RELATING HUMAN KNOWLEDGE OF TASKS TO THE REQUIREMENTS OF PLAN LIBRARIES [1]

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Technical Report 88-33

Abstract

This report explores the fundamental issues of plan knowledge acquisition from domain experts. The general question is: *Are humans with their knowledge of a domain and its procedures able to provide a planner with the necessary information for automatic planning?* To answer this question we first review the requirements of the plan library of a situation calculus based planner. Then we review existing frameworks for the representation of human activity knowledge and investigate to what extent these frameworks address the requirements. A major factor in evaluating the frameworks is the psychological reality the framework has to the individual. From this review and interviews we conducted in a pilot study, we construct a framework for task recall. In this framework, the representation of a recallable activity is called and act. An act consists of a goal, a pre-situation, an operations-list and a post-situation. Acts can be decomposed and put into sequences.In experiments with the framework, we find support for all our hypotheses except the one dealing with effects. Further investigation of this issue is discussed.

[1] This work is supported by the Air Force Systems Command, Rome Air Development Center, Griffiss Air Force Base, New York 13441-5700, the Air Force Office of Scientific Research, Bolling Air Force Base, District of Columbia 20332, under contract F30602-85-C-0008 and Ing. C. Olivetti & C., S.p.A..

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1 Introduction

This report investigates the possibility of direct knowledge acquisition from domain experts. We are interested if domain experts, who are not experienced in artificial intelligence or computer science, can specify plans for a planning system without the help of computer personnel. To answer this general question we have to investigate the relation of human task accomplishment to the way planners accomplish the same task. In addition, we have to identify human knowledge representation structures and knowledge elicitation techniques. Our approach to plan acquisition is unique for the following reasons: First, we intend to acquire plan knowledge directly from end users, second, we develop a dedicated cognitive model for task recall, and third, we use a cognitive engineering approach to do this.

Planning is an area of ongoing research in artificial intelligence [Cha87], [CRM80]. In everyday terms, planning means deciding on a course of action before acting. The plan is the representation of the course of action. A plans contains a goal, which is the major objective of the plan and subgoals which have to be achieved before that goal can be achieved. The plans which achieve the subgoal are called subplans and might themselves have subgoals on an even lower level. At the bottom of this hierarchy are primitive problem solving operators. In accordance with the POLYMER system [CL87], we will call these primitive operators "actions". Although a finished plan is a linear or partial ordering of actions, the goals achieved by the actions often have a hierarchical structure.

Both planning and expert systems employ deductive reasoning to solve problems. The world is described by a knowledge base which can be transformed from state to state by applying operators. Planning differs from expert systems in some major aspects. In expert systems the start state might be known and a set of operators will be applicable to this state. A conflict resolution strategy picks the most appropriate operator, which is in turn executed. The application of the operator changes the knowledge base (state of the world). Again an operator is selected and applied. This forward chaining process is repeated until the problem is solved. Backward chaining follows a similar strategy. Instead of knowing the start state, the end state is known and evidence for this state is sought by applying the operators backwards. In planning on the other hand, both the start state and the end state (goal state) are known. The question is not: what will the resultant state be when an optimal sequence of operators is applied? but: Which sequence of operators brings us from the start state to the goal state? The operators in an expert system are IF-THEN rules, which are much simpler in structure than plans, the operators of planners, which consist of many slots and which might be arranged in a hierarchical order.

Previous work in the area of planning was mostly concerned with plan formalisms: How to generate a plan to satisfy a high level goal, given a sufficient plan library; or in the case of plan recognition: Given a sufficient plan library, which plan do the observed operations fit best? [Tat77], [Sus75], [Sac77], [Wil84]. The plan libraries for these systems were hand crafted by the system developers. They were written in the same language as the plan formalism, mostly concerned toy problems (the blocks world) and were very difficult to interpret for anybody but the programmer and the system itself.

To address real world problems, a quick and cheap way of building adequate plan libraries is necessary. No tools exist that would allow the end user to specify plans and there has been no specific model of human activity representation that could immediately be applied to planning. This report will present a cognitive foundation for the acquisition of plan knowledge from end users.

