

# The Use of Knowledge Preconditions in Language Processing\*

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## Abstract

If an agent does not possess the knowledge needed to perform an action, it may privately plan to obtain the required information on its own, or it may involve another agent in the planning process by engaging it in a dialogue. In this paper, we show how the requirements of knowledge preconditions can be used to account for information-seeking subdialogues in discourse. We first present an axiomatization of knowledge preconditions for the SharedPlan model of collaborative activity [Grosz and Kraus, 1993], and then provide an analysis of information-seeking subdialogues within a general framework for discourse processing. In this framework, SharedPlans and relationships among them are used to model the intentional component of Grosz and Sidner's [1986] theory of discourse structure.

## 1 Introduction

For an agent<sup>1</sup> to be able to perform an action, it must satisfy both the physical and knowledge preconditions of that action [Moore, 1985, Morgenstern, 1987]. For example, for an agent to pick up a particular tower of blocks, it must (1) know how to pick up towers in general, (2) be able to identify the tower in question, and (3) have satisfied the (physical) preconditions or constraints associated with picking up towers (e.g., it must have a free hand). These conditions must hold whether the agent is planning an action on its own or is involved in a collaborative planning effort with other agents.

In this paper, we provide an axiomatization of knowledge preconditions for the SharedPlan model of collaborative activity [Grosz and Sidner, 1990, Lochbaum *et al.* 1990, Grosz and Kraus, 1993]. This model draws upon past work [Moore, 1985, Morgenstern, 1987], but

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<sup>1</sup>Unless otherwise indicated, we will use the term "agent" to refer to both individual agents and sets of agents.

adapts it to the collaborative situation. We briefly describe the SharedPlan framework in Section 2, and then, in Section 3, present our axiomatization of knowledge preconditions. In Section 4, we demonstrate the use of knowledge preconditions in accounting for information-seeking subdialogues, such as those in Figure 1. We then compare our approach to the alternative accounts [Litman and Allen, 1987, Lambert and Carberry, 1991, Ramshaw, 1991].

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- (1) E First you have to remove the flywheel!
  - (2) A How do I remove the flywheel?
  - (3) E First, loosen the two allen head setscrews holding it to the shaft, then pull it off.
  - (4) A OK
  - (5) I can only find one screw. Where's the other one?
  - (6) E On the hub of the flywheel.

Figure 1 Information-Seeking Subdialogues [Grosz 1974]

## 2 SharedPlans

The SharedPlan formalism is a mental-state model of collaborative plans with roots in Pollack's [1990] work on single-agent plans. For a group of agents  $GR$  to have a *full SharedPlan* (FSP) for an act  $a_i$ , they must satisfy the requirements given in Figure 2. When the agents have satisfied only a subset of these requirements, they are said to have a *partial SharedPlan* (PSP).<sup>2</sup> The bracketed terms in Figure 2 indicate the operators used by Grosz and Kraus [1993] to formalize each requirement.

Requirement (1) in Figure 2 refers to the agents' *recipe* [Pollack, 1990] for  $a$ . Recipes are modeled in Grosz and Kraus's definitions as sets of constituent acts and constraints. To perform an act  $a$ , an agent must perform each constituent act in  $a$ 's recipe according to the constraints of that recipe. Actions themselves may be further decomposed into act-types and parameters. We will represent an action  $a$  as a term of the form  $a(p_1, \dots, p_n)$ .

This description of a PSP is only a rough, though useful, approximation to the formal definition given by Grosz and Kraus [1993].

