurs in story (14d).

PAM uses knowledge about the possible situations that might arise from a goal conflict to explain subsequent events. The following is an instance of a story PAM understands in this manner:

PAM Example:

INPUT: JOHN WANTED TO WATCH THE FOOTBALL GAME. HE HAD A PAPER DUE THE NEXT DAY. JOHN WATCHED THE FOOTBALL GAME. JOHN FAILED CIVICS.

Question:

INPUT: WHY DID JOHN FAIL A COURSE?

RESPONSE: BECAUSE HE FAILED TO HAND IN AN ASSIGNMENT.

PAM uses the presence of a deadline to infer a conflict. Since John pursues one of the goals, PAM infers this is a goal abandonment situation and infers the failure of John's other goal.

4. GOAL COMPETITION

Stories usually have more than one character. Goal competition arises when the fulfillment of one character's goal will interfere with the fulfillment of the goals of the other character.

Goals can compete with one another for reasons similar to those underlying goal conflict. However, the situations that can arise from goal competition are substantially different. Consider the following stories:

(15) John told Mary he wanted to watch the football game. Mary said that she wanted to watch the Bolshoi ballet.
(a) Mary put on channel 3. John got out the lawnmower.
(b) John got the old black and white TV out of the attic.
(c) Mary put on channel 3. John punched Mary in the mouth and put on the ball game.
(d) John told Mary he would take her out to the ballet if she would watch the football game with him.
(e) Mary put on channel 3. She found out that the ballet was postponed until later that day.

These stories are instances of the following types of goal competition situations:
(1) Independent goal pursuit, in which each character pursues his goals without regard to the other characters. Story (15a) contains an instance of this situation.
(2) Anti-planning, in which a character tries to interfere with another character's plan. Anti-planning occurs in examples (15c) and (15d).
(3) Easing the competition, a situation where a character tries to undo an underlying cause of the competition. An example of this is story (15b).
(4) External competition removal, in which the goal competition is removed by some action not taken by one of the competitors, as in story (15e).

4.1. Anti-planning

Anti-planning, or the process of countering one's opponent, is the most complex of these story situations. The following forms of anti-planning *are* distinguished:
(1) Physical Elimination
(2) Sabotage
(3) Persuasion
The plans applicable to (1) and (3) are the general plans for overpowering someone and for persuading someone, which have been discussed elsewhere (see Schank and Abelson (1977) and Wilensky (1973)). Also, Bruce and Newman (1978) point out that story situations involving several characters often involve deception. In the scheme of things used here, deception is a variation of plans of persuasion in which some of the argument used by the persuader is known to the persuader to be false. These variations are called trick options. For example, a trick option in the BARGAIN plan may be to bargain away some object one does not possess; a trick option in the THREATEN plan is to bluff, or pretend that some object is a weapon that is not (e.g., a toy gun). PAM does not currently know about the trick options of any plan, however.

4-1.1. Sabotage

Consider the following story:

(16) John and Bill both wanted to marry Mary. John began spreading nasty rumors about Bill.

John is using an anti-plan to stymie Bill's goal in order to maintain the possibility of fulfilling his own. This anti-plan is called UNDO-PRECONDITION. It involves pursuing a plan whose goal is to remove a precondition for someone else's plan. For example, in the story above, John employs the UNDO-PRECONDITION anti-plan against Bill by trying to get Mary to dislike Bill, since Bill's plan to get Mary to *marry* him probably requires that she be favorably disposed toward him.

The following is a computer example of PAM processing a story involving sabotage:

PAM example:

INPUT: JOHN WANTED TO WIN THE STOCKCAR RACE. BILL ALSO WANTED TO WIN THE STOCK-CAR RACE. BEFORE THE RACE, JOHN CUT BILL'S INGITION WIRE.

Question:

INPUT: WHY DID JOHN BREAK AN IGNITION WIRE?

RESPONSE: BECAUSE HE WAS TRYING TO PREVENT BILL FROM RACING.

Because John's goal and Bill's goal constitute mutually exclusive states, PAM infers the presence of goal competition. Since having a vehicle in good condition is a prerequsite for being in a race, PAM infers that John is using the UNDO-PRECONDITION plan to anti-plan against Bill.

4.1.2. Avoiding Danger

A special set of anti-planning rules is required for understanding goal competition situations based on generating a preservation goal. A particularly interesting subset of these situations occurs when a character may wish to execute a plan so as to avoid causing someone else to have a goal competitive with his. These are called anticipated preservation goal situations. For example, consider the following stories:

(17) John wanted to get the treasure, but it was guarded by a huge dragon.
(a) John tiptoed past the beast.
(b) John threw a rock on the other side of the beast and then got the treasure when the dragon ran over to investigate the disturbance.
(c) John poisoned the dragon's lunch.

Each of these stories demonstrates a plan that can be used to execute another plan without generating an anticipated preservation goal. These plans are given the following names:

(1) AVOID-DETECTION - executing a plan in such a way so as not to be detected by one's opponent. This is the case in story (17a).
(2) DISTRACT - turning one's opponent's attention elsewhere. In story (17b), John executes a plan to divert the dragon's attention, after which John will presumably pursue his plan to get the treasure.
(3) OVERPOWER - physically pre-empting one's opponent. John tries to reduce the dragon's physical abilities in story (17c) so that the execution of his plan for getting the treasure does not generate a preservation goal.

The following is a computer example of PAM understanding a story involving an anticipated preservation goal:

PAM example:

INPUT: JOHN WANTED TO GET THE TREASURE, BUT IT WAS GUARDED BY A DRAGON. JOHN WALKED OVER TO THE TREASURE QUIETLY.

Question:

INPUT: WHY DID JOHN SNEAK OVER TO THE TREASURE?

RESPONSE: BECAUSE HE WAS TRYING TO GET THE TREASURE AND HE WANTED TO PREVENT THE DRAGON FROM KNOWING WHERE HE WAS.

PAM infers two explanations for John's behavior. First, that he is executing a plan to get near the treasure, and second, that he was also using the AVOID-DETECTION anti-plan to prevent generating opposition from the dragon.

5. CONCLUSION

Stories are typically about interesting dramatic situations. Many such situations are based on interactions between goals. In order to build an understander that can comprehend stories about real world situations, it is necessary to have a theory of plans and goals that reflects the complexity of the real world. PAM uses such a theory to find explanations for characters' behavior. However, such knowledge should also be applicable to a broader range of AI problem areas. For example, problem solving requires a planner to consider situations in which a number of goals are present. The theory of goal relationships presented here should be useful for planning for and acting in these situations as well as for understanding them.

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Using Plans in Chess

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The purpose of this research is to investigate the extent to which knowledge can replace and support search in selecting a chess move and to delineate the issues involved. This has been carried out by constructing a program, PARADISE Pattern recognised Applied to Directing SEarch), which finds the best move in tactically sharp middle game positions. It encodes a large body of knowledge in the form of production rules. The program uses the knowledge base to discover plans during static analysis and to guide a small (tens of nodes) tree search. PARADISE does not place a depth limit on the search (or any other artificial effort limit), and has found combinations as deep as 19 ply. This paper describes plans how they are produced, and how they are used to guide the search. A complete description of PARADISE appears in [12]

1. Introduction

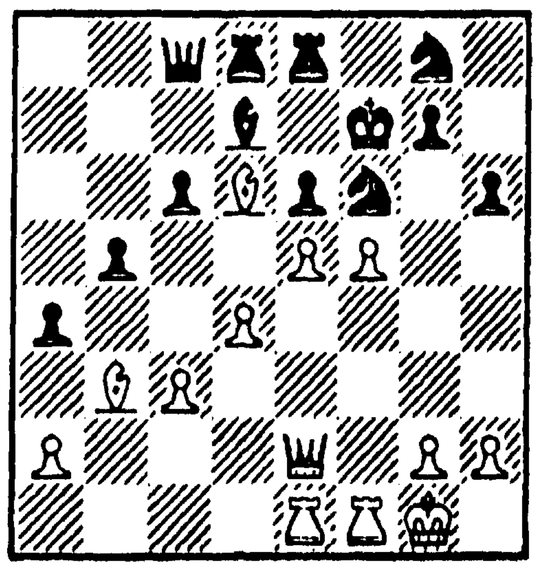
One of the central concerns of artificial intelligence is expressing knowledge and reasoning with it. Chess has been one of the most popular domains for AI research, yet brute force searching programs with tittle chess knowledge play better chess than programs with more chess knowledge. There is still much to be learned about expressing and using the kind of knowledge involved In playing chess. CHESS 4.7 is probably the best chess program, and Its authors make the following comments in [I ll

> *But why is the program so devoid of chess knowledge! .. Our problem Is that the programming tools we art presently using an not adequate to the task. Too much work Is needed to encode the sizable body of knowledge needed to significantly improve the quality of play.*

Human masters, whose play is still much better than the best programs, appear to use a knowledge intensive approach to chess (see [2]). The purpose of this research is to investigate the issues Involved In expressing and using pattern-oriented knowledge to analyze a chess position, to provide direction for the search, and to communicate useful results from the search. To reduce the amount of knowledge that must be encapsulated, the domain of the program has been limited to tactically sharp middle game positions. The phrase "tactically sharp" is meant to imply that success can be judged by the gain or a material rather than a positional advantage. The complexity of the middle game requires extensive search, providing a good testing ground for attempts to replace search with knowledge and to use knowledge to guide the search and communicate discoveries from one part of the tree to another.

Since, In our chosen domain, the attacking side can generally win material with correct play, the program uses different models for the offensive and defensive players. The offensive player uses a large amount of knowledge, suggests many esoteric attacks, and Invests much effort in making sure a plan is likely to work before suggesting it. The defensive player uses less knowledge and effort, tries any defense that might work, and tries only obvious counter attacks. Trying every reasonable defense enables the offense to satisfy itself that a line really does win. The site of the tree Is kept small because the offensive player often finds the best move immediately.

For a knowledge based program to achieve master level performance, it seems essential that the knowledge base be amenable to modifications and additions. PARADISE provides for easy modification of and addition to its knowledge base (without adversely affecting program performance), by having the knowledge base composed of largely independent production rules which are written in a straightforward Production-Language (see [12]). The goal is to build an expert knowledge base and to reason with it to discover plans and verify them with a small tree search. As long as this goal is reached, the amount of execution time used is not important. When a desired level of performance is reached, the program could be speeded up considerably by switching to a more efficient representation at the cost of transparency and ease of modification.



1.	Q-R5ch	NxQ
2.	PxPch	K-N3
3.	B-B2ch	K-N4
4.	R-B5ch	K-N3
5.	R-B6ch	K-N4
6.	R-N6ch	K-R5
7.	R-K4ch	N-B5
8.	RxNch	K-R4
9.	P-N3	any
10.	R-R4 mate	

Figure 0 - white to move

Because it grows small trees, PARADISE can find deeper combinations than most chess programs. Figure 0 is an example of such a combination from an actual master game. White can mate by sacrificing his queen and playing nine additional moves (against black's line of longest resistance), the next to last move not being a check. Thus the search tree must go at least 19 ply deep to find this combination. This is considerably deeper than any other current chess program could probe in a reasonable amount of time, but PARADISE solves this problem after generating a search tree of 109 nodes, in 20 minutes of CPU time on a DEC KL-10.

2. Overview of PARADISE

PARADISE uses a knowledge base consisting of about 200 roduction rules to find the best move *in* chess positions. very production has a pattern (i.e., a complex, Interrelated set of features) as its condition. Each production can be viewed as searching for all instances *of* its condition pattern in the position. For each instance found, the production may, as its action, post concepts (described In the next section) in the data base for use by the system in its reasoning processes. The data base can be considered as a global blackboard where roductions write information. The productions are built up y levels, with more primitive patterns (e.g„ a pattern which matches legal moves) being used as building blocks for more complex patterns. A search tree (the major component of most chess programs) is used to show that one *move* suggested by the pattern-based analysis Is in fact the best.

To offset the expense of searching for patterns in the position, roblems must be solved with small search trees. In fact, ARADISE can be viewed as shifting some of Its search from the usual chess game tree to the problem of matching patterns. PARADISE shows that Its pattern-oriented knowledge base can be used In a variety of ways to significantly reduce the part of the game tree which needs to be searched. This reduction is large enough that a high level of expertise can be obtained without placing a depth limit (or any other artificial effort limit) on the search, the various ways in which the knowledge base is used are briefly mentioned below.

Calculating primitives. PARADISE'S knowledge base contains about twenty patterns (productions without actions) which are primitives used to describe a chess position. These patterns are matched once for each position. They range from matching legal moves to matching any move which can be made without immediate loss of material. The primitives are relatively complex and calculating them is expensive.

Static analysis. Given a new position, PARADISE does an expensive static analysis which uses, on the average, 12 seconds of cpu time. This analysis uses a large number of productions in the knowledge base to look for threats which may win material. It produces plans which should guide the search for several ply and should give information which can be used to stop the search at reasonable points.

Producing plans. The knowledge base *is* used to produce lans during static analysis and at other times. Through plans, ARADISL uses Its knowledge to understand a new position created during the search on the basis of positions previously analyzed along that line of play, thus avoiding a static analysis. Plans guide the search and a static analysis *i$* only occasionally necessary In positions created during the search. Producing a plan is not as simple as suggesting a move, it involves generating a large amount of useful Information to help avoid static analyses alone many different lines and to help detect success or failure of the plan as it is executed. (Examples are given later.)

Executing plans. The execution of a plan during the tree search requires using the knowledge base to solve goals specified in the plan. This use of the knowledge base could be viewed as a static analysis where the system's attention is focused on a particular goal or aspect of the position. Such a focused analysis can be done at a fraction of the cost of a full analysis which examines all aspects of the position.

Generating defensive moves. PARADISE does static analyses and executes plans only for the offense (the side for which It is trying to win material). To prove that an offensive plan succeeds, the search must show a winning line for all reasonable (I.e., any move which might be effective) defensive moves. Productions in the knowledge base are used to generate all the reasonable defenses.

Quiescence searches. When a node is a candidate for termination of the search, PARADISE uses a quiescence search to determine its value. This quiescence search may return Information which will cause the termination decision to be revoked. Productions in the knowledge base provide much of the knowledge used in PARADISE'S quiescence search. Quiescence searches in PARADISE investigate not only captures but forks, pins, multi-move mating sequences and other threats. Only one move Is investigated at each node except when a defensive move fails.

Analysis of problem upon failure. When either the defense or offense has tried a move that failed, the search analyzes the information backed up with the refutation in an attempt to solve the problem. The knowledge base is used in this analysis to suggest plans which thwart the opponent's refutation. In this way PARADISE constructs new plans using the Information gained from searching an unsuccessful plan.

Answering questions. The search often requests certain kinds of information about the current position. The knowledge base is used to provide such information. The most frequent requests ask if the position is quiescent and If there are any obviously winning moves In the position.

The above list describes eight general functions the knowledge base performs for PARADISE. This paper explains how plans are produced and executed. The productions, the static analysis, the tree search, and mechanisms for communicating information from one part of the tree to another are discussed in [12]

3. The Need for Concepts

To understand a chess position, a successful line of play must be found. Human masters understand concepts which cover many ply in order to find the best move. A knowledge based program must also have the ability to reason with concepts that are higher level than the legal moves in a chess position. The following position from [I] Illustrates this.

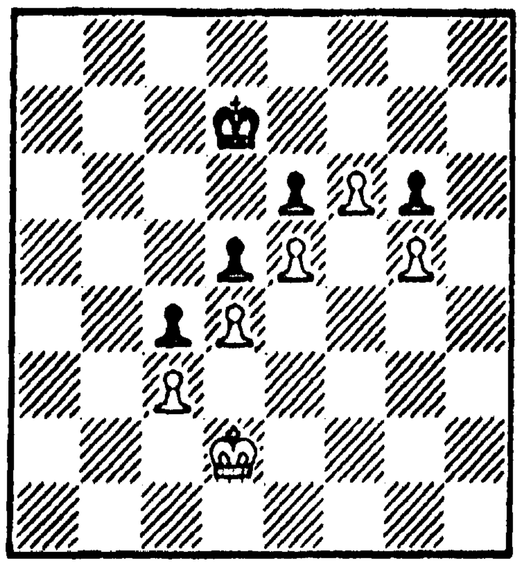


Figure 1 • white to move

In the above position, most computer chess programs would search the game tree as deep as their effort limit allowed and decide to play K-K3 which centralizes the king. They cannot search deep enough to discover that white can win since white's advantage would take more than 20 ply to show up in most evaluation functions used by computer programs. The point is that the solver of the above problem uses conceptual reasoning to solve it, and the concepts must be higher level than the legal moves in a chess position. A human master would recognize the following features (among *others)* in the above position: the black king must stay near his KBI to prevent white's king bishop pawn from queening, the pawns form a blockade which the kings can't penetrate, and the kings can bypass this blockade only on the queen rook file.

For a knowledge based program to solve this problem, it must be able to express concepts at the level of conceptualization used above. The system must combine and reason with these concepts in unforseen ways. In the above example, the blockading concept would be used to develop the plan of moving the white king to the queen rook file In order to bypass the blockade, but if both black and white had pawns on their QN4 then the blockading concept would be used to decide that neither king can invade the other's territory. Expressing and using concepts *is* a major problem for a knowledge based chess program.

To clarify the problems involved in using concepts to reason about chess, a comparison to a well-known "expert" system such as MYCIN is helpful. The following phrase is the action part of a typical MYCIN rule (from [3]): *then there is suggestive evidence (.7) that the identity of the organism is bacteroides.* Such an action effectively adds to the plausibility score for some possible answer. This presupposes that any one writer of all the rules knows every possible solution since such rules will never create a diagnosis that has not been mentioned in the action part of some rule. Such an approach is not satisfactory for the type of reasoning needed in figure 1.

Using actions similar to those used in MYCIN rules would be similar to a chess system where the action part of each rule was to add to the plausibility score of either I; one or more of the legal moves in the position, or 2) some prespecified object which could lead (through other rules) to recommending a legal move. Such a system would not be able to reason that a king must get past a pawn blockade to attack an opponent's pawn chain since objects cannot be prespecified (e.g., the extent of the blockade and whether or not the kings want to get around it must be determined dynamically). PARADISE must reason by linking concepts to create plans that are not implicit in the knowledge base, instead of filling in prespecified slots. To compare actual production rules, MYCINs actions mention the names of objects while PARADISE'S actions involve many variables whose instantiation is not determined until execution of the action.

4. Knowledge Sources and Concepts

When a production in PARADISE matches, it may have an action part which posts various concepts in the data base. The program is able to express and use concepts by dividing its knowledge base Into various Knowledge Sources. Each Knowledge Source (KS) provides the knowledge necessary to understand and reason about a certain type of concept. In its simplest form, a KS is a group of productions which knows about some concept and a list of variables such that an instantiation of the variables represents an instance of this concept. For example, the SAFE KS in PARADISE has two variables, PI and SQ, and contains productions which know how to make the particular square SQsafe for the piece PI. With this KS, the system can use the concept of a square being safe for a piece in its reasoning, in the expression of plans, and in the communication of discoveries from the tree search. Such concepts are a level above the patterns recognized by the productions themselves.

When a concept has a corresponding KS, PARADISE will eventually treat each instance of that concept which is present in the data base as a subgoa! and use the corresponding KS to solve the subgoa) in an attempt to produce a plan to realize that instance of the concept. (This may be done by creating other instances of other concepts.) There may also be concepts that have no corresponding KS and are not treated as subgoals. Such concepts are inspected by patterns attempting to match and by the searching routines. When a concept or an instance of a concept corresponds to a KS, it will sometimes be *referred* to as a goal or subgoa l

Concepts In the data base must contain all the information that will be needed to execute other KSes and to guide the search (see [12]). Among other things, KSes usually expect information on how likely a goal Is to succeed and on how threatening a goal is (this is useful in deciding if a sacrifice is warranted). PARADISE stores information about concepts on a list of attribute-value pairs, called an attribute list. For reasons discussed in [12], a particular concept is expressed by giving its name, an instantiation of its arguments, and a list of attribute lists (one for each reason the concept was suggested).

When a production accesses the values of attributes in a concept, it may not care which attribute list the values come from, or it may require that the values for each attribute come from the same list, or It may want the "best" (In some *sense)* value for each attribute whether the different values come from the same list or not, or it may want values for one attribute to come from lists which have some particular value for another attribute. This accessing of the information in a concept *is so* complex that it can be looked on as pattern matching in itself. Thus the productions in a KS can be looked upon as matching patterns in the given chess position and matching patterns in different concepts.

Concepts and their accessing are quite complex. Intuitively, the productions in PARADISE are not making deductions, per se, but coming up with ideas that may or may not be right. Thus there are no "facts" that have certain deduced values that can be reasoned with. The complexity of later analysis requires that a production essentially put down "why it thought of an Idea. In this way, other productions can decide if the idea still looks right In light of what is known at that time. Most production systems avoid this complexity because the firing of a production Is a deduction which adds a new piece of knowledge to the system. This piece of knowledge is assumed right and the system is not prepared to later decide that it wasn t right to make that deduction.

5. Pl ens

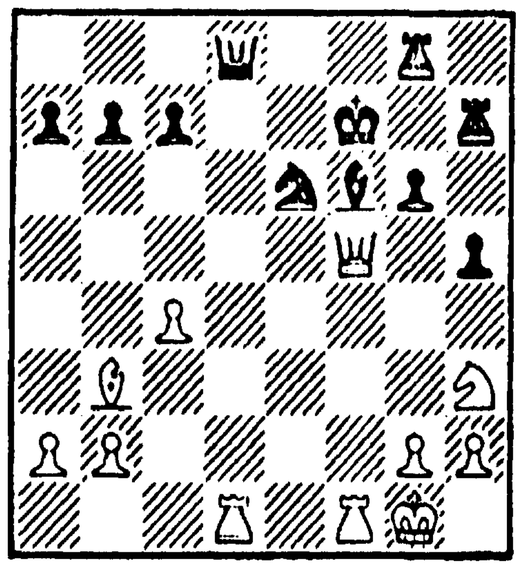
The goal of the static analysis process in PARADISE is to produce plans. Plans seem to play an important role In the problem solving process of move selection for good human chess players. Alexander Kotov in (6] writes:

*. . . it is better to follow out a plan consistently even if it isn*t the best one than to play without a plan at all. The worst thing is to wander about aimlessly, (p. 148)*

Most computer chess programs certainly do not follow Kotov's advice. In a knowledge based program, the cost of processing the knowledge should be offset by a significantly smaller branching factor in the tree search. Plans help reduce the cost of processing knowledge by immediately focusing the program's attention on the critical part of a new position created during the search, thus avoiding a complete re-analysis of this new position. Having plans also reduces the branching factor in the search by giving direction to the search. Consider, for example, that most programs may try the same poor move at *every* alternate depth in the tree, always re-discovering the same refutation. PARADISE can detect when a plan has been tried earlier along a line of play and avoid searching it again if nothing has changed to make it more attractive. Most programs also suffer because they intersperse moves which are irrelevant to each other and work towards different goals. PARADISE avoids this by following a single idea (its plan) down the tree.

Plans in PARADISE can be considered as special instances of concepts since each plan has a list of attribute lists. Instead of a list of instantiations for a set of variables (as in a concept), a plan has an expression in the Plan-Language. The Plan-Language expresses plans of action for the side about to move, called the offense. In general, the offense wants to have a reply ready for every defensive alternative. A plan cannot therefore be a linear sequence of goals or moves but must contain conditional branches depending on the opponent's reply. When the offense is on move, a specific move or goal is provided by the plan. When the defense is on move, a list of alternative sub-plans for the offense may be given. Each alternative begins with a template for matching the move made by the defense. Only alternatives whose template matches the move just made by the defense are tried in the search. PARADISE has the following templates which adequately describe defensive moves in terms of their effects on the purpose of the plan being executed (P and SQ, are variables which will be instantiated in an actual plan to particular pieces and squares, respectively): (P SQ) matches when the defense has moved the piece P to the square SQ (NIL SQ) matches when the defense has moved any piece to SQ, (P NIL) matches when the defense has moved P (to any square), (ANVBUT P) matches when the defense has moved some piece other than P, and NIL matches any defensive move.

The plan for an offensive move can be one of two things: a particular move or a goal. A particular move *ii* simply the name of a piece and a square. Such a plan causes PARADISE to immediately make that move with no analysis of the position other than checking that the move is legal. A goal is simply the name of a KS followed by an instantiation for each argument of the KS. When executing a goal, PARADISE will construct an instance of the KS's concept in the data base by using the given instantiations and the attribute lists of this plan as a whole. The KS will then be executed for this concept-instance (goal). Any plan produced by this execution will replace the goal in the original plan and this modified plan will be used. This process expands and elaborates plans. If executing the KS does not produce a plan then the original plan has failed.



```
(((WN N5) (((BN N4) (SAFEMOVE WR Q7)
      (((BK NIL) (SAFECAPTURE WR BR))
         ((ANYBUT BK) (SAFECAPTURE WR BK))))
  ((BN N4)(CHECKMOVE WR Q7)(BK NIL)(SAFECAPTURE WR BQ))))
((THREAT (PLUS (EXCHVAL WN N5)(FORK WR BK BR)))(LIKELY 0))
((THREAT (PLUS (EXCHVAL WN N5) (EXCH WR BQ))) (LIKELY 0)))
```

Figure 2
a plan produced by PARADISE (white to move)

Figure 2 shows a problem and one of the plans PARADISE'S static analysis produces for it. (''WN" means white Knight, ''N5" means the square N5, etc. It should be obvious to which white rook "WR" refers.) The last two lines of the plan are attribute lists. The first five lines are the Plan-Language expression for the plan which can be read as follows:

Play N-N5, If black captures the knight with his knight, attempt to safely move the rook on Q1 to Q7. Then, if black moves his king anywhere try to safely capture the black rook on R7, and if black moves any piece other than his king, try to safely capture the king with the rook. A second alternative after black captures the knight is to attempt to safely move the rook on Ql to Q7 with check. Then, if black moves his king anywhere try to safely capture the black queen with the rook.

SAFEMOVE, SAFECAPTURE, and CHECKMOVE are all KSes in PARADISE. After playing N-N5 and NxN for black in the tree search, PARADISE will execute either the CHECKMOVE goal or the SAFEMOVE goal. Executing the SAFEMOVE goal executes the SAFEMOVE KS which knows about safely moving a piece to a square. This KS will see that R-Q7 is safe and produce this as the continuation of the original plan, causing the system to play R-Q7 with no further analysis. If for some reason R-Q7 was not safe then the SAFEMOVE KS will try to make Q7 safe for the rook (by posting a SAFE concept). If some plan Is found, the original plan will be "expanded" by replacing the SAFEMOVE goal with the newly found plan. In general, the newly found plan will contain (SAFEMOVE WR Q7) though it may come after a sacrificial decoy or some other tactic. If posting the SAFE concept does not produce a plan, then the SAFEMOVE goal has failed, and the alternative CHECKMOVE goal will be tried. If It also fails, a complete analysis of the position must be done. If black had answered N-N5 with a King move, it would not match the template (BN N4) and a complete analysis of the position would be undertaken without attempting to make Q7 safe for the rook.

A detailed description of the static analysis process in PARADISE Is given in [12]. PARADISE suggests the plan in

figure 2 for two different reasons. One of these two ways of suggesting this plan is briefly traced below. The system begins by posting a THREAT concept since the THREAT KS has productions which look for threats. One production recognizes the white rook could skewer the black king and rook from Q7 so it posts a MOVE concept which says the white rook would be well placed on *Q1* A production *in* the MOVE KS, that recognizes that R-Q7 is *unsafe,* matches and posts a SAFE concept for making *Q1* safe for the white rook. While executing the SAFE KS, one production notices that the black knight blocks the white queen's protection of Q7, and posts a DECOY goal. The DECOY KS has a production which posts a FORCE goal suggesting N-N5 as a move to decoy black's knight. The plan in figure 2 has been built up at this point, although *more* KSes are executed (to check for effects) before the final plan is posted.

6. Discussion of plans in PARADISE

By use of conditionals, a plan can handle a number of possible situations which may arise. The most important feature of the Plan-Language is that offensive plans are expressed in terms of the KSes. This has many advantages. Relevant productions are immediately and directly accessed when a new position is reached. The system has one set of concepts it understands (the KSes) and does not need to use a different language for plans and static analysis. The system has been designed to make the *writing* of productions and thus the forming of KSes reasonable to do. Thus the range of plans that can be expressed is not fixed by the Plan-Language. By forming new KSes, the range of expressible plans may be Increased without any new coding (in the search routines or anywhere else) to understand the new plans. This is important since the *usefulness of the* knowledge base is limited by Its ability to communicate what it knows (e.g., *through* plans).

Given a number of plans *to execute, the tree* search must make decisions about which plan to search first, when to forsake one plan and try another, when to be satisfied with the results of a search, and other such things. To make such decisions, it must have information about what a plan expects to gain and why. Such information was available to the productions which matched to produce the plan and must be communicated In the attribute lists of the plan so as to provide many different types of access to this knowledge. Unlike most search-based chess programs, PARADISE must use its information about a plan at other nodes In the tree since it executes a plan without analyzing the newly created positions.

To use the information about plans in an effective manner, PARADISE divides a plan's effects into four different categories which are kept separately (i.e., their values are not combined in any way). These four categories are: THREAT which describes what a plan threatens to actively win, SAVE which describes counterthreats of the opponent a plan actively prevents, LOSS which describes counterthreats of the opponent not defended against and functions the first piece to move in a plan will give up by abandoning its current location (thus providing new threats for the opponent), and LIKELY which describes the likelihood that a plan will succeed. These four categories have emerged during the development of PARADISE. Experience seems to indicate the system must have at least these four dimensions along which to evaluate plant in order to adequately guide the tree search.

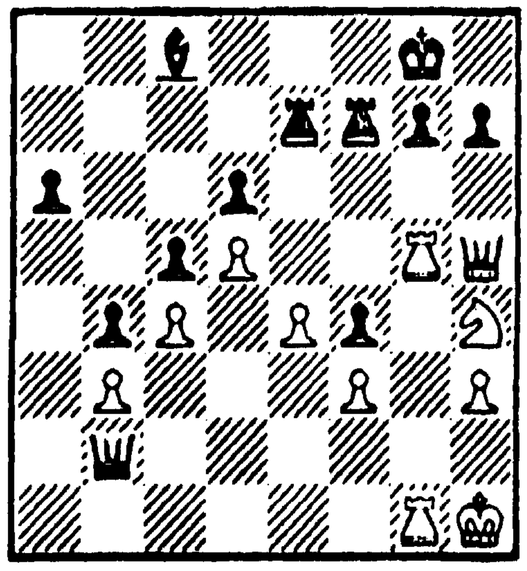
Since the values for these categories must evaluate correctly at different nodes in the tree, they cannot be Integers. Instead they (except LIKELY) are expressions *in* the Threat-Language ([12]) which can describe threats in a sophisticated manner. These expressions are evaluated in the context of the current position and may return different values for different positions. The value of LIKELY is an integer which represents the number of unforced moves the defense has before the offense can accomplish its plan. The most likely plans to succeed (e.g., the plan in figure 2) have a LIKELY of zero (every move is forcing).

The system must quickly recognize when a plan Is not working and abandon it before effort is wasted investigating poor lines. On the other hand, it is expensive to completely analyze a position, so the system wants to use its plan as long as possible, To achieve a balance, plans must adequately express the purpose they intend to achieve. Productions must carefully formulate their Plan-Language expressions at the right level of detail using appropriate goals and descriptions of defensive moves. When executing a plan, the system will retrieve a goal or move from the plan to apply to a new position. Care must be taken to ensure that this move or goal is reasonable in the new position. For example, a plan which specifies that any check be played may lack detail and cause many poor checks to be investigated. On the other hand, if the plan specifies an actual move to attack the king, it may be too detailed since this move may no longer check the king in the new position (again a poor line is investigated). Plans should express their purpose by describing how the king should be attacked.

A plan should handle as many replies as possible without causing a re-analysis, but it should avoid suggesting poor moves. The templates for describing defensive moves in the Plan-Language and the various KSes have been developed to allow PARADISE'S plans to accurately express their purpose. The results have been Quite satisfying: the productions in PARADISE now create plans which rarely suggest poor moves but which can still be used for as many ply as a human might use his original idea.

7. Using Plans to Guide the Search

Figure 3 depicts a position from [8] and shows the plan PARADISE suggests as best after a static analysis. To show how such plans are used to guide the search, PARADISE'S search for this position *is* sketched below.



