NUDGE, A KNOWLEDGE-BASED SCHEDULING PROGRAM

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Abstract. Traditional scheduling algorithms (using the techniques of PERT charts, decision analysis or operations rrsrarrh) require well-defined, quantitative, complete sets of constrainls*. They are insufficient for scheduling situations where the problem description is ill-defined, involving incomplete, possibly inconsistent and generally qualitative constraints. The NUDGE program uses an extensive knowledge base to debug scheduling requests by supplying typical values for qualitative constraints, supplying missing details and resolving minor inconsistencies. The result is that an informal request is converted to a complete description suitable for a traditional scheduler.

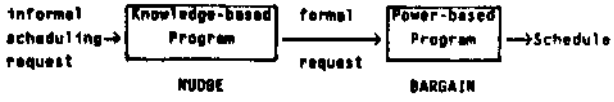
To implement the NUDGE program, a knowledge representation language — FRL-0 — based on a few powerful generalizations of the traditional property list representation has been developed. The NUDGE knowledge base defined in FRL-0 consists of a hierarchical set of concepts that provide generic deseriptions of the typical activities, agents, plans and purposes of the domain to be scheduled. Currently, this domain is the management and coordination of personnel engaged in a group project.

NUDGE constitutes an experiment in knowledge-based, rather than power-based AI programs. It also provides an example of an intelligent support system, in which an AI program serves as an aid to a decision maker. Finally, NUDGE has served an experimental vehicle for testing advanced representation techniques.

1. INTRODUCTION

A classic issue in AI is the knowledge versus power controversy [Minsky & Papert 74]. The knowledge position advocates that intelligence arises mainly from the use of a large store of specific knowledge, while the power theory argues for a small collection of general reasoning mechanisms. This paper reports *on* an experiment in which a knowledge-based program NUDGE has been implemented for the scheduling domain, a domain in which power-based programs have long been the dominant paradigm.

Traditionally, scheduling programs apply simple but powerful decision analysis techniques to finding the optimal schedule under a well-defined set of constraints. The performance of NUDGE confirms that for well-defined, formal situations, the traditional power-based approach is appropriate. But for the problem of defining these formal situations when given only informal specifications, a knowledge-based approach is necessary. By an informal specification, wc mean a scheduling request that is potentially incomplete, possibly inconsistent and qualitative. (See Balzer [74] for an analysis of informal program specifications.) Thus, the NUDGE program accepts informal requests and produces a calendar containing possible conflicts and an associated set of strategies for resolving those conflicts. A domain-independent search algorithm BARGAIN then resolves these conflicts by traditional decision analysis techniques.

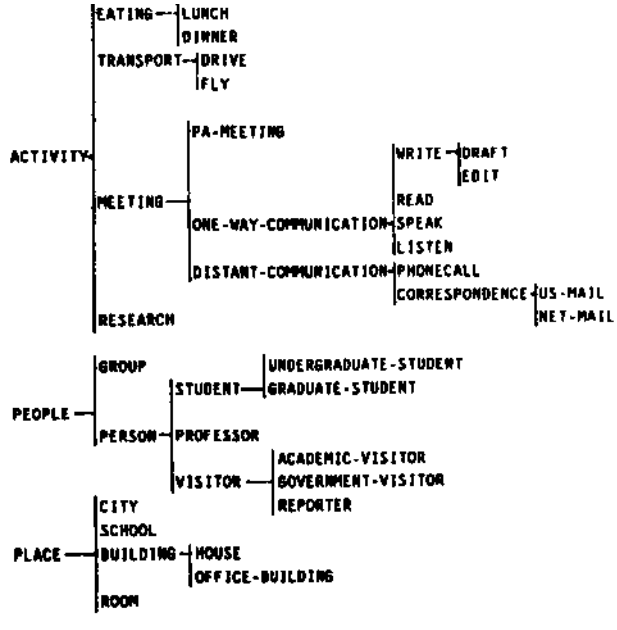


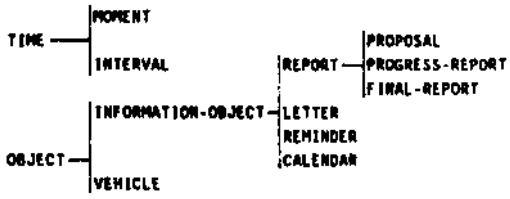
NUDGE uses a broad data base of knowledge to expand and debug informal scheduling requests. The database is used to supply missing details, resolve inconsistencies, determine available options, notice necessary prerequisites and plan for expected outcomes. To manage this large store of knowledge, a representation language -- FRL-0 — has been implemented. FRL-0 extends the traditional attribute/value description of properties by allowing properties to be described by comments, abstractions, defaults, constraints, indirect pointers from other properties, and attached procedures.

These are not new representation techniques. Abstraction, for example, was discussed in Quillian [68], and attached procedures have become a common property of AI languages since PLANNER [Hewitt 69]. However, the strengths and weaknesses of these representation techniques and their potential interactions is still not well understood. For this reason, we have chosen not to include as many representation capabilities as are currently being implemented in KRL [Bobrow & Winograd 76] and OWL [Martin 77]. Wc view FRL-0 as an experimental medium to study the utility of a few specific capabilities and their interactions.