For a group of agents  $GR$  to have an FSP for  $\alpha$

- 1  $GR$  must have mutual belief of a recipe for  $\alpha$
- 2 For each single-agent constituent act of the recipe there must be an agent  $G_\beta \in GR$ , such that
  - (a)  $G_\beta$  intends to perform  $\beta$ , [Int To]
  - (b)  $G_\beta$  believes that it can perform  $\beta$ , [BCBA]
  - (c)  $G_\beta$  has a full individual plan for  $\beta$  [FIP]
  - (d) The group  $GR$  has mutual belief of (2a) (2c)
  - (e) Each member of  $GR$  intends that  $G_\beta$  succeed [Int Tb]
- 3 For each multi agent constituent act of the recipe, there must be a subgroup of agents  $GR_\beta \subseteq GR$  such that
  - (a)  $GR_\beta$ , mutually believe that they can perform  $\beta$ , [MBCBAG]
  - (b)  $GR_\beta$  has a full SharedPlan for  $\beta$  [FSP]
  - (c) The group  $GR$  has mutual belief of (3a) (3b)
  - (d) Each member of  $GR$  intends that  $GR_\beta$ , succeed [Int Tb]

Figure 2 FSP Requirements

where  $\bar{\alpha}$  represents the act-type of the action and the  $p_i$  its parameters

### 3 Knowledge Preconditions

Grosz and Kraus [1993] use the operators BCBA (read "believes can bring about") and MBCBAG (read "mutually believe can bring about group") to formalize respectively requirements (2b) and (3a) in Figure 2. Although these operators are intended to specify the conditions under which an agent is able to perform an action, their definitions explicitly require only that an agent satisfy the physical preconditions or constraints associated with an action to be able to perform it. Because an agent is not truly capable of performing an act unless it possesses the appropriate knowledge, the definitions of BCBA and MBCBAG must be augmented with an axiomatization of knowledge preconditions. The following observations made by Morgenstern [1987], but recast in our terminology, must be represented in such an axiomatization

- 1 Agents need to know recipes for the acts they perform
- 2 All agents have some primitive acts in their repertoire
- 3 Agents must be able to identify the parameters of the acts they perform
- 4 Agents may know only some descriptions of an act
- 5 Agents know that the knowledge necessary for complex acts derives from that necessary for their component acts

Our axiomatization of knowledge preconditions is based on Morgenstern's observations, but adapted to the requirements of individual and shared mental-state plans.<sup>3</sup> We use the predicates *has recipe* and *id params*

<sup>3</sup>A comparison of our formalization with those of Morgenstern [1987] and Moore [1985] can be found elsewhere [Lochbaum, 1994]

to represent explicitly observations (1) and (3) above. The remaining observations are implicitly represented by the way in which these two knowledge precondition relations are defined. Observation (2) is modeled as the base case of *has recipe*, and observation (5) is modeled by the use of *has recipe* within the recursive plan definitions.

Observation (4) requires that the knowledge precondition relations be intensional, rather than extensional within their scope it should not be possible to freely substitute one representation of an action for another. We thus define *has recipe* and *id params* to hold of action descriptions, rather than actions. Action descriptions are intensional objects, one action description can be substituted for another only if the descriptions are the same. For example, although 555-1234 and *phone-number(speech-lab)* may be extensionally equivalent, the descriptions "555-1234" and *phone-number(speech-lab)*<sup>4</sup> are not. By convention, we will omit the corner quote notation in what follows and simply take the appropriate arguments of the predicates to represent action descriptions rather than actions.

Although Morgenstern's observations are most naturally expressed informally in terms of knowledge, we formalize them using belief to allow for the possibility of an agent's being incorrect. Although it is true that an agent cannot successfully act unless its beliefs about recipes and parameters are correct, having to *know* the recipes and parameters is too strong a requirement for collaborating agents [Lochbaum 1994].