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(((WQ R7) (BK R2) (CHECKMOVE WR R5) (BK NIL) (ATTACKP BK))
 ((THREAT (PLUS (WIN BK) (EXCHVAL WQ R7))) (LIKELY 1)))
```

Figure 3 (white to move)

The search commences execution of this plan by playing QxPch and producing a new board position. The defense suggests both legal moves, KxQ, and K-BI, but tries KxQ, first. Since this move matches the (8K R2) template in the plan, PARADISE has (((CHECKMOVE WR R5) <BK NIL) (ATTACKP BK)) as its best plan at ply 3 of the search. Execution of the CHECKMOVE KS produces ((WR R5) (BK NIL) (ATTACKP BK)) as a plan which causes R-R5ch to be played. Black plays his only legal move at ply 4, K-NI, which matches the (BK NIL) template in the plan. Thus PARADISE arrives at ply 5 with (ATTACKP BK) as its plan. Executing the ATTACKP KS posts many concepts, including MOVE and SAFE concepts, and ((WN N6) ((NIL (SAFEMOVE WR R6)) (NIL (SAFEMOVE WN K7))) is produced as the best plan in this position. After playing N-N6, the position *in* figure 4 *is* reached.

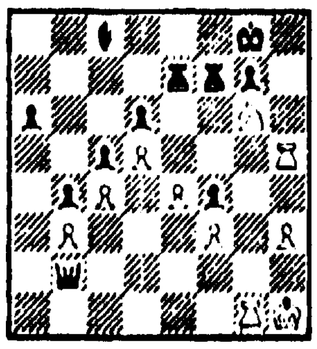

Figure 4

Productions which know about defending against R-R8 suggest (BB R6)(BB Q2)(BB N2)(BR B4)(BR 63)(BR BI), Black plays BxP first in an effort to save the bishop from the ensuing skewer. At this point the plan branches. Since both branches begin with a null template, they both match any black move at ply 6. Thus PARADISE has two plans at ply 7: (SAFEMOVE WR R8) and (SAFEMOVE WN K7). Before executing a plan for the offense, PARADISE executes the QUIESCENCE KS which looks for obviously winning moves. Here R-R8 is suggested by the QUIESCENCE KS which causes the (SAFEMOVE WR R8) plan to be executed immediately. PARADISE plays R-R8, finds that black is mated, and returns to ply 6 knowing that black's BxP leads to mate. All this has been accomplished without a static analysis; the original plan has guided the search.

At ply 6, black uses KSes to refute the mating line. No new moves are found since all reasonable defenses have already been suggested. PARADISE has a causality facility which determines the possible effects a move might have on a line of play. Using the tree generated for the mating line, the causality facility looks for effects a proposed move might have (such as blocking a square which a sliding piece moved over, vacating an escape square for the king, protecting a piece which was attacked, etc.). The causality facility recognizes that neither B-Q2 nor B-N2 can affect the mating line found for BxP so they are rejected without searching. Black plays R-Bi next, the causality facility having recognized that this move opens a flight square for the black king. Again PARADISE has both (SAFEMOVE WR R8) and (SAFEMOVE WN K7) as plans at ply 7. Both SAFEMOVE goals would succeed, but R-R8 has a higher recommendation and *is* played first. Black plays his only legal move at ply 8, K-B2. PARADISE no longer has a plan at ply 9. Before trying a static analysis, it executes the QUIESCENCE KS in an attempt to find an obviously winning move. R-KB8 is suggested and PARADISE immediately plays this move without doing a static analysis. This is mate so PARADISE returns to ply 6 to look for other defenses. Both R-B3 and R-BI are tried and both are quickly refuted by playing R-R8 from the SAFEMOVE goal of the original plan, K-B2, and R-KB8 from the QUIESCENCE KS. The search then returns to ply 2 and tries K-BI In answer to QxPch. The template in the original plan does not match K-BI so there is no plan at ply 3. However, the QUIESCENCE KS Quickly suggests Q-R8 and PARADISE returns from the search convinced that QxPch will mate.

PARADISE'S plans are not always so accurate but space prevents presentation of a longer search. The above analysis uses about 130 seconds of cpu time on a DEC KL-10. It goes to a depth of 9 ply while creating only 21 nodes in the tree. Because of the guidance provided by the original plan, no static analysis was performed except on the original position. By comparison, the TECH2 program (an Improved version of TECH [5]) at a depth setting of 6 discovers that it can win material with QxPch although the horizon effect hides the mate from it. For this analysis, TECH2 uses 210 seconds of cpu time and creates 439,459 nodes by making legal moves (it also makes and retracts 544,768 illegal moves).

8. Measuring PARADISE's performance

To aid in evaluating performance, PARADISE was tested on positions in [8). This book contains tactically sharp positions from master games which are representative of tactical problems of reasonable difficulty. PARADISE'S knowledge base was developed by writing productions which would enable the program to solve, In a reasonable manner, fifteen chosen positions from among the first 100 In [81 The 85 positions not chosen were not considered during this development. This development process produced one version of the program, called PARADISE-0. Six positions were then picked at random from the remaining 85 and accurate records were kept on the work involved in getting the program to solve these reasonably. The version of the program which solves all 21 positions is called PARADISE.

PARADISE'S performance on a problem is classified into one of three categories: I) problem solved as is (possibly with a minor bug fix), 2) problem not solvable without a change to the program or a major change to the knowledge base, or 3) problem solvable with a small addition to the knowledge base. Category 3 helps measure the modifiability of the knowledge base. It is meant to include solutions which require no changes whatsoever to the program and only a small addition to the knowledge base. Small means that it takes less than 20 minutes total of human time to identify the problem and write or modify one production which will enable PARADISE, with no other changes, to solve the problem in a reasonable way (i.e., no ad hoc solutions).

Of the six positions chosen at random, two were in category 1, three were In category 3, and one was in category 2. This latter one inspired the only program changes between PARADISE-0 and PARADISE. These results speak well for the modifiability of the knowledge base, but shed little light on the generality of the program. To better test generality, PARADISE has been tested on the first 100 positions. These positions are divided into 5 groups of 20 and Reinfeld claims an increase In difficulty with increase in group number. (Eight endgame positions were eliminated, so the groups actually have 18, 19, 18, 20, and 17 positions.) PARADISE is considered to solve only the problems In category 1, while PARADISE-2 solves both category I and 3 problems. PARADISE would

become PARADISE-2 simply by leaving in the productions written to solve problems in category 3. The following table shows what percentage of these problems can be solved by PARADISE, PARADISE-2, CAPS [I] TECH [51 CHESS 4.4 [II] running on a CDC 6400, and a human rated as class A [I]. PARADISE was limited to 45 minutes of cpu time per problem while the other programs were limited to 5 minutes.

	PARADISE	PARADISE-2	CAPS	TECH	C-4.4	HUMAN
Group I	78%	100X	67X	78X	94X	89%
Group 11	66%	95X	74X	84%	95X	95X
Group 111	94X	100X	61X	61X	78X	94X
Group IV	70X	9SX	50%	40X	70X	80X
Group V	65X	94X	41X	47X	76X	S3X
AH 92	75X	97X	59X	61X	83X	83%

There were 20 problems in category 3 in the first 100, but only 13 productions were written to solve them. In two instances, an already existing production was modified. In five instances the same production solved 2 different category 3 problems. This is a strong Indication that the productions being written are fairly general and not tailored to the specific problem. PARADISE already exhibits more generality in this domain than programs like TECH and CAPS. The figures for PARADISE-2 show that these problems do not push the limits of the expressibility of the production language nor the ability of the program to control the tree search. These results indicate that the generality of PARADISE is reasonable and that the modifiibility of the knowledge base is excellent.

It should be noted that PARADISE uses considerably more cpu time and produces trees with considerably fewer nodes than either of the other programs. The following statistics were complied for the 89 problems which PARADISE-2 solved In these 92. PARADISE averaged *five* and one-half minutes of cpu time per problem (it ranged from 19 seconds to 1958 seconds), and generated an average of 38 nodes per problem (ranging from 3 nodes to *215).* On the average, PARADISE spent 53* of its time calculating primitives. There were an average of 3.7 static analyses done per problem, and less than 9% of the nodes generated had static analyses done on them. This shows that the plans do a good Job of guiding the search.

9. Comparison to Plans in Robot Problem Solving

Plans are used In many domains of AI research, especially robot problem solving. ABSTRIPS [91 NOAH [10] and BUILD [4] are examples of planning systems in robot problem solving environments. Plans in these systems are very different from those in chess so a summary of these differences is more appropriate than a detailed comparison. These differences are explained in greater detail in [12] Robot planning is frequently done in abstracted spaces which have been defined, and which omit details. Such an approach is much more difficult in chess, at least with mankind's current understanding of the game. It is not clear how to define abstracted spaces. Small details are very important in chess and cannot be readily ignored.

In the robot planning systems, the effects of an action are well defined. The program can easily and quickly determine the exact state of the world after an action. In chess, moves (actions) may subtly affect everything on the board. Chess plans cannot make many assumptions about the state of the world in the future, but must describe the expected features of new states In the plan itself and then test for these features while executing the plan.

In most robot planning systems, tests for havine achieved the goal or the preconditions of an action are trivial and give well defined answers. In chess, there may be only very subtle differences between a position where a particular action is rood and positions where the same action is wrong. It is also hard to know when a goat has been achieved, since there Is always a chance of obtaining a larger advantage (except when the opponent has been checkmated). Thus in chess it Is necessary for the plan to provide a considerable amount of information to help in the making of these decisions. This is done in PARADISE through the attribute lists in plans.

The number of things PARADISE can consider doing at any point in a plan is about an order of magnitude larger than the number of things most robot problem solvers usually contend with. There are an average of about 38 legal moves in a chess position (see [2]). When planning farther in the future than Just the first action, the chess planner has many more choices than the 38 legal moves. The inability to make assumptions about future states often prevents mentioning actual moves in a plan. Instead a description of the intent *is* needed, and the number of such descriptions is much larger than the number of legal moves that might be made. A robot usually has a much smaller number of possible actions, so the two types of plans explode at very different rates.

The robot planners have the flavor of establishing a sequence from a small number of well-understood operations until the correct order *is* found, while chess planners have more a flavor of "creating" the correct plan from the many possibilities. For this reason, a system which produces good chess plans needs a large amount of knowledge and non-trivial reasoning processes to produce plans. Plans in PARADISE differ from those in robot problem solvers by specifying powerful knowledge to be applied in new situations. Plans essentially give PARADISE a perspective to use when analyzing a new position.

10. Comparison to Plans in Chess

Pitrat's program [7], which solves chess combinations, is the most important example of the use of plans in chess. The language Pitrat uses for expressing plans has four statements with the move statement and modification statement being the most important. The move statement specifies that the piece on one particular square should move to another particular square. It may also be specified that the move must be a capture. The modification statement describes a modification to be made to a particular square. This can be one of four things: removal of a friend, removal of an enemy, moving a friend to the square, or getting an enemy to move to the square.

Plans in PARADISE provide much more flexibility in expression than Pitrat's move statement. In PARADISE, types of moves other than captures can be specified (e.g., safe moves). Also, particular squares do not need to be named in PARADISE since it can use a variety of goals to express the plan. The important square to move to may change depending on the opponent's move so it Is not always possible to specify such a square in advance. Pitrat's modification statement is a goal which the system tries to accomplish. These modifications are too simple to express the purposes behind their suggestion. For example, the system may want to decoy the black queen to

make a square that it protects safe for white. Pitrat would express this goal as removing an enemy from the black queen's location which does not express the purpose of the plan. It will work well for the winning combination but will also allow many wrong moves since the queen may be decoyed to a square from which she can still protect the square in question. PARADISE would specify that the black queen must be decoyed to make the particular square safe, and only decoys which remove the black queen's protection would be considered. PARADISE attempts to express the purpose of each plan while Pitrat's plans express side effects that will happen if the purpose is accomplished (e.g., a square becoming vacant). Unfortunately, the same side effects may also happen when the purpose is not accomplished, causing the system to waste effort searching poor lines.

Plans in PARADISE have two more major advantages over the plans in Pitrat's system. First, PARADISE has conditionals which allow specification of different plans for different replies by the opponent. The advantages of this are obvious: the system can Immediately try the correct plan Instead of searching an inappropriate plan and backtracking to correct itself. Second, PARADISE'S plan language is modifiable. Simply by writing new productions, new goals and concepts can be created for expressing plans and the system will automatically understand these new plans. This property Is necessary for any system that wishes to extend its domain or incrementally increase its expertise. Significant additions to Pitrat's plan language would seem to require a major programming effort.

It should be noted that Pitrat's program processes nodes much faster than PARADISE and therefore can handle larger trees. It may be the case that programs will obtain better performance by using larger trees and less sophisticated plans, but the use of knowledge Is only starting to be investigated by programs such as PARADISE and it is too early to draw conclusions.

11. Summary

PARADISE exhibits expert performance on positions it has the knowledge to understand, showing that a knowledge based approach can solve some problems that the best search based programs cannot solve because the solutions are too deep. The knowledge base is organized into KSes which provide concepts for PARADISE to use in its reasoning processes. These concepts are at a higher level than the ideas produced by simply matching patterns. PARADISE'S knowledge base is amenable to modification. Production rules (and therefore KSes) can be quickly written and inserted In the knowledge base to improve system performance without adverse affects.

The concepts provided by the KSes are used to create plans during static analysis. The concepts communicate enough information that they can be rejected after being posted. Tne same concepts are used to express plans for guiding the search, and the KSes execute the plans during the search. By communicating plans down the tree, PARADISE can understand new positions on the basis of its analysis of previous positions. By having particular goals in mind when looking at a new position, the system quickly focuses on the relevant part of the data base and avoids using all its patterns. Plans in PARADISE express their purpose fairly well, without being too general or too specific. Because of the successful communication of knowledge through plans, PARADISE is able to solve a number of chess combinations with small trees and without a depth limit on its search.

One of the major Issues In creating concepts is their generality. If the concepts are too general then too many details are lost, and the system does not have the necessary facts to do certain reasoning. If not general enough, the system leans toward the extreme of needing a production for every possible chess position. The concepts in PARADISE have been constructed to be as general as possible without sacrificing expert-level performance to the loss of detail. The tradeoff of generality and specificity in concepts Is closely related to the tradeoff of search and knowledge. With much specific knowledge the use of knowledge becomes expensive, but fewer mistakes need to be corrected in the search. With more general knowledge, analysis is cheaper but more time must be spent correcting mistakes in the search. PARADISE uses a mix of search and knowledge which involves more knowledge and less search than previous programs which include chess middle games in their domain. This type of research should strive for generality within the confines of its commitment to knowledge-based expert performance.

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SPEECH ACTS AND MULTIPLE ENVIRONMENTS

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This brief paper outlines joint work that implies a view of the explication of Speech Acts different from those current in AI. It is exploratory at present, but we intend that it should lead to programs as soon as possible. We propose a system that engages in dialogue with a human user so as to discuss others and in doing so, interprets the appropriate communicative force of the user's utterances. The three key features of the explication of communicative force presented are:

1. multiple environments: the ability to interpret an expression or a description relative to some particular knowledge, e.g. relative to the beliefs of one person about another. It is a generalization of the computer science approach to expression evaluation, using the notion of an environment to fix the interpretation of names occurring in the expression.
2. dual knowledge representation: an "experiential" representation is used to memorize sentences or other episodes (exemplified by pseudo-tests, or PTs), while a frame-type representation is used to memorize knowledge needed more generally for reasoning.
3. a least effort principle of understanding: considered to be a language universal, which requires (a) that the system maintain as much representation as possible in the frame-like forms, rather than in PTs, and (b) that the system maintain a highly redundant representation in the PTs, achieved by a process we call percolation of belief.

1. INTRODUCTION

Speech Acts (SAs) originated as a notion in philosophy [1] , [9] much preoccupied with the logical properties of sentences like "I promise to pay you five pounds" and, later, with access to the intentions in a speaker's head. Linguists worked with these notions subsequently but, like AI workers, they have added little that is distinctive to the original perception that utterances have a distinctive communicative force (as a threat, a promise, a warning, etc.), in addition to literal content. We believe that an AI approach to this area that is to contribute distinctively will have to make use of general principles concerning the environmental embedding of beliefs, etc., as well as a least effort maxim for their manipulation. The first of these, advocated by Bien in 1975 [2] , has been used by Cohen [5] and others of the Toronto group, but the distinctive feature we discuss here concerns the maintenance and change of such environments under a general requirement of cognitive efficiency.

2. TIRESIAS

We propose a system able to engage in a limited conversation with a human user: let us call It TIRESIAS for a reason that will appear. The topic of the conversation would be the relationships of a group of friends (see [7]) known in varying degrees to both TIRESIAS and the user. We expect sample dialogues such as:

$1 USER: Frank is coming tomorrow, I think.
$2 TIRESIAS: Perhaps I should leave.
U Why?
T Coming from you, $1 is a threat.
U Does Frank hate you?
$3 T I don't know-but you think he does, and that is what is important right now.

The important feature we require here is TIRESIAS' ability to evaluate its descriptions of persons differently in different environments Thus, at $1, TIRESIAS detects a threat (not in itself necessarily interesting) on the basis of evaluating its representation of itself, inside that of Frank, inside that of the user, which we might write (given that [P] is the data-structure for P inside Q, that is, Qs model of P):

{{TIRESIAS / FRANK / USER / TIRESIAS}} Note that all the data-bases are in TIRESIAS, so an outer TIRESIAS bracket exists round all evaluations, though we may sometimes omit it.

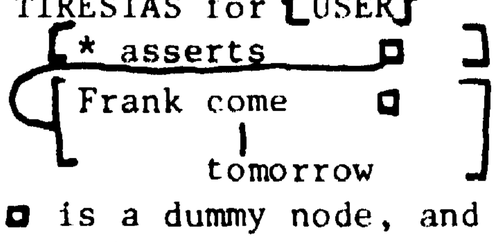
whereas at $3, when questioned, TIRESIAS is seeking to evaluate simple Frank's view of him, or {{TIRESIAS / FRANK / TIRESIAS}}

where he discovers that he has no specific information on what Frank thinks of him. The generation of $2, and TIRESIAS understanding of $1 as a threat, may, let us suppose, depend on a specific belief that the user believes that Frank dislikes TIRESIAS (but as $3 shows, not a belief by TIRESIAS that Frank dislikes him). Let us follow this through by examining inferences plausibly generated by TIRESIAS' construction of the two nestings of environments shown above and comparing their results.

The crucial difference here is between the evaluation of {FRANK} in {USER} and in {TIRESIAS}. Another assumption is important to what follows: the nesting of environments {FRANK / USER} that the example requires will not in general exist already in the system (as it does in [5] et al). as a partition of the space of beliefs: we find it implausible and comptationally overweight to assume that all such partitions are already marked in the system. {FRANK / USER} will here be constructed by "pushing down" {FRANK} into {USER}. To put it simply, TIRESIAS will construct the user's view of Frank by inference from his views of the two participants: he will assume that user believes about Frank what he does, unless explicit information about Frank likes the user, and that Frank believes that he (Frank) hates the user, then {{FRANK / USER} / TIRESIAS} will contain Frank dislikes user, since the belief of the user, that Frank likes the user, is overridden by explicit counter information. Thus, beliefs are transferred by counting in what it is reasonable for TIRESIAS to believe others believe, rather than counting out: that is to say, believing about another's beliefs only what we have explicit evidence for. To see how such structures are obtained, we must consider briefly the form of knowledge representations in the system.

3. FRAMES AND PSEUDO-TEXTS

The notion of frame is now well known [8], and here we assume in addition a variant called a pseudo-text [11] which is an information structure that is the semantic representation of a text, obtained by a semantics-driven parser such as [10]. A PT is an interconnected set of proposition representations, called templates, each of which consists of three principal nodes or terminals, that represent in right-left order, the actor, action, and object of an event. The terminals are, in fact, trees of semantic primitives, but here we shall place the English names of those trees at the terminals. In such a notation, we may write the template for "Frank is coming tomorrow", said by the user, as follows in the PT in TIRESIAS for {USER}



where ◘ is a dummy node, and * is a pointer to the name of the PT in which we are ({USER} in this case). The same sentence would be parsed into a corresponding representation in {FRANK} with * now replacing "Frank" rather than "user". It should be emphasized that the PTs are a surface semantic representation of such sentences, and are not frames in the sense of a structure with an a priori determined list of slot and filler names to facilitate inferencing; they are essentially episodic text representations, but it is those we shall need, in addition to some frame information, to deal with the example to hand.

It will be evident that, in the description of input we have given, there is no general representation of Frank: information about him will be clustered in {FRANK}, but will also appear, as we saw, in {USER} and possibly many other PTs.

We have postulated in various publications [2] [10] the operation of a general principle of preference in language: one that asserts that the effectiveness of natural languages depends on them being constructed so that, in general, correct interpretations are those found with least effort: one could put this by saying that a system should prefer those representation that it is easiest to construct and maintain.

Now consider again the contrasting evaluations of {{TIRESIAS / FRANK / USER / TIRESIAS}} and {{TIRESIAS / FRANK / TIRESIAS}}

If we further assume that at the privileged shallow level there is always a frame structure corresponding to the episodic PT, which contains standard slot names such as DISLIKE, then we may expect:

[ϕ DISLIKE *]

in {TIRESIAS} given that the system knows no one who dislikes it, although in {USER} may be a template (corresponding to a belief of the user)

[Frank dislikes Tiresias]

Then, on "pushing down" {TIRESIAS} into {FRANK} to get {[TIRESIAS / FRANK / TIRESIAS]} in the way we sketched in the last section, no inconsistency of content is noted and no beliefs are reset. But on pushing the value of this object down into USER to get the deepest nesting shown earlier, we encounter

[Frank dislikes Tiresias]

as well as the two connected templates for $1 shown earlier in this section, and both of these items will become part of the constructed "systems view of USERs view of Frank".

4. BELIEF PERCOLATION AFTER PUSH-DOWN

Two effects may now be expected:

i) the inference from Frank dislikes Tiresias in {USER}; together with plausible inference rules about dislike, fear, and leaving places, will generate the reply $2 even though no such consequence was derivable in {{TIRESIAS / FRANK / TIRESIAS}} alone as we see at $3.

ii) on a least effort principle, the key template belief Frank dislikes Tiresias that will have been copied from {USER} into {TIRESIAS / FRANK} [*dislikes Tiresias] and into {TIRESIAS / TIRESIAS} as [Frank dislikes*] during the construction of the desired viewpoint, will now remain present when the push-down is, as it were, pulled apart: it remains in the PT copy. In this way, the beliefs of the user about Frank (about Tiresias) percolate to {TIRESIAS / FRANK}, or rather to the relevant part of {FRANK} (the privileged shallow level), and similarly to {TIRESIAS / TIRESIAS}.

This resulting, highly redundant, representation may seem a paradoxical result of a least effort principle but we maintain that this spread of beliefs from PT to PT, via push-down evaluation, leads to a structure requiring less effort when the same or similar input is encountered in the future. This is because a push-down of environments as we have described it may be considered to require considerable resources: so, for example, {FRANK} should be checked, before being evaluated in {USER} : to see if that push-down had been done lately, and, if it had, it *need* not be done again, since the relevant beliefs, Frank dislikes Tiresias in this case, would already have percolated into it. One may notice that such percolations, if they exist, deny the whole basis of intensional logic (the denial of p believes x -> x), but seem consistent with common sense, and more technically with the sleeper effects [6] , the inference of beliefs from unreliable sources.

It should not be emphasized that we are not trespassing into possible worlds: for they require the assignment of all variables. In the recursive pushing down of PTs we envisage only relevant beliefs will be reset. It is certainly true, however, that these suggestions will impinge on the area on intensional logic (see [2] and, of course, Tiresias in the Greek myth was the seer who knew that Jocasta was the mother of Oedipus (who knew that Jocasta was the wife of Oedipus, and even that Jocasta was Jocasta, but NOT that key fact known to Tiresias). But there is no space to explore these connexions, although we do believe that even the simple considerations set out here could lead to a richer procedural explication of SAs than those current in AI.

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RELATING PROPERTIES OF SURFACE CURVATURE TO IMAGE INTENSITY*

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Reflectance map techniques make explicit the relationship between image intensity and surface orientation. In general, however, trade-offs between image intensity and surface shape emerge which cannot be resolved in a single view. Existing methods for determining shape from a single view embody assumptions about surface curvature. The image Hessian matrix is introduced as a convenient viewer-centered representation of surface curvature. Properties of surface curvature *are* expressed as properties of the Hessian matrix. For several classes of surfaces, image analysis simplifies. This result has already been established for planar surfaces. Similar simplification is demonstrated for singly curved surfaces and for the subclass of doubly curved surfaces known as generalized cones. These studies help to delineate shape information that can be determined from object boundaries and shape information that can be determined from shading.

1. THE REFLECTANCE MAP

The apparent brightness of a surface element depends on the orientation of that element relative to the viewer and the light sources. Different surface elements of a nonplanar object will reflect different amounts of light towards an observer as a consequence of their differing attitude in space. A smooth opague object will thus give rise to a shaded image (i.e., one in which brightness varies spatially) even though the object may be illuminated evenly and covered by a surface material with uniform optical properties. Shading provides essential information about the object's shape and has been exploited in machine vision [1-8].

A convenient representation for the relation between scene radiance and surface orientation is the "reflectance map", introduced by Horn [4]. A reflectance map R(p,q) gives scene radiance as a function of surface gradient (p,q) in a viewer-centered coordinate system. If z=f(x,y) is the elevation of the surface above a reference plane lying perpendicular to the optical axis of the imaging system, and if x and y are distances in this plane measured parallel to orthogonal coordinate axes in the image, then p and q are the first partial derivatives of z=f(x,y) with respect to x and y:

$$p = \frac{\partial f(x,y)}{\partial x} \qquad q = \frac{\partial f(x,y)}{\partial y}$$

The reflectance map is usually depicted as a series of contours of constant scene radiance. It can be measured directly using a photogoniometer or indirectly from the image of an object of known shape. Alternatively, a reflectance map may be derived from phenomenological models of surface reflectance or calculated from analytic models of surface microstructure. Recently, a unified approach to the specification of surface reflectance in terms of both incident and reflected beam geometry has been proposed [9]. The result has been called the bidirectional reflectance-distribution function (BRDF). The reflectance map, as defined here, can be derived in terms of the

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BRDF [10].

Figure 1 shows the reflectance map corresponding to the phenomenological model of a perfectly diffuse (lambertian) surface which appears equally bright from all viewing directions. This reflectance map is given explicitly as:

$$R(p,q) = \frac{\rho(1+pp_s+qq_s)}{\sqrt{1+p_s^2+q_s^2}\ \sqrt{1+p^2+q^2}}$$

where p is a surface reflectance factor and (p.q_s) is the gradient pointing in the direction of a single distant point source of illumination. Here, R(p,q) = pcos(i) where i is the angle of incidence. Cos(i) has been expressed as the normalized dot product of the surface normal vector [p,q,-I] and the vector [Ps»qs>~I] which points in the direction of illumination.

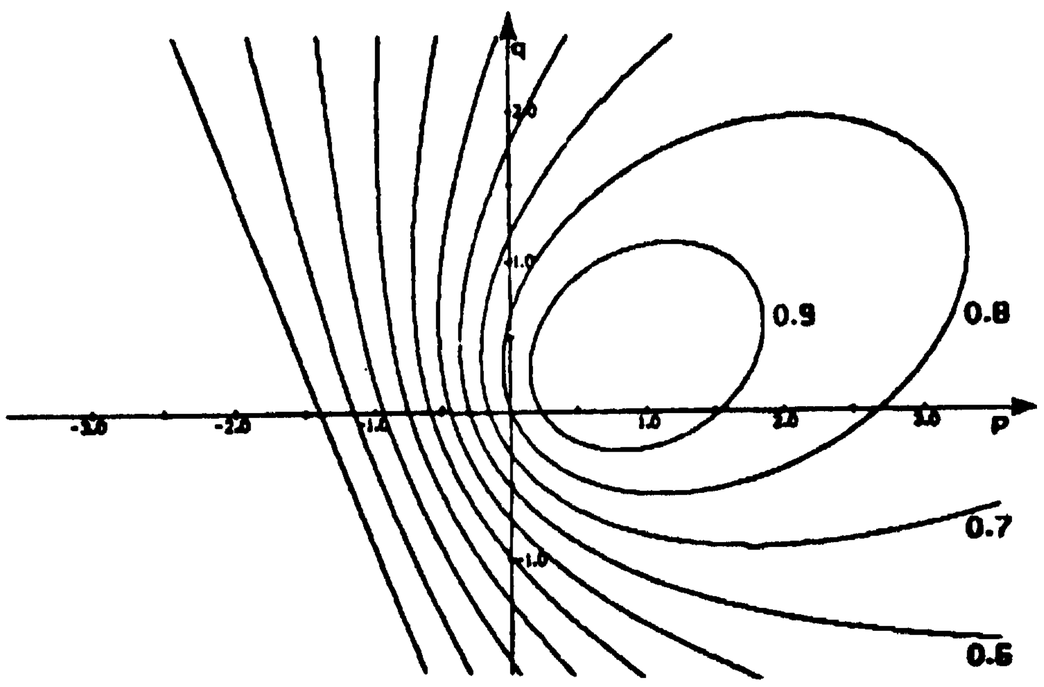

Figure 1 The reflectance map for a lambertian surface illuminated by a single distant point source with p_s = 0.7, q_s = 0.3 and P = 1. The reflectance map is plotted as a series of contours spaced 0.1 units apart.

An ideal imaging device produces image irradiance proportional to scene radiance, If (x,y) is the image irradiance at image point (x,y), then the relevant equation is:

$$I(x,y) = R(p.q). \qquad (1)$$

Until recently, the calculation of shape from shading could be performed only by a rather tedious method involving the direct solution of the above nonlinear first-order partial differential equation, using something like the method of characteristic strip expansion [3]. Progress has been made in the development of an iterative, local method based on relaxation [5]. Both methods, however, embody assumptions about surface curvature.

One can view (1) as a single equation in the two unknowns p and q. In order to determine p and q, additional information must be provided. Knowledge of surface curvature can provide the required additional information,

2. THE IMAGE HESSIAN MATRIX H

Curvature at a point (x,y) on a surface z=f(x,y) can be specified in terms of the two principal radii of curvature r] and r2 and associated directions [11]. Such a specification corresponds to an object-centered definition of surface curvature. It is convenient for image analysis to specify surface curvature in the same viewer-centered coordinate system used to define the reflectance map R(p,q).

Let H be the matrix given by:

$$H = \begin{bmatrix} \frac{\partial^2 f(x,y)}{\partial x^2} & \frac{\partial^2 f(x,y)}{\partial x \partial y} \\ \frac{\partial^2 f(x,y)}{\partial y \partial x} & \frac{\partial^2 f(x,y)}{\partial y^2} \end{bmatrix} \qquad (2)$$

H is the standard Hessian matrix of the function z=f(x,y) [12], Here, H is called the image Hessian matrix of the surface *z=f(x,y).*

One can write the (approximate) equation:

$$[dp\ dq]' = H[dx\ dy]' \qquad (3)$$

('denotes vector transpose) to illustrate that the matrix H relates a movement [dx,dy] in the image to the corresponding change in surface orientation [dp,dq]. If two linearly independent directions $[dx_1,dy_1]$ and $[dx_2,dy_2]$ and the corresponding $[dp_1,dq_1]$ and $[dp_2,dq_2]$ are known, then H is determined by:

$$H = \begin{bmatrix} dp_1 & dp_2 \\ dq_1 & dq_2 \end{bmatrix} \begin{bmatrix} dx_1 & dx_2 \\ dy_1 & dy_2 \end{bmatrix}^{-1} \qquad (4)$$

Image intensity determines one correspondence. By taking partial derivatives of equation (1) with respect to x and y, two equations are obtained which can be written as the single matrix equation:

$$[I_x\ I_y]' = H[R_p\ R_q]' \qquad (5)$$

(subscripts denote partial differentiation). Thus, (4) can be rewritten as:

$$H = \begin{bmatrix} I_x & dp \\ I_y & dq \end{bmatrix} \begin{bmatrix} R_p & dx \\ R_q & dy \end{bmatrix}^{-1} \qquad (6)$$

Image intensity determines the change in surface orientation corresponding to a movement in the image in the direction given by $|R_p,R_q|$. This observation is the basis of Horn's original method for determining shape from shading [3]. But, equation (6) still admits an infinite number of solutions. Further constraint on the matrix H is required.

When additional properties of surface curvature are known 'a priori', they can provide the needed constraint on the matrix H. One set of constraints relates to the positive/negative definiteness of H.

Theorem:
An object surface z=f(x,y) is convex/concave with respect to the viewer if and only if the corresponding image Hessian matrix H is positive semi-definite/negative semidefinite.

The use of convexity was explored in [5,6]. Another set of constraints relates to the eigenvalue structure of H.

Definition:
Let z=f(x,y) be the equation of a smooth surface and let λ_1 and λ_2 be the two eigenvalues of the corresponding Hessian matrix H at image point (x_0,y_0). The surface z=f(x,y) is said to be planar at (x_0,y_0) if and only if $\lambda_1 = \lambda_2 = 0$. The surface z=f(x,y) is said to be singly curved at (x_0,y_0) if and only if one (but not both) of λ_1 and λ_2 is equal to zero. The surface z=f(x,y) is said to be doubly curved at (x_0,y_0) if and only if λ_1 and λ_2 are not equal to zero.

3. PLANAR SURFACES

Objects whose surfaces are planar, as defined above, form the familiar blocksworld polyhedra domain. This is a degenerate case in that both I_x and I_y are everywhere zero. Horn has shown, however, that whenever at least three planes meet at a point, the orientation of each plane can be determined using the reflectance map R(p,q) [4]. The technique combines the quantitative approach to interpreting line drawings developed by Mackworth [13] with the additional constraint provide by image intensity.

4. SINGLY CURVED SURFACES

An important class of surfaces are those that have the property that, through every point on the surface, there passes at least one straight line lying entirely on it. In differential geometry, such a surface is called a ruled surface. The straight line lying entirely on the surface is called a ruling. If a ruled surface has the additional property that all points on a given ruling have the same tangent plane, then the surface is called a developable surface (or a torse) [11]. Huffman charmingly refers to developable surfaces as "paper" surfaces and proposes that such surfaces possess a complexity that is midway between that of a completely general surface and that of a plane surface [14].