Because a knowledge-based approach requires a large store of specific data, it was necessary to choose a particular domain to carry out our experiment. Our criterion was to select a realm in which scheduling requests are typically informal. This criterion ruled out such scheduling problems as those of an assembly line. (See Tongr [63] for an AI treatment of this problem.) Instead, we selected office scheduling; in particular, assisting a manager in scheduling his team. This environment includes scheduling meetings, monitoring the progress of subgoals assigned to team members, alerting the manager to deadlines, and real-time rescheduling.

In providing NUDGE with the knowledge necessary for these functions, our research serves a third purpose beyond (1) exploring the relation between knowledge-based and power-based scheduling and (2) exercising various representation strategies. It provides insight into the categories of knowledge that are necessary for office scheduling (independent of their representation). NUDGE contains a hierarchy for activities involving information transfer, for people in various roles related to this transfer, for the plans governing these transfers, and for the associated demands on time, space and personnel. The hierarchy is on the average five levels deep and includes approximately 100 objects, each described by a generalized property list called a frame. An abridged version of this hierarchy appears below, with specialization indicated by nesting.





The term "frame" as used in FRL-0 was inspired by Minsky's [7.5] development of frame theory. Frame theory contends that (!) intelligence arises from the application of large amounts of highly specific knowledge, at opposed to a few general infercnong mechanisms, and (2) this is accomplished through the use of a library of frames, packets of knowledge that provide descriptions of typical objects and events. These descriptions contain both an abstract template providing a skeleton for describing any instance and a set of defaults for typical members of the class. The defaults allow the information system to supply missing detail, maintain expectations, and notice anomalies.

We have yet to investigate with equal care related area* of knowledge not strictly involved in scheduling the information flow between members of a research team — this includes space allocation, budgeting, and travel scheduling. The last of these is the focus of the GUS system developed by Robrow ct al [76]. Gus IS is a frame-based dialog system that addresses many of the issues raised here. The major difference is that GUS focusses on the use of frame representations to support dialog comprehension while NUDGE focusses on their use to support sophisticated scheduling.

Finally, although developed for the office scheduling domain, the NUDGE knowledge base does have a broader applicability. The use of a hierarchy of successively more abstract concepts allows highly specific information to be clearly segregated from more general facts about the world. Furthermore, some of the concept hierarchies such as those for time and place apply *in toto* to many other applications.

2. SCENARIO

The following request is typical of those understood by NUDGE.

(SI) *NUDGE* schedule a meeting with Bruce for next Tuesday.*

SI is an informal specification in that such facts as the following are left unsaid:

Where the meeting is to be held.
Which Tuesday is next Tuesday.
What time on Tuesday is preferred.
How long the meeting is should last.
Whether there arc any prerequisites.
What to do if Rruce is unavailable.

As such it is typical of the requests made by people of one another. Given a knowledge of the individuals involved, their roles and the context, NUDGE expands SI to the more complete S1\ where the added information is in italics.

(SI') I UNDERSTAND YOUR REQUEST TO MEAN: SCHEDULE A MEETING WITH BRUCE *AND ME AT 3 IN THE AFTERNOON* NEXT TUESDAY *ONE WEEK FROM TOMORROW LASTING ONE HOUR IN MY OFFICE TO DISCUSS THE PERSONAL ASSISTANT PROJECT.*

When processed by the the language comprehension component of NUDGE [Bullwinkle 77], SI causes the construction of a frame gcstalt, a data structure of instantiated frames containing all information in SI*. (The actual text of SI* is generated by the text output procedures associated with the frames in this gestalt.)

The knowledge-based phase of the scheduling concludes with the conversion of the information in the frame gcstalt to a calendar containing possible conflicts and an associated set of strategies for resolving those conflicts. The BARGAIN program then reports the highest utility compromise to the user.

(RI) YOUR PREFERRED TIME FOR MEETING WITH BRUCE ON TUESDAY IS ALREADY FILLED BY A MEETING WITH MARK. HOWEVER, MARK'S PURPOSE IS TO DISCUSS LANGUAGE RESEARCH AND CANDY IS AVAILABLE. SHALL I RESCHEDULE MARK TO SEE HER INSTEAD.

Mark's purpose is not specifically to se Ira, and hence, a member of Ira's group can be substituted to see Mark. Observe that access to a diverse set of scheduling strategies has made it unnecessary to juggle the possible time of the meeting between Ira and Rrucc, producing a compromise not entirely satisfactory to cither. Instead, a sufficiently broad perspective has allowed NUDGE to identify the option of finding an alternative participant by referencing the purpose of the conflicting appointment. A knowledge-based phase in the scheduling thus avoids the myopia a purely power-based approach can exhibit.

Continuing the scenario:

(52) *Yet.*

(R2) THE MEETING WITH BRUCE IS SCHEDULED. SHOULD BRUCE PREPARE A WRITTEN PA PROGRESS REPORT?