In the related field of rule based expert systems, a similar development can be observed [Pro86,Pro87]. As the transfer of expert knowledge became a bottleneck, due to a lack of trained knowledge engineers and an increased demand for real-world expert systems, researchers began to think about knowledge acquisition tools for end-users. Anticipating an analogous process in the area of planning, we intend to build a system that is capable of acquiring plans, without the help of a knowledge engineer, directly from the end user. We base this system on a model of the user's understanding and perception of what the system views as plans. We cannot simply use cognitive models and acquisition techniques developed in the expert systems area, as the focus of planning and the structure of the knowledge are considerably different. In this report, we develop a model of human knowledge representation with a focus on tasks performed by the user. We define a task as a high level procedure that "gets a job done" in a certain domain, e.g. the task of purchasing an item for a secretary or the task of changing a flat tire for a motorist. We emphasize that fact that the tasks are performed by those who will report them, therefore we refer to them as "subject performed tasks" [BNC86]. From this model we will draw implications for a system that enables anybody who performs a task, to specify this task as a plan.

In section 2 we review the requirements imposed by planners. We also review human knowledge representation and knowledge elicitation techniques and their relation to the requirements of the planner. In section 3 we present a framework for human task representation and recall. Section 4 reports the first pilot study and section 5 reports a large scale experiment testing our framework from section 3. Section 6 repairs a flaw in our framework and section 7 draws implications from this report for a plan specification system.

2 Frameworks for Human Task Representation and Elicitation

A correctly programmed planner with an appropriate plan library is able to accomplish some of the tasks a domain expert can perform. This fact implies an equivalence of these two information processing systems (planner and domain expert) with regard to the achieved results. It does not imply a structural equivalence and/or an equivalence of their respective cognitive processes. The human knowledge structure might differ considerably from the planner's knowledge representation formalism. This can be formalized in the following way: Let the domain expert be denotated as cognitive system DE with the knowledge structure S_{de} and cognitive processes P_{de}.

$$DE = < S_{de}, P_{de} > \tag{1}$$

Let the AI-planner be denotated as cognitive system AIP with the plan library S_{aip} and the reasoning processes P_{aip}.

$$AIP = < S_{aip}, P_{aip} > \tag{2}$$

Result equivalence can be expressed by the value of an execution function on these cognitive systems. For a finite set of tasks that can be achieved in a domain, we can state the following: Let F be a set of execution functions defined on DE and AIP and let R be a set of accomplishable tasks then:

$$\forall\ R_i \in R\ \exists\ f_j, f_k \in F\ s.t.\ f_j(AIP) = f_k(DE) = R_i \tag{3}$$

(In plain words: a domain expert$< DE >$ and a planner $< AIP >$ can produce the same results R_i when given appropriate instructions $f_{i,j}$). It does not follow necessarily though, that

$$S_{de} = S_{aip}\ and/or\ P_{de} = P_{aip} \tag{4}$$

Most planners are built in such a way that the plan library S_{aip} must be augmented to enlarge the range of accomplishable tasks of the planner. Changing the reasoning processes P_{aip}, would be the same as developing a new planner. The best domain experts can do to augment the power of a planner is to add knowledge to the plan library. The question that directly arises from this fact is: ***Are domain experts with their knowledge of the domain and its procedures able to provide a planner with the necessary information for automatic planning?*** Formally we can rewrite this question to:

$$\exists\ \mathcal{F}\ s.t.\ \mathcal{F} : \{S_{de}, P_{de}\} \mapsto \{S_{aip}\} \tag{5}$$

To answer this crucial question we have to examine the components of plans that are to be mapped into, the components of the human knowledge representation of tasks and the way this knowledge can be elicited.

2.1 Components of Plans

Our research is part of the POLYMER project at the University of Massachusetts [CL87]. POLYMER is a planner based on situation calculus. The following discussion is based on the formalism POLYMER uses to represent plans. It can easily be extended to other situation calculus based planners as well.

A complete and unambiguous plan in POLYMER has a goal, which is the primary effect of the plan. A plan is applied to achieve the goal, i.e. to create a state in the knowledge base, where the situation stated in the goal is true. The application of a plan may also cause changes known as side effects. Preconditions serve to verify the relevance of a plan in a given state of the world. They are a set of conditions that must be true in order for the plan to be applicable. Each plan may be decomposed into the steps that must be performed in order to accomplish its goal. Each step may be either a goal (usually referred to as a subgoal), or another plan. Part of the planning process is determining an ordering for actions and assuring that their effects are protected until they are required. While most step orderings and protection intervals must be dynamically determined during the generation of a plan, some information may be provided in the plan description. All constraints that apply to items employed in the plan, which are not covered by the precondition or the orderings must be specified in the constraints part. Agents are those people, tools, etc. responsible for satisfying goals by performing activities and actions. Resources are entities which may be produced or consumed by certain agents during the execution of an activity. Thus the plan library can be written as

$$\begin{aligned} S_{aip} \; = \; & < Goal, Decomposition, Precondition, Side-Effects, \\ & Orderings, Constraints, Agents, Resources > \end{aligned} \tag{6}$$