The notion of a singly curved surface, as defined above, is equivalent to that of a developable surface (except that planar surfaces, while certainly developable, will not be considered singly curved). It can now be shown that, from an image analysis point of view, singly curved surfaces do indeed possess a complexity that is between that of a completely general surface and that of a plane surface.

For surfaces expressed in the form z=f(x,y), the equation:

$$\frac{\partial^2 f(x,y)}{\partial^2 x} \frac{\partial^2 f(x,y)}{\partial^2 y} = \left| \frac{\partial^2 f(x,y)}{\partial x \partial y} \right|^2 \qquad (7)$$

is the differential equation characterizing developable surfaces. In the current notation, this equation is equivalent to the equation:

$$\det|H| = 0 \qquad (8)$$

Equation (8) is satisfied at an image point (x,y) if and only if a least one of the eigenvalues of the corresponding H is zero at (x,y). For convenience, assume that at least one of λ_1 and λ_2 is nonzero at each image point (x,y). (If both eigenvalues of H are zero for all image points (x,y), then the equation z=f(x,y) describes a plane). Thus, a nonplanar surface z=f(x,y) is developable if and only if it is singly curved.

Let z=f(x,y) be a singly curved surface. Suppose that a point (x_0,y_0) in the image is known to have gradient (p_0,q_0). Then, the Hessian matrix H at (x_0,y_0) is completely determined. H is given as the matrix product:

$$H = \begin{bmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{bmatrix} \begin{bmatrix} \lambda & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{bmatrix} \qquad (9)$$

where $$\lambda = \frac{\sqrt{I_x^2 + I_y^2}}{R_p \cos(\alpha) + R_q \sin(\alpha)}$$

and $$\tan(\alpha) = \frac{I_y}{I_x} .$$

As above, I_x and I_y denote the first partial derivatives of $I(x,y)$ at (x_0,y_0) and R_p and R_q denote the first partial derivatives of $R(p,q)$ at (p_0,q_0).

Given any initial image point (x_0,y_0) known to have gradient (p_0,q_0), equations (3) and (9) can be used to trace out an arbitrary family of curves on the surface $z=f(x,y)$. For singly curved surfaces, one is not confined to tracing out characteristics in the direction $|R_p,R_q|$ as required by Horn's original method for obtaining shape from shading [3].

The fact that H has one zero eigenvalue means that there is one direction of movement in the image which results in no change to surface orientation. This direction is orthogonal to the direction α determined by the vector $|I_x,I_y|$. The component of any movement $|dx,dy|$ perpendicular to $|I_x,I_y|$ is in the direction of a ruling on the surface and thus does not cause a change in gradient (p,q). The component of $|dx,dy|$ in the direction $|I_x,I_y|$ causes a change in gradient $|dp,dq|$ in the direction α where the "scale factor" for that change is given by λ.

The gradients (p,q) corresponding to points on an arbitrary singly curved surface $z=f(x,y)$ are constrained to lie on a one-parameter curve in p-q space. This illustrates that singly curved surfaces possess a complexity midway between that of a planar surface, where surface points map into a single point in p-q space, and that of a completely general surface, where surface points map into a two-parameter region in p-q space.

Figure 2 is the image of a right circular cone of base radius b and height a synthesized using the reflectance map of figure 1. (For this example, a = 2b.) The gradients corresponding to points on a right circular cone lie on the one-parameter curve in p-q space given parametrically by:

$$p = \tan(t) \qquad (10)$$

$$q = \frac{b}{a} \frac{1}{\cos(t)}$$

where $-\pi/2 < t < \pi/2$. The parameter t has a physical interpretation. The circular cross-section of the cone can be represented, in cylindrical coordinates, by the function $r(o) = 1$, where 0 measures angular position about the y-axis. If o is chosen so that $0 = 0$ points in the direction of the viewer, then the parameter t in (10) and (11) is this angle e.

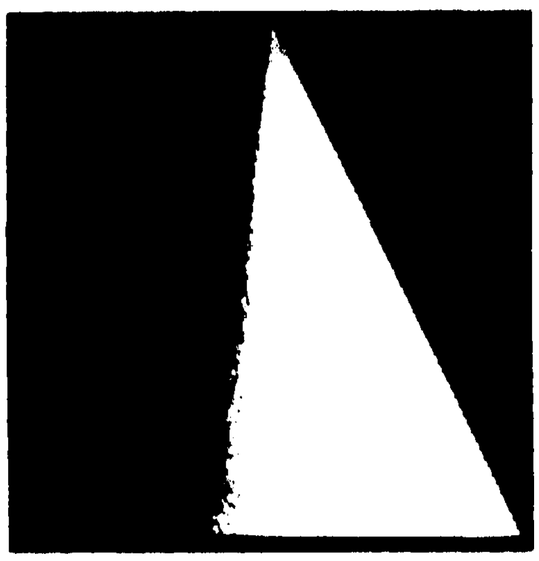

Figure 2 The synthesized image of a right circular cone, with height equal to twice the base radius and axis parallel to the image plane. The surface reflectance is lambertian with a single distant point source at $p_s = 0.7$ and $q_s = 0.3$.

Figure 3 shows the curve in p-q space determined by (10) and (11) superimposed on the reflectance map used to generate figure 2. There exists a 1-1 continuous mapping between any horizontal intensity profile from figure 2 and the curve in p-q space determined by (10) and (11). Thus, finding the point (p,q) corresponding to any image intensity point $I(x,y) = x$ from figure 2 simplifies to the problem of determining reflectance map values on the curve given by (10) and (11) for which $R(p,q) = a$. Since all 1-1 continuous mappings are monotonic, multiple solutions can be resolved by systematically scanning each image line from left to right. The required ratio b/a can be determined from the boundary contour in figure 2. For singly curved surfaces, image analysis using the reflectance map is straightforward.

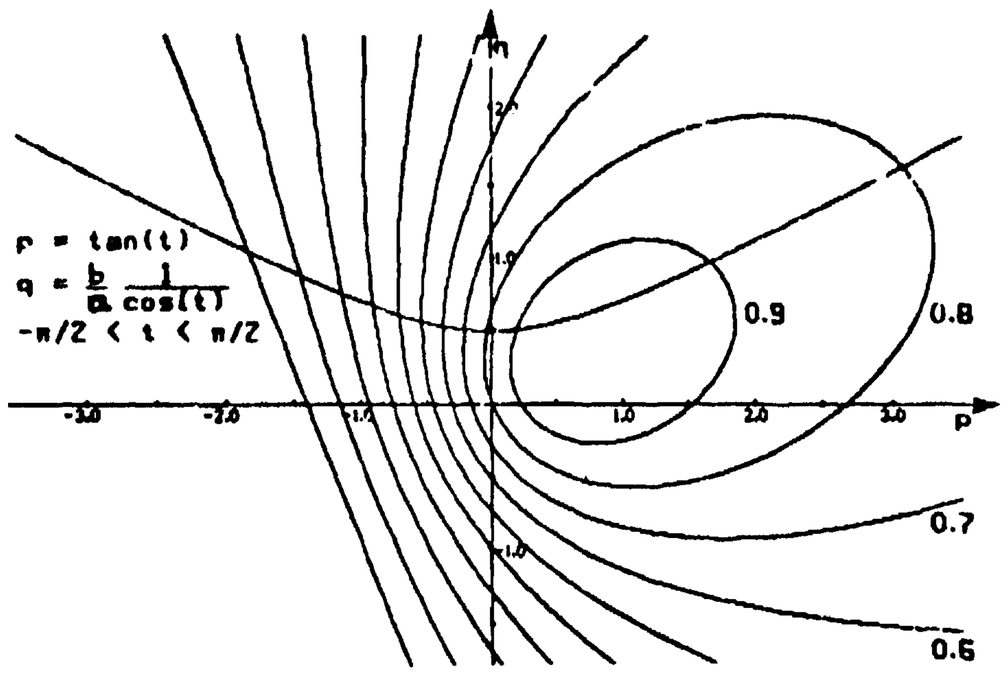

Figure 3 The one-parameter curve in p-q space corresponding to points on the cone o figure 2.

5. GENERALIZED CONES

A generalized cone is defined to be the surface swept out by moving a simple smooth cross-section r(o) along a straight axis A, at the same time magnifying or contracting it in a smoothly varying way [15]. The concept of a generalized cone has its genesis in the generalized cylinder representation of Agin and Binford [16]. There, generalized cylinders were used as a convenient representation scheme for describing complex shapes. In [15|, however, the generalized cone emerges not so much as a representation scheme but as an interpretation that is forced if one tries to develop a theory of how to infer the shape of objects from their silhouettes.

Some additional terminology is required. Let h(x) be the axial scaling function, where x denotes distance along the A axis. The angle *i*> between the axis A and a plane containing a cross-section is called the eccentricity of the cone. If IP=TT/2, then the cone called a rijht generalized cone. In addition, if the cross-section is circular, then the cone is called a right generalized cone with circular cross^ sectjipn.

Generalized cones are, in general, doubly curved. The curvature of a generalized cone, however, conveniently decouples in its object-centered representation. For appropriate viewing conditions, this decoupling carries over to images of generalized cones. These images can be analyzed "almost" as if the surface were singly curved, as will now be shown.

Consider a right generalized cone with circular cross-section. Without loss of generality, one can assume that the axis A passes through the center of the circle. For the moment, one additional assumption is needed. Assume that the axis A is parallel to the image plane. For convenience, let the image X-Y axes be chosen so that A coincides with the image Y-axis. Distance along the A axis is then equal to distance along the Y-axis so that the axial scaling function can be denoted as h(y). Further, let the circular cross-section be denoted by r(e) = 1, where 6 = 0 points in the direction of the viewer. The gradients corresponding to points on such a generalized cone lie in the two-parameter region in p-q space given parametrically by:

$$p = \tan(\theta) \tag{12}$$

$$q = \frac{-h'(y)}{\cos(\theta)} \tag{13}$$

where h'(y) denotes the derivative of h(y) with respect to y and e varies between -TT/2 and ir/2.

Figure 2 was an example of a right generalized cone with circular cross-section. There, h'(y) = -b/a. In general, (12) and (13) define a two-parameter region in p-q space. The relevant observation, however, is that when the axis A is parallel to the viewing plane, the value of h'(x) can always be determined directly from the boundary contour. In this case, finding the (p,q) corresponding to a given image intensity point I(x,y) = a simplifies to a two step process. First, for the particular y, determine h*(y) as the rate of change of object radius with respect to y (equivalently, as 1/2 the rate of change of object diameter with respect to y) at the object boundary along image line y. Second, as in the case of a singly curved object, scan a left to right profile to determine the correct reflectance map point on the curve given by (12) and (13).

Figure 4 illustrates. Here, the axial scaling function is a sinusoid while the cross-section remains circular. Figure 5 superimposes a collection of the curves given by (12) and (13) on the reflectance map used to generate figure 4. The surface depicted in figure 4 is everywhere doubly curved. Yet from the given viewing direction, the curvature decouples so that, from an image analysis point of view, the surface behaves as if it were single curved.

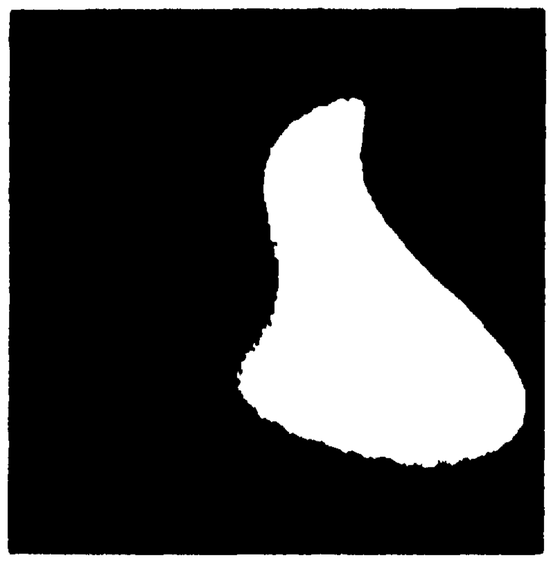

Figure 4 The synthesized image of a right generalized cone with circular cross-section and axis Λ parallel to the image plane. The axial scaling function h(y) is a sinusoid. The surface reflectance is lambertian with a single distant point source at $p_s = 0.7$ and $q_s = 0.3$.

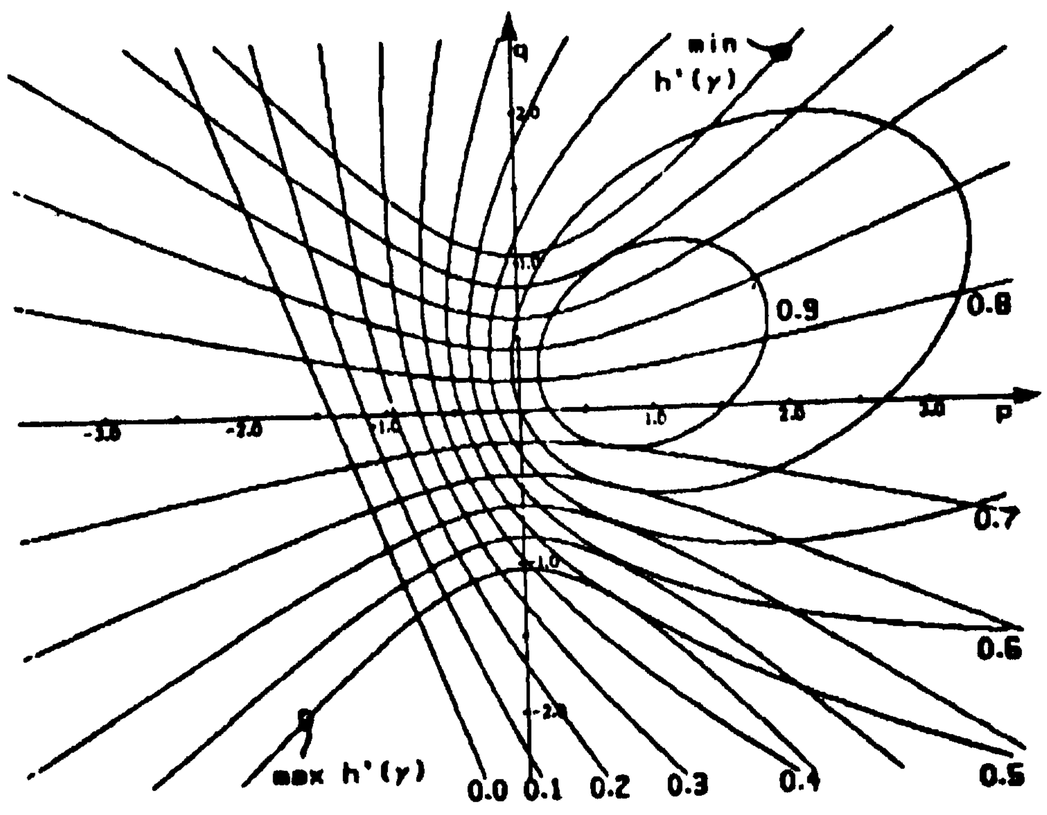

Figure 5 The region in p-q space corresponding to points on the right generalized cone of figure 4, plotted as a family of curves. The included region in p-q space lies below the curve determined by the minimum value of h'(y) and above the curve determined by the maximum value of h'(y),

Suppose now that Λ is not parallel to the image plane. Nevertheless, the image X-Y axes can still be chosen so that the projection of Λ coincides with the image Y-axis. Let the angle between the Λ axis and the viewing plane be ϕ (measured so that positive ϕ implies that Λ is tilted towards the viewer). In this case, distance along the Y-axis is the foreshortened distance along Λ given by:

$$y = \lambda\cos(\phi)$$

so that $$h'(\lambda) = \cos(\phi)h'(y)$$

The gradients corresponding to points on such a generalized cone lie in the two-parameter region in p-q space given parametrically by:

$$p = \frac{\sin(\theta)}{\cos(\phi)[\cos(\theta) - \sin(\phi)h'(y)]} \qquad (14)$$

$$q = -\tan(\phi) + \frac{-h'(y)}{\cos(\phi)[\cos(\theta) - \sin(\phi)h'(y)]} \qquad (15)$$

where $h'(y)$ and θ are as before. If ϕ is known, then one can proceed as before, with only a slight complication in the mathematical expressions required. If ϕ is unknown, two difficulties arise. First, without knowing ϕ, the curve generated by (14) and (15) cannot be determined. Second, without knowing ϕ, the image profile corresponding to a fixed value of λ cannot be determined. At best, it is possible to estimate the value of ϕ which is most consistent with the hypothesis that the image corresponds to a right generalized cone with circular cross-section.

Greater difficulty arises when the cross-section is allowed to be an arbitrary smooth convex function. Roughly speaking, it becomes impossible to resolve the trade-off between axis tilt and cross-section shape using the intensity values recorded in a single view. Let the cross-section function be given, in cylindrical coordinates, by $r = r(\theta)$. To avoid unnecessary complication, suppose once again that the axis Λ is parallel to the viewing plane. The gradients corresponding to points on such a generalized cone lie in the two-parameter region in p-q space given parametrically by

$$p = \frac{r(\theta)\sin(\theta) - r'(\theta)\cos(\theta)}{r(\theta)\cos(\theta) + r'(\theta)\sin(\theta)} \qquad (16)$$

$$q = -h'(\lambda)\frac{r(\theta)}{r(\theta)\cos(\theta)+r'(\theta)\sin(\theta)} \qquad (17)$$

where $h'(\lambda)$ denotes the derivative of $h(\lambda)$ with respect to λ and $r'(\theta)$ denotes the derivative of $r(\theta)$ with respect to θ.

For an arbitrary smooth convex $r(\theta)$, it is not necessarily true that the "left" boundary contour corresponds to $\theta = -\pi/2$ and the "right" boundary contour to $\theta = \pi/2$. If the left boundary contour corresponds to the value θ_L (where $-\pi < \theta_L < 0$) and the right boundary contour corresponds to the value θ_R (where $0 < \theta_R < \pi$), then $h'(\lambda)$ is given by:

$$h'(\lambda) = \frac{\text{rate of change of object diameter}}{\sin(-\theta_L) + \sin(\theta_R)}$$

The information required to determine $h'(\lambda)$ is still contained in the boundary contour but it can be used only if the values θ_L and θ_R are known. The values of θ_L and θ_R, in turn, depend on $r(\theta)$. Thus, although the decoupling between $h(\lambda)$ and $r(\theta)$ exists in the cone's object-centered representation, it is not possible to discover this decoupling from the object silhouette.

6. CONCLUSIONS

Methods for determining shape from the intensity values recorded in a single view embody assumptions about surface curvature. Such assumptions may arise from an analysis of boundary contour or from an analysis of intensity gradations across sections of smooth surface. Reflectance map techniques help make such assumptions explicit. When properties of surface curvature are known 'a priori', they can be exploited in image analysis.

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PLAN-GUIDED ANALYSIS OF NOISY DYNAMIC IMAGES

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A wide variety of processes in biology, medicine, or engineering are recorded on video tape or cine film as moving images. Computer analysis of a moving image, however, requires too much time, if whole areas of a large number of consecutive frames are examined in detail. This paper describes how a plan-guided analysis, which utilizes both a priori and acquired knowledge about the dynamic image, can efficiently and correctly extract necessary information from the video tape or cine film image. It first analyzes a coarse picture and makes a plan, which is then used in the next fine data collection and processing of the record; the plan specifies (1) frames to be sampled, (2) regions to be analyzed, covering important portions of the dynamic image, and (3) suitable operators and their parameters to be applied to the regions. The effectiveness of the method is shown by an example that analyzes a sequence of noisy radiographic images, a cine-angiogram, which needs to reliably detect curves of specified properties in a large number of frames.

1. INTRODUCTION

A wide variety of processes observed in experiments of medicine, biology, or engineering are recorded on video tape or cine film as moving images. Analysis of these images, however, have been tedious tasks of human beings; they must keep watching a large number of frames to point out feature patterns and measure their parameters. In recent years, computer analysis of moving images [1,2], such as motion analysis of hearts [3,4] or micro organisms [5,6], have been studied to reduce the human labor and extract more reliable information from the records in short time.

Because of a large amount of information content of a moving image, too much computing time is spent if whole areas of consecutive frames are examined in detail. Although a special parallel processor system could significantly reduce the computing time for preprocessing, feature extraction, or change detection, we should avoid to waste the computing power for unnecessary processing. Analysis of moving images does hot require all information in the records, but only a small fractions are utilized; for example, we analyze only small subareas covering moving objects for tracking, or abruptly changing frames are more carefully examined than almost still ones for motion pattern analysis. Most motion analyzers have been designed to save the computation by utilizing models of objects in already analyzed frames to predict their locations or shapes in the current frame [1,2].

We have extended these ideas to organize a new system, a plan-guided analyzer of moving images. The plan-guided analysis is not a new idea, but has been studied to analyze complex static pictures; for example, identification of human faces [7] and analysis of chest radiographic images [8]. However, the idea is most effectively applied to analysis of a long sequence of high resolution pictures, because the computing time is of primary importance and one can significantly reduce it by utilizing the contextural information about the images in consecutive frames. The feature of our system is to fully utilize its knowledge, both a priori and acquired knowledge, about the dynamic image so as to extract correct information from the record at an extremely low computation cost. A priori knowledge contains general properties such as 'the moving objects are dark and blob-like/, which is useful to design efficient procedures. However it lacks quantitative information about a particular record, such as locations, velocities, brightness levels, and shapes of objects. The analyzer, therefore, examines a small number of low resolution pictures of the record to collect such information and make a coarse model, a sketch, of the process, by which it can estimate which frame and what regions in it are worthy examining, or what type of a feature extractor is most effective at each point in the regions. Now, the system makes a plan, specifying (1) frames to be sampled, (2) regions to be examined, and (3) effective feature extractors to be applied. Since more accurate knowledge is acquired as a result of this plan-guided analysis of a frame, the coarse model is replaced with a fine and more reliable one, describing exact properties of the objects in the current frame, which is then used to make a more effective plan of sampling and analyzing next pictures. By iterating this process, planning, analyzing and updating, the system constructs a final model of the process, containing all information required.

The purpose of utilizing the plan is not only for minimizing the computation cost, but also for increasing reliability of extracted information. Thus, the plan selects feature extractors and their

parameters, considered to be most reliable, at each point. However, it is not easy to find the correct feature at every point in a noisy dynamic image such as a sequence of radiographic images. Optimization methods [9,10] are known as useful to search noisy pictures for curves or regions of specified properties. We can apply one of them to the dynamic image by embedding the properties of the object in a figure of merits. The optimization method, however, requires too much memory space and computing time, especially when a global shape property such as smoothness over a wide range is speicified, since we are forced to solve it as a high dimensional non-serial optimization problem. We, therefore, propose an improved method which utilizes an efficient search for the optimal sequence of linear segments instead of the already known inefficient search for the optimal series of pixels.

t. HARDWARE SYSTEM

Fig.l shows a block diagram of the hardware system. The computer used is aHP-2108A,a 16bit machine with 32kw of memory, a disc (15Mbytes), a printer/plotter, a storage tube display and three terminals under a multi-user operating system. A picture memory, 256kbytes 800nsec/2bytes cycle time, is connected to the computer. We utilize this memory as a flexible buffer for video input and output from/to a VTR (video tape recorder), a TV camera, and a color display. The memory is also used as high speed random access files of dynamic images; a software subsystem swaps picture data in a segment of the memory for necessary data in disc files, on the basis of first in first out [11].

Our system is provided with a computer controlled film projector, which selects a specified frame by sending 35mm film at a rate of 15 frames/sec. At present, the TV camera is used as the transducer of the projected image, which is transformed into a 256 by 256 6bit digital picture.

3. ANALYSIS OF MOTION PATTERNS

3.1 ANALYSIS OF CINE-ANGIOGRAMS

In recent years, people have studied computer analysis of a cine-angiogram, a cine film record of a radiographic image of a beating heart in which Xray opaque dye is intermittently injected through a catheter. Their primary interest is in measuring temporal change in the volume of the heart; the computer detects the internal surface of the heart in each frame, and calculates the volume by utilizing a three dimensional model of a heart.

In this paper, a more advanced analysis is described, which detects both internal and external surfaces of the heart, and measures the spatial and temporal change in thickness of the heart wall, which gives us important measure of heart diseases.

The usual methods detect a boundary of a left ventricle by rather simple procedures; for example, an adaptive threshold method detects candidates points for the boundary, and then a simple statistical method examines their neighbors to fit line segments to the boundary [3]. A reason why such a level detecting method is applicable is that the film is taken and developed so as to show rather sharp contrast in gray values between the light ventricle and the dark background. Such a photographic noise reduction technique, however, is not applicable to a cine-angiogram for analyzing a heart wall, which has usually intermediate gray values in our radiographic images. As a result, the pictures contain much noise, masking small gray value changes on or near the surfaces. Moreover, an accurate detection of both surfaces is needed, since small errors in the locations of points on a surface cause considerable errors in the thickness measurement of the heart wall.

Another important problem, which has been already discussed, is the computation efficiency. The computer needs to examine a large number of high resolution pictures, because the heart wall occupies only a small fraction of each horizontal scan of the input pictures.

3.2 PLAN-GUIDED ANALYSIS OF WALL THICKNESS

We have developed a plan-guided analyzer for detecting both surfaces of a wall of a left ventricle and measuring temporal changes in thickness at each portion of the wall. The features of the system are as follows: (1) detection of edge points in the first frame is guided by a plan which specifies regions to be examined and promising feature extractors to be used, (2) smooth boundaries of the wall are obtained by an efficinet search method, and (3) another plan is utilized to analyze consecutive frames; it selects next frame to be sampled and guides the analyzer so as to examine it in a much more efficient manner than the first frame.

The analysis is divided into the following five phases.
(1) planning of feature extraction of first frame.
(2) search for smooth boundaries.
(3) selection of next sampling frame.
(4) analysis of consecutive frames.
(5) measurement of thickness.

3.3 INPUT PICTURES

Input of the system is a sequence of Xray images of a left ventricular chamber recorded on 35mm cine film at a rate of 60 frames/sec; thus, a record of one beating cycle contains about 50 frames. A frame is converted into a 256 by 256 6bit digital picture. Fig.2 shows an example and the result of applying a simple 3 by 3 gradient operator to it. The picture contains much noise, especially significant non-uniformity of gray values is observed in the ventricular chamber near the internal surface, where muscles and tissues attached on the surface generate much noise.

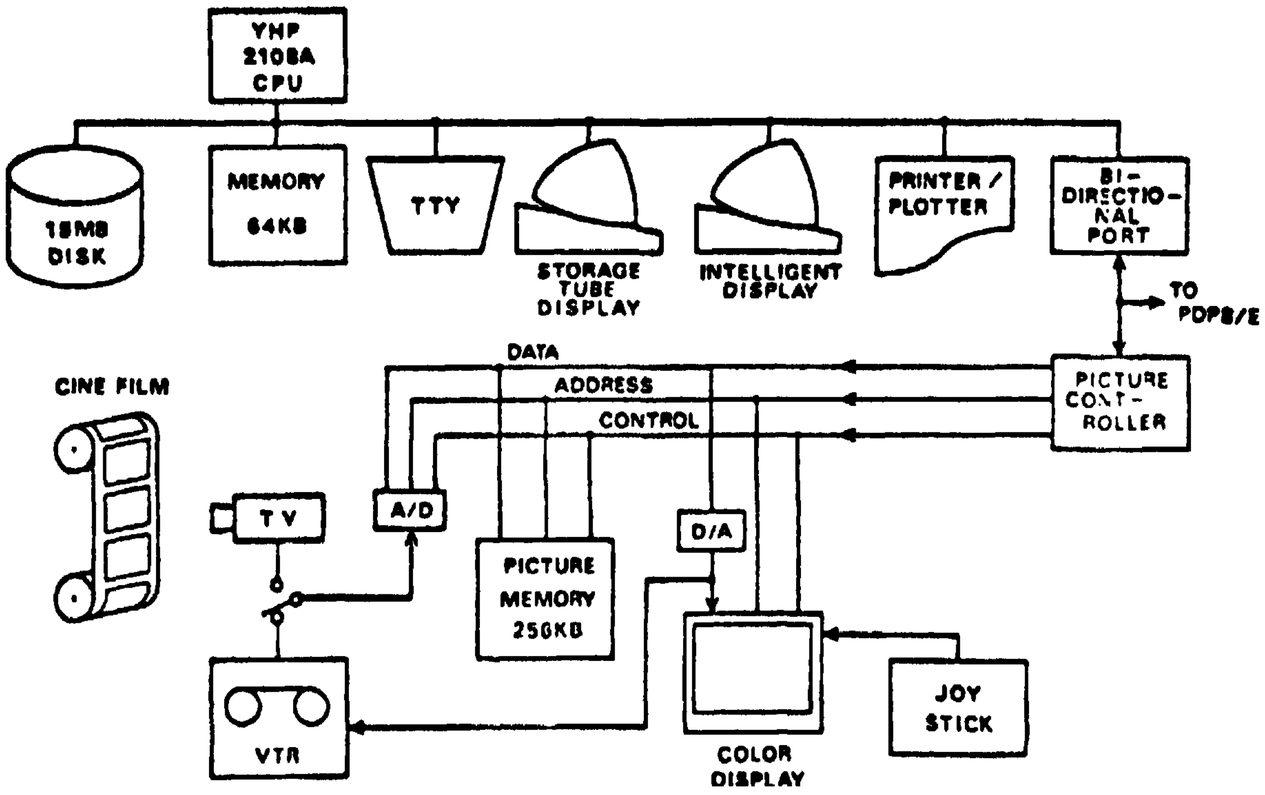


Fig. 1. Block diagram of hardware system.

Contrast of gray values between both sides of each surface is very low, since the gray values in the wall gradually increase, as the mean, with the distance from the external surface.

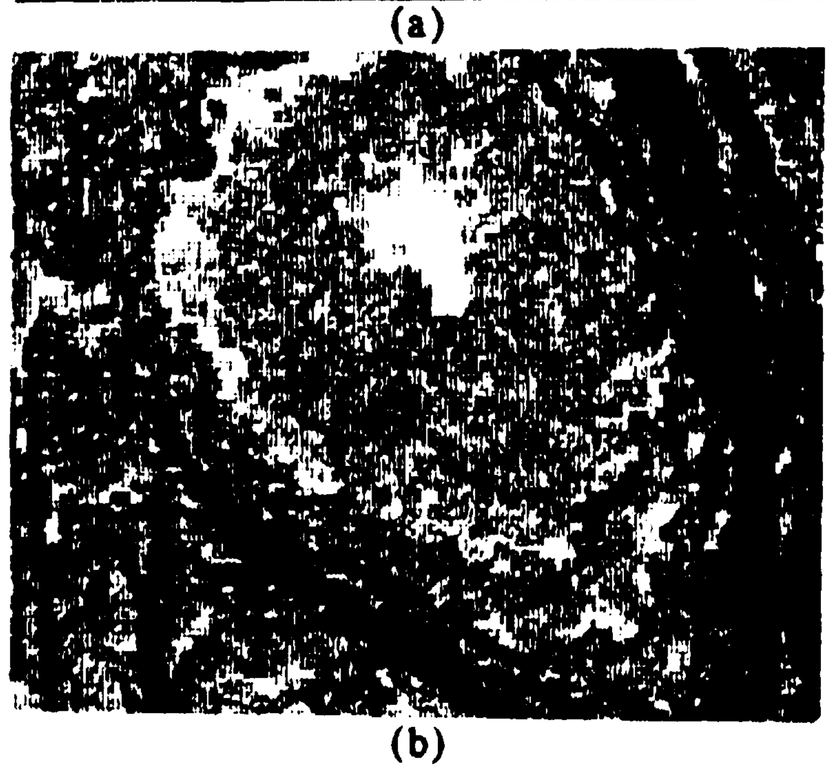
3.4 PLANNING OF FEATURE EXTRACTION

Because of the low picture quality of a cine-anglogram, such as low contrast and much noise, a level detecting method cannot reliably find a heart wall. If we apply a gradient operator to a small area, say a 3 by 3 window, around every point in the picture, then the enhanced noise by the operator masks the boundaries of the wall. In order to reliably detect edge points in a noisy picture, edge features should be extracted from averaged gray values in some larger local areas. Since the heart wall is a narrow region, a group of paired rectangular areas of different directions shown in Fig.3 are used as the smoothing areas. A pair of local areas, of which absolute difference of average gray values is largest in the group, are selected at every point in the picture. Each selected pair gives reliable features of the edge at that point; the edge strength and direction are decided from the already computed maximum difference and the direction of the selected areas. When this procedure is applied to a point on the boundary of the wall, it automatically selects paralielly directed areas to the boundary, therefore its output is less sensitive to the noise and is not blurred by the averaging.

This method, however, requires too much time. If differences of averaged gray values in a pair of 10 by 1 areas are computed and compared for 12 different directions at every point in a 256 by 256 picture, then a minicomputer HP-2108A spends about one hour for the computation.

We, therfore, have developed a plan-guided edge detection method to shorten the computation time. The system first compresses a 256 by 256 original

(a)



(b)

Fig. 2. (a) An input picture.
(b) The result of applying 3x3 gradient operator.

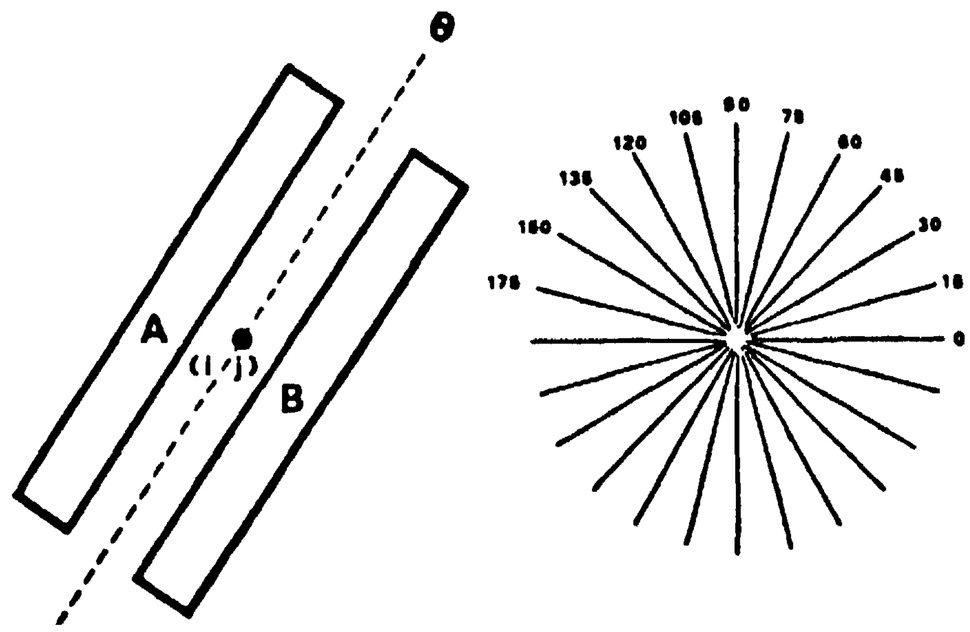


Fig. 3. Smoothing areas for edge detection and their directions.

picture into a small picture of 64 by 64 picture. Each point in the small picture is the averaged value of the 16 points in a 4x4 neighborhoods in the original picture. Applying a simple 3 by 3 gradient operator to every point in the compressed picture and thresholding it, the system decides (1) analysis regions, regions to be examined further, and (2) an approximate direction of an edge at each point in

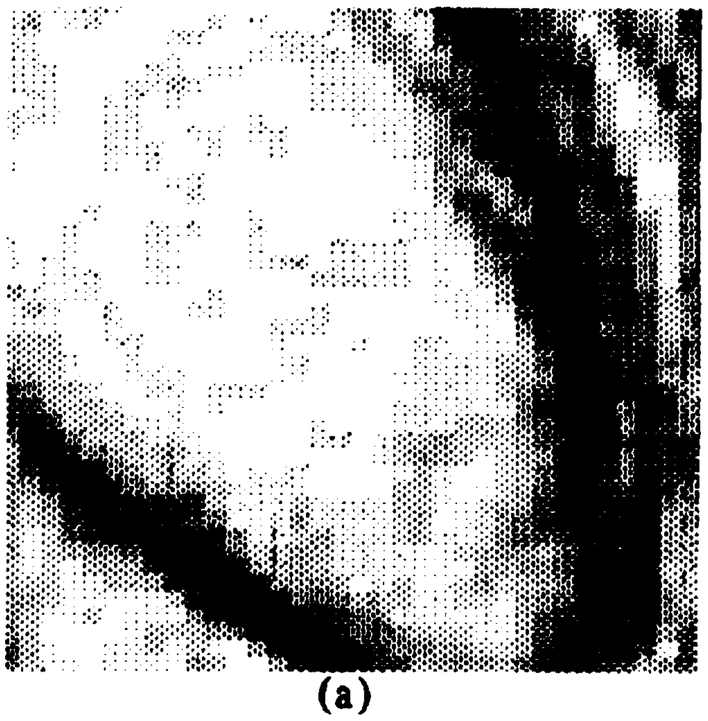


Fig. 4. (a) An edge picture of a compressed picture of Fig.2 (a), (b) Analysis regions specifying directions of edges.

them. Fig.4 (a) shows edges detected in the compressed picture by the gradient operator. This picture is less noisy than Fig.2 (b), the result of applying the same operator to the original picture, because of noise reduction by the averaging in the windows. A plan of the next edge detection is described as a map containing the analysis region and the directions of edges in them, as shown in Fig.4 (b). The analyzer utilizes this map to efficiently find features; an edge feature at each point in the analysis regions is detected by a pair of rectanglar areas perpendicular to the direction. Since the analysis regions occupy 1/3 of the input picture (we could considerably reduce them by using a higher threshold value or utilizing more heuristics) and only one selected edge direction from 12 variations is examined at each point, the computation for edge finding by this method is (I/3)x(I/12)=I/36 of that without the plan. The gradient operation to each point in the compressed image is iterated about 4000 times, 1/16 of that required for the original picture, and the operation is much simpler, therefore its computation cost is also inexpensive. The result of applying the plan-guided edge detecting method to Fig.2 (a) is shown in Fig.5, which seems much better than Fig.2 (b).

$.5 EFFICENT SEARCH FOR SMOOTH BOUNDARIES

Next phase to the edge detection is to recover the outer and inner boundaries of the heart wall in the analysis regions. Since the edge picture still contains considerable noise, and since precise detection of the boundaries is needed, usual curve followers are not applicable. Optimization methods are known as useful to find a curve of specified properties in a noisy picture. They embed the property into a figure of merit and search for the curve as a sequence of consecutive points which minimize the figure of merit, by a dynamic programming technique [9] or a heuristic method [10]. Many practical examples, and also this analysis of the heart wall, need to find smooth curves over a wide range, since small unevenness on a detected curve is considered as statistically meaningless.

In order to find a smooth curve hidden in noise, the usual methods embed a property of smoothness of a curve into a part of the figure of merit as a sum of a curvature at each point. If the smoothness over a wide range is embedded, then we are forced to sove it as a high dimensional non-serial optimization problem, which requires too much computing time and memory space.

A different approach has been studied to avoid this difficulty [12]. Since the curve to be detected is smooth, we can approximate it with a sequence of linear segments. We embed the smoothness over a wide range of a sequence of linear segments connecting points x_1 , x_2 ,..., x_n into a figure of merit $c(x_1, x_2, \ldots, x_n)$ as

$$C(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} e(x_i) + k_1 \sum_{i=1}^{n-1} |\theta(x_{i-1}, x_i) - \theta(x_i, x_{i+1})| \quad (1)$$

Where $e(x_m, x_n)$ is a mean of edge strength along the segment connecting x_m and x_n , $\theta(x_m, x_n)$ is the inclination angle of the segment, and k_1 is a constant.

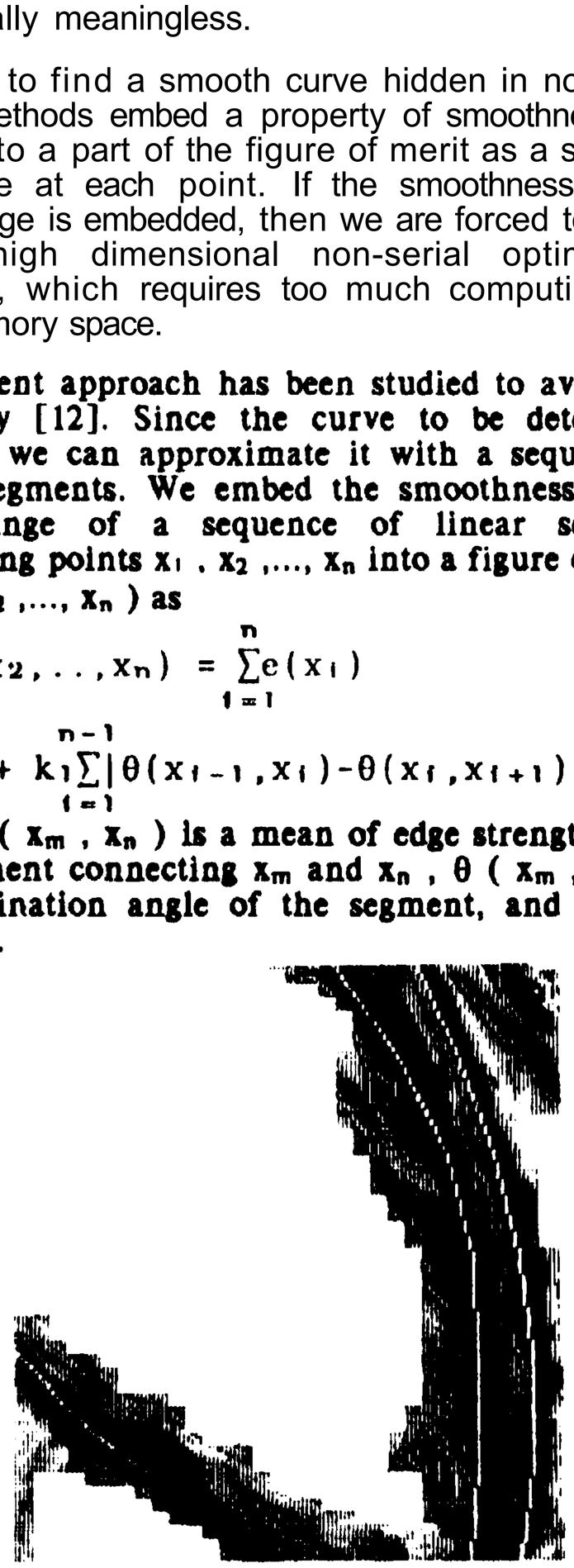


Fig. 5. Result of the plan-guided edge detection.

Now, we apply this method to detection of the wall boundaries in the edge picture. Starting points of the search are decided from a priori knowledge about the boundaries; the both boundaries have directions between 0 ' and 90 * at the upper part of the ventricle. A sequence of 10 successive edge points on a ridge of such a direction are selected as starting points.

We apply a heuristic search to find a solution of this optimization problem, and the results are successful to many input pictures. The search, however, sometimes fails, when the outer and inner boundaries are close together at the end of the expansion period of the ventricle. Since the edge strength on the inner boundary is much larger than that of the outer one, a search for the external surface happens to cross the wall and follow the inner boundary. In order to avoid this difficulty, we utilize another knowledge that gray values on the outer boundary are darker than those on the inner one. Thus, we use a figure of merit evaluating edge strength, smoothness, and gray values, as follows.

$$C(x_1,\ldots,x_n)=\sum_{i=1}^{n} e(x_i)+k_1\sum_{i=1}^{n-1}|\theta(x_{i-1},x_i) - \theta(x_i,x_{i-1})|+k_2\sum_{f=1}^{n}|g(x_i)-G| \qquad (2)$$

Where g(xm , xn) is the mean gray value of points on the line segment connecting xm and xn , G is a mean gray value of a group of candidates for starting points, and k1 , k2 are constants. Fig.S shows an example of results obtained by this method. The detected boundaries are arranged into a model which guides the selection and analysis of consecutive frames.

3.6 SELECTION OF FRAMES FOR ANALYSIS

In order to reduce computation for the consecutive frames, we effectively utilize the model obtained from the result of the previous analysis. First of all, narrow analysis regions are selected on the both sides of the detected boundaries, as shown in Fig.6. At present, the width of the regions is set at a length of 7 pixels. We can save the computation by examining only picture data in these regions, which are much smaller than those used for the analysis of the first frame.

As mentioned before, the system should select frames worthy examining from a great number of frames in the record. Because of intermittent movement of the heart, it is reasonable that the analyzer skips over consecutive frames in which little changes from the previously analyzed one are observed. We use a simple temporal differnce method to measure the degrees of changes. If the wall boundaries move to some extent, then there exist significant changes in the analysis regions. Sums of a gray value change at each point in the regions from that of the previously analyzed one are computed for a coming input frame, and if at least one of the sums is greater than a

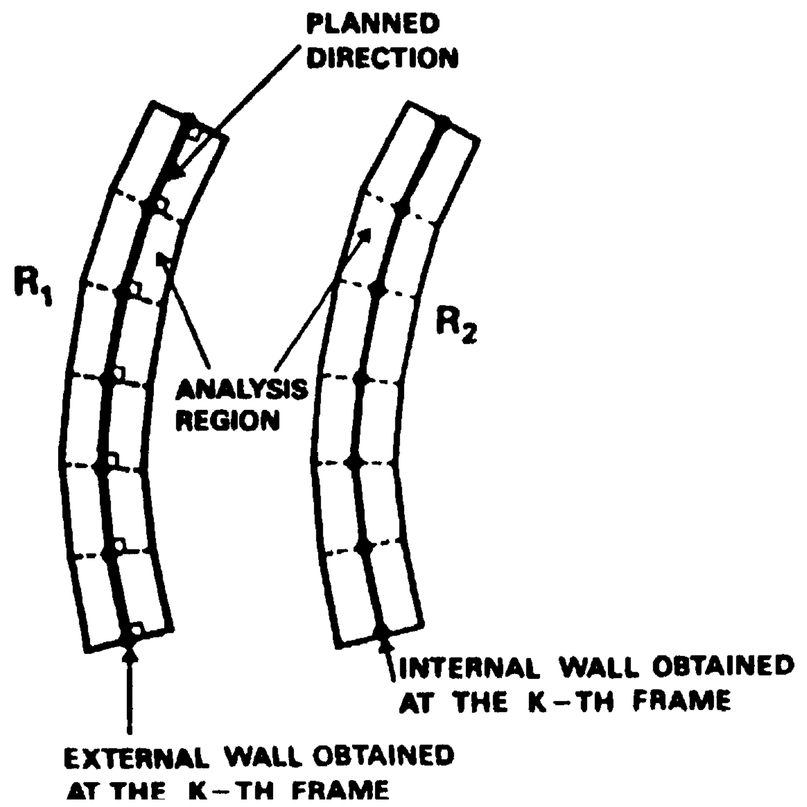


Fig. 6. Analysis regions for consecutive frames.

threshold, then the frame is analyzed, else it is skipped. Utilizing this criterion for sampling, the system analyzes about 1/3 of frames in a record as a mean, and only 1/16 at the end of the contraction or expansion period, when a wall shows very slow movement.

3.7 ANALYSIS OF CONSECUTIVE FRAMES

Edge detection and search for the boundaries in the sampled frame is guided by the model of the previously analyzed frame. The analyzer measures an edge component parallel to the nearest boundary at every point in the analysis regions. Then it searches each analysis region for a boundary using the figure of merit of (2).

3.8 MEASUREMENT OF WALL THICKNESS

In order to measure the dynamic behavior of the heart wall, we establish a correspondence between portions of the wall in successvely analyzed frames. Those areas having tissues or mustles on the internal surface of the heart are useful for finding the correspondence. Therefore, we first determine such areas having characteristic gray-level distribution along the internal boundary in the first frame. The variance of gray levels in the local area of 7x7 points is examined at every point along the internal boundary. Then, the areas where the variance of gray levels in it is the local maxima in its neighborhood and is larger than a certain threshold are selected as the areas to make correspondence.

The selected areas are then matched to those along the internal boundary in the next analyzed frame by a simple correlation method. The thickness of the heart wall is measured at these corresponded points in each frame. Fig. 7 shows the result of thickness measurement at those corresponded points of the internal boundary between the frames.

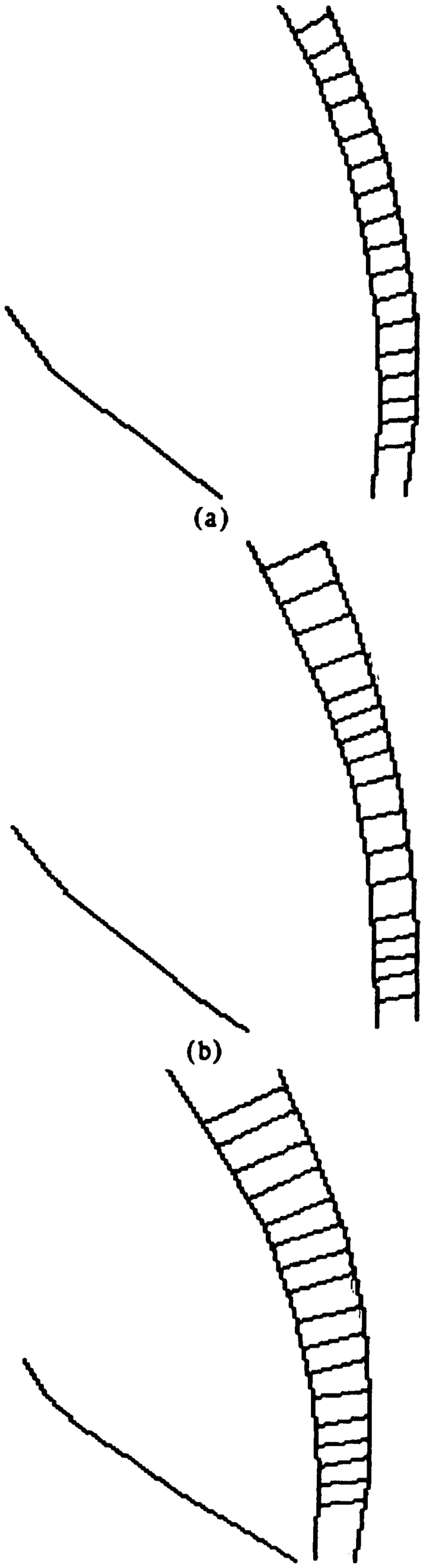


Fig. 7. Thickness of a heart wall in (a) 10th, (b) 26th and (c) 34th frames.

4. CONCLUSION

The plan-guided analysis is very effective to extract correct information from noisy dynamic images such the cine-angiogram. The system is efficient since plans select (I) frames to be sampled, (2) analysis regions of small areas, and (3) directions of edges to be detected. We have also developed a new efficient search method for a smooth curve in a noisy picture. The computation time was about 6 minutes for 1st frame, 14 seconds for analyzing a next sampled frame, and less than 1 second for deciding whether an input frame is skipped or not. We believe this approach is essential for analysis of high resolution dynamic images.

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A KNOWLEDGE DIRECTED LINE FINDER FOR ANALYSIS OF COMPLEX SCENES

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As a part of complex scene analysis system, this paper presents a line finder which can find a globally good line with respect to the knowledge available of the line to be sought. A variety of knowledge available of the line to be sought can be communicated to the line finding system simply in the form of descriptions so that the higher level of the program can easily use this line finding system. The optimization method is utilized to detect a globally good line with respect to the given knowledge of the line. In order to reduce the required storage space and computation time in the optimization process, we use the following techniques: 1) represent a line by a sequence of linear segments and find the good sequence of segments by the optimization method and 2) use a locus model of search to prune unpromising iines during the optimization process. Some experimental results applied to various scenes with different amount of noise and knowledge are given in the paper.

1. *INTRODUCTION*

Boundary detection Is an important and critical stage in scene analysis to segment an input picture into meaningful regions. This process usually consists of the following two steps: (1) detection of short edge elements, and (2) connecting these edge elements Into boundaries. Many methods have been proposed to detect short edge elements which apply local operations to every point of the input picture. An operator tuned up for characters of edges to be detected is usually used to enhance the edges to be sought in noisy pictures. In order to detect edge elements in noisy pictures, relatively large operators are often used to examine statistic properties of local regions. When edge elements have been found, then they are connected to form boundaries or lines. This line finding process must utilize properties about lines to be detected and must find globally good lines with regards to the properties in order to distinguish meaningful edges in noisy pictures. These properties of the lines to be sought must be separated from the line finding program and given in the form of data to the program, since minor changes of the characteristics of the sought boundary may require a major reprogramming if the properties are embedded in the program[l].

An optimization method is known to be an excellent method to find a globally good line with respect to given properties of the sought line in noisy pictures. Montanari[2] has embedded properties of lines to be detected in a merit function and utilized a dynamic programming method to determine an optimal sequence of points with respect to the given merit function from a number of possible combinations of points. Although the method is good for finding lines in noisy pictures, its drawbacks were the required computation time and storage space, and Martelli[3] has proposed an more efficient method which finds sub-optimal lines instead of optimal lines using a heuristic search method.

Both of the methods represent a line as a sequence of consecutive points, and need much computation time and storage space if they are applied for high-resolution pictures which are utilized in many applications such as medical images, aerial photographs,etc. Furthermore, shapes that the iines are expected to have, such as 'smoothness', are very important criterion to discriminate lines from noise. However, they need too much computation time and storage space if these shape information is embedded to the merit function because number of combinations of points to be searched expands to a large amount.