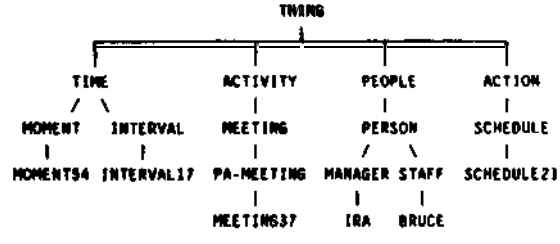
(53) *Yes.*

(R3) I WILL REMIND BRUCE ABOUT THE REPORT.

Section 3 describes the frame gcstalt representing NUDGE's completion of the SI request. Section 4 discusses the representation techniques of FRL-0 supporting the creation of the gcstalt. Section 5 analyzes the underlying knowledge of activities and individuals represented with these techniques.

3. THE FORMATION OF FRAME GESTALTS

A frame gestalt consists of a set of generic frames, instantlated appropriately for a particular scheduling request. The generic frames are selected on the basis of clues implicit in the scheduling request; knowledge-based reasoning begins with a recognition process. Information missing in the request is then computed from defaults, constraints, and procedures -- all associated with these generic frames. For SI, the gcstalt includes the frames shown below, with daughters of a frame representing its specializations. Many other interrelations among these frames arc not shown.



The goal of the knowledge-based phase is to compute this frame gestalt.

The input to the gestalt formation process is a set of partially instantiated frames representing the information actually present in the informal request. This input is generated by a natural language front end consisting of the Wait-and-See-Parser developed by M. Marcus [76] and a frame-based semantics designed by C Bullwinkle [77]. There are four partially instantiated frames: MEETING37, SCHEDULE21, INTERVAL17, MOMENT54.

MEETING37 is the frame for the proposed meeting and initially contains information regarding the participants and time of the event extracted from the English request.

```
MEETING37
   AKO      SVALUE   FA-MEETING   [SOURCE:  PRAGMATICS  S I]
   WHO      $VALUE   IRA          [SOURCE:  PRAGMATICS  S I]
                     BRUCE        [SOURCE:  SEMANTICS   S I]
```

MEETINC37 reports that the participants arc Bruce and Ira. Bruce it known from the semantic interpretation of SI, while Ira is inserted on the basis of pragmatics, i.e. that the person requestmr the meeting wishes to be included among the part icipants. MEETINC37 has been identified by pragmatics as A-KIND-OF (AKO) PA-MEETING on the basis of knowledge regarding the common activities of Ira and Bruce. Had no such special knowledge existed, the sentence would simply have triggered an instance of the MEETINC frame.

The first element of these frame structures is the name of the frame name and each remaining item is a slot. Each slot has one or more values, explicitly marked by the IVALUE facet. A frame is thus simply a multi-level association list. The semantics of attached procedures and inheritance is enforced by the access functions.

4. REPRESENTATION TECHNOLOGY

The formation of a frame gcstalt occurs by expanding the the frames extracted from the initial request in terms of the knowledge stored in the FRL database. This section discusses this process in terms of the contributions made by six representations techniques embedded in FRL-0: comments, abstraction, defaults, constraints, indirection and procedural attachment.

O Comments. The first generalization of property lists in FRL-0 is the inclusion of comments attached to values. Comments are used in these examples to record the source of the value in each slot. So far, the only *tourcc* is the semantic and pragmatic interpretation performed by the language comprehension process. Alternative sources are inferences made by attached procedures and inherited properties. Other kinds of commentary provide numerical utilities for use by the scheduler, and describe differences between multiple procedural methods attached to the same slot.

This commentary provides guidelines both for BARGAIN to judge the reliability and and strength of various constraints and for NUDGE to debug inconsistencies arising from conflicting contributions by different frames during the gcstalt formation process. The former would arise if conflicts existed between the generic information of the IRA and BRUCE frames, while the Litter is exemplified by Si being part of a dialog. The sentence "The meeting should be tomorrow in my office." would override the default suggested by generic knowledge. Our use of commentary to guide a debugging process derives from research by Sussman [73] and Goldstein [74].

Self-knowledge, in the form of machine understandable annotations, also facilitates the system's ability to explain its inferences to a user. This is critical if the user is to become confident in the system's capabilities.

(2) Abstraction. The second property list generalization is to allow information to be inherited between concepts. In essence, this is an implementation of Quillian's SUPERCONCEPT pointer, but between property lists rather than nodes in a semantic net. For example, details of the meeting between Bruce and Ira are inherited from a generic description of PA-MEETINGs. This description includes answers to such questions as where such meetings are typically held, when, why, who is involved, what prerequisites are required and what consequences result.

Since the answers to some of these questions is clearly applicable to a broader set of activities than meetings of the PA-GROUP, the information is distributed in a hierarchy of successively more general frames, thereby achieving both power and economy.

