PLAN RECOGNITION
USING A HYPOTHESIZE AND REVISE PARADIGM: An Example

Charles F. Schmidt and N.S. Sridharan

Departments of Psychology and Computer Science
Rutgers University, New Brunswick, NJ 08903

A great deal of research has focused on the problem of how to generate a plan that satifies a given goal [2]. The problem of plan recognition is to take as input the sequence of actions performed by an actor and to identify the goal pursued by the actor and also to organize the action sequence in terms of a plan structure. This plan structure explicitly describes the goal-subgoal relations among its component units. Our concern with plan recognition has arisen from our research [4,5,6,7] in the development of a theory of how persons understand the observed actions of others. A variety of experiments [7] have demonstrated that the summary as well as the recall protocols of an action sequence can be predicted if it is assumed that the observer is actively reconstructing from the observations the plan or plans that the actor is executing.

The psychological theory of plan recognition, BELIEVER, consists of a set of knowledge structures and processes defined within the AIMDS system (11]. The specification of the knowledge sources for the BELIEVER model arose from considerations of the properties of the problem domain and do not rest on any particular psychological assumptions about properties of the human information processing system. For example, the observed sequence of actions that serve as input to a plan recognition system do not provide information that identifies which of the set of outcomes associated wxth an action sequence corresponds to the goal or goals of the actor. In fact, the actor's plan may have failed or been abandoned or interrupted in which case the goal outcome would not be represented at all in the action sequence. If cases such as these are to be recognized, then a plan recognition process must be capable of counterfactual reasoning that shows how a hypothesized goal could have been achieved had some aspect of the physical world been otherwise. Further, actions are linearly ordered and unbounded in time. Plans are bounded, hierarchical, and nonlinearly ordered based on the logical connection between an enduring outcome of one action and the precondition of some subsequent action. Further, a plan is well-formed with reference to the planner's beliefs about the world rather than with respect to the actual state of the world. For these and similar reasons, we have argued that any process of plan recognition must use meta-knowledge about plans and the psychological constraints which define a well-formed plan. Knowledge of only the physical constraints on action does not provide sufficient information to recognize plans [8].

In this paper we present, by means of an example, those aspects of a plan recognition process that have been implemented in BELIEVER. The properties of this process have been motivated primarily by our desire to incorporate within this process certain psychological assumptions about characteristics of the human plan recognition process. The two major assumptions are that the human process is: (1) a general non-specialized process; and (2) is based on a hypothesize and revise strategy. The remainder of this paper is concerned with conveying the meaning of these labels. However, it will be useful to first explicate these ideas in an informal way.

Because of interest in application or for methodological reasons, much of the recent work in AI has been concerned wxth the representation of expert knowledge within a relatively narrow domain. Chess, restaurants, flush toilets and particular electronic circuits are well-known examples of this approach. An expert's knowledge is, by definition, highly specialized and customized to a particular domain. This has led researchers to encode this knowledge in similarly specialized and customized forms which are often generically referred to as scripts [3). The use of script-like knowledge is an important aspect of the human information processing capability.

However, very few of us are expert in everything and none of us are born that way. Specialized, customized knowledge must be acquired using quite general and schematic knowledge [9], Accordingly, the system we have designed and implemented uses multiple communicating knowledge sources to customize and specialize the general knowledge about acts and plans to specific observational input.

The knowledge needed by a process of plan recognition has been decomposed into three major knowledge sources. These knowledge sources together with some of the major lines of communication between them arc shown in Figure 1. In this figure the knowledge sources are referred to as the Person, Plan, and World Domains. Each knowledge domain defines the concepts, relations, and logical dependencies oetween concepts that govern the representation of particular instances of objects within that domain. The boxes labeled Person Model (PM), Expectation Structure (EG), and World Model (WM) graphically represent the different contexts within which particular assertions are maintained. The WM consists of the assertions that the system believes to be true of the current physical situation. This set of assertions is constantly changing and being updated as a new description of an observed action is input to the system. In Figure 1 the beginning of such an input stream is shown and referred to as Input Action Sequence. The PM contains assertions about what the sytem believes the actor believes, wants, and likes, etc.

The ES represents the plan structure that the system currently believes the actor is executing. This attribution of a plan to the actor requires that: (1) the incoming act sequence match the partial order of the plan structure; (2) the actor have certain beliefs and wants (the Person Model Requirements); and (3) that certain assertions about the physical world be true (the World Model Requirements). We will show that by defining the ES appropriately and using this knowledge decomposition, the ES can be used by the plan recognition process to compute the PM and WM requirements. Further, by matching the plan units of the ES to the incoming actions the schema variables of the ES can be bound and used to further customize and specialize the ES to the observatinal context. In this way the basic process of plan recognition is reduced to various types of matching Drocesses.