In this paper, we propose an efficient search method of lines in noisy pictures which represent a line as a sequence of linear segments instead of a sequence of points and find near-optimal sequence of line-segments with respect to a given figure of merit. We believe that there is little problem to approximate a line by a sequence of linear segments since (1) Small variations on a line is considered as statistically meaningless, (2) Lines we would like to find are smooth ones in many applications, and (3) Since edge elements are determined by statistical distribution of gray levels, it seems natural to determine line segments by statistical distribution of edge elements.

The advantage of the proposed method comparing with the existing methods are as follows:
(a) The required storage space and computation time is much smaller and therefore much more efficient since number of lines among which the optimum is sought is much less than the point-wise search.

(b) It can find lines in noisier pictures since shape information of the line we want to detect can be easily embedded in the figure of merit.

In order to further decrease the required storage space and computation time, we utilize the locus model of search which has been proposed by Rubin et al[4] in image interpretation task. We will utilize this search method for finding lines where only a beam of near-miss alternatives around the best line are extended to determine a near-optimal line.

For complex scenes containing many kinds of objects, analysis is usually performed in the following steps[5]: 1) detect distinct lines as the initial information that can be easily found in the scene, 2) select models of objects which contain these extracted lines and propose the lines to be examined utilizing the models of objects and their contextual relations, and 3) examine the proposed lines using the knowledge of the sought lines given by the above higher level of program (or scene analyzer) for final interpretation of the scene.

In such a scene analysis system, a line finder which can find a globally good line with respect to the knowledge given by the scene analyzer is necessary. The knowledge available on the line to be sought is not only properties of the line which can be embedded in the merit function, but also a variety of knowledge such as expected location, when to terminate the line following.etc. All of these variety of knowledge available of the line to be sought must be easily expressed by and communicated to the line finder. We will describe a line finding system which can find a good line with respect to the knowledge given in the form of descriptions by the scene analyzer.

2. FINDING SMOOTH LINES IN NOISY PICTURES

2.1 MULTISTAGE OPTIMIZATION PROCEDURE

Let us first briefly review the multistage optimization procedure. In general, an optimization problem can be formulated as follows: given a merit function $f(x_1, x_2, ..., x_N)$, where $0 \le x_i \le n_i$, $i=1,..., N$, find (a) the maximal value M of the merit function f, and (b) a value $(X_1, X_2, ..., X_N)$ for which the maximum is achieved. If the merit function f can be expressed by a sum of terms, each of which depends on only a few variables, then a multistage optimization procedure applies. For example, if f has a simple form as

$$f(x_1,\ldots,x_N)=f_1(x_1,x_2)+f_2(x_2,x_3)+\ldots+f_{N-1}(x_{N-1},x_N) \quad (1)$$

then the following recursion formula can be used:

$$h_1(x_1)=0$$

$$h_{k+1}(x_{k+1})=\max_{0\le x_k\le n_k}(f_k(x_k,x_{k+1})+h_k(x_k)) \quad (2)$$

where $k=1,..., N-1$ and $0 \le x_{k+1} \le n_{k+1}$. At each stage, the values $h_{k+1}(x_{k+1})$, $0 \le x_{k+1} \le n_{k+1}$, and the values $m_{k+1}(x_{k+1})$ of x_k for which the maximum is achieved must be saved in a table with n_{k+1} entries. At the end of this process, maximum value M of f can be obtained as

$$M=\max_{x_N} h_N(x_N) \quad (3)$$

The values $(X_1, ..., X_N)$ for which the maximum is achieved are obtained by tracing back the tables with the recursion formula:

$$X_N=m_N=\arg\max_{x_N} h_N(x_N)$$

$$X_k= m_{k+1}(X_{k+1}) \qquad k=N-1,\ldots,1 \quad (4)$$

2.2 REPRESENTATION OF A LINE BY POINTS

The existing methods to find a line in noisy pictures, represent a line as any sequence of points P_1, $k=1,..., N-1$, are neighbors. The properties of the sought line are embedded in a merit function f and an optimal line is searched with respect to a given merit function using the optimization method. Let us first consider a simple problem of finding a low-curvature line having high gray values. Then, a good merit function will be the sum of gray levels along the line, minus the sum of the curvature at every point. If we denote the coordinate vectors of a point P_i by $z_i = (x_i , y_i)$ and slope of the line by $\theta (z_i , z_{i+1})$, then a curvature of a point P_i defined by three points can be given as
$\theta (z_{i-1} , z_i)- \theta (z_i- z_{i+1})$.
Then, a merit function is given as

$$f(z_1,\ldots,z_N)=\sum_{i=1}^{N} g(z_i) - k\sum_{i=2}^{N-1} |\theta(z_{i-1},z_i) -\theta(z_i,z_{i+1})| \quad (5)$$

where $g(z_i)$ are gray level of a point P_i. This is a merit function of the form

$$f(z_1,\ldots,z_N)=f_1(z_1,z_2,z_3)+\ldots+f_{N-2}(z_{N-2},z_{N-1},z_N) \quad (6)$$

and can be solved by the multistage optimization procedure.

However, this measure of curvature defined at such a small length causes serious erroneous results. Fig. 1 shows a simple example of such cases where the problem is to find a smooth line connecting A and F. In the figure, values of points marked as o are one and the others are zero. The optimization method with the merit function defined in (5) finds a path A-B-C-D-F as the optimal solution, because sum of curvatures of this path is smaller than another path. However, we perceive another path A-B-E-D-F as more meaningful or good-shaped and the path B-C-D as the line caused by noise. This error has been caused by the very local measure of curvature defined only by three consecutive points. To avoid this problem, more global properties of the line defined over a wider range should be embedded into the merit function.

If the property of the line defined by a wider range, say k points, are embedded into the merit function, it becomes the form of

$$f(z_1)=f_1(z_1,\ldots,z_k)+f_2(z_2,\ldots,z_{k+1})+\ldots$$
$$+f_i(z_i,\ldots,z_{i+k-1})+\ldots \quad (7)$$

where all terms are functions of k variables. This is called a merit function of type k, and it is known that the required tables and computation time are exponetial with k to solve the problem with multistage optimization procedure.

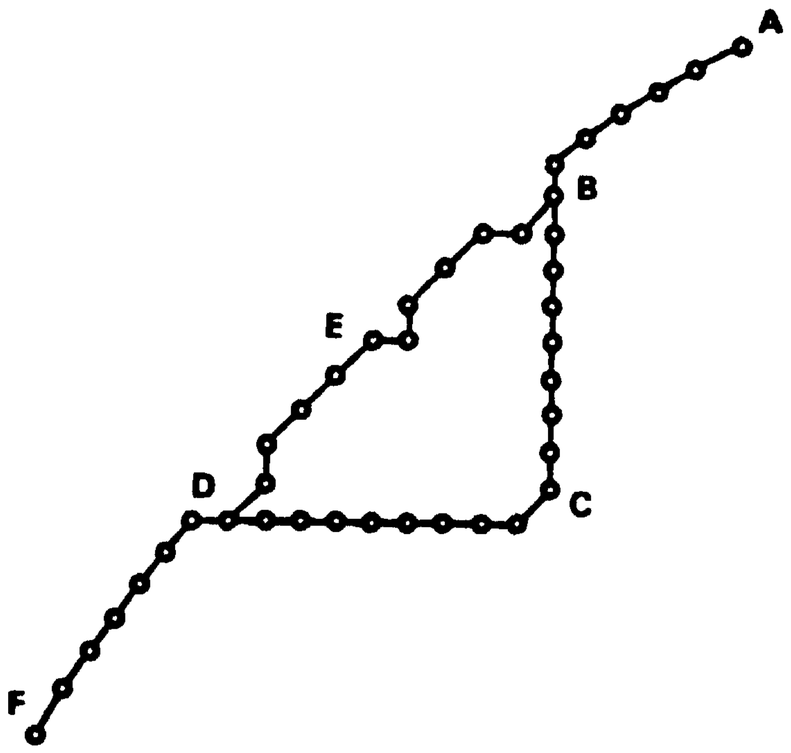


Fig. 1. An example in which curvature defined at a small length causes erroneous result.

1.5 REPRESENTATION BY LINEAR SEGMENTS

We have studied a different approach to avoid this difficulty, in which a line is represented by a sequence of connected linear segments L1 , L2 LN of length l instead of consecutive points , as shown in Fig. 2. Let us represent a linear segment L by an ordered pair of their endpoints (Z1 , z2) and call Z1 the head and z2 the tail of the segment. Then two linear segments L and L' are called connected if the tail of L coincides with the head of L If we call a connected linear segment of a segment L a successor of L, then each segment of length l has *lilt* possible successors as shown in Fig. 3. However, since the line we want to detect are smooth ones, successors having curvatures less than a certain threshold a are considered as 'legal' successors. That is, if e (Z1 , Z2) denotes the direction of the segment L (Z1 , z 2), then segments *V* (z', , z'i) having

$$|\theta'(z'_1,z'_2)-\theta(z_1,z_2)| \leq \alpha \quad (8)$$

are legal successors as shown in Fig. 3.

With this representation, a merit function to find a low-curvature curve having high gray levels in which the curvature is defined by the length of 2 l points can be given as

$$f(z_1,\ldots,z_N)=\sum_{i=2}^{N} g(z_{i-1},z_i)$$
$$-k\sum_{i=2}^{N-1}|\theta(z_{i-1},z_i)-\theta(z_i,z_{i+1})| \quad (9)$$

with the constraint defined in (8) , where $g(z_{i-1}, z_i)$is a mean of gray values of the points lying on the line L_{i-1} (z_{i-1} , z_i). It will be noted that the problem of type 2 ℓ if the curve is represented by a sequence of points is reduced to the problem of type 3 with this representation. Number of stages necessary to find a curve of N points is also reduced from N stages with pointwise search to N/ℓ stages with this linewise search. Next, we will describe an algotithm to find optimal sequence of linear segments with respect to a given merit function.

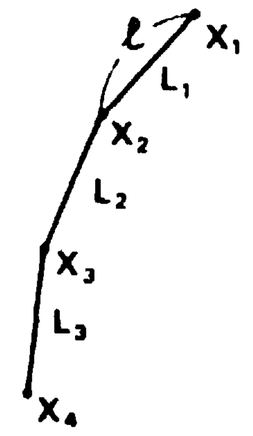
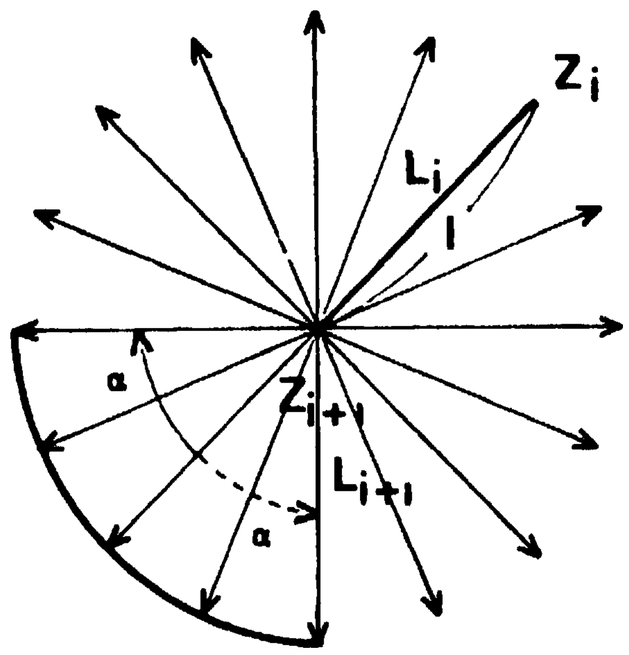


Fig. 2. Representation of a line by a sequence of linear segments L_1, L_2, ..., L_N.



Legal successors

Fig. 3. Legal successors of line L.

2.4 FINDING THE OPTIMAL SEQUENCE

For the sake of simplicity, let us first consider the problem of extracting from a picture a curve which starts in the first row and ends in the last row. First of all , for each admissible Z1 , successors Z2 are determined with a constraint *nie (z1 , z2) < 2 n .* Then , at the k-th stage , successors zK+1 are expanded

for each admissible z_k with the constraint

$$\theta(z_{k-1}, z_k) - \theta(z_k, z_{k+1}) \leq \alpha$$

where k=2,..., N-1. For every value of z_k and z_{k+1}, we compute

$$h_k(z_k, z_{k+1}) = H_{k-1}(z_{k-1}, z_k) + g(z_k, z_{k+1}) + k|\theta(z_{k-1}, z_k) - \theta(z_k, z_{k+1})| \quad (10)$$

where $h_1(z_1, z_2) = g(z_1, z_2)$ and H_{k-1} is the value of the output of the previous stages for all addmissible z_{k-2}. Then we obtain the maximal value of h_k, H_k, with respect to z_{k-1} and the value of z_{k-1}, Z_{k-1}, for which the maximum is achieved. These values, H_k and Z_{k-1}, are stored in the table for every value of z_k and z_{k+1} at each stage.

This process terminates at the N-th stage when some of the segments (z_{N-1}, z_N) intersect with the last column. At this stage, the tail of each segment, z_N, which intersects with the last column is determined as the intersecting point of the segment (z_{N-1}, z_N) and the last column. For every value of z_{N-1} and z_N, we compute h_{N-1} defined in (10) and obtain the maximal value of $h_{N-1}(z_{N-1}, z_N)$, $H_{N-1}(z_{N-1}, z_N)$, and the value of z_{N-2}, Z_{N-2}, for which the maximum is achieved. Then, for all admissible z_{N-1}, we compute the maximum of $H_{N-1}(z_{N-1}, z_N)$maximum of $H_{N-1}(z_{N-1}, z_N)$ with respect to z_{N-1} and the value of z_{N-1}, Z_{N-1}, for which the maximum is achieved. Finally, we obtain the maximal value of $H_N(z_{N-1}, z_N)$, $M(H_N)$, and a value of z_N, Z_N, for which the maximum is achieved. Then, tracing back the tables with the recursion formula defined in (4), we obtain Z_N, Z_{N-1}, ..., Z_1 for which the maximum has been achieved.

2.S LOCUS MODEL OF SEARCH

In order to decrease storage space and computation time, we introduce the locus model of search to this line finding system. In the multistage optimization process, all the paths generated during the optimization process are saved and evaluated until the last stage. However, it is usually not necesary to find the optimal path but it is sufficient to find good or near optimal solutions in practical applications. Therefore, we prune unpromising paths from the search tree at each stage. That is, after computing H_k at each stage, those paths having Hk less than a certain threshold are not saved in the table; and therefore, their successors are not generated at the subsequent stages. Let us denote the maximum value of Hk at the k-th stage as M(Hk), then the threshold is set as $t \cdot M(Hk)$, $0 < t < 1$. This search method suppresses exponential growth of successors and only a beam of near-miss alternatives around the best path are retained as shown in Fig. 4.

S. FINDING A LINE WITH GIVEN KNOWLEDGE

In this section, we will describe a line finding system which finds a globally good line with respect to the knowledge of the line given by the scene analyzer. A variety of knowledge is available on the line to be sought. These various knowledge of the sought line must be easily expressed by and communicated to the line finder. The line finder consists of three components; a menu, a line finding program and an interpreter as shown in Fig. 5. The menu is a list of knowledge which can be utilized by the optimization process. Then the properties of the sought line can be expressed simply by descriptions which specify which items of the menu should be used in finding the line. The descriptions given by the scene analyzer are interpreted and embedded into the line finding program by the interpreter.

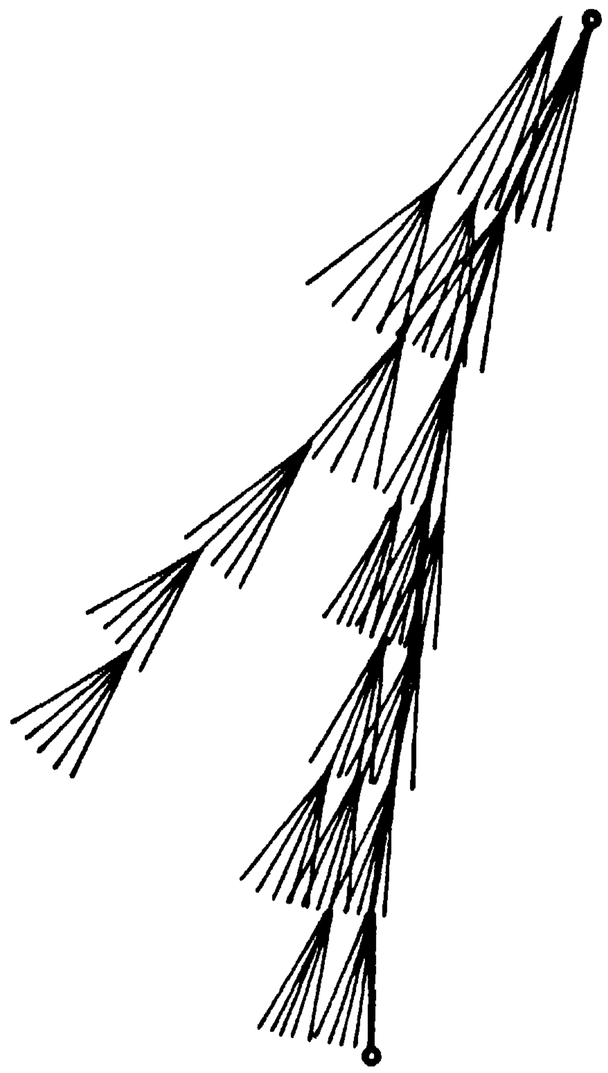


Fig. 4. A locus model of search supresses exponential growth of successors.

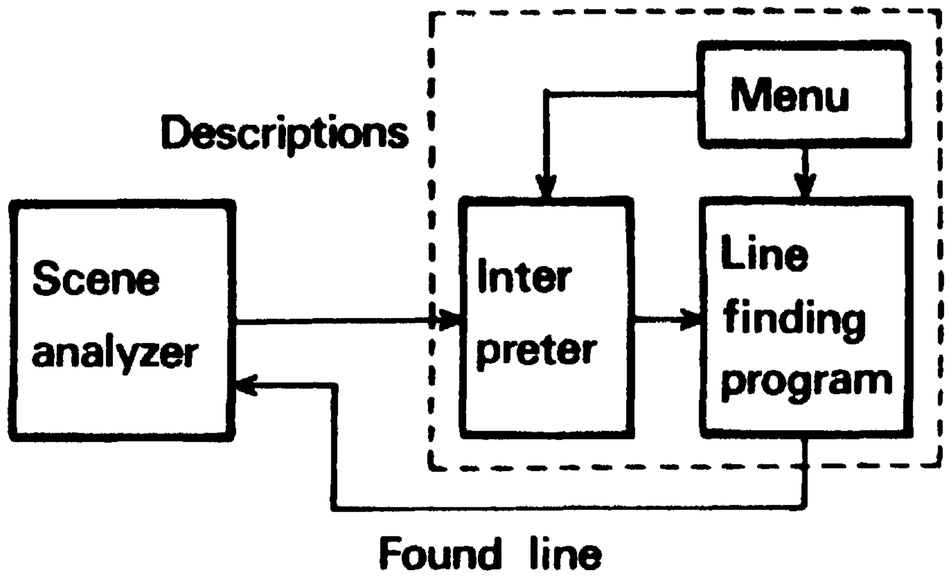


Fig. 5. Line finding system.

3.1 MENU AND INTERPRETER

The menu consists of properties of the line, some constraints on the line, constraints on the starting point, and terminating conditions, each of which is described below.

3.1.1 PROPERTIES OF THE UNE

The menu for the properties of the line is listed in table I. The properties of the sought line are specified by the format (item, weight, parameter). For example, if we would like to find the low-curvature line of homogeneous gray level showing strong edgeness, then descriptions are given to the line finder as:
(HOMGRY k,),(EDGE k2),(LOWCURV k3). Then, these properties on the line are embedded into the merit function as follows:

$$f = k_1 f_1 + k_2 f_2 + k_3 f_3$$

3.1.2 SOME CONSTRAINTS ON THE UNE

Constraints on the line which are difficult to embed in the merit function are given to the line finder as follows.

Search region: the expected location of the sought line is known using the relationship with the already found lines. This knowledge is given to the line finder as the search boundary of the line. The search boundary is given to the line finder by a sequence of representative points as (SEARCH (X1 , y1) ,(x2,y2 , y_2) ....). If the search boundary is given, a line is sought in the region bounded by the search boundary as shown in Fig. 6. This information greatly reduces the computation time and storage space, and increases reliability of the extracted line.

Length of linear segment *l* - we have four values for the length l ; S, 10, 20, 30, and one of them can be specified considering the maximal curvature of the line to be sought. If it is not specified, length 20 is utilized.

Constraint on the successors a : the parameter a determines number of successors generated and is given considering the maximal curvature of the line to be sought. If it is not specified, 1 radian is used for

Threshold *t* ' the threshold *t* determines the width of the beam, that is a number of lines saved in the table at each stage. If *t* is not given, 0.5 is used as *t*.

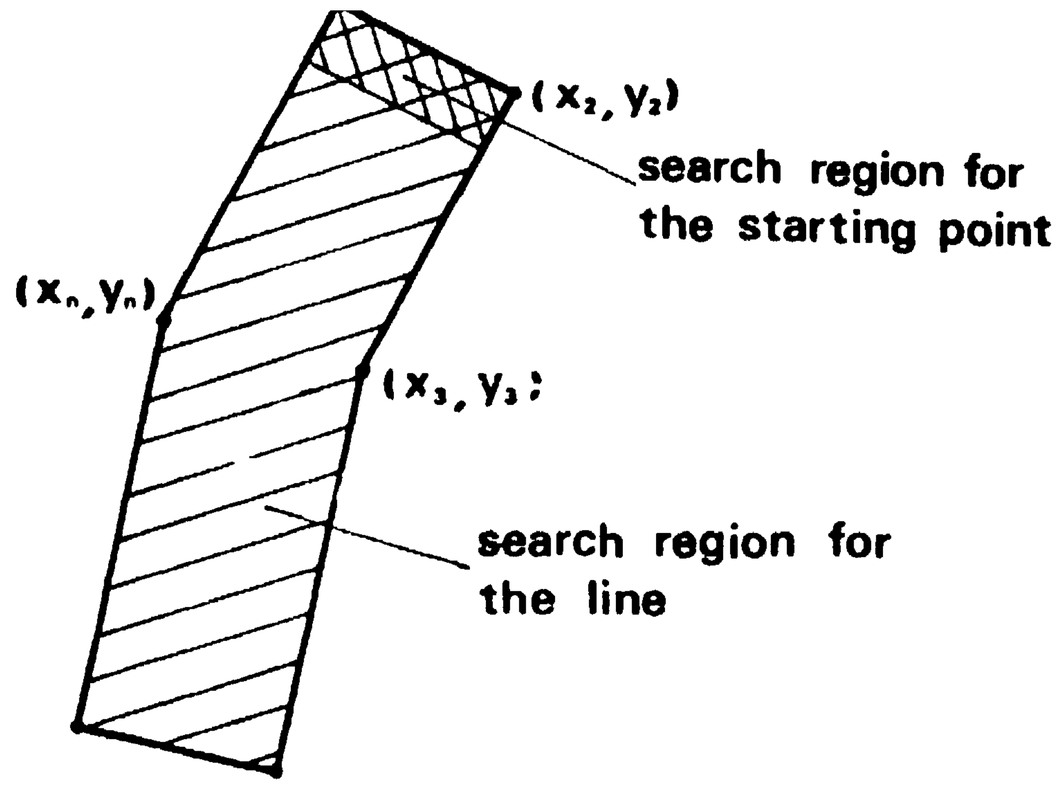


Fig. 6. Search region for the line and for the starting point.

Table I. Properties of the line

EDGE	**Find a line having strong edgeness**	$\sum e(z_k, z_{k+1})$
GVNGRY	**Find a line having gray level G**	$\sum g(z_k, z_{k+1}) - G$
HOMGRY	**Find a line having homogeneous gray levels**	$\sum g(z_{k-1}, z_k) - g(z_k, z_{k+1})$
GVNDIR	**Find a line having edge direction D**	$\sum d(z_k, z_{k-1}) - D$
HOMDIR	**Find a line having homogeneous edge direction**	$\sum d(z_{k-1}, z_k) - (z_k, z_{k+1})$
GVNSLP	**Find a line having slope θ**	$\sum \theta(z_k, z_{k+1}) - \theta$
LOWCURV	**Find a low-curvature line**	$\sum \theta(z_{k-1}, z_k) - \theta(z_k, z_{k+1})$
CONCURV	**Find a constant-curvature line such as a circle**	$\sum (\theta(z_{k-2}, z_{k-1}) - \theta(z_{k-1}, z_k)) - ((z_{k-1}, z_k) - \theta(z_k, z_{k+1}))$
GVNCURV	**Find a line having the curvature C**	$\sum \theta(z_{k-1}, z_k) - \theta(z_k, z_{k+1}) - C$

E (z_k, z_{k+1}); mean value of edgeness of the segment (z_k, z_{k+1})
G (z_k, z_{k-1}); mean value of gray level of the segment (z_k, z_{k+1})
D (z_k, z_{k+1}); mean value of edge direction of the segment (z_k, z_{k+1})
θ (z_k, z_{k+1}); slope of the segment (z_k, z_{k+1})

3.1.3 CONSTRAINTS ON THE STARTING POINTS

Selection of the starting points of the line is very important to reduce growth of successors in subsequent stages. We have two constraints on selecting the starting point; 1) search boundary for the starting points and 2) properties of the starting point. In many cases, more restricted search boundary is available for the starting point than for the sought line. This search boundary is given to the line finder by a sequence of representative points as

(SSERCH (x1 , y1) , (x2 , y2) ....).

If a search boundary is given, the starting point is sought in the region bounded by the search boundary. If it is not given, the search boundary for the line is utilized.

Properties of the starting point listed on the menu are gray level, edgeness and edge direction. The properties on the starting point is given in the similar manner to the line. For example, if we would like to find the points having strong edgeness and edge direction D with weights k1 and k2 respectively, then the following descriptions are given*.

(SEDGE k,),(SDIREC k2 D).

Then the following merit function is generated by the interpreter:

$$f=k_1*e(z)+k_2*|d(z)-D|$$

Then, the promising points are selected with respect to the merit function for the starting point in the search region.

3.1.4 TERMINATING CONDITIONS

There are four terminating conditions in line following as follows.

1) Line segments of the current stage intersect with line segments of the first stage. This terminating condition is used when the sought line is closed.

2) Line segments of the current stage intersect with the other lines which are already found in the picture.

3) Line segments of the current stage intersect with the line L specified as the terminating one.

4) There is no promising line segment at the current stage. That is, score of the best line segment at the current stage Mk is much smaller than the score of the best line segment of the last stage Mk . such as Mk < Mk-1 where s < 1.

If we would like to use the terminating conditions, for example 1 and 4, then the descriptions are given to the line finder as follows;

(TERM 1), (TERM 4 s),

where s is a threshold.

3.2 LINE FINDING PROGRAM

When the descriptions on the sought curve are given, these are interpreted and embedded into the line finding program by the interpreter as described before. Then the line finding program seeks a globally good line with respect to the given knowledge as follows.

1) Compute the value of merit function f(z1) for every point Z1 in the search region for the starting point, and select promising starting points. Let us denote the maximum of f(Z1) as M (f(Z1)), then those points having value of f(z1) larger than T*M(f(zi)) are selected as promising starting points.

2) At the first stage, determine successors z2 for each selected points z1 and select promising ones among Z2. For each selected point Zi , its successors Zi are determined with the constraint that z? must be in the search region for the line , and the merit function $f(z_h\ zi)$ are computed. Then those segments having f(Zi , Zi) larger than £*M(f(Zi , z*)) are selected as promising ones. If the search region for the starting point is given around the middle of the sought line, then two beams are obtained as shown in Fig. 7. In this case, one of them is followed first.

3) At the k-th stage, determine the successors z_{k+1} for each z_k and select promising ones among z_{k+1}. For each z_k , its successors are determined with constraints that z_{k+1} must be in the search region and $\theta(z_{k-1}, z_k) - \theta(z_k, z_{k+1}) \leq \alpha$. If the given merit function is type i ($2 \leq i \leq 4$), then we compute

$$h_k(z_k, z_{k+1}) = H_{k-1}(z_{k-1}, z_k) + f_k(z_{k-i+2}, \ldots, z_{k+1}) \qquad (11)$$

for every value of z_{k-i+2} ,... , z_{k+1}. We obtain the maximal value of h_k , H_k , with respect to z_{k-i+2} and the value of z_{k-i+2} , Z_{k-i+2} , for which the maximum is achieved , for every value of z_{k-i+3} ,... , z_{k+1}. Let us denote the maximum of H_k as M (H_k). Then, those points z_{k+1} having H_k larger than t*M (H_k) are selected as promising points. The value of H_k and Z_{k-i+2} of the promising points z_k are saved in the table.

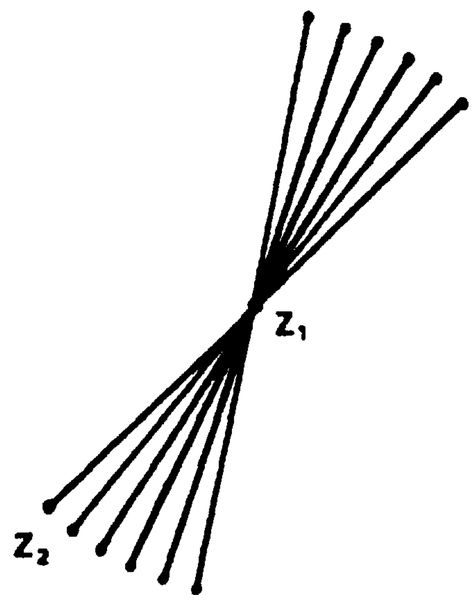


Fig. 7. Two beams are obtained if the starting point is found around the middle of the line.

4) Check the terminating conditions. If one of the terminating conditions specified by the descriptions is satisfied, then the line following is terminated. At this last stage, the tail of each segment zN is determined as the intersecting point of the segment (ZN-I, ZN) and the line specified by the terminating conditions.

5) Try to follow the other end of the line using the above-mentioned procedure , with (Z2 . Z1) as the starting line segments. When both sides terminate, then obtain the maximal value of the merit function, and a sequence of line segments for which the maximum is achieved by tracing back the tables.

4. EXPERIMENTAL RESULTS

The proposed line finding system was implemented in Fortarn IV on a HP-2108 computer and was utilized for analysis of heart walls, blood vessels and complex industrial parts. We show a result on the test image shown in Fig. 8(a) by adding different amount of noise to the image. The image consists of 256 by 256 points, each point having 16 levels of gray. Our purpose is to detect smooth line 1 in the presence of noisy lines 2 and 3. In the image, the gray levels of the lines 1, 2 and 3 are 10, 11 and 12 respectively and the gray level of the background is S. In Fig. 8 (b) and (c), independent amount of noise is added to every point. The statistical distribution of the noise at every point is normal, with mean value zero and standard deviation 4 and 6, respectively. Note that the line is recognizable in Fig. 8(b) but quite unrecognizable in Fig. 8(c).

The knowledge available of the curve is smooth, has large value of gray, starts in the first row and ends in the last row. Therefore, the descriptions given to the line finding system are as follows:
(EDGE 1), (LOWCURV 5), (SSERCH (1,0,(256,1))
(TERM3(1,256),(256,256))

Fig. 9(a) and (b) show the results for the image? of Fig. 8(b) and (c). It will be noted that the line is detected correctly even in the presence of heavy noise. If the second description is eliminated, that is the low-curvature is not utilized, then the pass 2 is selected as shown in Fig. 9(c) which is the result for the image of Fig. 8(b).

5. CONCLUSION

We have presented a line finding system that can detect a globally good line with respect to the given knowledge of the line. The proposed method is very efficient since 1) size of tables required at each stage and number of stages is greatly reduced by representing a line by a sequence of linear segments, 2) a locus model of search is utilized to supress the exponential growth of search trees, and 3) several constraints available of the sought line are utilized to limit search space or growth of successors, such as search boundary, constraints on the starting point, etc.

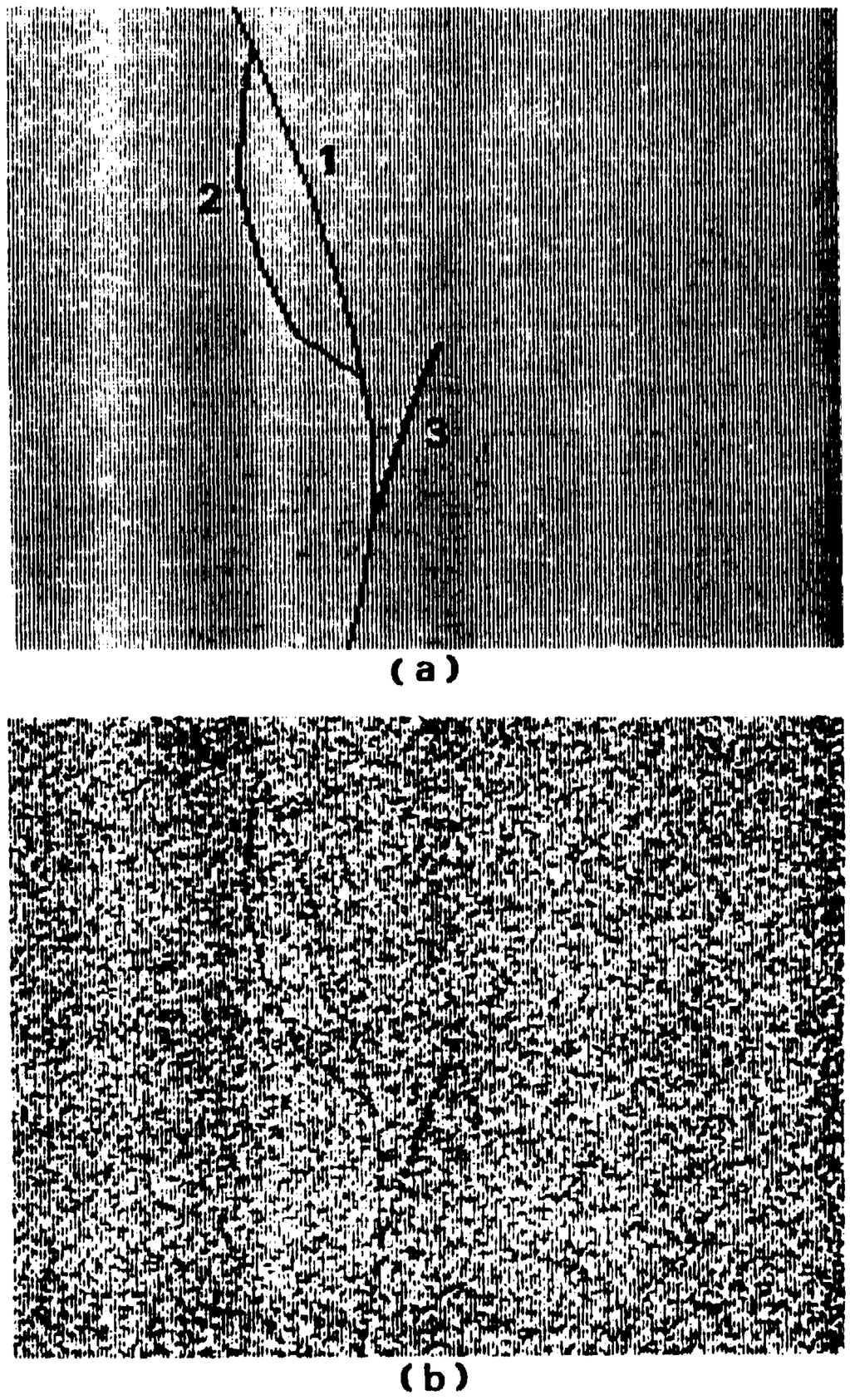


Fig. 8. Input pictures with different amount of noise.

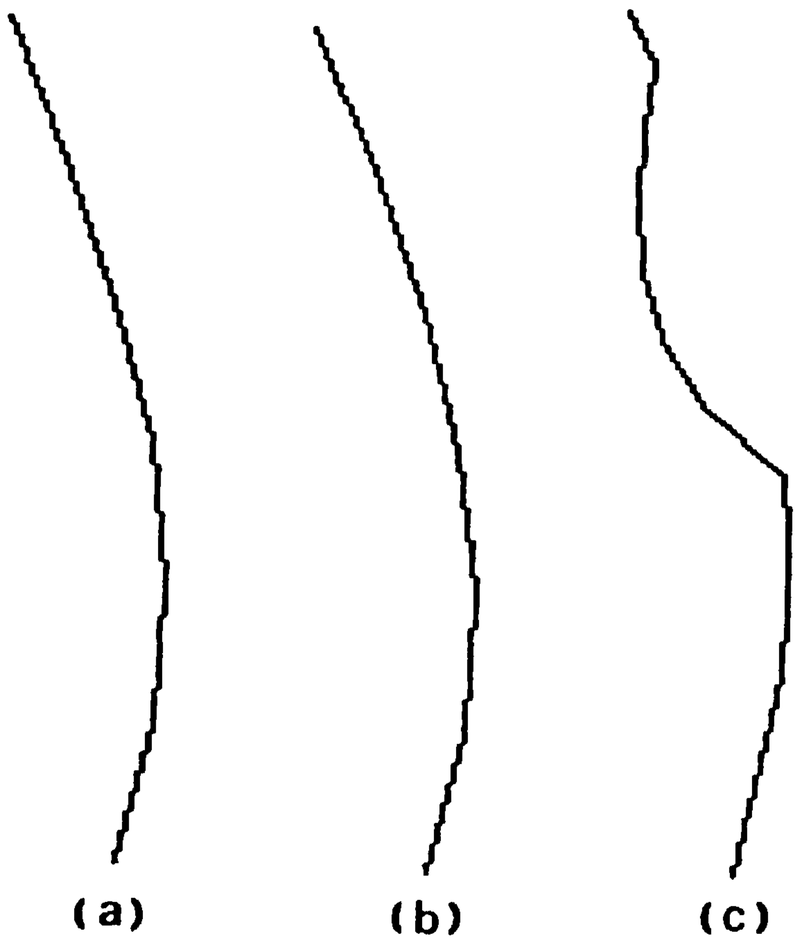


Fig. 9. Results obtained (a) for Fig. 8(b); (b) for Fig. 8(c); and (c) for Fig. 8 (b) without the knowledge of shape.

The length of linear segment *l* seriously affects computational efficiency. Therefore, if the sought curve is smooth and can be approximated by long linear segments, then large value should be given to *l* . On the contrary, if small variations on the line is important or the sought line has high curvature, then small value must be given to *l* . However, it is more efficient that we first obtain an approximate line with large *l* and then obtain more details with small *l* in the neighborhoods of the approximated line than obtaining the line with small *l* from the beginning.

We have used a locus model of search instead of the best first search of A* algorithm for obtaining sub-optimal solution. The reason of this selection is that its control structure is simpler than the A* algorithm and it is easier to understand the behavior of search process since the locus model does not need backtracking. Another reason which is more important is that it permits parallel computation of all the linear segments at every stage.

In this system, it is very easy to communicate the knowledge of the sought line to the line finder since a variety of knowledge can be expressed simply in the form of descriptions. The menu provided in the system is sufficient for our current tasks. However, it is easy to change the menu if it is necessary.

We have applied the proposed method for a variety of scene analysis tasks and the results have shown the effectiveness of the proposed method to find a globally good line with respect to the given knowledge. However, for complex scenes where many kinds of objects exist and a priori knowledge on the scene is not available, we must first extract distinct lines as initial information on the scene to select possible models of objects in the scene. For this purpose of extracting initial information, there exist several methods such as planning! [6], detection of distinct edges[7] and extended Hough transformation!; 8]. The proposed line finder is then used to find subtle lines using knowledge of the objects and their contextual relations.

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BOUNDARY DETECTION OF TEXTURED REGIONS

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It Is not easy to find exact locations of boundaries of textural regions since statistical properties around the boundary show mixed properties of two neighboring regions. This paper presents a method to detect exact locations of boundaries of textural regions in the scene. We first propose 'a measure of boundary' which shows large value on the boundary and very small value in other locations. Then we propose a method to find globally good boundaries with respect to the defined measure of boundary using the optimization procedure.

The initial segmentation is performed on the reduced version of the input image using multiple textural properties by the recursive thresholding method. This segmentation result on the reduced image is then utilized as a plan for detecting exact locations of textural boundaries in full size image by the proposed textural boundary detector. The proposed method has been applied to a number of textured images, and some of the results will be given in the paper.

1. INTRODUCTION

Texture is an important property for segmentation of input pictures into regions in scene analysis. Many methods have been proposed to extract meaningful textural properties of local regions such as coarseness or orientation [1]; however, few attempts have been made for detection of exact textural boundaries. Usual methods apply local operators sensitive to some statistical properties of local regions, and then the textural boundary is obtained as the boundary of regions having homogeneous textural properties.

Hbwever, such a simple method cannot find correct location of textural boundaries. The reason is that statistical properties do not change abruptly on the boundary, but gradually change from one region to another region. Therefore, there are relatively broad regions having mixed properties of two neighboring regions around the boundary. Thus, existing methods find a boundary somewhere in this broad region around the true boundary. In this paper, we propose a good measure of textural boundary and a method to find a globally good boundary with respect to the defined measure of boundary.

2. MEASURE OF TEXTURAL BOUNDARY

For the sake of simplicity, let us first consider the problem of finding the boundaries of two textural regions R1, and *R2* that are known to have homogeneous properties *P1* and *P2* respectively. As shown in Fig. 1, the boundary exists in the region S between two homogeneous regions *R1* and *R2* and the local properties of the region S are not homogeneous and have some mixed properties of two regions. Let us define a local operator that has two regions r1 and r1 on both sides of a center line L as shown in Fig. 2, and denote the local properties of r1 and *r2* as p1 and p_2 respectively. Then, if the operator lies on the boundary, the following conditions must be satisfied:

1) p_1 is similar to P_1 and different from P_2.
2) p_2 is similar to P_2 and different from P_1.

Let us define the similarity of textural properties of p_1, p_2, P_1 and P_2 as

$$D_{11} = p_1 - P_1$$
$$D_{12} = p_1 - P_2$$
$$D_{21} = p_2 - P_1$$
$$D_{22} = p_2 - P_2$$

Then the above conditions can be stated as:

$$1)\ D_{12} > D_{11},\ \text{and}\ 2)\ D_{21} > D_{22}$$

Therefore, we define the measure of textural

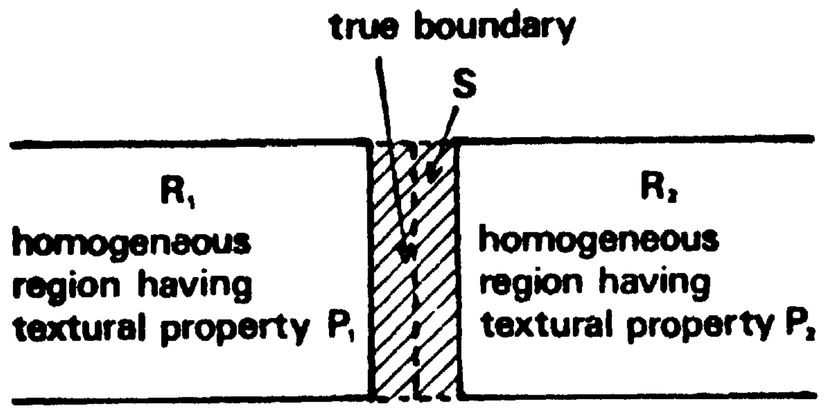


Fig. 1. Textural boundary exist somewhere between two homogeneous regions R_1 and R_2.

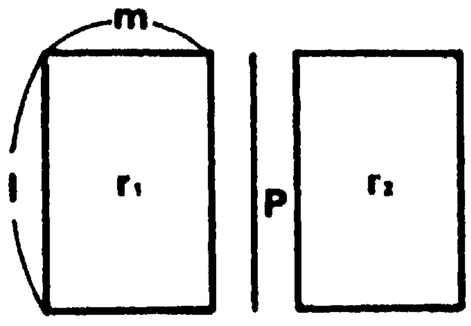


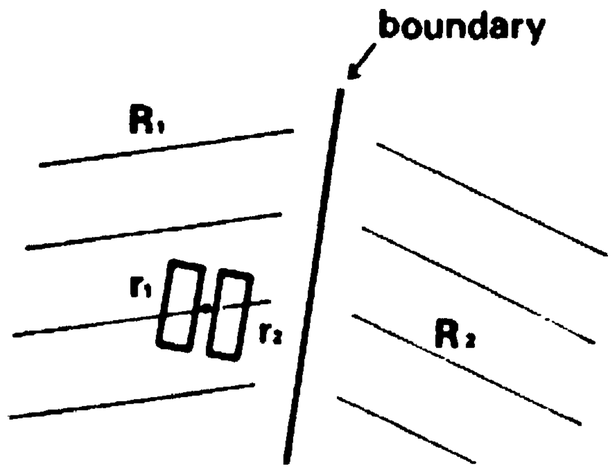
Fig. 2. A local operator.

boundary M as:

$$M=(D_{12}+D_{21})-(D_{12}+D_{21}) \quad (1)$$

The value of the measure M is large when the operator is on the boundary and is very small in other places. Fig. 3 shows the values of D_{11} D_{12}. D_{21}. D_{22} and M when the operator is on the right of the boundary.

Then, the boundary can be found by searching the region S for points having large value of M. However, local decisions such as finding points having local maximum of M cannot produce a good boundary since noise causes many false boundary points and gaps on the true boundary. We utilize the optimization method to find a globally good boundary with respect to the measure M in the region S.



D_{11}: small
D_{12} :large
D_{21}: small
D_{12} :large
M : small

Fig. 3. The values of D_{11}, D_{12}, D_{21} and D_{22} when the operator is on the right of the boundary.

J. *GLOBAL DETECTION OF BOUNDARY*

Let us represent a line by any sequence of oonnected linear segments L_1. L_2....L_N of length l, and define a merit function f of the line (L_1, L_2....L_N) as

$$f(L_1,L_2,\ldots,L_N) = M(L_1)+M(L_2)+\ldots+M(L_N) \quad (2)$$

Where M(L_i) is the measure of the boundary of the linear segment L_i computed by the local operator parallel to the linear segment L_i , as shown in Fig. 4.

Then, the sequence of linear segments L_i. . . .LN having the maximum value in the region S can be considered as the globally good boundary. Therefore, the problem of finding the globally good boundary becomes the problem of finding the sequence of linear segments L_i. . . .L_N which maximizes the merit function f given in (2). This problem can be solved by the multistage optimization procedure. An efficient method for solving this problem is described by the authors [2]. We may embed shape information such as smoothness into the merit function f as

$$f(L_1,\ldots,L_N)=\sum_{i=1}^{N} M(L_i) - k\sum_{i=1}^{N-1}|\theta(L_i)-\theta(L_{i+1})| \quad (3)$$

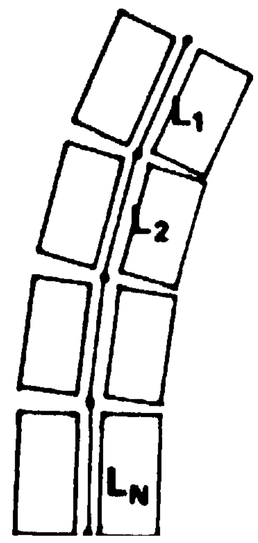


Fig. 4. Representation of a line by a sequence of linear segments L_1, L_2....L_N. A local operator is set parallel to each linear segment.

Where e (Lt) is the slope of the line L_1 and k is a constant. This merit function find a boundary having large value of M and low-curvatures.

4. INITIAL SEGMENTATION OF PICTURES

We have described a global method to find exact location of boundaries in the region S. In this section, we will briefly describe a method of the initial segmentation of a picture into regions having homogeneous textural properties. Fig. 5 shows a flowchart of the initial segmentation procedure. First, the input picture is averaged to obtain the reduced version of the image. The initial segmentation is performed on this reduced image and the segmentation results are used as a plan for detecting exact locations of textural boundaries in the full size image. We use not only a single textural property but also multiple textural properties such as gray-level distribution, edges per unit area or edge direction for segmentation. After obtaining these textural properties in the image, a non-linear averaging operator proposed by Tomita and Tsuji[3] is applied to smooth textural properties of each point in the image. Then, the recursive thresholding method proposed by Tomita et al[4] is applied to segment the image using multiple textural properties.

First, the histograms of the entire image are computed for all textural properties. Then, by analyzing these histograms, the most promising property for partitioning the image is selected. That is, the property whose histogram has deep valleys between two prominent peaks is selected as the promising property for partitioning and the threshold is determined as the value of the bottom of the valley. Then, the image is segmented by the selected threshold of the selected property. For each of the segmented regions, we apply the same procedure as described above until each region has only one prominent peak in the histograms.

These segmented regions of the reduced image are utilized as the plan for detecting exact locations of the boundaries of textural regions in the full size

image by the textural boundary detector described before. The plan gives the textural boundary detector the following two things: 1) search region of the boundary, and 2) textural properties of two neighboring regions to be utilized in finding the boundary.

5. EXPERIMENTAL RESULTS

To show the ability of detecting exact locations of textural boundaries, we tested the proposed method on the image shown in Fig. 6. Fig. 7 shows the initial segmentation procedure obtained for this image. Fig. 8 shows the boundaries detected by the textural boundary detector.

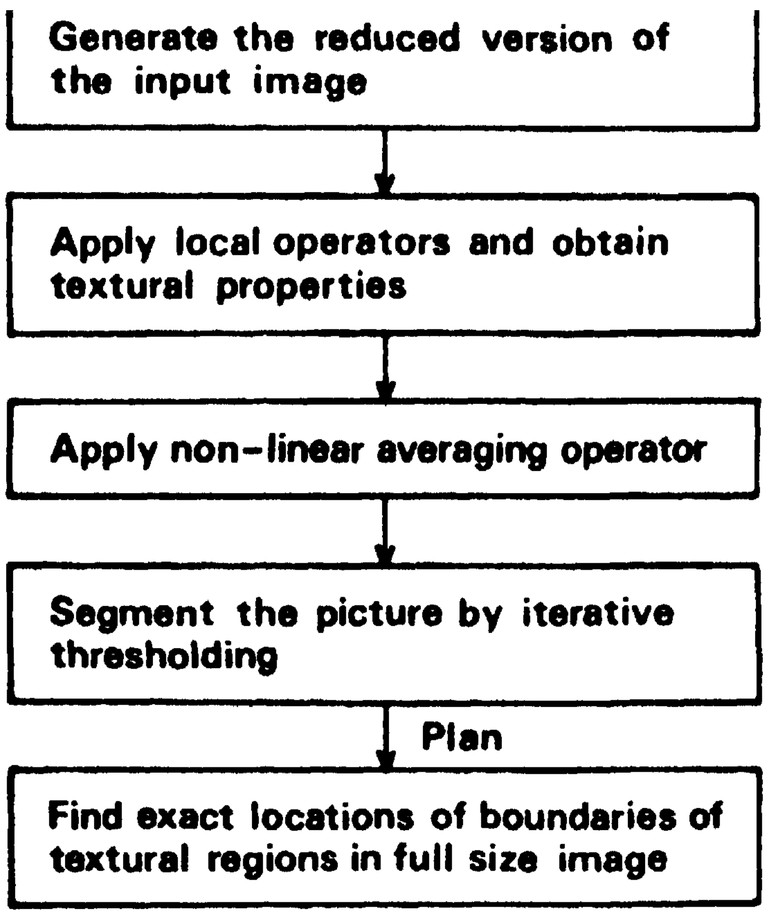


Fig. 5. A flowchart of the initial segmentation procedure.

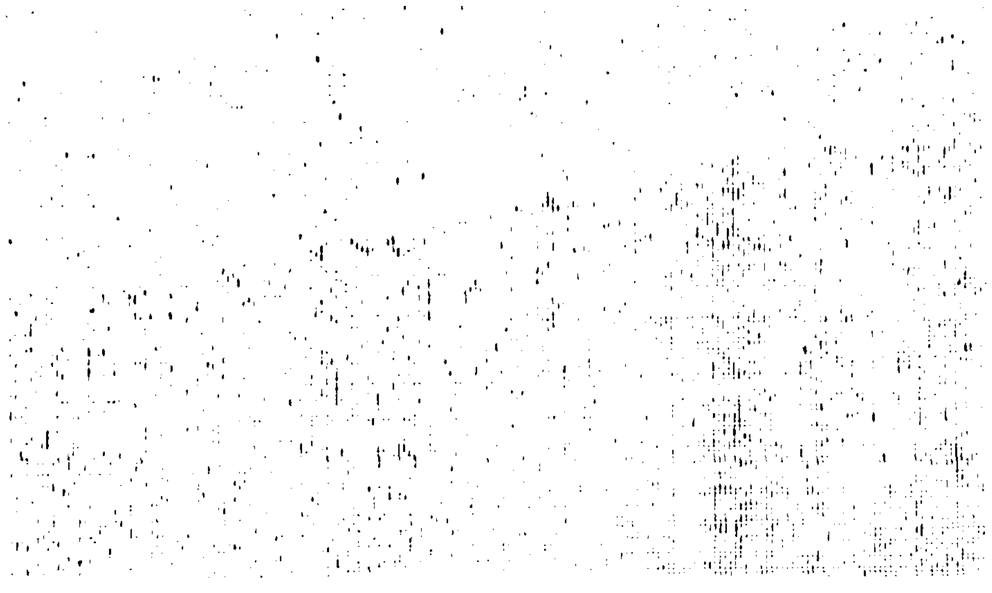


Fig. 6. Picture containing four regions. Picture size is 256 by 256 points.

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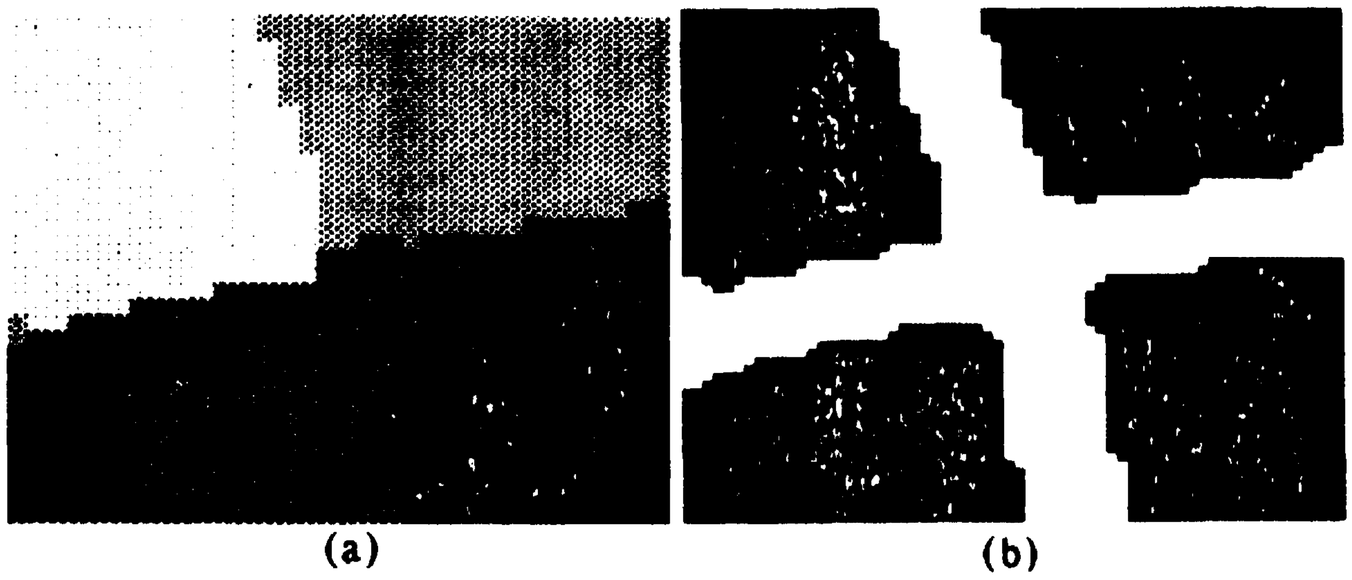

Fig. 7. Initial segmentation procedure for the input picture shown in Fig. 6. (a) Result of applying the non-linear averaging operator to the reduced image of Fig. 6. Picture size is 64 by 64 points, (b) Plan region for the exact detection of boundaries.

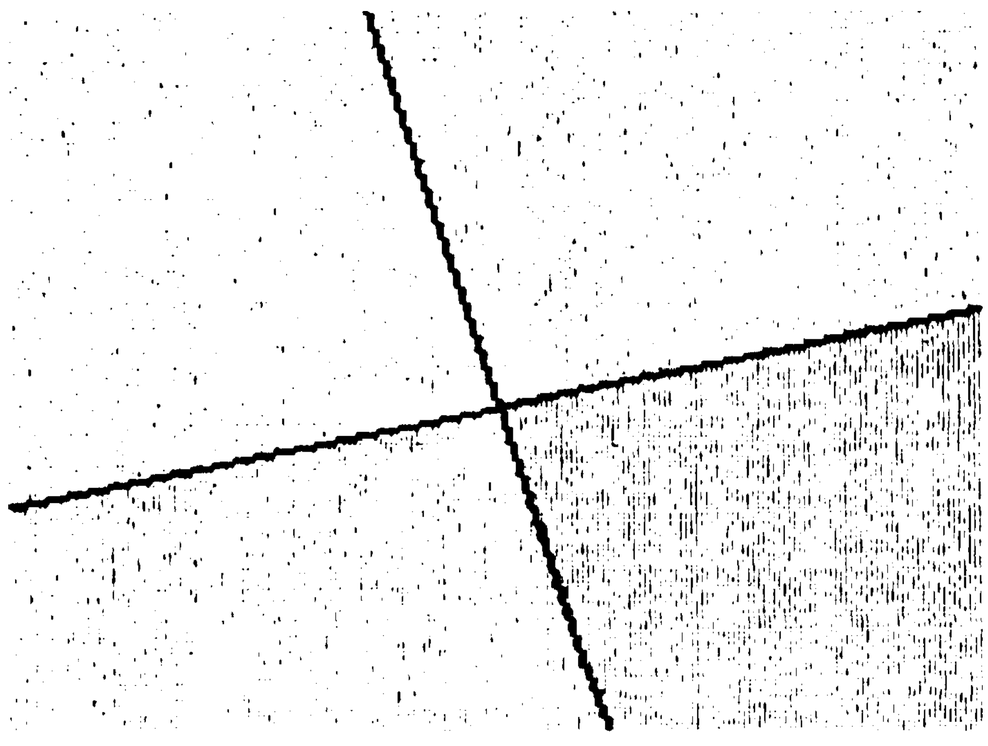

Fig. 8. Boundaries obtained by the textural boundary detector.

KNOWLEDGE-DRIVEN INTERPRETATION OF ESCA SPECTRA

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A system i'or automatically interpreting raw spectral data of an ESCA (Electron Spectroscopy for Chemical Analysis) is described. This system can remove background noise from the spectrum, identify each spectral peak, assign each peak to a corresponding atomic orbital and can obtain the chemical composition of a sample. A knowledge-driven method enables the system to identify very small peaks and rider peaks, and to obtain the most reliable assignment to each peak on the basis of specific chemical knowledge. Utilization of knowledge in low Level processing is our main interest, while higher-level logical inference is emphasized in other knowledge-based systems, for example DENDRAL and MYCIN.

1. INTRODUCTION

An ESCA spectrometer is an important equipment which gives much information about chemical composition, bond nature and electronic structure of a sample. Considerable efforts have been done for removing large background noise[l] and for analysing bond nature from this spectrum. In this version of our system we intend to perform the composition analysis by a wide-range ESCA spectrum. It would be the first attempt to deal directly with the wide-range spectrum and to obtain a extensive result automatically.

Chemical knowledge is effectively utilized for identifying a p)eak and giving rational assignment to each peak. This paper briefly explains the automatic interpretation system and demonstrates an experimental result.

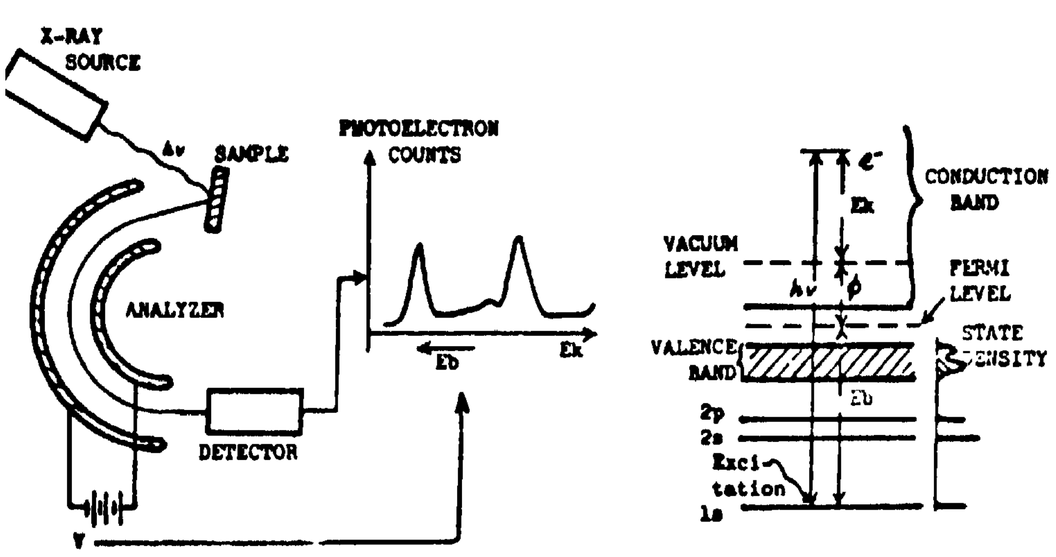

Fig.l ESCA spectrometer and the photoelectric effect

2. ESCA SPECTROMETER

The ESCA spectrometer is illustrated in Fig.1. A monochromatic X-rays ($E_{hv} = h\nu = 1486.6$ev) is used to irradiate a sample in a vacuum. The ejected photoelectrons have a variety of kinetic energy, depending on which element and which level they come from. The binding energy E_b relative to the Fermi level is calculated by the following equation:

$$E_b = h\nu - E_k - \phi \qquad (1)$$

where E_k is the measured kinetic energy and ϕ is the work function of a sample.

Both an element and orbitals can be determined by the particular positions of a set of peaks. Relative quantity of each element can be calculated by measured peak area, or the integrated intensity, and theoretical cross section value.

3. INTERPRETATION PROCESS

3.1 Outline

Fig.2 shows in outline the identification and assignment process. Firstly, in the preprocessing stage, background noise of low frequency is removed. Secondly, in the knowledge-driven identification stage, obvious peaks and peaks related to them are identified, then peak-assignment pairs (P-A pairs) are made from these peaks and the corresponding possible assignments. This stage is carried out efficiently by making use of chemical knowledge. Thirdly, in the bottom-up identification stage, all the

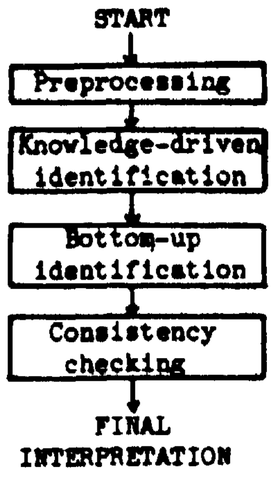

Fig. 2. Outline of the process

remaining peaks that are not relevant and are not related to other peaks are identified by a conventional statistical test. Finally, in the consistency checking stage, the Reliability and other properties of the P-A pairs are determined and the final interpretation is obtained.

3.2 Knowledge used

The chemical knowledge which will be used in the following sections consists of the expected binding energy and cross section values[2]. The former corresponds to peak position, and the latter to the peak area. These values are stored in ESCATBL as follows:

$$\text{ESCATBL} = (\text{KNLG}_1, \text{KNLG}_2 \cdots \text{KNLG}_n) \quad (2)$$

$$\text{KNLG}_i = (\text{ASS}_{i1}, \text{ASS}_{i2} \cdots \text{ASS}_{im}) \quad (3)$$

$$\text{ASS}_{ij} = (\text{ATOM}_i \ \text{LEVEL}_{ij} \ \text{EBE}_{ij} \ \text{CRS}_{ij}) \quad (4)$$

In this formula, EBE_{ij}, the expected binding energy, and CRS_{ij}, the theoretical cross section value, are represented for each LEVEL_{ij} of ATOM_i. Fig.3 shows part of this knowledge table.

The CRS_{ij} are normalized by setting the value of Carbon 1s to 1.000. Let S_{Ai} be that of level i of the element A, and let S_{Bj} be that of level j of the element B. The composition ratio is calculated as

$$A : B = S_{Ai}/\text{CRS}_{Ai} : S_{Bj}/\text{CRS}_{Bj} \quad (5)$$