Each frame points to its generalization by means of its AKO slot. The process by which information in a generic frame is acquired by a specialised instance of that frame is called inheritance. MEETING37, for example, inheriU information from its generalisation, the PA-MEETINC frame.

```
PA-MEETING
   AKO      SVALUE     MEETIN6
   WHY      SVAIUE     PA-PROJECT
   WHERE    SOEFAULT   AI-PLAYROOM
   WHEN     SOEFAULT   ((ON FRIDAY) (FOR 1 HOUR))
   WHO      SOEFAULT   IRA      [ROLE:  MANAGER]
                       BRUCE    [ROLE:  FRL]
                       CANOY    [ROLE:  SEMANTICS]
                       MITCH    [ROLE:  SYNTAX]
```

(3) Defaults. The third generalisation that naturally accompanies a hierarchy of frames is default information, as the slots of a generic activity typically supply default answers to the common questions asked about such events. The utility of such default information was a major insight of Minsky's original frames research. Their use »s prevalent throughout the NUDGE database, and give the scheduler much of its power.

For example, PA-MEETING supplies the information that such activities typically involve four people, occur on Fridays in the AI Lab Playroom and last one hour. The IDEFAULT atom distinguishes defaults from values. We shall refer to the different kinds of information associated with a slot as its facets. The role commentary information associated with the participants of PA-MEETINGs is used by the PERSON-SWAPPING scheduling strategy of the BARGAIN program. (Managers are optimistically defined to know all of the team members* roles.)

In forming a frame gestalt, the defaults of superior frames are used unless they are overridden by information from a more reliable source, such as the explicit constraints of the original request. Thus, the WHERE default would apply to the MEKTING37 gestalt. The WHEN default, however, is overridden by the explicit request in SI that the meeting occur on Tuesday.

Defaults arc also useful to the natural language understanding system by supplying expectations that aid the parser and semantics m processing ambiguity and ellipsis. However, we do not develop that application here.

W Constraints. A knowledge representation language must accommodate descriptions of properties if it is to support the recognition of new instances of a generic concept. FRL-0 allows constraints to be attached to a slot by means of facets for requirements and preferences. These constraints are illustrated in the MEETINC frame, which is the immediate generalization of PA-MEETING.

```
MEETING
   AKO      $VALUE      ACTIVITY
   WHO      SREQUIRE    (EXISTS ?WHO (HAS-ROLE 'CHAIRMAN))
   WHEN     SPREFER     (NOT (> (DURATION ?WHEN) (HOUR 1.5)))
```

Requirements arc predicates which must be true of the values in a slot. Preferences can be relaxed yet leave a valid slot. The IREQUIRE facet of MEETING stipulates that a chairman he present at all meetings. The IPREFER facet states that meetings should not last longer than 90 minutes.

It is possible to collapse defaults, preferences and requirements into a single CONSTRAINT facet. However, we have found it convenient to preserve the distinction, given the use of these facets by a scheduler. Requirements cannot be relaxed. Preferences, however, can be negotiated. Defaults are preferences that offer specific alternatives, rather than acting as predicates on a set.

KRL's development of "perspectives" in which a frame is described from a particular viewpoint is a more elaborate kind of constraint than we typically employ. While a frame pattern matcher can, in essence, specify a perspective, we have not generally used such a device for the narrowly defined world of office scheduling. Whether an extended description mechanism will be needed for more complex applications remains to be seen. Our current plans are to see where FRL-0 fails before we incorporate more powerful, but more complex techniques.

(5) Indirection. Not all of the relevant description of MEETING37 is contained in abstractions of the meeting ronrrpi. Frames in orthogonal hierarchies also supply constraints. For example, activities involve agents, and the frames for these agents have relevant information. The frame system has separate hierarchies for activities and people, interconnected by indirection. The IRA frame exemplifies this.

```
IRA
  AKO                $VALUE     PERSON
  (MEETING WHEN)     $PREFER    (DURING AFTERNOON)
                                (ON FRIDAY)
  (MEETING WHERE)    $DEFAULT   NE43-819
                     $PREFER    (IN 545-TECH-SQUARE)
  (PA-MEETING WHEN)  $DEFAULT   (AT 3 PM)
                                (AT 10 AM)
                     $PREFER    (ON TUESDAY)
```

The first atomic slot identifies Ira as a person. The remaining non-atomic slots (ie, slots with compound names) provide information regarding various activities with which IRA is typically involved. For example, in general IRA prefers MEETINGS on Friday afternoons in his office. This information is not stored directly in the activity frame since it not generically true for the activity, but only applicable when IRA is involved. IRA's default of NE43-819 as the place to hold meetings supplies the value of the WHERE slot of MEETING37.

The indirect information appears in the frame gestalt if both the agent and activity frames arc triggered. For SI, triggering IRA and MEETING together resulted in the frame gestalt supplying the missing information regarding the location of the meeting. Thus, indirection provides links between different hierarchies, extending the frame system to include a network of contingent facts.

Indirection is a simplified kind of mapping between concepts. FRL differs from MERLIN [Moore & Newell 73] (in whieh general mapping is allowed) by providing a restricted but more structured environment. Mapping occurs, in essence, only between agent ami activity frames through indirection and between concept and superconcept frames through inheritance.