#### 3.1 Determining Recipes *has recipe*

For an agent to be able to perform an act  $\alpha$ , it must know *how* to perform  $\alpha$ , i.e., it must have a recipe for the act. The relation *has recipe*( $G, \alpha, R, T$ ) is used to represent that agent  $G$  has a recipe  $R$  for an act  $\alpha$  at time  $T$ . It is formalized as follows:

$$\begin{aligned}
 \text{has recipe}(G, \alpha, R, T) \Leftrightarrow & \\
 (1) \quad & [\text{basic level}(\alpha) \wedge \\
 & \quad \text{BEL}(G, \text{basic level}(\alpha), T) \wedge R = R_{\text{Empty}}] \vee \\
 (2) \quad & [\neg \text{basic level}(\alpha) \wedge \\
 (2a) \quad & R = \{\beta_1, \rho_1\} \wedge \\
 (2a1) \quad & \{[|G| = 1 \wedge \text{BEL}(G, R \in \text{Recipes}(\alpha), T)]\} \vee \\
 (2a2) \quad & \{[|G| > 1 \wedge \text{MB}(G, R \in \text{Recipes}(\alpha), T)]\}]
 \end{aligned}$$

Clause (1) of the definition models Morgenstern's second observation, namely that agents do not need a recipe to perform a *basic level* action, i.e., one executable at will [Pollack 1990].<sup>4</sup> For non-basic-level actions (Clause (2)), the agent of  $\alpha$  (either a single agent (2a1) or a group of agents (2a2)) must believe that some set of acts,  $\beta_i$ , and constraints,  $\rho_j$ , constitute a recipe for  $\alpha$ .

#### 3.2 Identifying Parameters *id params*

An agent must also be able to identify the parameters of an act  $\alpha$  to be able to perform it. For example, if an agent is told "remove the flywheel," as in the dialogue of Figure 1, the agent must be able to identify the flywheel in question. The relation *id params*( $G, \alpha, T$ ) is used to represent that agent  $G$  can identify the parameters of act  $\alpha$  at time  $T$ . If  $\alpha$  is of the form  $\bar{\alpha}(p_1, \dots, p_n)$ , then *id params*( $G, \alpha, T$ ) is true if  $G$  can identify each of the

<sup>4</sup>Basic level actions are by their nature single-agent actions.

$P_1$  To do so,  $G$  must have a description of each  $p_i$ , that is suitable for  $a$ . The relation *id params* is defined as follows

$$\text{id params}(G, \bar{\alpha}(p_1, \dots, p_n), T) \Leftrightarrow (\forall i 1 \leq i \leq n) \text{ has sat descr}(G, p_i, \mathcal{F}(\bar{\alpha}, p_i), T)$$

The ability to identify an object is highly context dependent. For example, as Appelt points out [1985, pg 200], "the description that one must know to carry out a plan requiring the identification of 'John's residence' may be quite different depending on whether one is going to visit him, or mail him a letter." The function  $F$  in the above definition is an oracle function intended to model the context-dependent nature of parameter identification. This function returns a suitable *identification constraint* [Appelt and Kronfeld 1987] for a parameter  $p$ , in the context of an act-type  $a$ . For example, in the case of sending a letter to John's residence, the constraint produced by the oracle function would be that John's residence be described by a postal address.

The relation *has sat descr* $\{G, P, C, T\}$  holds of an agent  $G$ , a parameter description  $P$ , an identification constraint  $C$ , and a time  $T$ , if  $G$  has a suitable description, as determined by  $C$ , of the object described as  $P$  at time  $T$ . To formalize this relation, we utilize Kronfeld's [1986] notion of an individuating set. An agent's individuating set for an object is a maximal set of terms such that each term is believed by the agent to denote that object. For example, an agent's individuating set for John's residence might include its postal address as well as an identifying physical description such as "the only yellow house on Cherry Street." To model individuating sets, we introduce a function  $IS(G, P, T)$ , the function returns an agent  $G$ 's individuating set at time  $T$  for the object that  $G$  believes can be described as  $P$ . This function is based on similar elements of the formal language that Appelt and Kronfeld [1987] introduce as part of their theory of referring. The function returns a set that contains  $P$  as well as the other descriptions that  $G$  has for the object that it believes  $P$  denotes.