```
ESCATBL (
   (H E1S 13.595 0.0002)
   (HE E1S 24.580 0.0082)
          :
   (O E2P3/2 13.614 0.0128)
   (O E2P1/2 7.0 0.0065)
   (O E2S 24.0 0.1405)
   (O E1S 532.0 2.93)
          :
   (PB E6P3/2 1 0.0291)
   (PB E6P1/2 1 0.0148)
          :
   (PB E4P1/2 764 2.12)

        )
```

Fig.3 Segment of the knowledge

3.3 Knowledge-driven identification stage

Obvious peaks and peaks related to them are identified, and possible P-A pairs are obtained as the output of this stage. The knowledge-driven mehtod used here consists of the following four steps (see Fig.4):

STEP1: The process begins by finding large peaks. A list HPEAKS of large peaks that are higher than a threshold TH is constructed by scanning through the preprocessed data DP

$$\text{HPEAKS} = (\text{PEAK}_1, \text{PEAK}_2 \cdots \text{PEAK}_n) \quad (6)$$

This TH is determined by an operator for terminating this stage.

STEP2: The highest peak is selected from the HPEAKS. All assignments which are consistent with the existence of this peak are chosen, and P-A pairs are made and stored in PALIST. A peak k is charactorized by a triplet as

$$\text{PEAK}_k = (\text{HGT}_k \ \text{POS}_k \ \text{BE}_k) \quad (7)$$

where HGT_k means peak height, POS_k peak position, and BE_k the binding energy value corresponding this position. From Eqs.(4) and (7), a P-A pair is represented as follows:

$$\text{P-A} = (\text{PEAK}_k \ \text{ASS}_{ij})$$

$$= ((\text{HGT}_k \ \text{POS}_k \ \text{BE}_k)(\text{ATOM}_i \ \text{LEVEL}_{ij} \ \text{CRS}_{ij}) \quad (8)$$

Comparing BEs with EBEs, matching torelance should be determined by estimated instrumental error and the possible chemical shift.

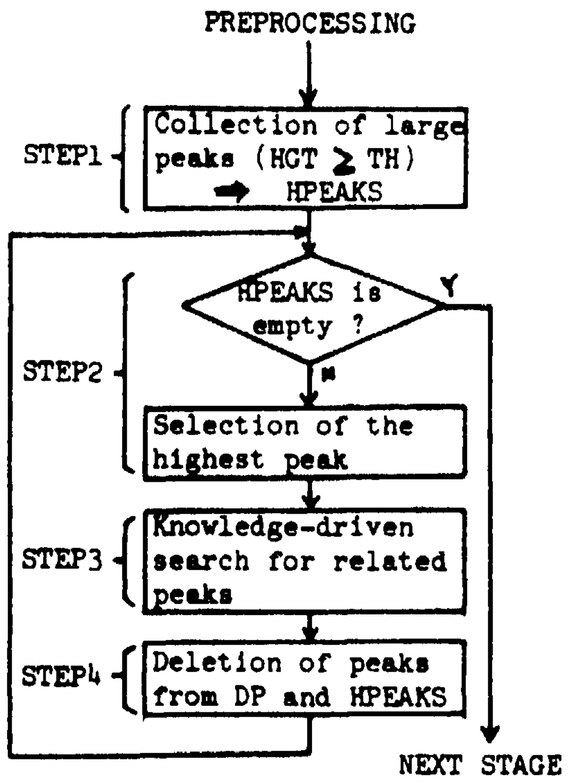

Fig. 4. Knowledge-driven identification stage

STEP3: For every candidate element the related peaks are knowledge-drivenly searched for, and all possible assignments are chosen. The P-A pairs are then made and added to the PALIST.

STEP4: The process deletes all peaks mentioned above from HPEAKS and DP. It then returns to STEP2, and repeats STEP2 through STEP4 until there remains no peak higher than the TH.

3.4 Consistency Checking stage

We explain three typical checking routines.

(1) Reliability test for P-A pairs: Let A be an element, suppose it has m levels and CRSi CRS:, ,CRSbe the cross section values, reliability factor RF is then defined as

$$RF = \frac{\sum_{i=1}^{m} \alpha_i \, CRS_{a,i}}{\sum_{i=1}^{m} CRS_{a,i}} \qquad (9)$$

where $\alpha_i = \begin{cases} 1, & \text{if such P-A pair is found} \\ -2, & \text{if such P-A pair is not found} \end{cases}$

Only reliable set of P-A pairs are selected based on this criterion.

(?) Calculation of the composition formula: Estimating peak areas on the original spectrum, calculate Eq.(5).

(3) Test of chemical shift: The chemical shift, a small deviation of a peak position, should be approximately equal for the same element and the same chemical state. So, if only a few shifts are clearly different from others under these conditions, a rational explanation of the fact would be that the identification stage- has frilled to find a correct peak and has found instead neighbouring one. There are two cases; 1) the correct peak is too small to identify and 2) the correct peak is a rider peak.

4.EXAMPLE

Fig.5 shows a 1024 point spectrum of a super conductive materials Pb Mo S . In the preprocessing stage step-like background noise was removed (Fig.6). Next, knowledge-driven identification began by finding the highest peak 'a!