2.2 Cognitive Psychology Frameworks for Knowledge Representation

Three major paradigms for knowledge representation exist in cognitive psychology: Production Systems, Frame Systems and Semantic Nets. In addition to these three frameworks we also include the GPS model because of its importance and relatedness to our problem. We will review each framework and investigate its conceptual power to express planning knowledge. We will take a closer look at each item from S_{aip} and see if and how it can be represented by one of the notational frameworks. We will also consider the naturalness of this representation. Our second criterion is the observable procedural character of the knowledge represented. We are interested in procedural knowledge and skills of domain experts, not in language or mental operations. Procedural knowledge means to us the knowledge about operations in the real world that achieve a change in the state of affairs. The third criterion is the way the procedural knowledge is specified in the respective framework. We are interested in an operational definition, not only in semantic names for procedures. An operational definition of procedural knowledge is given in terms of primitives of an underlying problem space. The last criterion concerns the subjective reality of notation to the individual. Many notations are scientific shorthands to describe phenomena which are not immediately accessible to subjects themselves. We need to know if domain experts can report their knowledge in the structure of the notational framework or if any other aspect of the notation can be used immediately to make assumptions about the form of the reported knowledge.

2.2.1 Production Rules

Production systems for the representation of human knowledge are a collection of `IF A THEN B` type rules. Many theories of human task representation [And83,AB73,PK85] use rules in conjunction with a declarative knowledge base. The `IF` part of the productions is matched against declarative knowledge, possibly in the working memory. Several strategies exist to handle conflict resolution in case more than one rule applies. The goal and the preconditions of S_{aip} are easily captured in the `IF` part, making this part of the rule more structured. [And83] splits the `IF` part of rules in this way but in an inconsistent manner. Decomposition can be accomplished by calling on primitive actions or by setting up subgoals in the `THEN` part. Side-effects can also be specified in the `THEN` part. The `IF` part and the `THEN` part of these rules are propositional expressions. Actors and objects are primitives in propositions. Constraints can also be expressed through propositions. Figure 1 shows the equivalent of the top level plan for purchasing an item in rule notation. Being able to specify our example in rule notation does not imply though that subjects are able to report knowledge in this form.

This review shows that S_{aip} can be expressed by a carefully modeled

```
IF      the goal is to have an item and you have money
        and an order form
THEN    create the following subgoals: Have a completed
        order form, have a filed copy of it, mail the
        order, receive the item, pay the invoice.

IF      the goal is to have a completed order form
THEN    input your own address;
        input the destination address;
        input the item information where the item is the
        same item as in the rule calling this one;
        input the item price where the item is the same as
        before.

                        .
                        .
                        .

IF      the goal is to purchase an item and you have received
        and paid it
THEN    you are in legal possession of that item and you have
        less money.

(This set of rules is not complete but illustrates the major
points.)
```

Figure 1: Purchase Task expressed by Rules.

set of production rules. It does not say that rules are the best or the most efficient way to express this knowledge. Rules are very efficient in expressing procedural task knowledge. Matchings are done in the IF part and actions are taken in the THEN part. This makes rules an efficient and successful notation in psychology for expressing procedural knowledge. The awareness individuals have of these rules is very limited. Recent work in knowledge acquisition for expert systems shows that subjects are not able to report high or low level knowledge in rule form [Pro86,Pro87]. Production rules are assumed to be at a deep level in human cognition. Because of these objections, the rule framework is not optimal as a basis for the elicitation of

```
GOAL:            Have-Item
DECOMPOSITION:   Fill-Out-Order-Form, File-a-Copy, Mail-Order,
                 Receive-Item, Pay-Invoice
PRECONDITION:    Have-Money, Have-Order-Form
SIDE-EFFECTS:    Have-Less-Money, Have-Copy
ORDERINGS:       (Same sequence as in DECOMPOSITION Slot)
CONSTRAINTS:     Item-Price < Money-Available
```

Figure 2: Purchasing Task expressed in a Frame.

task knowledge.