For an agent to suitably identify a parameter described as  $P$ , the agent must have a description,  $P'$ , of the parameter such that  $P'$  is of the appropriate sort. For example, for an agent to visit John's residence, it is not sufficient for the agent to believe that the description "John's residence" refers to the place where John lives. Rather, the agent needs another description of John's residence, one such as "the only yellow house on Cherry Street," that is appropriate for the purpose of visiting him. To model an agent's ability to identify a parameter (described as  $P$ ) for some purpose, we thus require that the agent have an individuating set for the parameter that contains a description  $P'$  such that  $P'$  satisfies the identification constraint that derives from the purpose. The definition of *has sat descr* is thus as follows<sup>5</sup>

$$\text{has sat descr}(G, P, C, T) \Leftrightarrow \{(|G| = 1 \wedge (\exists P') BEL(G, [P' \in IS(G, P, T) \wedge \text{ suff for id}(C, P')], T)) \vee$$

<sup>5</sup>A more precise account of what it means to be able to identify an object is beyond the scope of this paper, for further details, see the discussions by Hobba [1985], Appelt and Kronfeld [1985, 1986, 1987], and Morgenstern [1988]

$$\{(|G| > 1 \wedge (\exists P') MB(G, (\forall G, \in G)[P' \in IS(G, P, T) \wedge \text{ suff for id}(C, P')], T))\}$$

The predicate *suff for id* $(C, P')$  is true if the constraint  $C$  applies to the parameter description  $P'$ . The oracle function  $\mathcal{F}(\bar{\alpha}, p_i)$  in *id params* produces the appropriate identification constraint on  $p$ , given  $\bar{\alpha}$ .

#### 4 The Role of Knowledge Preconditions in Language Processing

We now show how the requirements of knowledge preconditions can be used in discourse processing. Our model of discourse processing is based on the theory of discourse structure proposed by Grosz and Sidner [1986]. According to their theory, discourse structure consists of three interrelated components: a linguistic structure, an attentional state, and an intentional structure. The linguistic structure consists of discourse segments<sup>6</sup> and an embedding relationship among them, the bold rule in Figure 1 indicates the linguistic structure of that discourse. Attentional state is an abstraction of the discourse participants' focus of attention, it serves as a record of those entities that are salient at any point in the discourse. Intentional structure is comprised of discourse segment purposes and their interrelationships, particularly that of dominance. A discourse segment purpose, or DSP, is a Gricean-like [1969] intention that leads to the initiation of a discourse segment. One DSP is dominated by another if the satisfaction of the first provides part of the satisfaction of the second.

Intentional structure plays a central role in discourse processing, an agent's comprehension of the utterances in a discourse relies on the recognition of this structure [Grosz and Sidner 1986]. Grosz and Sidner [1990] proposed SharedPlans to provide a basis for recognizing intentional structure. They argued that discourses are fundamentally collaborative, and hence that a model of *shared plans* provides a more appropriate basis for discourse processing than a model of single-agent plans. However, the connection between SharedPlans and intentional structure was never specified.

##### 4.1 SharedPlans as Intentional Structure

We have developed a model of discourse processing that provides that connection [Lochbaum, 1994]. Figure 3 illustrates the role of SharedPlans in modeling intentional structure. Each segment of a discourse has an associated SharedPlan. The purpose of the segment is taken to be intention that (Int Th [Grosz and Kraus, 1993]) the discourse participants form that plan. This intention is held by the agent who initiates the segment. In what follows, we will refer to that participant as the initiating conversational participant or ICP, the other participant is the OCP [Grosz and Sidner, 1986]. Dominance relationships between DSPs are modeled using *subsidiary* relationships between SharedPlans. One plan is subsidiary

<sup>6</sup>The term discourse segment is a generalization of the term subdialogue. Whereas the term discourse segment applies to all types of discourse, the term subdialogue is reserved for segments that occur within dialogues.



thus subsidiary to that in  $DSP_1$  by virtue of a knowledge precondition requirement of the latter plan

Figure 4 illustrates this analysis. Each box in the figure corresponds to a discourse segment and contains the SharedPlan used to model the segment's purpose. The SharedPlans are labeled so as to be co-indexed with the DSPs discussed above. The arrows indicate subsidiary relationships between SharedPlans, as explained by the text that adjoins them. When plan  $P_j$  is subsidiary to plan  $P_1$ ,  $DSP_j$  is dominated by  $DSP_1$ .