(6) Procedural attachment. A knowledge representation must allow procedural as well as declarative knowledge. Procedural attachment provides this capability in FRL-0.

There are typically three kinds of procedural attachment, ami all are provided in FRL-0. These are if-added, if-ncedcd, and if-rcmow-d methods. A difference from traditional AI languages is that three procedures are attached to the slots of a frame rather than to assertions of an arbitrary form. FRL-0 is thus a more structured environment than languages like PLANNER and COWIVKH [McDermott & Sussman 72]. Providing a mechanism for triggering arbitrary procedures by adding a value to a slot supports the fundamental operation of FRL-0 which is instantiation; that is, creating an instance of a frame and filling in values for its slots.

For example, when the time of MEETINC37 is arranged (a value of the WHEN slot is assigned) its name is entered in a calendar for easy reference. The method for doing this is supplied by the WHEN slot of the ACTIVITY frame.

```
ACTIVITY
  AKO       $VALUE      THING
  WHO       $REQUIRE    (AKO PERSON)
            $IF-NEEDED  (ASK)       [TYPE: REQUEST]
                        (USE TOPIC) [TYPE: DEDUCE]
  WHEN      $IF-ADDED   (ADD-TO-CALENDAR)
            $REQUIRE    (AKO INTERVAL)
```

ACTIVITY also illustrates if-ncedcd methods. These methods •How access to arbitrary procedures for supplying values. For example, examine the WHO slot of ACTIVITY. There are two if-needed methods there. The first, (ASK), is a function that requests the value from the user. Its purpose is indicated by the comment TYPE: REQUEST. The other method, (USE TOPIC), attempts to deduce the participants by accessing the WHO slot of the frame provided as the value of the TOPIC The comment on this method indicates that it is of TYPE: DEDUCE. The TYPE comments are used by the function controlling the overall instantiation process (the if-ncedcd method of INSTANCE in THING, which all frames inherit) Their function is to allow deductive methods to be used in preference to interactive requests if possible.

If-needed methods have widespread use. Defaults can be viewed as a special kind of if-ncedcd method, so useful and widespread that a special facet of a 6lot is devoted to it. Idiosyncratic forms of inheritance (using other than the AKO link) can be imbedded in an if-necded method for appropriate slots.

Attached procedures are also used to maintain the integrity of the database. For example, AKO and INSTANCE are slots that provide a two-way link between a frame and its generalisation. This linkage is maintained by a pair of if-added and if-removed methods. The procedures which implement this mechanism appear in THING, the most general frame in NUDGE.

```
THING
  AKO        $IF-ADDED     (ADD-INSTANCE)
             $IF-REMOVED   (REMOVE-INSTANCE)
  INSTANCE   $IF-NEEDED    (INSTANTIATE-FRAME)
             $IF-ADDED     (ADD-AKO)
             $IF-REMOVED   (REMOVE-AKO)
```

Subtleties. We conclude our discussion of FRI.-O as a representation language with a consideration of first some of the subtleties involved in the use of these six techniques and then some of FRL-O's current limitations.

i. *There i* more than one kind of inheritance.*

Additive and restrictive inheritance arc two kinds of inheritanre strategics that correspond to two common forms of specialization. Additive inheritance is appropriate where specialization adds new non-contradictory facts to the more general concept. Restrictive inheritance is appropriate where specialisation overrides the information contained in the more general concept. Commentary is employed to inform the inheritance mechanism whether to stop or to continue up an AKO chain once the first datum is found.

2. *Method* can conflict.*

Procedural attachment can be troublesome. For example, care must be taken to avoid loops: a method in slot A may add a value to slot B that in turn adds a value to slot A. An endless loop results. We handle this by using comments to describe the source of information. It is up to the individual method to access this commentary.

Scheduling multiple methods associated with a single slot may be required, when the methods have an a implicit order. Currently, the frame system executes the methods in a fixed order. If more subtle ordering is required, the user must combine the methods into a single procedure, with this method responsible for performing the proper ordering.

3. The dittinction between value and requirement i not nhnrp.*

Requirements have been presented as predicates to filter out unwanted values. To the extent that NUDGE can reason directly from them, however, they can be used in place of values. For example, an if-needed procedure can use the requirement to select the generic category when instantiating a new frame to fill a slot.

4. *A frame it more than the turn of* iff *parts.*

In our initial conception of a frame system, we did not provide for a SELF slot to contain idiosyncratic information about the frame itself. Our hypothesis was that all of the information in the frame could be represented in the individual slots. However, the need arose

to represent global information about the frame, not local to any slot. Two examples are knowledge of how to print the frame in English and knowledge of the preferred order in which to instantiate the solts of the frame. For these reasons, a SELF slot was introduced with a set of facets appropriate to the various classes of global information it contains. At present these include a SDISCIJSS facet which contains a procedure for describing the frame in prose, and an SORDER facet which contains a procedure that orders the slots at the time of instantiation.