2.2.2 Frames

A frame is a collection of named slots. Every slot may take a value from a predefined set of values (domains). Frame based systems are collections of such frames. [SA77] constructed one of the best known frame based systems for human knowledge representation. The POLYMER system, our plan formalism, is written in KEE, a knowledge representation system based on frames [KEE,CL87]. This fact makes it obvious that S_{aip}, almost by definition, can be expressed in a frame based system. Goals, preconditions, side-effects, decomposition and all the rest can easily be represented by slots of frames. Values for these slots come from the domain of actors, objects, relations and predicates. Figure 2 shows the top level plan of the purchasing task in a frame. Frames were developed to represent plots of stories and concepts. They were not intended to allow for the operational definition of activities. Frames only call on procedures to perform actions, they do not specify them operationally.

There exists no evidence that frames can actually be reported by individuals or that the recall of knowledge in the frame notation is better than the recall of knowledge in any other notational form. Part of the reason reasons for this might be again that frames are at too deep a level of cognition to possess psychological reality to people.

2.2.3 Semantic Nets

Semantic nets are the third general framework for knowledge representation developed in cognitive psychology. A semantic net consists of labeled nodes and labeled or unlabeled arcs connecting the nodes. A detailed description of semantic nets for human knowledge representation can be found in [LN77]. Semantic nets are less structured than frames and less action oriented than rules. This low grain size gives them a greater expressiveness. Goals can be represented by a goal node, decomposition is represented by arcs labeled *decomposition* which connect the goal node the other goal nodes, which can be viewed as subgoal nodes. Preconditions can be represented by arcs to clusters of the net which in turn stand for a certain condition, i.e. they represent objects and actors and certain relations and constraints among them. Effects can be dealt with in the same way. Actions can be represented by corresponding nodes. All the information in S_{aip} can therefore be expressed in a semantic net. Again, this tells us nothing about the effectiveness or adequacy of this representation, it just tells us that it is possible. Semantic nets, like frames, are a notation to represent declarative knowledge. This makes them awkward for the representation of procedural knowledge. Clearly rules are more appropriate then semantic nets or frames for the representation of procedural knowledge. The subjective psychological reality of semantic nets is as low as for the other two frameworks. The phenomena expressed in the semantic net notation are not open to introspection or recall. Subjects do not report their knowledge in the form of nodes and labeled arcs.

2.2.4 GPS-Operators

GPS [NS72] is included in this discussion because it is one of the fundamental systems for both AI-planning and information processing psychology. Both areas draw on ideas and concepts developed in GPS. GPS is therefore neither just an AI-planner, nor a cognitive model but somewhere in between. This makes GPS central to our work, as we are interested in the connection between planning and the equivalent human process. The GPS-operator corresponds to our S_{aip}. It is used to transform states of the world. In [NS72] there is, however, no detailed structure for the operators. Goals and decomposition are not explicitly mentioned. Operators are defined by a pragmatic name, a precondition list and an effect list, e.g. ***Name:** Stack-Two-Cubes; **Precondition:** Cube 1 is free and cube 2 is free; **Effect:** Cube 1 is on top of cube 2 and cube 1 is no longer free*. Operators are selected by a higher process. This process determines operators that are applicable in a certain state of the world and then selects one of them according to the change it will cause towards the desired state of the world. The operator itself is simply an action that will then be executed. Operators have no

	Can express S_{aip}	Action oriented	Operational specification	Subjective awareness
Rules	yes	yes	yes	no
Frames	yes	no	no	no
Nets	yes	no	no	no
GPS-op.	no	yes	yes	no

Table 1: Summary of review of knowledge representation frameworks.

goals. The selection process in GPS is responsible for reducing the distance between the current state and the goal state. The lack of explicit goal and decomposition definitions along with difficulties in constraint definition make it impossible to express S_{aip} without turning the GPS-operator into something else.

Operators are either generated by a task analysis or by observing subjects acting in a problem domain. The first case, extraction from task analysis, bears no psychological relevance. The observation of subjects makes no claims about the reality the operator has to the subjects and their awareness of it.

2.2.5 Summary of Psychological Frameworks

We see that all frameworks, except GPS-operators, can be used to express the knowledge captured in S_{aip}. Nets and frames are less suitable for the representation of action oriented knowledge because of their declarative character. The three major representations (rules, frames, nets) are notations used by scientists. They were developed in order to explain phenomena which not necessarily possess psychological reality to individuals. Those phenomena may not be conscious to individuals at all, at least in their notational form. These shortcomings make none of the above immediate candidates for a solution to our problem. Table 1 summarizes the results of the reviews of frameworks in this chapter.