The requirements derived from the current ES are logical requirements that must be met if the actions are to be interpreted using that particular ES. Consequently, a mismatch signals the violation of an expectation and indicates that the ES must be revised. After presenting the operatin of this basic matching orocess we will show how the results of this mismatch can be used to trigger and guide a strategy of ES revision. This hypothesize and revise strategy is congruent with our goal of using knowledge stated at a general level in plan recognition. The revision rules are anchored on classes of mismatches between ES requirements and the observations. Consequently, we have been able to avoid anchoring these revision rules to particular ES structures.

This hypothesize and revise strategy is further motivated by our assumption that human observers do not use a strategy of heuristic search to explore a large space of possible interpretations of a sequence of actions. Rather the observer is assumed to explore only a few, usually only one, hypotheses at a time. This hypothesis is adapted to the realities of the observations by a process of refinement and revision. This strategy does not insure correctness nor completeness. However, this is not our goal. Rather, we hope that this strategy will allow us to predict the conditions under which the human observer will succeed or fail in the task of plan recognition.

The Process of Interpretation

The process we define below takes a sequence of act descriptions and by re-representmg them as plan units, produces a plan structure that is supported by and is consistent with the world model and the person model.

Hypothesize and Revise

The three main steps of the process are: (1) [SETUPES] An appropriate ES is set up and this ES is customized for use in the current context. The ES may be simply summoned from memory, constructed by a plan generator from knowing the goal of the planner, or may be postdictively assembled unit by unit from the incoming observations. (2) [ACTINPUT] The input act description is used to update the world mode1 and is then matched against an expected plan unit in the ES. A proper match produces bindings for the variables in the E5 thus making the further expectations more specific. The details of this expectation guided matching process are reported in [10]. (3) [REVISE] Conflicts that arise between the expectations and observations trigger rules for hypothesis revIsion.

The structure of ES schemata

The ES consists of a number of plan units with specified "morderto" relations among them which constitutes a partial order. The starting plan units and the final unit are identified. The goal of the final unit is also the goal assigned to the ES. The set of triples [PI S *92]* called the "inordertoprops" is formed from those plans PI and P2 such that the goal proposition S of PI is among the preconditions of P2. For this it should also be the case that no other plan unit occuring in between P1 and P2 undoes the proposition S. The "modelrequirements" are pairs [S P] with propositions S, which are opportunities for a plan unit P in the ES, such that there is no other plan 0 set up to accomplish S. Each such proposition is required to be satisfied in the initial world model.

Monitoring these propositions aids the interpretation process in developing further expectations and j.n the recognition of conflicts and failed plans. As input actions are matched against expected plan units, they are shiftea into the Hypothesis set H, to designate that they are supported by observations and are no longer "expected" to occur. This distinction between 11 and E is represented graphically in Figure 1 where those units in H are linked to input actions that have been taken up by the system. As a plan unit is shifted from the set E to the set H, other members of E are considered to be "next expected" plan units. A next expected member has its modelrequirements checked against the world model. If such a modelrequirement proposition is true in the person model and false in the world model, then this plan unit is flagged as "expected to fail". If a modelrequirement proposition is false in both the person model and world model, then a plan to accomplish the proposition is generated and inserted into the ES. If the modelrequirements are satisfied in both these models, the inordertoprops are checked. If the proposition mentioned in an inordertoprops was in fact accomolished by an earlier plan but is no longer true then the assumption of "inorderto" between the two plans is not supportable.

The diagnosis and analysis of the currently attributed plan is performed by a decision tree [8] using information maintained in a structure called INTERPRETATION . Each terminal node of this decision tree calls for a corresponding revision rule. The revision rules perform actions that could range from accommodating the next observed action as being optional, or including it as part of the present plan, or generating and inserting plans to accomplish failed modelrequirements, or claiming that the planner failed in successfully carrying out his plan, or as drastic as abandoning the current assumptions and developing a different plan structure using whatever information can be meaningfully carried over from the present plan structure. We illustrate below the actions of the three components of the hypothesize-revise procedure.

Example of DasIc Match Process and Conflict Resolution

An example expectation structure is presented below using KRL-like [1] conventions. The notation [refer: V) introduces a variable name and all subsequent uses of the variable designate the same entity. This ES is constructed by SETUPES from eight plan units that use variables to make references to objects and locations in the world model. The eight plan units form a connected partially ordered structure shown in Figure 1.

```
(a EXPECTATION STRUCTURE
Assernble/and/Eat with
[Varlables
   (LIST A LI L2 L3 01 02 03 04)]
(agent (a PERSON [refer: A])])
```

The actions embedded within the ES are listed below.

```
DESCRIPTION of Assemble/and/Eat
Expectation Structure:
 (a WALK with
    [toloc (a LOCATION [refer: LI])])
 (a TAKE with
    [object (a OBJECT [refer: 01]
             with [loc LI]
             which IsEdible)]
    [inordertoof (the last WALK)])
 (a CARRY with
```