```
RF = 0.93
((565 857 163.1) ( S E2p3/2 165 1.11))      - g
((565 857 163.1) ( S E2p1/2 165 0.567))     - g
RF = 0.86
((158 479 532.2) ( O E1s 532.0 2.93))       - h
RF = 0.93
((88 987 36.1) ( MO E4p3/2 35 0.86))        - f
((88 987 36.1) ( MO E4p1/2 35 0.445))       - f
((1003 789 229.5) ( MO E3d5/2 227 5.62))    - a
((491 786 232.4) ( MO E3d3/2 230 3.88))     - b
((302 620 394.5) ( MO E3p3/2 392 5.94))     - c
((162 602 412.1) ( MO E3p1/2 410 3.04))     - d
((53 505 506.8) ( MO E3s 505 2.34))         - e
RF = 0.68
((61 1004 19.5) ( PB E5d5/2 19 1.58))       - i
((32 1002 21.5) ( PB E5d3/2 22 1.11))       - j
((643 882 138.6) ( PB E4f7/2 138 12.73))    - k
((432 877 143.5) ( PB E4f5/2 143 10.01))    - l
((162 602 412.1) ( PB E4d5/2 413 13.02))    - d
((98 578 435.5) ( PB E4d3/2 435 8.87))      - m
((42 363 645.5) ( PB E4p3/2 645 6.33))      - n
```

Pb : Mo : S = 1 : 7.4 : 9.5

Fig.7 Result obtained

Candidate assignments were selected as Sulfur 2s , Molybdenum 4d3/2, and Molybdenum 4d5/2. In STEP3 other peaks of Sulfur and Molybdenum were searched for, all the possible assignments were chosen for these peaks, and P-A pairs were made. Thirty-three pairs were produced on 14 peaks in this example. Reliability factor was then calculated for each element. s, Mo, Pb and 0 were verified and Ti, W, Ne, C and F were rejected. Final assignments and the composition ratio are shown in Fig.7. Difference of about *?0%* from the correct composition ratio (= l:6:ft) is thought to be due to Inaccuracy of evaluated peak areas.

5. CONCLUSION

We have presented a system for interpreting MSCA spectra on the basis of chemical knowledge. Core-level peaks are identified and given rational assignments. The chemical composition of a sample is obtained. An example have shown effectiveness of our method in some difficult cases, for example, in finding a small peak, detecting a rider peak and choosing the most reasonable assignment from many alternatives.

RftI'tfKKNCES

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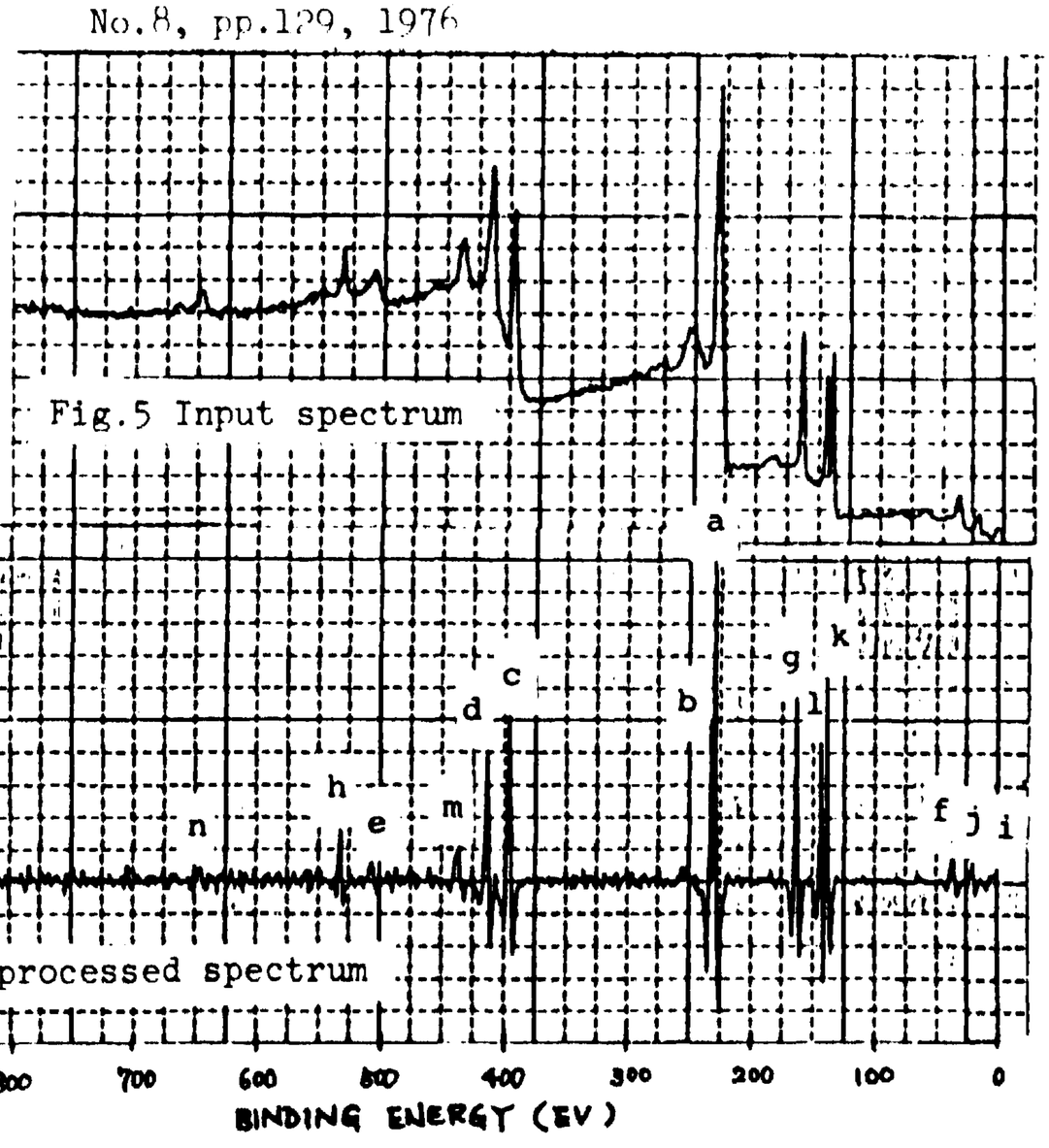

Fig.5 Input spectrum

Fig.6 Preprocessed spectrum

SYSP : A New Programming Language to the Next Generation

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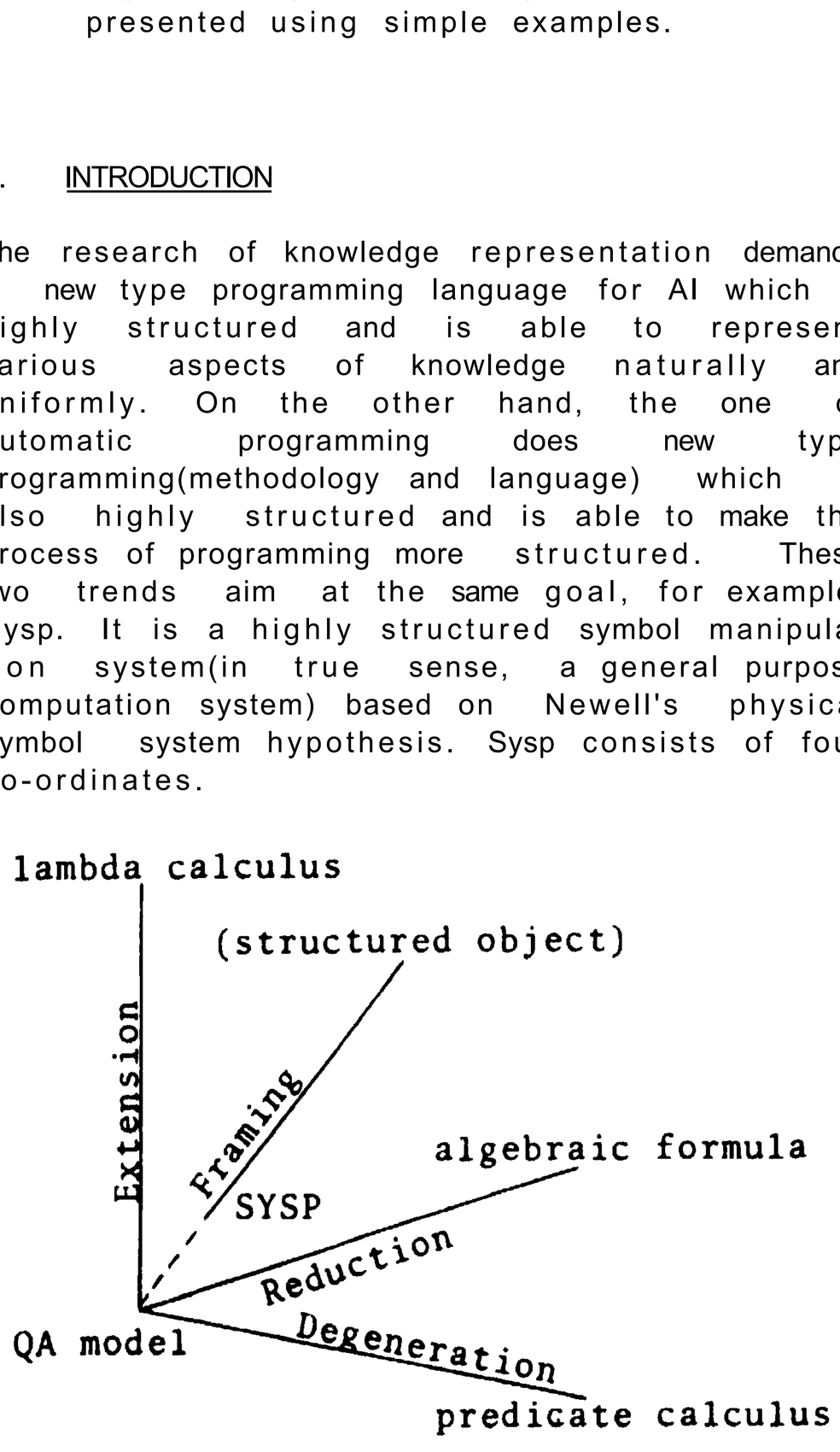
Sysp(Structured Symbol System Processer) is a base programming language for knowledge representation, and also a non-procedural and non-von Neumman style programming language to the next generation. Logic programming, functional programming, object oriented programming etc. are integrated into a simple and transparent mechanism based on the message passing computation(QA model of computation). An overview of Sysp's framework is presented using simple examples.

1. INTRODUCTION

The research of knowledge representation demands a new type programming language for AI which is highly structured and is able to represent various aspects of knowledge naturally and uniformly. On the other hand, the one of automatic programming does new type programming(methodology and language) which is also highly structured and is able to make the process of programming more structured. These two trends aim at the same goal, for example, Sysp. It is a highly structured symbol manipulation system(in true sense, a general purpose computation system) based on Newell's physical symbol system hypothesis. Sysp consists of four co-ordinates.



In followings, Sysp is outlined along Extension, Degeneration and Reduction co-ordinates.

'?. EXTENSION to QA model

Lambda calculus is a computation model which is able to express the higher order computation naturally. So, it is available so much for the basic mechanism and semantics description of various programming languages and is extended to make its ability more powerful for this purpose. Recursion, Landin's J-operator, Reynolds's escape expression, Steele & Sussman's tail transfer mechanism and continuation function were introduced. These extensions were arranged into message passing mechanism like Actor formalism etc.fl]. The distinctive features of the mechanism are as follows.

(a) By preserving execution environment on heap instead of stack, send and receive actions are able to express coroutine and parallel computation directly.

(b) Multiple-value return and naming without side effect become possible. The composition and decomposition of data structure are expressed in non-procedural manner.

(c) The history of computation is preserved completely and easily, so that the well fitted mechanism to the evaluation of nondeterministic program is gained.

(d) In co-operation with static binding mechanism, truly necessary execution environment for a computation is clearly specified.

Moreover, QA model of computation, puts its stress on well-formed communication(question answering) mechanism for the natural and rigid representation of a problem solving process(computation). So, appropriate synchronization mechanism etc. are included

inherently and the communication mechanism is made more structured.

One method of making the mechanism more structured is on message sent and received. In natural language, a sentence is classified into some types, declarative, interrogative, imperative or exclamative, so that, a listener is able to understand the intention of a speaker so easily. And moreover, in interrogative sentence, it is expressed clearly what sort of answer is expected, yes-no or answer to interrogative(When... , Where... , How many... , What kinds of... etc.). Similarly, in QA model, various message types are provided. And a computation is represented as a natural "question-answering(QA) sequence".

The other method of making the communication mechanism more structured is on QA sequence. First, QA sequence is restricted to the following communication manners.

(1) When a question is sent/received, the answer must he received/sent.
(2) To send/receive the answer to the latest received/sent question.

With these restrictions, sequences starting with an action on a question and ending in an action on the corresponding answer are nested with one another. Such a sequence is called "well-structured QA sequence". The simplest well-structured QA sequence is to send/receive a question and then to receive/send the answer. These are called "atomic QA sequence".

QA sequence(computation) is reduced into some sub-QA sequence(subcomputation). Therefore, the description among sub-QA sequences gives the structure of the original QA sequence. This description is called "compound QA sequence". For example, factorial function in Lisp,