2.3 Models from Human-Computer Interaction

In this section we will review models for human knowledge representation and task execution developed in the area of human-computer interaction. This area was especially creative and innovative, as many researchers had a background in the cognitive sciences and were interested in human performance with computer systems. Models of complex human information processing in work environments were rare prior to the arrival of human-computer interaction research (except for [HR80] and other industrial psychologists). Human-computer interaction is a special case of work that depends heavily on the humans information processing capabilities. Parts of the models form human-computer interaction can be generalized from work with computers and the human's knowledge about this work to tasks that depend heavily on cognitive abilities in general. In this section we will review the GOMS model [CMN83], practical and situated actions [Suc85], /cite-suchman:art, [BIPS87] and other frameworks from the human-computer-field, e.g. [ND86], [Mor81], [GP84]. The review-criteria will be the same as in the previous section:

- adequacy of the model for expressing S_{aip}.
- procedural character of the knowledge representation.
- operational specification of procedural knowledge.
- conscious awareness of the knowledge in the form stated by the model.

2.3.1 GOMS Model

The GOMS model [CMN83] is rooted in the GPS [NS72] tradition. GOMS itself is an acronym for the major components of the model: goals, operators, methods and selection rules. [CMN83] define goals as

> a symbolic structure that defines a state of affairs to be achieved and determines a set of possible methods by which it may be accomplished. ... The dynamic function of a goal is to provide a memory point to which the system can return on a failure or error and from which information can be obtained about what is desired, what methods are available, and what has been already tried. (p. 144)

Individuals strive to achieve goals. At every point in time an individual has a set of goals in a goalstack. Goals may be decomposed into subgoals which in turn go on the stack. To achieve a goal, a method must be applied. A method is a collection of ordered operators. [CMN83] define as follows:

> A method describes a procedure for accomplishing a goal. It is one of the ways in which a user stores his knowledge of a task. The description of a method is cast in a GOMS model as a conditional sequence of goals and operators , with conditional tests on the contents of the user's immediate memory and on the state of the task environment. ... Methods are learned procedures that the user already has at performance time; they are not plans that are created during a task performance. They constitute one of the two major ways in which familiarity (skill) expresses itself. The particular methods that the user builds up from prior experience , analysis and instruction reflect the detailed structure of the task environment. (p. 145)

The point that is important for our purpose is that methods are available to the user at performance time. Methods do not need to be generated when they are needed through problem solving processes by the human. Methods can simply be called upon.

Methods are associated with goals. Methods give rise to operator sequences. An operator is the lowest level construct. Operators are

> perceptual, motor or cognitive acts, whose execution is necessary to change any aspect of the user's mental state or to effect the task environment. ... Behavior is assumed to consist of the serial execution of operators. An operator is defined by a specific effect (output) ... . (p. 144)

As GOMS is a performance model, most emphasis is put on the duration of an operator execution. The operator itself is specified by a verbal description, e.g.

> GET-NEXT-PAGE. Turning the manuscript page. Starts when the user's eyes begin to turn towards the manuscript; ends when the turned page falls flat. (p. 155)

The effect of the operator, though it can easily be deduced (in the case of GET-NEXT-PAGE it would be *see a new page*), is not explicitly specified.

If there are two methods to achieve a goal, a selection rule will be invoked that decides which method should be used. In each GOMS model there is a set of selection rules for this purpose. These rules are of the form "if such-and-such is true in the current task situation, then use method M". Figure 3 shows our standard example in the GOMS notation. The important differ-

```
GOAL:PURCHASE-AN-ITEM           (this is the top level goal)
   GOAL:FILL-OUT-ORDER-FORM     (first subgoal)


GOAL:FILL-OUT-ORDER-FORM        (definition of a method)
- INPUT-OWN-ADDRESS             (first operator in method)
- INPUT-DESTINATION-ADDRESS     (next operator)
- INPUT-ITEM-INFORMATION        (next operator)
- INPUT_PRICE                   (last operator of method)


GOAL:MAKE-A-COPY                (selection rule)
- [select: if you have little money use
   CARBON-PAPER-METHOD
   if you have a xerox machine use
   XEROX-MACHINE-METHOD]
```

Figure 3: Purchase Task expressed in GOMS Notation.

ence between GOMS and GPS operators lies in the way of their derivation. GPS isolates operators through an analysis of the domain. GOMS could do that too but GOMS can derive its operators also from an analysis of protocols of subject behavior. Behavior is assumed to consist of the serial execution of operators. This makes GOMS operators psychologically more valid. Still the operators are not reported by the individuals themselves. This makes the GOMS model not an ideal candidate for our purposes.