The information represented within each SharedPlan in Figure 4 is separated into two parts. Those beliefs and intentions that have been established at the time of the analysis are shown above the dotted line, while those that remain to be established, but that are used in determining subsidiary relationships, are shown below the line. The index in square brackets to the right of each constituent indicates the FSP requirement from which the constituent arose.

As indicated in Figure 5, the initiation of the second subdialogue in Figure 1 is explained similarly. This time however, it is the need to identify parameters of acts (requirement (2) above) that leads to the initiation of the subdialogue. In addition, the parameter in question is a parameter of an act in a subsidiary individual plan of the Apprentice's.

### 4.3 Discussion

In this paper, we have shown that information-seeking subdialogues may be explained on the basis of knowledge precondition requirements. Our account of such subdialogues fits within a general framework for discourse processing in which the purpose of a subdialogue is modeled using a SharedPlan and is related to the purposes of other subdialogues based on the requirements of the FSP definition. Elsewhere [Lochbaum, 1994], we show that correction and subtask subdialogues, among others, may also be accounted for in this manner.

In contrast, alternative plan-based accounts of dialogue understanding introduce multiple types of plans to account for the utterances in a discourse. For example, Litman and Allen [1987], propose the use of two types of plans to model clarification and correction subdialogues: *discourse plans* and *domain plans*. Domain plans represent knowledge about a task, while discourse plans represent conversational relationships between utterances and plans. Litman and Allen provide operators for the following discourse plans:

- INTRODUCE-PLAN: introduce a new plan for discussion
- CONTINUE-PLAN: execute the next action in a plan
- TRACK-PLAN: talk about the execution of an action
- MODIFY-PLAN: introduce a new plan by modifying a previous one
- CORRECT-PLAN: correct a plan
- IDENTIFY-PARAMETER: identify a parameter of an action in a plan

Under our approach, the recognition of discourse plans is unnecessary. The *fact* that a speaker is using an utterance to, for example, introduce a plan, or track a plan, or identify a parameter, need not be explicitly recognized for the purposes of utterance interpretation. Furthermore, we would argue that such facts are not intended to be recognized (cf. Grice [1969]). Rather, they simply fall out of recognizing the relationship of an utterance to the current discourse structure, i.e., the currently active SharedPlans. For example, INTRODUCE-PLAN corresponds to initiating a new discourse segment, CONTINUE- or TRACK-PLAN to contributing to the current segment, and IDENTIFY-PARAMETER to initiating a new segment to satisfy a *has sat descr* knowledge precondition requirement. Although the initiation of a new SharedPlan corresponds to the initiation of a new discourse segment under our approach, it is the SharedPlan that must be recognized and not a discourse plan that refers to that SharedPlan.

Lambert and Carberry [1991] have extended Litman and Allen's approach by introducing a third type of plan: *Problem-solving plans*, such as BUILD-PLAN and INSTANTIATE-VARS, are used to model the process by which agents construct domain plans. Under our approach, the need to explicitly recognize problem-solving plans is also avoided. The fact that an agent is building a plan or instantiating a variable is a byproduct of understanding an utterance by relating it to the current discourse structure. BUILD-PLAN corresponds to initiating a new discourse segment to satisfy a *has recipe* knowledge precondition requirement, while INSTANTIATE-VARS corresponds to initiating one to satisfy a *has eat descr* requirement. Unlike Lambert and Carberry's approach, however, and Litman and Allen's as well, our approach actually recognizes this structure. The other approaches are essentially utterance-to-utterance based and thus do not recognize discourse segments as separate units.