```
FACT:(LAMBDA (N) (IF (= N 0) 1
                     (* N (FACT (- N 1)))))
```

,is represented as QA sequence.

```
Fact:=>(0  ?) Then 1.=>
     =>(n  ?) Then (n  1  ?)=>-=>m.
                   then (m  ?)= Fact= m.
                        then (n  m  ?)=>*=>m.
                             Then m.->
```

3. DEGENERATION to predicate calculus

It is possible to make two actions, to receive a question and to send the answer, degenerate into one action, to assert the fact. In the same manner, two actions, to send a question and to receive the answer, are made degenerate into one, to interrogate the fact. Futhermore, two actions, to assert a fact and to interrogate on the fact, are made degenerate into one object, a predicate(atomic formula).

By regarding assert and interrogate actions as atomic QA sequences, compound QA sequence is made degenerate. It is called "degenerate (compound) QA sequence". The factorial function is transformed into a partially degenerate QA sequence.

```
Fact:<=>(0 1)
     <=>(n ?m3) because (n 1 ?m1)<=>-   then
                        (m1 ?m2)<=>Fact then
                        (n m2 ?m3)<=>*
```

In this sequence, variables in the messages have some sort of indication(input or output) and the evaluation order are fixed. Next, this is transformed into a fully degenerate QA sequence.

```
<=>(Fact: 0 1)
<=>(Fact: n m3) because (-: n 1 m1)<=>   and
                        (Fact: m1 m2)<=> and
                        (*: n m2 m3)<=>
```

In this one, the variables have no indication and the fixation of the evaluation order is taken away. In order to make the meaning of Degeneration clearer, the factorial function is represented in Horn set,

```
+(Fact: 0 1)
+(Fact: n m3),-(-: n 1 m1),-(Fact: m1 m2)
              ,-(*: n m2 m3)
```

Assert action corresponds to positive clause and interrogate action does to negative clause. And further, pattern directed invocation of assert action by interrogate action corresponds to the application of Resolution rule.

In the current research on logic programming[2], it has tried to make clear the correspondence between computation structures and proof strategies without any explicit construct for control structure. By the following reasons, however, it needs to introduce appropriate procedural aspects into logic programming.

(1) Many computation sequences are condensed into one logical formula by abstracting certain aspects of the sequences, but only some of them are able to have actual meanings. That is, it is hard to say that it represents computation exactly.

(2) Proof mechanism like Resolution is powerful as basic computation mechanism, but very primitive. So, higher structures of computation can not be represented by proof strategy only.

It is so easy to introduce procedural elements for claptraps, but never desirable. Sysp makes it possible to define strict meanings of procedural elements by introducing the successive Degeneration process from QA model to predicale calculus.

4.. REDUCTION to algebraic formula

Along Extension co-ordinate, lambda calculus, an applicative computation system, is extended to include imperative features preserving the advantages as it is. And again, QA model is reduced into algebraic formula, a typical applicative system. But this never means that Extension co-ordinate is traced conversely.

Send action is reduced into the composite function of receiver and message. Receive action is reduced into environment modifier function. Namely, a message is regarded as a functional form and a variable is regarded as a function which yields the value from environment as well as in GEDANKEN. Receive action is regarded as a functional form which tests whether or not the actual argument matches the message pattern and, if matched, modifies the environment by naming, Continuation(next) relation is represented as the composition of functions. In this way, a simple QA sequence is reduced mechanically into an applicative form. And further, Reduction process goes on. The factorial function is partially reduced to

```
Fact=(1•=>(0 ?);
      m:•=>m•*•(n m ?):•=>m•Fact•(m ?):•=>m•
           -•(n 1 ?):•=>(n ?))
```

Further, this is fully reduced into

```
Fact=(1•=>0•I;
      *•(I  Fact•-•(I  1):):)
```

through the transformation which simplifies environment modifier function and eliminates variables by substitution (introducing selector function). Thus, a QA sequence is reduced into an algebraic formula, its semantics is formalized as lows of algebra and it becomes possible to prove its various properties by formula manipulation, as Backus etc. point out. For comparison, the example is represented in Backus's FP[3],

Def `!=eq•[id, 0] -> 1; *•[id, !•-•[id, 1]]`

For each type of compound QA sequence, corresponding functional forms are provided. The applicative form obtained in this way is called "reduced QA sequence".

Functional programming is related to QA model through successive Reduction process. By this way, its weakpoints are covered up and its ability is extended as follows.

(1) The appropriate and natural interpretation of functional form are obtained.
(2) Advantages of other computation models, including history sensitivity, are added to in a very natural way.

5. CONCLUSION

The method for knowledge representation must be powerful, natural and formal. It must be powerful in order to represent complicated and higher order knowledge, natural in order to make it easy to use and understand, and formal in order to make possible for a computer to process represented knowledge mechanically. Sysp satisfies these three conditions sufficiently over a wide range by integrating four representative methods into one transparent mechanism. For example, factorial function is able to give natural looks in Sysp,

```
Fact:<=>(0  I)
     =>(n  ?) Then (-.(n 1):   ?)=>Fact=>m.
              Then *•(m  n):.=>
```

At present the main part of Sysp is implemented on EPICS-Lisp. In other papers[4], Sysp is described in more details.

AKNOWLEDGEMENTS: The authors wish to express their gratitude for the encouragement from the head of their division, Dr. H. Nishino.

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HIERARCHICAL CONCEPTS STRUCTURE FOP NATURAL LANGUAGE UNDERSTANDING SYSTEM

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Hierarchical concepts structure is introduced to widen acceptability of input sentences of natural language understanding system.

It consists of a set of defined concepts (SDC) and scenarios each of which is a set of scenario elements. A scenario is one utilized everywhere. In our SDC concepts are defined with another concepts related through basic semantic relations. Types of these relations are presented with some examples. As compound semantic relations are composed of basic ones it is enough to construct SDC with only basic semantic relations.

1. Hierarchical concepts structure

Instead of efficiency of inference, use of scenarios[1]) is in the opposite direction to afford those rich features of natural language to the system.

To overcome this situation, we introduced a set of defined concepts (SDC) and constructed a hierarchical concepts structure with scenarios.

A hierarchical concetps structure consists of a SDC and scenarios and a scenario is a set of scenario elements.

A scenario element is a partial scenario that correspond to a small part of story, and therefore can easily prepare, delete or correct.

SDC gives general (closer to natural language) definition of each concept by using basic semantic relations (and view-points) with other concepts so that it functions as to widen acceptability of input sentences of natural language understanding system.

An input sentence is analysed syntactically and the conceptual dependency representation with respect to the sentence (CDRS) is generated CDRS is a directed, labeled graph which represents dependency relaitons among concepts expressed by words appearing in the sentence.

Figure 1 is a CDRS of a sentence "I go to school." Using this CDRS the system chooses a scenario element from a suitable scenario, say "GO TO SCHOOL" scenario and attaches this CDRS to it as an instance. We call scenario element with an instance attached in this way as semantic graph[2]),[3]) (with respect to a sentence).

Figure 2 shows a part of "GO TO SHCOOL" scenario element with attached instance (sematic graph).

However, there may be no scenario element that fits to an input sentence "I go to school to meet my son" in any scenario. In this case, the system tries to find out general definition of "<GO>" in the SDC.

As SDC has definition for every concept, it fits to wide variety of CDRSs. Figure 3 shows "<GO>" element of SDC.

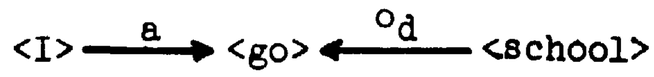


Figure 1. CDRS of " I go to school".

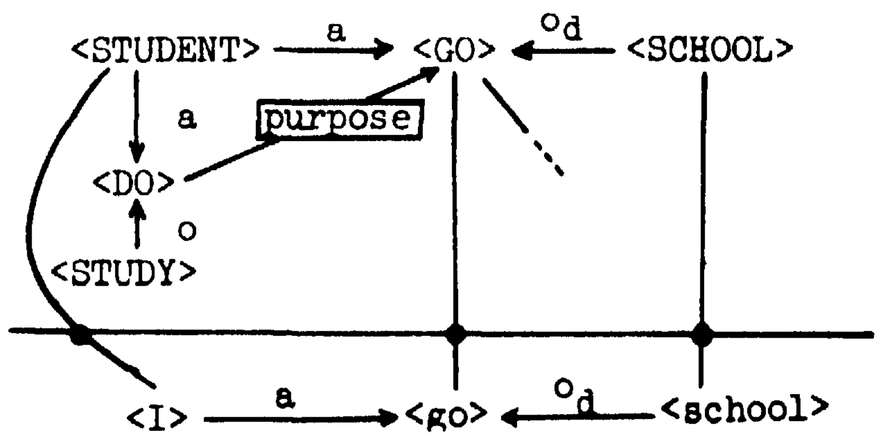


Figure 2. Semantic graph with respect to a sentence "I go to school".

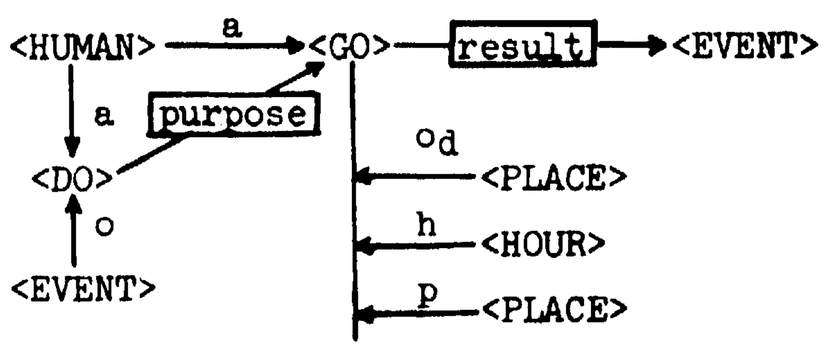


Figure 3. "<GO>" element of SDC.

2. Construction of SDC

2.1. Types of concept

Concepts are classified into four types that roughly correspond to the concepts expressed by concrete nouns, verbs, adjectives/adverbs and abstract words as follows(see Notations).
(i) 'concrete object' concepts (ii) 'event' concepts (iii) 'modality[1] concepts
(iv) 'abstract thing' concepts: Abstract concepts that are designated by 'aspects (movements or modalities) of things', 'relations among things'or 'time and place'.

2.2. Semantic relations among concepts

There are following eight basic semantic relations among concepts.
(i) Super concept-subconcept relation (kind or extention relation)
(ii) Aspect relation: Relation among a 'concrete object' concept and concepts that give aspects of the concepts. This relation is given by using basic view-points such as "purpose of use", "color", "amount (thickness)". Basic view-points necessary to define <PRODUCT THING> like <PAPER> are given in Table 1.

Aspect relation	Basic view-point
Aspects about use	purpose of use, ways of use (what to use) (how to use)
Aspects about manufacturing	material, how to make
Aspects about structure	parts, arrangement,•••
Aspects about property	physical, mental,•••
Aspects about quantity	number, weight, length,•••
Aspects about aspect	color, shape, value, •••
Aspects about time	existing time
Aspects about place	existing place

Table 1. Basic view-points for <PRODUCT>.

(iii) Case relation
(iv) Cause-effect relation
(v) event-event relation other than cause-effect relation
Five relations of "logical", "accompanying", "before and after wrt. time", "condition" and "direct (indirect)" belong to this,
(vi) Descriptive definition relation
This relation describes an event using with another basic semantic relations and concepts,
(vii) Modality relation
View-points used in this relation are given by classifying "modality" concepts.
(viii) Synonym and antonym relation

2.3. Construction of SDC

i) Definition of concrete objects
Concrete objects are defined by using kind relation and aspect relation. View-points belonging to these relations are called "basic view-points" (Table I).
a. Definition of subconcepts
Properties possesed by a super concept is inherited to its subconcepts unless otherwise stated in the definitions of them.
b. Definition of supreme concepts
It is very important that SDC contains every supreme (most general) concrete object concept that appears as a supreme concept of a given event concept in the case relation. For example, the supreme concept of the given event concept <EAT> in the (object) case relation is <things that can be objects to eat>(Figure 4), This gives judging conditions (or requirements) whether any given type of concept statisfies case relation with a given event concept. For example, if "plastic eraser" satisfies conditions "soft", "not hot", ••• then "human being" can "eat" it.

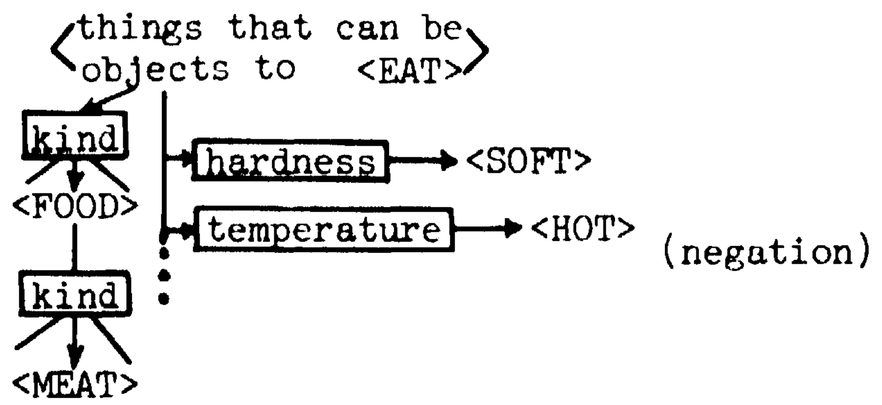


Figure 4. The supreme concept in the object case relation of <EAT>

ii) Definition of an "event" concept
This concept is defined by using case relation, cause-effect relation, event-event relation, descriptive definition relation, modality relation and synonym-antonym relation,
iii) Definition of a 'modality' concept
This concept is defined by using case relaiton, descriptive definition relation, cause-effect relation, modality relation and synonym-antonym relation.
iv) Definition of an "abstract thing" concept
This concept is defined by using case relation, cause-effect relation, modality relation, descriptive relation, kind relation and synonym-antonym relation.

3. Composition of view-points

There can be many finer view-points other than basic ones.
Is it necessary to define a concept using

all of these finer view-points?

We are getting rid of this problem by composing these finer view-points of basic semantic relations, basic view-points and other concepts.

Let **r** be an arbitrary m-ary semantic relation and $\alpha_1, \alpha_2, \cdots, \alpha_m$ be concepts for which **r** $(\alpha_1, \alpha_2, \cdots, \alpha_m)$ can be asserted.

We obtain a relation,

$$\lambda x \mathbf{r}(\alpha_1, \alpha_2, \cdots, x, \cdots, \alpha_m)$$

from **r** $(\alpha_1, \alpha_2, \cdots, \alpha_m)$,
where x is a concept variable and λ is an abstraction operator.

We express a concept α for which a certain semantic relation $\mathbf{r}(\alpha)$ is asserted[4]) as,

$$\alpha \leftarrow\!- \mathbf{r}(\alpha)$$

For example,

$$\alpha \leftarrow\!- \alpha \xrightarrow{\boxed{\text{kind}}} \beta$$

means that α is a concept for which $\alpha \xrightarrow{\boxed{\text{kind}}} \beta$ is asserted.

Let (1) and (2) asserted.

$$\mathbf{r}(\alpha_1, \alpha_2, \cdots, \alpha_i, \cdots, \alpha_m) \quad \cdots (1)$$

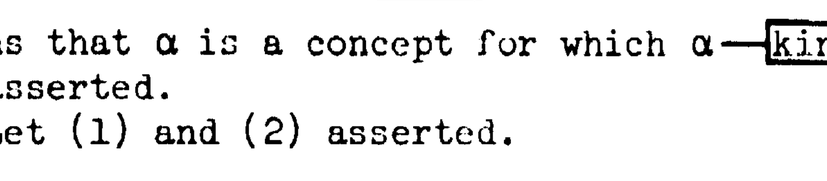
$$\alpha_i \leftarrow\!- \mathbf{r}_1(\alpha_1', \alpha_2', \cdots, \alpha_i, \cdots, \alpha_n') \quad \cdots (2)$$

Where **r**, $\mathbf{r}_1$ are semantic relations and $\alpha_1, \alpha_2, \cdots, \alpha_n'$ are concepts. In this case composition of relation is defined as follows.

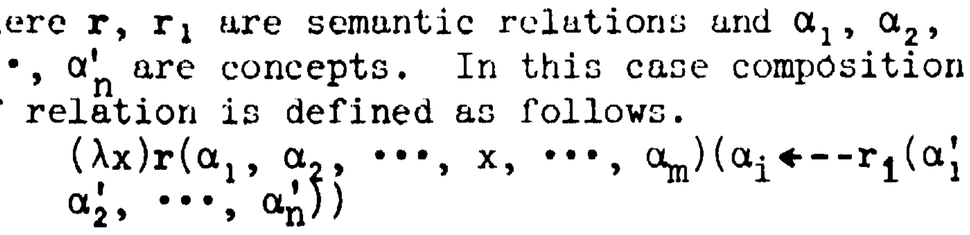
$$(\lambda x)\mathbf{r}(\alpha_1, \alpha_2, \cdots, x, \cdots, \alpha_m)(\alpha_i \leftarrow\!- \mathbf{r}_1(\alpha_1', \alpha_2', \cdots, \alpha_n'))$$

By repeated application of composition and abstraction to semantic relations, we can obtain any relation from only basic semantic relations and basic view-points.

On the other hand, any sentence is expressed by CDRS briefly explained in chapter 1 by using semantic relations listed in chapter 2. For example, 'He hate him very much.' has the following CDRS.



From this CDRS, we can define a binary hate-relation $(\lambda xy)\mathbf{r}_h(x,y)$ as follows.



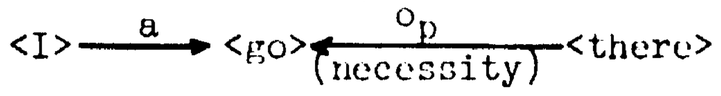
Therefore, we can define any semantic relation if we could give definition of the semantic relation by sentences (hence CDRS).

4. Concluding remarks

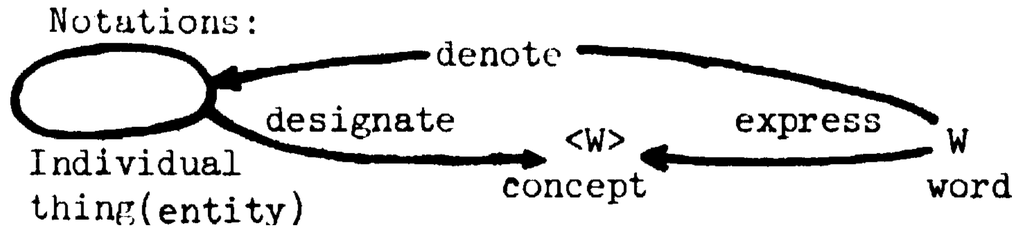
We discussed about general structure of SDC necessary for constructing natural language understanding system.

We proposed to introduce a hierarchal concept system in which essentially the same semantic relations are used to define concepts in each stage of hierarchy.

We could not discuss about 'mode' in this paper. For example, CDRS of a sentence, 'I should go there.' is given as follows.



Here the information given by (necessity) is a 'mode' of an event concept <go>. We singled out eighty four such modes which are used in ordinary written sentences[5]). Detailed composition rules of semantic relations including these mode will be discussed in our forth-coming paper.



Definition of "denote", "designate" and "express"

Acknowledgements

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APPROXIMATE REASONING BASED ON FUZZY LOGIC

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During the past several years, the emergence of expert systems as a field of considerable practical as well as theoretical importance within AI has provided a strong impetus for the development of theories of approximate reasoning and credibility assessment of inference processes in knowledge-based systems.

The approach to approximate reasoning described in this paper is based on a fuzzy logic, FL, in which the truth-values and quantifiers are defined as possibility distributions which carry linguistic labels such as true, quite true, not very true, many, not very many, several, almost all, etc. Based on the concept of a possibility distribution, a set of translation and Inference rules is developed and their application to inference from imprecise premises is illustrated by examples.

1. INTRODUCTION

It has long been recognized that much, perhaps most, of human reasoning is approximate rather than exact in nature.** And yet, logicians and cognitive scientists have devoted scant attention to the development of theories of approximate reasoning, partly because of the deeply entrenched tradition of respect for what is precise and disdain for what is fuzzy, and partly because there was no compelling need for such theories before the advent of artificial intelligence.

In recent years, however, the rapid growth of interest in natural language processing and the emergence of expert systems as an important application area within AI have made it increasingly clear that a better understanding of the processes of approximate reasoning is a prerequisite to the development of knowledge-based systems which can manipulate information that is imprecise, incomplete or not totally reliable.

In a series of papers starting in 1973 [2-7], we have advanced the view that conventional logical systems do not provide an appropriate basis for approximate reasoning and have suggested a fuzzy logic, FL, for this purpose. In contrast to two-valued and multi-valued logics, the truth-values of FL are linguistic rather than numerical, as are quantifiers exemplified by many, most, not very many, few, several, almost all, etc. Furthermore, the rules of inference in FL are approximate rather than exact. Thus, in spirit as well as in substance FL represents a sharp break with the long-standing tradition of extreme precision in logic and a move toward an accommodation with the pervasive imprecision of human thought, perception, language and decision-making.

Another important difference between FL and classical logical systems centers on the concept of truth. Thus, whereas in the latter systems [8,9] the truth of a proposition serves as a starting point for the definition

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**The terms "approximate reasoning" and "fuzzy reasoning" are frequently used interchangeably in the literature. A comprehensive exposition of the foundations of fuzzy reasoning may be found in the paper by B.R. Gaines [a].

of various basic concepts, the corresponding role in FL is played not by truth but by the concept of a possibility distribution, by which is meant a mapping associated with a variable X, π_X: U → [0,1], which assigns to each point u in the domain of X, U, the possibility that X could take u as a value. The concept of truth, then, is employed to express the compatibility of the possibility distribution induced by a proposition p with that of a reference proposition r. In this sense, the truth of a proposition is a relative concept and is a measure of its compatibility or consistency with a collection of propositions which constitute a database.

Our main concern in the present paper is with (a) the establishment of translation rules for various types of imprecise propositions; (b) inference from such propositions; and (c) the development of a conceptual framework for dealing with the issues of belief and credibility. The latter issues play a particularly important role in expert systems [10-17] as well as in the theories of evidence and decision analysis [18-24].

2. THE CONCEPT OF A POSSIBILITY DISTRIBUTION

As a preliminary to the consideration of translation rules for various types of propositions, it will be helpful to establish some of the properties of possibility distributions which will be needed in later sections.*

Informally, if X is a variable taking values in U, then a possibility distribution, Π_X, associated with X may be viewed as a fuzzy (or elastic) constraint on the values that may be assigned to X. Such a distribution is characterized by a possibility distribution function π_X: U → [0,1] which associates with each u ∈ U the "degree of ease" or the possibility that X may take u as a value.

In some cases, the constraint on the values of X is physical in origin. For example, if X is the number of students in a classroom which has, say, 50 seats, then $\pi_X(u) = 1$ for u up to 50, with $\pi_X(u)$ gradually declining to 0 at, say, u = 75. In this case, an intermediate value of π_X, say $\pi_X(65) = 0.3$, would signify that, by some explicit or implicit criterion, the degree of ease with which 65 students could be crowded into the classroom is 0.3 (on the scale from 0 to 1).

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*An introductory exposition of possibility theory may be found in [29]. A historical account of the concepts of possibility and probability is contained in [30].

In most cases, however, the possibility distribution which is associated with a variable is epistemic rather than physical in origin. A basic assumption in fuzzy logic is that such epistemic possibility distributions are induced by propositions expressed in a natural language. In more concrete terms, this assumption may be stated as the

Possibility Postulate. If F is a fuzzy subset of U characterized by its membership function μ_F: U → [0,1], then the proposition "X is F" induces a possibility distribution Π_X which is equal to F. Equivalently, "X is F" translates into the possibility assignment equation $\Pi_X = F$, i.e.,

$$X \text{ is } F \longrightarrow \Pi_X = F \tag{1}$$

which signifies that the proposition "X is F" has the effect of constraining the values that may be assumed by X, with the possibility distribution Π_X identified with F.

As a simple illustration of (1), if in the proposition "X is small" small is regarded as a label of a fuzzy subset of U = {0,1,2,...} which is defined by*

$$\text{SMALL} = 1/0 + 1/1 + 0.8/2 + 0.6/3 + 0.4/4 + 0.2/5 \tag{2}$$

then

$$\begin{aligned} &\text{Poss}\{X = 0\} = 1 \\ &\text{Poss}\{X = 1\} = 1 \\ &\text{Poss}\{X = 2\} = 0.8 \\ &\text{Poss}\{X = 5\} = 0.2 \end{aligned} \tag{3}$$

where $\text{Poss}\{X = u\} = \pi_X(u)$ is the possibility that X may take u as a value.

An important aspect of the concept of a possibility distribution is that it is nonstatistical in nature. As a consequence, if P_X is a probability distribution associated with X then the only connection between Π_X and P_X is that impossibility (i.e., zero possibility) implies improbability but not vice-versa. Thus, Π_X cannot be inferred from P_X nor can P_X be inferred from Π_X.

As in the case of probabilities, one can define joint and conditional possibilities. Thus, if X and Y are variables taking values in U and V, respectively, then we can define the joint and and conditional possibility distributions

---

*The notation $F = \mu_1/x_1 + \cdots + \mu_n/x_n$ signifies that F is a fuzzy subset of the set $\{x_1,\ldots,x_n\}$, with μ_i, i = 1,...,n, being the grade of membership of x_i in F. Uppercase symbols (e.g., F, SMALL) are employed to denote names of sets (fuzzy or nonfuzzy).

through their respective distribution functions:

$$\pi_{(X,Y)}(u,v) = \text{Poss}\{X=u,\ Y=v\},\ u \in U,\ v \in V \qquad (4)$$

and

$$\pi_{(X|Y)}(u|v) = \text{Poss}\{X = u | Y = v\} \qquad (5)$$

where (5) represents the conditional distribution function of X given Y.

If we know the distribution function of X and the conditional distribution function of Y given X, then we can construct the joint distribution function of X and Y by forming the conjunction ($\wedge \triangleq \min$)

$$\pi_{(X,Y)}(u,v) = \pi_X(u) \wedge \pi_{(Y|X)}(v|u)\ . \qquad (6)$$

However, unlike the identity that holds in the case of probabilities, we can also obtain $\pi_{(X,Y)}(u,v)$ by forming the conjunction of $\pi_{(X|Y)}(u|v)$ and $\pi_{(Y|X)}(v|u)$:

$$\pi_{(X,Y)}(u,v) = \pi_{(X|Y)}(u|v) \wedge \pi_{(Y|X)}(v|u) \qquad (7)$$

In yet another deviation from parallelism with probabilities, the marginal possibility distribution function of X may be expressed in more than one way in terms of the joint and conditional possibility distribution functions. More specifically, we may have

(a) $$\pi_X(u) = \vee_v \pi_{(X,Y)}(u,v) \qquad (8)$$

where $\vee_v$ denotes the supremum over $v \in V$;

(b) $$\pi_X(u) = \vee_v \pi_{(X|Y)}(u|v) \qquad (9)$$

and

(c) $$\pi_X(u) = \pi_{(X|Y)}(u,\tilde{v}(u)) \qquad (10)$$

where, for a given u, $\tilde{v}(u)$ is the value of v at which $\pi_{(Y|X)}(v|u) = 1$, if $\tilde{v}(u)$ is defined for every $u \in U$.

Intuitively, (a) represents the possibility of assigning a value to X as perceived by an observer ((X,Y) observer) who observes the joint possibility distribution $\Pi_{(X,Y)}$. Similarly, (b) represents the perception of an observer ((X|Y) observer) who observes only the conditional possibility distribution $\Pi_{(X|Y)}$ and is unconcerned with or unaware of $\Pi_{(Y|X)}$. And (c) expresses the perception of an observer who assumes that v is assigned that value, if it exists, which makes $\pi_{(Y|X)}(v|u)$ equal to unity.

In relating π_X to $\pi_{(X|Y)}$ through the operator $\vee$ (supremum), we are tacitly invoking the principle of maximal restriction [4], which asserts that, in the absence of complete information about Π_X, we should equate Π_X to the maximal (i.e., least restrictive) possibility distribution which is consistent with the partial information about Π_X. In the case of (a), for example, this would be the supremum of $\pi_{(X,Y)}(u,v)$ over $v \in V$.

As will be seen in Section 3, the concept of a conditional possibility distribution plays a basic role in the formulation of a generalized form of modus ponens and in defining a measure of belief. What is as yet an unsettled issue revolves around the question of how to derive $\pi_{(X|Y)}$ and $\pi_{(Y|X)}$ from $\pi_{(X,Y)}$. Somewhat different answers to this question are presented in [25-27]. It may well turn out to be the case that, in contrast to probabilities, there does not exist a unique solution to the problem and that, in general, the answer depends on the perspective of the observer.

3. POSSIBILITY THEORY AND FUZZY LOGIC

As was alluded to already, the concept of a possibility distribution and the possibility theory which is based on it, play a central role in fuzzy logic by providing a means for the representation of the meaning of imprecise premises and the generation of propositions which follow logically from them.

Typically, a variable in fuzzy logic is treated as a linguistic variable [4], that is, a variable whose values are represented as words or sentences in a natural or synthetic language, with each such value defining a possibility distribution in the domain of the variable. In effect, what this implies is that a linguistic variable is a microlanguage with its own syntax and semantics. For example, in the case of FL, the linguistic values of the variable Truth may be generated by a context-free grammar and interpreted by an attributed grammar [28]. Thus, starting with (a) the primary term true and its antonym false; and (b) a finite set of modifiers and connectives such as and, or, not, very, more or less, quite, extremely, etc., the linguistic value of Truth may be represented as

true	false
not true	not false
very true	very false
not very true	not very false
more or less true	more or less false
quite true	quite false
not quite true	not quite false

not true and not false
not very_true and not very false

In FL, a linguistic truth-value is regarded as a composite label of a possibility distribution In the interval [0,1], which is the set of truth-values In Lukasiewicz's Laleph logic. What this means is that in FL we generally deal not with numerically-valued truth-values but with their possibility distributions.

An important distinction between FL and L_{Aleph1} is that in L_{Aleph1},—as in all other multi-valued logics—there are only two quantifiers all and some, whereas in FL we can employ a large variety of fuzzy quantifiers exemplified by few, several, many, most, almost all, very many, not very many, etc. This feature of FL makes it possible to translate, and infer from, imprecise premises exemplified by

Most tall women are not very fat.
Among the many men who are heavy smokers, quite a few are overweight and some are heavy drinkers.
Carol has several close friends who have many children.

The meaning of a quantifier in FL is based on the concept of the cardinality of a fuzzy set. Thus, if F is a fuzzy subset of a finite set U - $fu_1,,\ldots,u_n\}$ characterized as

$$F = \mu_1/u_1 + \cdots + \mu_N/u_N$$

where μ_i is the grade of membership of u_i in F, $i = 1,\ldots,N$, then the power of F--which is roughly a measure of its cardinality--may be defined as

$$|F| = \sum_{i=1}^{n} \mu_i \ . \qquad (11)$$

Alternatively, and perhaps more appropriately, the cardinality of F may be defined as a fuzzy number, as is done in [6]. Thus, if the elements of F are sorted in descending order, so that $\mu_n \leq \mu_m$ if $n \geq m$, then the truth-value of the proposition

$$p \triangleq \text{F has at least n elements} \qquad (12)$$

is defined to be equal to μ_n, while that of q,

$$q \triangleq \text{F has at most n elements} \ , \qquad (13)$$

is taken to be $1-\mu_{n+1}$. From this it follows that the truth-value of the proposition r,

$$r \triangleq \text{F has exactly n elements} \ , \qquad (14)$$

is given by $\mu_n \wedge (1-\mu_{n+1})$. An illustration of these alternative definitions of cardinality is provided by Example 5 in Section 4.

The translation rules for propositions expressed in a natural language form an important part of PRUF--a meaning representation language based on possibility theory [7].* In what follows, we shall present in a summarized form a subset of such rules which play a basic role in FL.

Translation Rules

1. Modifier rule. If

$$X \text{ is } F \rightarrow \Pi_X = F \qquad (15)$$

then

$$X \text{ is } mF \rightarrow \Pi_X = F^+$$

where m is a modifier such as not, very, more or less, etc., and F^+ is a modification of F induced by m. More specifically: If m = not, then $F^+ = F'$ = complement of F, i.e.,

$$\mu_{F^+}(u) = 1 - \mu_F(u) \ , \quad u \in U \ . \qquad (16)$$

If m = very, then $F^+ = F^2$, i.e.,

$$\mu_{F^+}(u) = \mu_F{}^2(u), \quad u \in U \ . \qquad (17)$$

If m = more or less, then $F^+ = \sqrt{F}$, i.e.,

$$\mu_{F^+}(u) = \sqrt{\mu_F(u)} \ , \quad u \in U \ . \qquad (18)$$

As a simple illustration of (15), if SMALL is defined as in (2), then

$$X \text{ is very small} \rightarrow \Pi_X = F^2 \qquad (19)$$

where

$$F^2 = 1/0 + 1/1 + 0.64/2 + 0.36/3 + 0.16/4 + 0.04/5 \ . \qquad (20)$$

It should be noted that (16)-(18) should be viewed as default rules which may be replaced by other translation rules in cases in which some alternative interpretations of the modifiers very and more or less are more appropriate.

2. Conjunctive, disjunctive and implicational rules. If

$$X \text{ is } F \rightarrow \Pi_X = F \text{ and } Y \text{ is } G \rightarrow \Pi_Y = G \qquad (21)$$

where F and G are fuzzy subsets of U and V,

---

*There are several implemented languages which have extensive facilities for the manipulation of fuzzy propositions and execution of fuzzy instructions. Prominent among these are FUZZY [23] and FSTDS [30].

respectively, then

$$\text{(a)}\quad X \text{ is } F \text{ and } Y \text{ is } G \rightarrow \Pi_{(X,Y)} = F \times G \tag{22}$$

where

$$\mu_{F\times G}(u,v) \triangleq \mu_F(u) \wedge \mu_G(v) \quad (\wedge = \min) \tag{23}$$

$$\text{(b)}\quad X \text{ is } F \text{ or } Y \text{ is } G \rightarrow \Pi_{(X,Y)} = \bar{F} \cup \bar{G} \tag{24}$$

where

$$\bar{F} \triangleq F \times V\ , \quad \bar{G} \triangleq U \times G \tag{25}$$

and

$$\mu_{\bar{F}\cup\bar{G}}(u,v) = \mu_F(u) \vee \mu_G(v)\ . \tag{26}$$

$$\text{(c)}\quad \text{If } X \text{ is } F \text{ then } Y \text{ is } G \rightarrow \Pi_{(Y|X)} = \bar{F}' \oplus \bar{G} \tag{27}$$

where $\Pi_{(Y|X)}$ denotes the conditional possibility distribution of Y given X, and the bounded sum $\oplus$ is defined by

$$\mu_{\bar{F}'\oplus\bar{G}}(u,v) = 1 \wedge (1-\mu_F(u)+\mu_G(v))\ . \tag{28}$$

As simple illustrations of (22), (24) and (27), if

$$F \triangleq \text{SMALL} = 1/1 + 0.6/2 + 0.1/3 \tag{29}$$

$$G \triangleq \text{LARGE} = 0.1/1 + 0.6/2 + 1/3 \tag{30}$$

then

$$X \text{ is small and } Y \text{ is large} \rightarrow \Pi_{(X,Y)} \tag{31}$$
$$= 0.1/(1,1) + 0.6/(1,2) + 1/(1,3) + 0.1/(2,1) + 0.6/(2,2) + 0.6/(2,3) + 0.1/(3,1) + 0.1/(3,2) + 0.1/(3,3)$$

and

$$\text{If } X \text{ is small then } Y \text{ is large} \rightarrow \Pi_{(Y|X)} \tag{33}$$
$$= 0.1/(1,1) + 0.6/(1,2) + 1/(1,3) + 0.5/(2,1) + 1/(2,2) + 1/(2,3) + 1/(3,1) + 1/(3,2) + 1/(3,3)\ .$$

3. Quantification rule. If $U = \{u_1,\ldots,u_N\}$, Q is a quantifier such as many, few, several, all, some, most, etc., and

$$X \text{ is } F \rightarrow \Pi_X = F \tag{34}$$

then the proposition "QX are F" (e.g., "many X's are large") translates into

$$\Pi_{\text{Count}(F)} = Q \tag{35}$$

where Count(F) denotes the number (or the proportion) of elements of U which are in F. By definition (11), if the fuzzy set F is expressed as

$$F = \mu_1/u_1 + \mu_2/u_2 + \cdots + \mu_N/u_N \tag{36}$$

then

$$\text{Count}(F) = \sum_{i=1}^{N} \mu_i\ . \tag{37}$$

As a simple illustration of (35), if the quantifier several is defined as

$$\text{SEVERAL} \triangleq 0/1 + 0.4/2 + 0.6/3 + 1/4 + 1/5 + 1/6 + 0.6/7 + 0.2/8 \tag{38}$$

then

$$\text{Several X's are large} \rightarrow \Pi_{\sum_{i=1}^{N} \mu_{\text{LARGE}}(u_i)} \tag{39}$$
$$= 0/1 + 0.4/2 + 0.6/3 + 1/4 + 1/5 + 1/6 + 0.6/7 + 0.2/8$$

where $\mu_{\text{LARGE}}(u_i)$ is the grade of membership of the i^{th} value of X in the fuzzy set LARGE.

4. Truth qualification rule. Let τ be a fuzzy truth-value, e.g., very true, quite true, more or less true, etc. Such a truth-value may be regarded as a fuzzy subset of the unit interval which is characterized by a membership function μ_τ: [0,1] → [0,1].

A truth-qualified proposition, e.g., "It is τ that X is F," is expressed as "X is F is τ." As shown in [5], the translation rule for such propositions is given by

$$X \text{ is } F \text{ is } \tau \rightarrow \Pi_X = F^+ \tag{40}$$

$$\mu_{F^+}(u) = \mu_\tau(\mu_F(u))\ . \tag{41}$$

As an illustration, consider the truth-qualified proposition

Bob is young is very true

which by (40), (41) and (17) translates into

$$\Pi_{\text{Age(Bob)}} = \mu_{\text{TRUE}^2}(\mu_{\text{YOUNG}}(u))\ . \tag{42}$$

Now, if we assume that

$$\mu_{\text{YOUNG}}(u) = (1 + (\tfrac{u}{25})^2)^{-1}, \quad u \in [0,100] \tag{43}$$

and

$$\mu_{\text{TRUE}}(v) = v^2, \quad v \in [0,1] \tag{44}$$

then (41) yields

$$\Pi_{\text{Age(Bob)}} = (1 + (\tfrac{u}{25})^2)^{-4} \tag{45}$$

as the possibility distribution of the age of Bob.

Used in combination, the translation rules stated above provide a system for the determination of the possibility distribution induced by a fairly complex composite proposition. For example, the proposition

> If X is not very large and Y is more or less small then Z is very very large.

induces the conditional possibility distribution described by

$$\pi_{(Z|X,Y)}(w|u,v) = 1 \wedge (1 - (1-\mu^2_{\text{LARGE}}(u)) \wedge \mu_{\text{SMALL}}(v) + \mu^4_{\text{LARGE}}(w))\ . \tag{46}$$

It should be noted that rules of this type have found practical applications in the design of fuzzy logic controllers in steel plants, cement kilns and other types of industrial process control applications in which instructions expressed in a natural language are transformed into control signals [31-33].

Rules of Inference

In our approach to approximate reasoning, the translation rules for imprecise propositions serve as a preliminary to the application of various rules of inference to the possibility distributions which are induced by such propositions, leading to other possibility distributions which upon retranslation yield the conclusions which may be drawn from the premises.

More specifically, the basic rules of inference in FL are the following.

1. Projection rule. Consider a fuzzy proposition whose translation is expressed as

$$p \rightarrow \Pi_{(X_1,\ldots,X_n)} = F \tag{47}$$

and let $X_{(s)}$ denote a subvariable of the variable $X \triangleq (X_1,\ldots,X_n)$, i.e.,

$$X_{(s)} = (X_{i_1},\ldots,X_{i_k}) \tag{48}$$

where the index sequence $s \triangleq (i_1,\ldots,i_k)$ is a subsequence of the sequence $(1,\ldots,n)$.

Furthermore, let $\Pi_{X_{(s)}}$ denote the marginal possibility distribution of $X_{(s)}$; that is,

$$\Pi_{X_{(s)}} = \mathrm{Proj}_{U_{(s)}} F \tag{49}$$

where U_i, $i = 1,\ldots,n$, is the universe of discourse associated with X_i;

$$U_{(s)} = U_{i_1} \times \cdots \times U_{i_k} \tag{50}$$

and the projection of F on $U_{(s)}$ is defined by the possibility distribution function

$$\pi_{X_s}(u_{i_1},\ldots,u_{i_k}) = \mathrm{Sup}_{u_{j_1},\ldots,u_{j_m}} \mu_F(u_1,\ldots,u_n) \tag{51}$$

where $s' \triangleq (j_1,\ldots,j_m)$ is the index subsequence which is complementary to s, and μ_F is the membership function of F.

Now let q be a retranslation of the possibility assignment equation

$$\Pi_{X_{(s)}} = \mathrm{Proj}_{U_{(s)}} F \,. \tag{52}$$

Then, the projection rule asserts that q may be inferred from p. In a schematic form, this assertion may be expressed more transparently as

$$\begin{array}{l} p \rightarrow \Pi_{(X_1,\ldots,X_n)} = F \\ \qquad\qquad \downarrow \\ q \leftarrow \Pi_{X_{(s)}} = \mathrm{Proj}_{U_{(s)}} F \end{array} \tag{53}$$

2. Conjunction rule. Consider a proposition p which is an assertion concerning the possible values of, say, two variables X and Y which take values in U and V, respectively. Similarly, let q be an assertion concerning the possible values of the variables Y and Z, taking values in V and W. With these assumptions, the translations of p and q may be expressed as

$$\begin{array}{l} p \rightarrow \Pi^p_{(X,Y)} = F \\ q \rightarrow \Pi^q_{(Y,Z)} = G \end{array} \tag{59}$$

Let F and G be, respectively, the cylindrical extensions of F and G in $U \times V \times W$. Thus,

$$\bar{F} = F \times W \tag{60}$$

and

$$\bar{G} = U \times G \,. \tag{61}$$

Using the conjunction rule, we can infer from p and q a proposition which is defined by the following scheme (the reverse arrow $\leftarrow$ denotes retranslation, i.e., reverse translation):

$$r \rightarrow \Pi^p_{(X,Y)} = F \tag{62}$$

$$q \rightarrow \Pi^q_{(Y,Z)} = G \tag{63}$$

$$\overline{r \leftarrow \Pi_{(X,Y,Z)} = \bar{F} \cap \bar{G}} \tag{64}$$

On combining the projection and conjunction rules, we obtain the compositional rule of inference (67) which includes the classical modus ponens as a special case.

More specifically, on applying the projection rule to (64), we obtain the following inference scheme

$$\begin{array}{l} p \rightarrow \Pi^p_{(X,Y)} = F \\ q \rightarrow \Pi^q_{(Y,Z)} = G \end{array} \tag{65}$$

$$\overline{r \leftarrow \Pi^r_{(X,Z)} = F \circ G}$$

where the composition of F and G is defined by

$$\mu_{F\circ G}(u,w) = \mathrm{Sup}_v(\mu_F(u,v) \wedge \mu_G(v,w)) \tag{66}$$

In particular, if p is a proposition of the form "X is F" and q is a proposition of the form "If X is G then Y is H," then (65) becomes

$$\begin{array}{l} p \rightarrow \Pi_X = F \\ q \rightarrow \Pi_{(Y|X)} = \bar{G}' \oplus \bar{H} \end{array} \tag{67}$$

$$\overline{r \leftarrow \Pi_{(Y)} = F \circ (\bar{G}' \oplus \bar{H})}$$

The rule expressed by (67) may be viewed as a generalized form of modus ponens which reduces to the classical modus ponens when F = G and F, G, H are nonfuzzy sets.

Stated in terms of possibility distributions, the generalized modus ponens places in evidence the analogy between probabilistic and possibilistic inference. Thus, in the case of probabilities, we can deduce the probability distribution of Y from the knowledge of the probability distribution of X and the conditional probability distribution of Y given X. Similarly, in the case of possibility distributions, we can infer the possibility distribution of Y from the knowledge of the possibility distribution of X and the conditional possibility distribution of Y given X.

It is important to note that the generalized modus ponens as expressed by (67) may be used to enlarge significantly the area of applicability of rule-based systems of the type employed in MYCIN and other expert systems. This is due primarily to two aspects of (67) which are not present in conventional rule-based systems: (a) in the propositions "X is F" and "If X is G then Y is H," F, G and H may be fuzzy sets; and (b) F and G need not be identical. Thus, as a result of (a) and (b), a rule-based system employing (67) may be designed to have an interpolative capability [6].

Note. Due to limitations on space, the sections dealing with credibility analysis and examples of approximate reasoning have been deleted. Full text of the paper is available on request.

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FROM HISTORY TO COMPUTER SCIENCE : A FORMALIZATION OF THE INFERENTIAL PROCESSES OF AN HISTORIAN

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The object of the present paper is to discuss the results of the work carried out to define as strictly as possible the formal system of representation of the inference procedures ("hypotheses") characteristic of the RESEDA project. RESEDA is a question-answering system which operates on a data base containing biographical information concerning characters involved in the medieval history of France.

1. INTRODUCTION

1.1 The RESEDA project aims to set up an advanced question-answering system operating upon a biographical data base. The information housed within this base concerns characters involved in the medieval history of France and their socio-historical background. Strictly formulated questions are presented to the system; responses, given in the same format, are obtained by direct-search through the data base or by inference procedures. The objectives of the first RESEDA/0 step of the project were to construct a general framework for the system and to verify the adequacy of descriptive metalanguage chosen for dealing with this special sort of data. A new phase RESEDA/1 has just recently commenced. It strives towards two goals : a) making the system fully operational, in progressing beyond the phase of demonstration tests to approximate a routine practical use of the data; b) examining in theoretical and practical detail the possibility of a partially automated construction of the inductive "hypotheses" which support the system's inference operations.

1.2 In preparing for the latter, the RESEDA team has had to restudy in depth the work already accomplished on hypotheses in the first phase of the project. It was in effect necessary to establish on a more strictly defined basis, the formal conventions under which the hypotheses are drawn up, and to define these conventions down to the smallest detail. This paper relates to the results of this thorough work. With regard to the metalanguage used to represent biographical data, discussed in the IJCAI/77 report [3], I will give no more information than is strictly necessary for the full understanding of my talk; the interested reader is referred to recent papers on this subject [3,6,7].

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2. AN EXAMPLE OF AN HYPOTHESIS

2.1 Fig. 1 shows the formal representation of one of the most simple hypotheses in the RESEDA system, the "hypothesis of a gift to a religious community".

2.1.1 Every hypothesis -inference procedure which can be interpreted in KRL "servant-triggers" terms, see [1]- consists of two separate parts, the "premiss" and the "condition".

2.1.1.1 The premiss provides the general framework capable of being adapted to the formal representation of any question, the answer to which car be found in the hypothesis under examination. If we use the distinction introduced by Smith [5] between "abstraction" and "generalization", we could say that the formal expression of the premiss is obtained by the abstraction of specific formulations, in RESEDA'S metalanguage, of different questions which can be associated with the hypothesis.

2.1.1.2 The condition is formed of a sequence of theoretical schemata ("condition schemata") of "planes", linked by "and", "or", "not". The term "plane" [4] is reserved for expressing the representation in the data base, in terms of the metalanguage, of each elementary "episode", each "fact" -expressed in natural language- which make up the fundamental stages for a biography. For an example, refer to the episode from Pierre l'Orfevre biography further below : "It is known

Hypothesis of a gift to a religious community

premiss : α

α) /-/-//k/-/-/-/
BE-AFFECTED-BY SUBJ 1
OBJ <good>
MODAL <acquisition-by-the-donor's-initiative>
SOURCE V1

restrictions on the variables of the premiss schemata :

k = <geographic-localisation>
1 = <religious-community>

condition :

(A V B V (C Λ D) V E V (F Λ D))

A) /-/-//k/-/-/-/
BE-PRESENT SUBJ V1

B) /-/-//-/k/-/-/
BE-AFFECTED-BY SUBJ V1
OBJ q

C) /-/-//-/k/-/-/
BE-AFFECTED-BY SUBJ V2
OBJ r

D) (V1 COORD1 V2) SPECIF <kinship>

E) /-/-//k/-/-/-/
soc+BE-AFFECTED-BY SUBJ 1
OBJ V1 SPECIF <member-of-an-organization>

F) /-/-//k/-/-/-/
soc+BE-AFFECTED-BY SUBJ 1
OBJ V2 SPECIF <member-of-an-organization>

restrictions on the variables of the condition schemata :

q Λ r = vault V <mark-of-identification>

figure 1

that around 1360 Pierre l'Orfevre was a member of the chapter of Senlis cathedral, as their dean", which will give rise to the plane 3 in fig. 3. Translation from episode to plane is done by separating out spatio-temporal data plus bibliographic references (the "thematic") from the description proper of the episode. In the "description part" of plane 3, BE-AFFECTED-BY is the "predicate" used in the translation of the episode; SUBJ, OBJ, are the "main cases" while SPECIF simply introduces a degree of precision with respect to the argument JEAN-L'ORFEVRE which fills the slot OBJ. "soc" is a "modulator" which enables us to specify the fact that the "state" defined by the predicate is inserted into a socio-professional context; "const" carries the meaning of "verified fact".

Returning now to the condition, the information which it enables us to find in the system's data base provides a possible interpretation of the fact (episode) represented by the specific plane to which the question has been reduced. The formal expression of the condition is obtained, by abstraction, from the coding relating to the planes which are shown to be capable of fulfilling an *a priori* undefined number of specific actualizations of the premiss.

2.1.2 With regards now to the formal details of the representation of fig. 1, let me take the Dremiss first. The symbols k, 1 and V1 which appear in the "scheme of premiss", a, are "variables of the premiss schemata". In order to be bound, theses variables must satisfy the "restrictions" connected with them (the restriction on V1 is shown implicitly : variables of the type Vn can only be satisfied by the name of one of the personages recognized by the system).

Going on to the condition : the symbol "A" which joins the two "condition schemata" C, D (F, D) has its usual meaning of "C and D" ("F and D"); "A V B" has the meaning of "A or B". The condition must therefore be interpreted in this way : an explanation of the episode represented by the premiss filled with elements drawn from the question, can be given by the planes of the data base which can be adapted to the "condition scheme" A, or to scheme B, or to two schemata C and D -which must in this case be satisfied together- or to scheme E, or to two schemata F and D.

2.2 Imagine now a question like "Why did Jean l'Orfevre at some unspecified time, but certainly before August 1412, the time of his death, give a latin bible by legacy to the Chapter of Senlis cathedral?"; the question would be coded as in fig. 2. A reply obtained by direct-match would show that it is possible to retrace in the data base a plane -containing at least all the information distinctly specified in the question- which should already be explicitly connected by a "pointer-correlator" [7: 16-17] of the type CAUSE to a second plane, or a succession of planes, which would so match with the variable x.

/avant-août-1412/b//Senlis/b/Senlis/b/

BE-AFFECTED-BY SUBJ cathedral-chapter
OBJ bible SPECIF latin
MODAL legacy
SOURCE JEAN-L'ORFEVRE
CAUSE1 ?x

figure 2

Let us now imagine that this explicit link does not exist; RESEDA will have to resort to the system of hypotheses to reply to the question

asked.

The predicate present in the question (in our case BE-AFFECTED-BY) identifies the set of inference procedures which must be examined in order to see if there exists at least one hypothesis whose premiss can *a priori* match the type of question proposed. When this test has been passed, a real match between the question and the premiss is required. In our case, and referring back to fig. 1 and 2,the result obtained will be that from this point onwards the variables k, 1 and VI will be connected to "Senlis" (the place associated with the "subject" of the attribution in the question thematic), to "cathedral-chapter", and to "Jean l'Orfevre".

Research on the data base of planes which can satisfy the six condition schemata begins with an examination of the "volume" associated with "Jean l'Orfevre" (volumes are permanent files -a file for each personage recognized by the system- containing "labels" identifying the planes in which the personage in question appears), in order to see if it is possible to retrace the planes of the form A, B, D and E -the condition schemata in which the (bound) variable VI is present. In our case, it can be assumed that the search will first retrace the plane 1 in fig. 3 : "Jean l'Orfevre lived in Senlis (location of the subject) for a period of which the starting date (code "-") is not known but which ended in August 1412".