S_{aip} can easily be expressed in terms of the GOMS model. Goals in S_{aip} correspond directly to goals in GOMS. Decomposition can be achieved by either creating subgoals or, equivalent to POLYMER, calling on methods that accomplish the goal directly (see the example). Preconditions can be expressed as *if parts* of selection rules. A certain precondition would translate into a certain rule that selects a method. An ordering of methods is achieved by the order of subgoals in the goalstack.

Constraints and effects are not explicitly captured. While coercing the model could possibly lead to an incorporation of constraints, effects are still a problem. This is surprising as GPS operators, the ancestors of GOMS operators, depended on a specification of effects to enable the selection process to make a choice. Again we face the problem of operational definition of procedural knowledge. GOMS operators are only defined by their procedural name, there is no element in the model that specifies the state of the world after the application of the operator, like goals or selection rules do for the state of the world *before* the application of operators. The meaning of the operator is hidden in the semantics of its name. This semantic way of specification might be useful for an analytic or descriptive model, it is not sufficient for a dynamic one.

Apart from the problem of effects specification, GOMS is the most suitable model encountered. It associates methods and operators with goals. It expresses human skills through its methods. It distinguishes the methods from plans, which are created during work.

2.3.2 Practical and Situated Actions

Situated and practical actions are the central themes in the work of Suchman [Suc85,Suc84]. Though we concentrate on Suchman's work, the basic principles for her ideas can be found in other works from social science and linguistics [BIPS87,GS70]. On first sight her work is related to our problem. Suchman investigates work in the office information systems area. Her work is centered on the human, his role and interactions in organizations. Suchman criticizes the Taylorian view of office procedures as blue prints for office work and offers a result centered view as an alternative approach to the problem of looking at office work [Tay11]. This approach views the incompleteness of procedural specification as an irremediable fact. It criticizes the uncertain relationship of procedural specifications to the work required to actually accomplish them. We have encountered this problem earlier by the name *operational definition*. According to Suchman [Suc84] p.321:

> The topic for study is the process of finding the "definite meaning" of office procedures as a constituent feature of the work for getting them done. The work of finding the meaning of organizational plans in actual cases is referred to as *practical action*. (italics in the original)

The concept of situated actions is aimed at a similar problem like that of practical actions. Situated actions, drawn from recent work in social science, are ad hoc responses to the actions of other people and to the contingencies of particular situations which can be integrated to form plans. While plans are top-down by nature, situated actions escape the top-down versus bottom-up paradigm. Situated actions are responses to the intent of situations. According to Suchman [Suc85],

> Problems in Cognitive Science's theorizing about purposeful action as a basis for machine intelligence are due to the project of substituting plans for actions, and representations of the situation of action, for the action's actual circumstance.

In her thesis Suchman is concerned with the background knowledge shared by the machine and the user, the mutual understanding, the machine's recognition of the user's plans and problem solving in general. All these issues are not central to our topic: representation and elicitation of the individuals task knowledge. Suchman proposes a change in paradigm. Situated actions are synthesized by humans to form something that eventually looks like a plan. She does not define situated actions formally. Her discussion and findings are on a different scientific level than our topic. Even though our problem of eliciting and describing subject performed tasks could be viewed from the planner perspective or the situated action perspective, it does not give us no new insights as to how individuals store and retrieve their task knowledge. We will show in section 3 how the situated action approach of humans can be used to specify plans in a top down manner.

2.3.3 Other Modeling Paradigms

Reisner [Rei84] investigated simple BNF models of dialogue syntax. The interesting point for our topic is that she tried to show the psychological validity of formal descriptions of action languages for users of interactive systems. Reisner tried to use BNF's to predict such variables as

- ease of learning,
- remembering of particular command sequences,
- performance times,
- likelihood of errors.

This model is geared towards the keystroke level, helping system and interface designers to evaluate design decisions. The subjects retrieval of commands is not explained in terms of information processing psychology but in stochastic ones. Reisner also makes no claims about the awareness individuals have about the psychological reality of their BNF's.

Task-action grammars and set-grammars are two similar formalisms to capture the "grammar in the head" of the user [PG86,GP84]. While this approach has been able to make good predictions on user behavior, it is not easily extendible to other tasks and it is unclear if individuals are aware of their own grammars.