5. *Inheritance of valuet and default* can conflict.*

A given slot may have both a default and a value in it* generalization frame. Which should dominate? Currently, the frame system treats values as more important than defaults, so all of the values of superior frames are checked before a default is accepted. However, this may not be appropriate in all cases. When it is not, the user of the frame system can obtain complete control by asking for the full heritage of the slot, i.e. all of the facets for the slot in the current frame and its superiors. The user can then select the desired datum.

Limitations. The following are limitations of version 0 of FRL.

1. No provision is made for multiple worlds in the frame system, although the BARGAIN program can consider alternative calendars.
2. Procedures cannot be attached to arbitrary forms, but only to values. For example, there is no way to have a procedure irigger when a new requirement is added.
3. Arbitrary data structures cannot be asserted. Only information of the form "frame, slot, facet, datum, comment" can be placed in a frame.
4. Hash coding is not currently used. Hence, it is expensive to find all the frames with a slot of a given name and even more expensive to find all the frames in which a given value appear*
5. Comments cannot be associated with arbitrary parts of a frame, but only cither with individual data or the SELF slot of the frame. There is no way to associate a comment with a sublet of the slots.
6. Mapping between frames is restricted to matching slots. A generalized mapping function, as in MERLIN [73] wherein one slot can be mapped to another, is not allowed.

Eventually, we may find that the more sophisticated capabilities of CONNIVER, MERLIN, KRL, or OWL arc needed. But the rapid rise and fall of PLANNER argues for caution in the introduction of complex new techniques. We plan to introduce additional techniques only as the simple generalized property list scheme of FRL-0 proves inadequate. At present, FRL is adequate to represent the knowledge described in the next section which comprises the basis of us scheduling expertise.

5. EPISTEMOLOGY OF SCHEDULING

NUDCE's ability to expand informal scheduling requests arises from the recognition of the request as an instance of various generic frames. This section provides snapshots of this generic knowledge, which includes frame hierarchies for activities, people, time, and plans.

(1) Activities. Most activities known to NUDGE involve information transfer. They span a set of events central to the scheduling domain and interesting in the subtleties they introduce for successfully debugging conflicting schedules. The "activity" subtree of the frame hierarchy shown earlier illustrates these information transfer activities and their disposition along generalisation chains.

The use of concept hierarchies is an alternative to the unstructured set of primitives proposed by Schank [73]. We find this approach powerful in that it facilitates the recognition of new objects and allows fine distinctions to be readily made. To illustrate the first point, SI could have been treated as referring to an instantiation of the MEETING frame, in the absence of recognizing a meeting between Bruce and Ira as a PA-MEETING. Later, if additional information allows this recognition, the AKO pointer of MEETING37 would simply be adjusted to point to PA-MEETING. Otherwise no change is needed.

The fine distinctions between information transfer activities represented in the activity hierarchy guides the time of scheduling, the preparations required, and the pattern of the consequences. A phone call need not be scheduled for a precise time while a formal meeting must. We find a separate frame useful, rather than representing phone and mail as different instruments to a single communication activity (as might be Schank's approach) because other information is clustered around the choice of means. A letter requires more preparation time than a phone call, implies a certain delay in communication, and leaves open whether a response will be received.

(2) People. Beyond the straightforward record of pertinent facts about a person -- their name, address, phone number, office -- lies the need to capture the alternate roles people play in different situations. Roles exists in their own abstraction tree. For scheduling purposes, the roles define an order of importance that dictates, in the case of conflicting defaults and preferences, the order in which they should be relaxed. Acquiring properties by virtue of playing a role is identical to inheriting information as a specialized instance of a frame; the AKO/INSTANCE links define the path along which this information flows. A particular feature of roles is that they are often transitory and conditional on the type of activity.

Originally, we maintained a strict hierarchy in FRL with each frame pointing to a single abstraction. Recently, we have allowed multiple AKO links. The motivation was that it appeared natural for a person to inherit from several roles. For example, in a given situation, Ira may be both a visitor and a professor. Insofar as the information inherited from multiple parents is non-conflicting, no difficulty arises from this bifurcation in the AKO path. If there is a conflict, it shows up in the frame gestalt with comments indicating the various sources of the conflicting information. It is up to the process using the gestalt to decide on a resolution.

For example, as a professor, Ira's preferences with respect to a meeting time would take precedence over a student. As a visitor to another university, they would not. The techniques for debugging schedules take account of this, treating the VISITOR role as overriding the PROFESSOR role.

People can be members of groups. A group has many of the same characteristics as a person insofar as it can appear in the WHO slot of an activity and may have its own "personal" facts: a name, an address, etc. The MEMBER and AFFILIATE slots record this dual relation in NUDGE.

(3) Time. In our earliest work on NUDGE, time was represented simply as points on a real-number line. This was adequate for the formal analysis made by the scheduler, but proved insufficient to represent the informal time specifications supplied by users. People's time specifications are generally incomplete and occasionally inconsistent. To handle these informal requests, we moved to a frame-based representation for time similar to the one described by Winograd [75].