```
1) /-/août-1412//Senlis/b/b/b//Bibl:Bozzolo/
   BE-PRESENT        SUBJ   PIERRE-L'ORFEVRE

2) (JEAN-L'ORFEVRE COORD1  PIERRE-L'ORFEVRE)
                           SPECIF  kinship

3) /vers-1360/b//Senlis/Senlis/b/b//Bibl:Bozzolo/
   const+soc+BE-AFFECTED-BY
                      SUBJ  cathedral-chapter
                      OBJ   JEAN-L'ORFEVRE
                              SPECIF  dean
```

figure 3

Secondly, we will have a series of "relation planes" (special planes without thematics) of the form D, which provide the personages V2 who are relatives of Jean l'Orfevre. A couple of planes which satisfy (F A D) are planes 2 and 3 of fig. 3 : "Around 1360 Pierre l'Orfevre, who is some non-specifiecl relative to Jean l'Orfevre, VI, was dean (specific term of the lexical tree <member...>) of the chapter of Senlis cathedral". The planes 1, 2 and 3 together form the reply to the question in fig. 2; the possible reasons for the gift to Senlis cathedral are therefore that Jean l'Orfevre was an inhabitant of this town and that his family had special relations with the cathedral, given that one of his relatives had held an important position within the chapter.

3. CONCLUSION

Detailed analysis of the hypothesis "gift", proves clearly the ad *hoc* nature of RESEDA's inference corpus. However, this ad hocness does not constitute a limit on the practical utility of the system. The degree of complexity and subtlety which can be reached by the inference procedures is sufficient to cover a very large number of possible deductions. However, it cannot be denied that, at the present, RESEDA is a system containing a limited number of non-evolving structures (hypotheses), whose capacity to enrich the system by finding new relations between characters or the situations in which these characters are involved, is restricted to a closed set of pre-determined contexts.

Thus the new phase RESEDA/1 of the project intends to use a semi-automatic technique for the formation of the hypotheses. Such a mechanism should help to alleviate the handicap mentioned above, at least in the sense of facilitating a rapid and continual development of the inference corpus, if only at the quantitative level. The procedure involved should be the classical one of learning by examples, see [2] . The intended mechanism should be capable of utilizing the syntactic-semantic properties of RESEDA's formal system, in order to create the framework enabling the association of the two poles, question and answer, of the new hypothesis which is to be constructed.

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CONTINUOUS RELAXATION AND LOCAL MAXIMA SELECTION

Conditions for Equivalence**

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It is also a good rule not to put overmuch confidence in the observational results that are put forward until they are confirmed by theory.

Sir Arthur Eddington, 1934

1. MOTIVATION

The study of speech and image understanding systems has largely been empirical. Representations have often been designed for task domains, while algorithms were designed to make use of these representations, as well as heuristic considerations about how the algorithm should behave. Thus it has been very difficult to compare different algorithms except for the results of a few examples, to state equivalences between algorithms in anything like certain terms, or to determine the theoretical requirements for solving a particular problem.

A number of common problems facing the designers of such systems have begun to emerge, however, which suggests that it may be possible to study the power of algorithms in terms of their ability to solve these problems. One such problem is the reduction of local ambiguities, and relaxation labeling processes are a class of algorithms that have been proposed for dealing with it [1]. While many recent applications offer some insight into the relaxation computation (for a review, see [2]) a formal analysis aimed at specifying this computation more precisely is required. It is impossible, for example, to know whether two different algorithms are really equivalent (in the sense that they are implementing the same abstract computation) simply by comparing their results on a small number of experiments. Rather, the relationships between them must be expressed in an analytical fashion so that they will hold for all experiments. This paper is the beginning of such an analysis for continuous relaxation processes. It specifies the relaxation computation in terms of another, much more widely used algorithm - local maxima selection- together with a set of conditions that are sufficient for guaranteeing convergence and equivalence between the two.

The specific reasons for studying the relationships between relaxation and local maxima selection are manifold. From the relaxation point of view, maxima selection provides a model for the decision process, or part of the decision process, that relaxation is implementing. In other words, if we consider the dynamics of a relaxation process as being composed of two stages, one in which a proper ordering of the labels is obtained given the compatibility relations and the initial state, and the other in which certain of these labels are selected, then maxima selection provides a non-iterative model for the second stage. From a practical point of view, when conditions sufficient for equivalence between the two algorithms are met, they can serve as stopping criteria for the relaxation process. More generally, however, these results show that when circumstances are structured well enough, the cooperative relaxation algorithm acts the same as if it were decomposed into a purely local maxima selection process. This is exactly the kind of relationship that is desirable between two algorithms: when the stronger one is necessary, it is functional; otherwise, it reduces to the weaker one.

There is another, morre abstract application of the theory that we are beginning to develop here. It derives from the decomposition result just alluded to (which is stated more formally in Sec. 3), and pertains to inferences about how local or global a given algorithm must be. In

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For a much more extensive discussion for. these ideas, together with references, see TR-7 8-15R Dept. of Elect. Eng., McGill University.

particular, cooperation can be viewed as one way in which information can be propagated between the local parts of an algorithm, hense making it more global (3). One surprising interpretation of our result is that circumstances exist in which this propagation is irrelevant. In other words, although a (globally) cooperative mechanism has been used in designing an algorithm for a given problem, the inherent structural complexity of the problem (in that representation) is still only local. Conditions such as those stated in the Equivalence Theorem (Sec. 3) provide a first step toward determining such requirements analytically. In turn, these computational requirements may imply certain constraints on the particular mechanisms and machinery that actually perform such functions [4].

2. BACKGROUND

The class of problems for which both relaxation and local maxima selection are applicable is one in which global labeling problems can be represented as networks of local ones. In other words, given a set of possible labels for each node in a network, the problem is to select a single label (or a smaller set of labels) to attach to each node. These labels might indicate, e.g., assertions about the presence of oriented line segments in an image [5], The nodes in the network would then correspond to the spatial positions to be labeled, while edges would indicate which nodes were spatial neighbours. Or, the labels might indicate disparity values [6). We shall denote such labels by the variable λ, and the full set of labels (at a node i) by Λ_i.

For continuous relaxation processes, a certainty measure is distributed over the label set at each node. We shall denote the certainty with which label λ is associated with node i by $p_i(\lambda)$. They satisfy $\sum_{\lambda \epsilon \Lambda_i} p(\lambda)=1$ and $0 \leq p_i(\lambda) \leq 1$. In the line labeling example, such a measure may be obtained from scaled feature (i.e., line) detector responses. Note that ambiguity enters the problem because feature detectors do not respond uniquely; i.e., many labels appear to be possible when looking only at the individual detector responses.

Perhaps the most common algorithm for selecting a label from among this initially ambiguous set is to perform local maxima selection (i.e., to pick the label with the maximal certainty at each node). Such an algorithm would be appropriate for our line example, if we knew that the line detector always responded most strongly at the correct orientation. This is, of course, not the case for real images, in which many different noise sources can corrupt the detectors' responses. Thus more powerful techniques seem to be necessary in general. However, as we shall show, there are instances in which such weaker techniques are appropriate.

The strength behind relaxation processes lies in their use of contextual information throughout the ambiguity reduction process. This context is based on an a priori notion of consistency or compatibility between labels on neighboring nodes, so that now some degree of cooperation takes place between nodes during the label selection process. In the line labeling example, label compatibility is an abstract way to introduce models for good continuation of orientation (i.e., orientation should vary smoothly along lines and curves) and of intensity (i.e., intensity values should vary smothly along the line and over the background); see [7]. In this paper, however, since we are discussing the relaxation mechanism in the abstract, we shall only consider compatibilities as functions over n-tuplos (usually pairs) of labels on neighboring nodes into [0.1], For example, $r_{ij}(\lambda, \lambda')$ indicates the compatibility between label λ on i and λ' on its neighbor j, where 0 corresponds to perfect incompatibility and 1 to perfect compatibility.

Given an initial labeling $p_i^0(\lambda)$, $\lambda \epsilon \Lambda_i$, $i \epsilon I$, the relaxation process iteratively updates each label's certainty factor by an amount proportional to an estimate of its consistency with the labeling over its neighborhood. If this neighbourhood consistency estimate indicates that a label is compatible with its neighbourhood labelings, then its consistency factor is increased; otherwise, it is decreased. Since many labelings may be partially consistent, the update is normalized with respect to the average neighbourhood consistency at each iteration. Thus we have updating rules of the form:

$$p_i^{k+1}(\lambda) = p_i^k(\lambda) \cdot \frac{Q_i^k}{\sum_{\eta \epsilon \Lambda_i} p_i^k(\eta)\, Q_i^k(\eta)} \qquad (2)$$

where $Q_i^k(\lambda)$ is the current consistency estimate between label λ on node i and the labeling over its neighbourhood.

The neighbourhood consistency is computed as a function of the current neighbourhood labeling and the compatibility functions. For comput-

ational reasons, this estimate has been decomposed into two parts: one in which an operation is performed to determine the pair (or n-ary) label consistency estimates; and the other in which these partial estimates are combined into a single neighbourhood estimate. The most widely used estimate is [1]:

$$Q_i^k(\lambda) = \sum_{j \in J_i} C_{ij} \sum_{\lambda' \in \Lambda_j} r_{ij}(\lambda,\lambda') p_j^k(\lambda') \quad (3)$$

where J_i is the set of nodes neighbouring i and the C_{ij} terms weight the total interaction between nodes i and j. The choice of arithmetic averages in (3), however, is only heuristic. The essential point is that the neighbourhood consistency estimate is a function of the labeling over the entire neighbourhood. To emphasize this generality, we shall rewrite (3) in a more general form, and prove all of our results using this form.

The general form that we shall consider is:

$$Q_i^k(\lambda) = \underset{j \in J_i}{\text{Mean}} \{\text{Norm}_{\lambda' \in \Lambda_j} r_{ij}(\lambda,\lambda') p_j^k(\lambda')\} \quad (4)$$

where Mean is any standard mean (or averaging) operator; and Norm is an operator that computes the norm (or length) of a vector.

3 CONSISTENTLY ORDERED LABELINGS AND THE EQUIVALENCE THEOREM

The traditional way of viewing continuous relaxation is as numerical process for updating certainty measures. However, if we consider these certainty measures as defining a partial ordering over the labels at each node, then another way of viewing relaxation labeling is as a process that changes this partial ordering. This is the point of view that we shall adopt for the remainder of this paper, because it suggests a study of the iteration at which the partial ordering of the labels at each node becomes fixed for all further iterations. We shall say, at this iteration, that the system has become consistently ordered. The particular partial ordering that we shall concentrate on is the one specifying the relationship between the maximal and all of the non-maximal labels at each node.

There are many possible dynamical situations that can give rise to consistently-ordered labelings. Perhaps the most common situation is for the maximal labels to mutually support one another, thus driving the weaker labels to zero. It is this situation that we shall now **attempt to characterize because, as we shall prove, it leads to a formal correspondence between relaxation and local maxima selection.**

To define the above notions more exactly, it is necessary to introduce some notation: Let

(i) Λ_i **be the full set of labels attached to node i.**

(ii) M_i^k **be the set of labels attached to node i that have the greatest certainty at iteration k;**

(iii) N_i^k **be the set of labels attached to node i with non-zero, non-maximal certainties at iteration k;**

(iv) Z_i^k **be the set of labels attached to node i with zero certainty at iteration k.**

Equivalence Theorem

If, for a given relaxation process, the conditions

(i) $$\underset{m_j \in M_j^{k_C}}{\text{Norm}}\ r_{ij}(m_i,m_j) p_j^{k_C}(m_j) > \underset{\lambda' \in \Lambda_j}{\text{Norm}}\ r_{ij}(n_i,\lambda') p_j^{k_C}(\lambda')$$

$$\forall m_i \in M_i^{k_C},\ \forall n_i \in N_i^{k_C},$$

$$\forall j \in J_i$$

and

(ii) $$r_{ij}(m_i, \lambda') = r_{ij}(m_i', \lambda')$$

$$\forall m_i, m_i' \in M_i^{k_C},$$

$$\forall \lambda' \in M_j^{k_C} \cup N_j^{k_C},$$

$$\forall j \in J_i$$

hold for every node $i \in I$, then

(a) **the labeling $\mathcal{L}^{k_C}$ in that process is consistently ordered everywhere, and**

(b) **the relaxation process will converge to a final labeling with**

$$\lim_{k \to \infty} P_i^k(\lambda) = \begin{cases} 1/\#M_i^{k_O} & \forall \lambda \in M_i^{k_O} \\ 0 & \text{otherwise} \end{cases}$$

where $\#M_i^{k_O}$ denotes the number of labels in $M_i^{k_O}$.

For the proof of this theorem, together with applications and interpretations, see the TR cited in the footnote on the title page.