Moran [Mor81] introduces a Command Language Grammar (CLG) which follows the same principles as the previous grammar approaches. Though CLG is more sophisticated than BNF it addresses the topic of psychological validity even less. In general, grammar systems focused on human-computer interaction and are not easily extendible to general task representation. The psychological validity of the concepts could be shown by prediction of response times and user errors but there has been no evidence that individuals are able to report grammars.

The same criticism holds for Kieras' and Polson's approach to the formal analysis of user complexity [PK85]. They propose a system consisting of two production systems: one for the simulation of user behavior and another one for the simulation of the machine's behavior. Interaction is formalized and can be modeled.

Newell and John worked on the recall of abbreviations for command languages [JN87]. Though this topic seems to relate computer systems to recall, we know from [BNC86] that there is a vast difference between recalling verbal and procedural material.

Norman presents a more general view of subject performed tasks in [ND86]. He presents a model for task performance consisting of sequences chosen from among seven stages of user activities:

1. establishing a goal;
2. forming an intention;
3. specifying an action sequence;
4. executing the actions;
5. perceiving the system state;
6. interpreting the system state;
7. evaluating the system state with respect to goals and intentions.

2.4 Methods for the Elicitation of Human Knowledge

So far we have concentrated on the representation of subject performed tasks with the psychological reality of this representation to the subject being a minor consideration in our evaluation. We want to investigate methods for the elicitation of human task knowledge. For this purpose we turn to the behavioral sciences and psychology as the science of human behavior, in particular. Experimental and Cognitive Psychology are based on data derived from human behavior. The need for all kinds of human behavioral data is essential to these disciplines. A vast array of methods and techniques has been developed to obtain these data:

- observation of free behavior;
- observation of constrained behavior;
- free interview;
- structured interview;
- reaction time;
- frequency of errors;
- free recall;
- forced recall;
- cued recall;
- recognition;
- introspection;
- questionnaires;
- free association;
- tests and grids.

Items on this list are not necessarily on the same methodological level. Some techniques might be specializations of others. More techniques could be generated by crossing techniques.

Some of the techniques can immediately be disregarded for the purpose of eliciting the subject's task knowledge in terms of S_{aip}. All forms of observation, association and interview require an observer and a sophisticated task or protocol analysis. Clearly these techniques were not designed to provide us with answers to question like the one expressed in equation 5. In the next section about expert systems and knowledge acquisition we will be more specific about our rejection of protocol and task analysis.

Introspection is a method that was heavily used by early psychologists, then condemned by the behaviorists, and is currently undergoing a renaissance The basic assumption of introspection is that one can observe one's own cognition at work. Apart from the apparent methodological controversy, introspection is not useful for our purposes as it is concerned with cognitive processes and structures. We are interested in content and reportability, not in the subject's ability to look at their own modus operandi.

Reaction time and frequency of errors are the most rigorous methods for obtaining data in Cognitive Psychology. Unfortunately these methods convey no semantic meaning in themselves and need to be interpreted. Goals, preconditions, etc. can not be extracted directly from reaction time or form errors.

Questionnaires, tests and personality grids are very structured methods that have been used with success in knowledge acquisition systems for expert systems [Pro86,Pro87]. This success was possible because of the relation between psychological scaling, which is the underpinning for all clinical tests and personality grids, and the need for hierarchies of concepts in expert systems. It is not possible though to operationally specify activities and procedures by means of scaling. We will return to these techniques in the section 2.5 for a more detailed view.

Recall and recognition are very general phenomena used to obtain data, mostly in memory experiments. A recall task usually consists of a list of verbal or geometrical items that subjects have to memorize and a recall phase in which subjects are asked to reproduce as many items from that list as possible. Recognition tasks consist of the same stimulus material in the memorization phase, but in the test phase subjects are also given stimuli which were either present in the first list or not. In the case that they were in the first list, subjects are to respond with *yes*, otherwise with *no*. These methods seem appropriate for our purpose as they are generally concerned with retrieval from memory. Expressing procedural knowledge is not a form of problem solving for the experienced domain expert but simply reporting procedural knowledge stored in long term memory. This process can be viewed as a form of recall. It is not recognition because there are no description of tasks we could give as comparison stimuli. The major difference between orthodox recall and the sort of recall we are interested in concerns the nature and the complexity of the material. Recall tasks are usually performed on simple lists of items. The most sophisticated recall studies concern the recall of the plot of stories. We want subjects to recall a complex, self-performed task. This difference in complexity has not been addressed in previous research. The nature of the items to be recalled also determines the results of the recall tasks. [BNC86] show that tasks performed by subjects themselves are better recalled than verbal material. Therefore we will consider recall in its different forms (free, cued, forced) as a very likely part of our answer to the question posed in equation 5.