Below is part of the generic frame for a moment in time:

MOMENT		
AKO	SVALUE	TIME
MINUTE		
HOUR	sIF-NEEDED	(ASK) [TYPE: REQUEST]
	$ IF-ADDED	(DAYTIME-EQUATION)
	SREQUIRE	(INTEGER-RANGE 0 23) [TYPE: SYNTAX]
		(DAYTIME-A6REEMENT)
DAY	SIF-NEEDED	(ASK) [TYPE: REQUEST]
	SIF-ADDED	(WEEKDAY-EQUATION)
	SREQUIRE	(INTEGER-RANGE 1 31) [TYPE: SYNTAX]
		(DAY-MONTH-AGREEMENT)
		(WEEKDAY-AGREEMENT)
	SDEFAULT	(CALENDAR-DAY (NOW))

WEEKDAY	SIF-NEEOEO	(ASK) [TYPE: REQUEST]
		(WEEKDAY-EQUATION) [TYPE: DEDUCE0]
	SREOUIRE	(WEEKDAY?) [TYPE: SYNTAX]
		(WEEKDAY-AGREEMENT) [TYPE: DEOUCEO]
DAYTIME	SIF-KEEDED	(ASK) [TYPE: REQUEST]
		(DAYTIME-EQUATION) [TYPE: DEDUCED]
	SREQUIRE	(DAYTIME?) [TYPE: SYNTAX]
		(DAYTIME-AGREEMENT) [TYPE: DEDUCED]
MONTH		"similar to day'
YEAR		"similar to day"

The MOMENT frame can represent an incomplete request by creatine; an instance with only a few of the slots instantiated. Thr attached procedures ~ WEEKDAY-EQUATION and DAYTIME-EQUATION — derive as many additional descriptors as possible.

A set of time predicates (BEFORE, DURING, AFTER, etc.) have been implemented that allow a user lo ask questions regarding his calendar. For example, using the natural language front end, the system can be asked: "Is Ira free on Monday, February 7?"

The predicates take instantiated time frames as input and perform their analysis on a "need to know" basis. That is, (BEFORE MI M2) will return T even if MI and M2 are incomplete, providing there is sufficient information to make the required judgment. For example, MI may specify a moment in January without saving precisely when and M2 a moment in February. In this case, the BEFORE question can be answered despite ignorance of the exact time involved. In this fashion, we go beyond Winograd's original discussion of frame-based time-representations in that he did not consider the issues raised by reasoning with incomplete time specifications. Of course, the nature of the incompleteness may be such that no answer is possible. In this case, the time predicates report that the frames are too incomplete for an answer.

The time predicates can also tolerate a certain degree of inconsistency. For example, suppose a user asks if a meeting is possible with Bruce on Tuesday, January 20, 1977. In fact, January 20 is Monday. But if the frame system knows that Bruce is on vacation all of January, it is more appropriate for it to reply: "I assume you mean Monday, January 20. Bruce will be on vacation then." rather than first asking for a clarification and then telling the user his request will fail.

Inconsistency is detected by if-added methods which, in the course of deriving values, observe that they have computed a slot value that conflicts with a user supplied value. A comment regarding the inconsistency is placed both at the slot level and at the frame level. For example, the MOMENT frame for the inconsistent time specification given above would be:

MOMENT12

WEEKDAY	SVALUE	TUESDAY	[SOURCE: USER]
		MONDAY	[SOURCE: DERIVEO]
SELF	SIOGICAt-STATE	INCONSISTENT	[SEE: WEEKDAY]

The time predicates report the inconsistency, and then attempt to answer the original question by reducing the inconsistency to an incompleteness. This is done by referencing an ordering on the slots corresponding to their relative reliability. Year dominates Month which dominates Day which dominates Weekday. The inferior slot values are ignored until the inconsistency is removed. The question is then answered using the resulting incomplete frame. At best, the time predicates have guessed correctly and the user has learned the answer to his question. At worst, he is alerted to the consistency and responds with a repetition of his original request with the inconsistency removed.

(4) Plans. It is uncommon to schedule isolated events. Typically, clusters of related activities are organized around a theme; a series of meetings to discuss the state of a group's research, work bv several people on a joint paper. These clusters embody two kinds of interrelations in addition to the AKO/INSTANCE bond already discussed. First, there is a logical ordering of activities, which in the realms of scheduling nearly always entails a chronological ordering to be enforced. Second, activities can be broken down into sub-activities; these represent sub-goals with respect to the purpose*; of the activity itself. Opposing PREREQUISITE/POSTREQUISITK links connect frames possessing a logical ordering. The values of a PREREQUISITE slot name frames which must immediately precede it. Analogous SUB/SUPER links connect frames subordinate one to another. A plan is a group of frames connected by these pointers. These implement a procedural net in the style of Saccrdoti [75], which served to unify the ideas of ABSTRIPS and NOAH as schemes for representing planning knowledge.

An example of using a plan is illustrated in the scenario. NUDGE's R2 response alludes to a PA Progress Report, whose frame contains the following planning links.