Ramshaw [1991] has added a different third type of plan, *exploration plans*, to Litman and Allen's two types. Exploration plans are intended to model the process by which agents explore courses of actions. Although we have not yet incorporated such reasoning into our model, we hypothesize that the exploration of plans can be modeled, without the introduction of a new plan type, by reasoning about an agent's *potential intentions* and the process by which they become full-fledged intentions [Grosz and Kraus, 1993, Bratman *et al.*, 1988].

These alternative approaches share an important property that distinguishes them from our approach: they take a *data-structure* view of plans, rather than a *mental phenomenon* view [Pollack, 1990]. Whereas data-structure plans are essentially "recipes-for-action," mental phenomenon plans are a "structured collection of beliefs and intentions" [Pollack, 1990, pg. 77].<sup>10</sup> Data-structure plans thus describe *what* an agent is doing with an utterance, but not *why* the agent is doing it. For ex-

<sup>10</sup>Although Lambert and Carberry [1991] adopt Pollack's [1990] terminology ID presenting their theory, their "plans" are not mental state plans in Pollack's sense.

ample, although the constraints of Litman and Allen's IDENTIFY-PARAMETER discourse plan force the plan to be related to another plan that involves the parameter to be identified, IDENTIFY-PARAMETER does not explain why this information is desired, it does not capture that agents need to know parameters *to be able to* perform acts involving them. It thus fails to model the essential knowledge precondition nature of identifying a parameter. Although it is possible to impose a mental phenomenon interpretation on top of a data-structure plan, doing so does not result in a mental phenomenon plan [Pollack, 1990]. Saying that GI *intends* to IDENTIFY a PARAMETER fails to address why GI intends to do so.

The need to explain an utterance is not unique to interpretation. Moore and Paris [1993] have shown that a similar need exists in generation. In particular, they have argued that RST-based text plans must be augmented with intentional structure. Otherwise, a system has no record of why it said what it did and is thus unable to respond effectively if a hearer does not understand or accept its utterances.

## 5 Conclusion

In this paper, we have presented an axiomatization of knowledge preconditions for the SharedPlan model of collaborative activity [Grosz and Kraus, 1993]. We have also shown how the requirements of knowledge preconditions can be used to account for information-seeking subdialogues in discourse. Our account of this phenomenon fits within a general framework for discourse processing in which SharedPlans and relationships among them are used to model the intentional component of Grosz and Sidner's [1986] theory of discourse structure. Unlike the alternative approaches, our approach recognizes and makes use of discourse structure. In addition, it does not require the introduction of new plan types.

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<sup>11</sup> Although Litman and Allen *describe* IDENTIFY PARAMETER as providing "a suitable description for a terra instantiating a parameter of an action such that the hearer is then able to execute the action" [Litman and Allen, 1987, pg. 173], the IDENTIFY-PARAMETER operator itself does not include a *formalization* of the last condition, i.e., that the parameter description should enable the execution of the action.