Interconnections describing its subgoals and the order in which thr> must be accomplished permit the creation of an instance mirroring this structure which satisfies the request. At R2 in the scenario, NUDGE makes a point of scheduling the preparation of a written progress report for Bruce which is clearly something to be accomplished before the newly scheduled meeting with Ira. The generic frame for PA-MEETING has a PREREQUISITE slot containing a requirement for this and an If-needed procedure to accomplish it.

PA-MEETING

PREREQUISITE	SREQUIRE	(AKO REPORT)
	IIF-NEEDED	(INSTANTIATE-AS-REQUIRED)

Frames and Knowledge. Frame systems have proved a eonvenient representation for knowledge that naturally falls into a taxonomy of successively more general categories. Individual frames are convenient for representing concepts that have multi-dimensional descriptions which may be potentially incomplete or inconsistent. However, the limits of frames as a representational scheme are not yet clearly understood. We plan extensions into different domains to understand these limitations.

6. BARGAINING BETWEEN GOALS

NUDGE translates an ill-defined, under-specified scheduling request into a complete specification, represented by the frame gestalt. This gcstalt becomes the input to a scheduling program, BARGAIN, that seeks the best time for the requested activity if the desired time is unavailable. Other traditional scheduling programs could be employed as the gestalt is a complete and formal request. We use BARGAIN since it improves upon traditional decision analysis programs by incorporating AI techniques to control the search process.

BARGAIN is power-based in the sense that its competence is predicated on efficient search. It engages in a best-first search, as controlled by a static evaluation function that measures (1) the number of violated preferences, (2) their respective utilities and (3) the number of remaining conflicts. BARGAIN was originally designed by Goldstein [75] and implemented in CONNIYER by F. Kern [75j

BARGAIN employs a set of 8 search operators which constitute debugging strategies for time conflicts. One set are "resource-drivon", i.e. they are experts on the physics of time and eliminate a conflict by altering the duration, interrupting, sharing or moving the event. The second set are "purpose-driven" and go outside the time domain to examine the topic of the meeting and alternative methods for accomplishing it An application of any one of these techniques produces a new calendar with the conflict resolved, and possibly new conflicts introduced. Each strategy has a cost associated with it. BARCAIN halts when it has found the best sequence of debugging

strategies that generate a conflict free calendar within various computational constraints.

The applicability of a search operator — especially the purposc-driven kind — can depend on the overall knowledge context. Hence, the power-based approach benefits from some hetcrarchy with the preceding knowledge-based phase. A given search operator may ask the frame system whether it applies. For example, a strategy to change participants must rely on knowledge of available candidates and the goals of the activity for suggesting suitable replacements.

The relative preference for different scheduling strategies is controlled by specific assertions in the HOW slot, which contains the names of strategies applicable to the activity in which it appears. For example, PA meetings can be postponed as a last resort and only reluctantly interrupted; as can be seen in this excerpt from the PA-MEETING frame.

```
PA-MEETING
    HOW    SDEFAULT  POSTPONE  [UTILITY: HIGH] [MAXIMUM:
                     INTERRUPT [UTILITY: MEDIUM]
```

n

Our approach to power-based scheduling parallels the conservative development of the knowledge-based component in thai the well-understood techniques of decision analysis have been augmented only as required. This augmentation has involved applying AI search techniques to improve the efficiency with which a best compromise is found.

7. CONCLUSIONS

(1) FRL-0 provides a simple, but powerful representation technology. Frames are generalised property list, sharing much of the simplicity of traditional attribute/value representation schemes. Yet the addition of a few capabilities -- comments, constraints defaults, procedural attachment, inheritance -- provides a great deal more power and economy in the representation. KRL and OWL are more ambitious and more complex, and may well apply to contexts in which FRL-0 proves insufficient. But this remains to be seen. We plan further experiments with FRL-0 to identify its strengths *amd* weaknesses.

(2) Whether FRL-0 or some other AI language is employed, our experience with the nature of informal requests, the issues raised by multiple inheritance paths, the interaction between a searrh program and a rich knowledge base, and the epistemology of information transfer activities, time, place and people will surely be relevant to the design of knowledge-based AI programs.

(3) FRL is an experiment in the utility of the frames. Our experience is that clustering the answers to common questions about the frame structure for a concept provides a useful representation paradigm. The frame gestalt derived from this frame structure supplies missing information similar to that generated by competent human schedulers to handle informal requests.

(4) The entire system can be viewed from another perspective. Since a frame's behavior is actually governed largely by the attached procedures, it can be viewed as an accessing scheme to the underlying procedural knowledge. Thus, frames implement goal-directed invocation (as in PLANNER), but with pattern matching replaced by the more general process of frame instantiation.

(5) NUDGE is a step towards an AI system with common sense. By generating a complete frame gestalt, the system minimr/.es the possibility of overlooking obvious alternatives. Defaults, preferences and requirements allow much to remain unsaid. A tolerance for minor inconsistencies is a benchmark of a robust knowledge system.

(6) NUDGE and BARGAIN are steps towards the creation of an automated office. Given the enormous information flow in a modern office, this is an important area for applied AI research.

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