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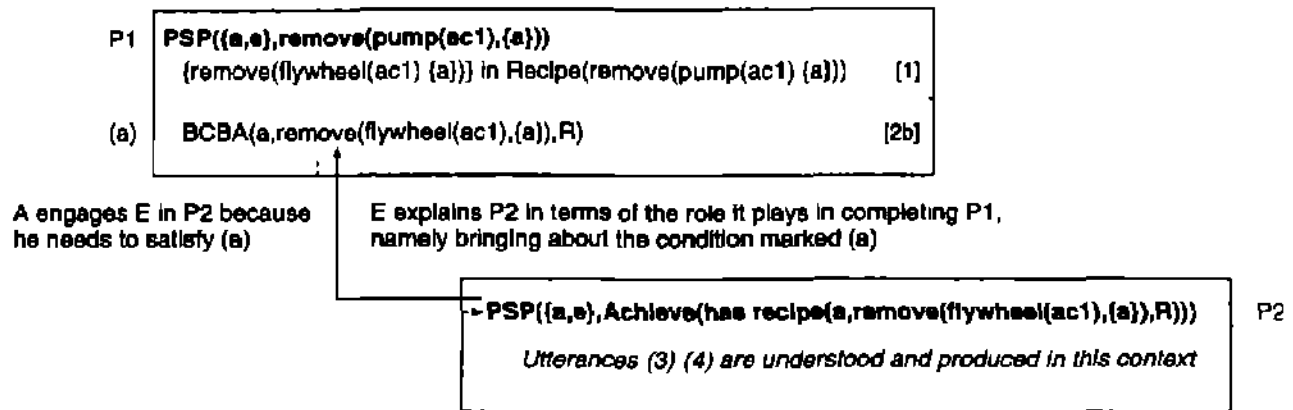


Figure 4 Analysis of the First Subdialogue in Figure 1

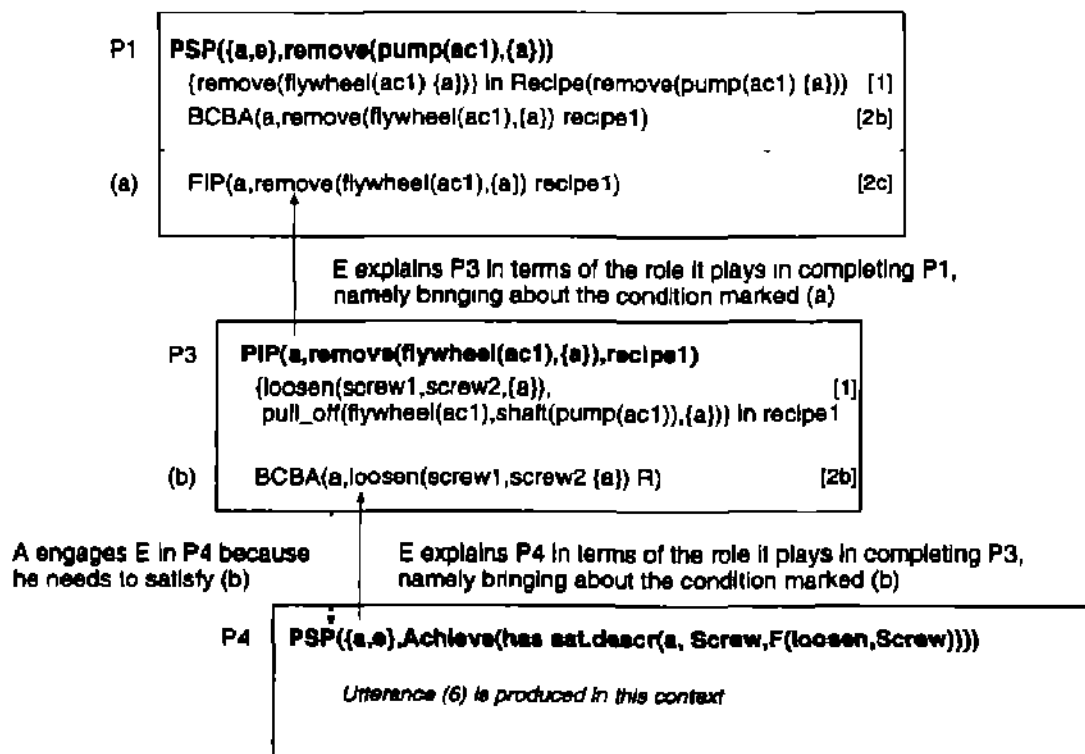


Figure 5 Analysis of the Second Subdialogue in Figure 1