Free association is a technique used mostly in psychoanalysis. Given a stimulus (a blob in the Rohrschach Test; a theme of a previous therapy session; a word fraught with emotions; etc.), subjects are asked to report associations elicited by the stimulus. These associations may become new stimuli and elicit new associations until a whole chain of associations grouped around a central problematic theme of the patient is generated. The data obtained by free association are usually interpreted in a certain psychoanalytic framework. But this technique is not necessarily restricted to clinical use. In combination with recall, details might be elicited by cueing the subjects with stimuli central or peripheral to a certain task.

2.5 Knowledge Acquisition Techniques used in Expert Systems

Knowledge acquisition in the area of expert systems has been concerned with the acquisition of concepts, hierarchical structure between concepts and cause-effect relationships. Systems differ in the domain to be acquired, the presentation of data, the amount of the systems inference, the techniques employed to elicit the expert's knowledge and many other aspects. TEIRESIAS [DL82], MORE [KNM85], MOLE [EM86], SALT [MMW85] SEAR [vdBBM86], ETS [Boo84], OPAL [MFCS86] and ROGET [Ben85] are only a few of the major systems in this area. A good overview can be found in [Pro86,Pro87].

Knowledge acquisition systems rely mostly on linguistic transmission of knowledge. Interview and protocol analysis must be applied through a knowledge engineer. Domain experts can not interact directly with the system. The same is true for task analysis.

Grids as introduced by [Boo84] and questionnaires/forms as used by [MFCS86] allow domain experts to shortcut the cumbersome process of interviewing and give them the possibility to transfer their knowledge directly to the system. While grids and triplet-distinction allow the construction of elaborated concept hierarchies and the limitation of state spaces for condition or effect specification, they can not be used for the operational specification of activities. The questionnaire/form approach does not carry these limitations. ONCOCIN [MFCS86] treatment plans can be operationally specified by using electronic forms and questionnaires that are closely adapted to the domain. For the specification of plans, which are not concept hierarchies and only in a limited sense production rules, this seems to be an appropriate technique because of its versatility, ease and power.

The lack of dedicated models of experts and their knowledge is another problem in simply transferring techniques from this field to planning. A great amount of time is spent distinguishing various types of knowledge, e.g. strategy knowledge, domain knowledge, process knowledge, content knowledge, etc.. These distinctions are made on a philosophical basis. None of the systems has a model that links the expert's cognitive structure and processes to the tools and techniques used in the system. At best, the system is custom built for a certain domain and the connection between the experts knowledge and systems lies in the appearance of similar terms and procedures. This is clearly too restricted an approach which is not suited for the scientific foundation of knowledge transfer.

2.6 Summary

In this section we examined frameworks, theories, models and techniques from psychology, human-computer interaction and expert systems. We were looking for facts that would at least partially answer the question of whether domain experts had conscious access to their knowledge that would allow them to specify plans. While there was no single theory or model that was completely satisfying, we found a number of candidates that could form a basis for further investigation:

- the GOMS model, for its application oriented character and its goal-directed ancestry;
- recall and association techniques, for their ease of application (no knowledge engineer);

- and electronic forms/questionnaires (instantiations of a recall technique) which have proven successful in operational specification.

In the next section we will start from these bases and develop a framework that is suitable for answering question 5 completely and sufficiently.

3 A Framework for the Recall of Subject Performed Tasks

In the previous section we reviewed models and theories for knowledge representation and elicitation. We discovered the advantages of the GOMS model, recall techniques and electronic forms. In this section we will tie these notions together, guided by the observations we made in the interview phase in our pilot study. We restrict the tasks to be recalled to those performed by the subjects themselves, hence the term subject performed tasks [BNC86].

3.1 Deriving a Framework

As we could find no theory that makes statements about structures and processes involved in the recall of complex subject performed tasks from long term memory, we started a series of interviews and experiments to gather behavioral data in order to construct a framework. Asking people how they conduct certain tasks usually leads to a description of an example. The following transcript of an interview with a secretary illustrates this:

Interviewer: How do you go about buying an item for the office?
Secretary: You mean something small like a paper holder?
Interviewer: Yes, what do you do?
Secretary: Well, first I'd have to find a catalog, an office equipment catalog, that lists the paper holder. When I found it in the catalog, I put down the vendor, the part number, the phone number of the vendor and so on ... all that stuff on the purchase order...
Interviewer: How do you continue?
Secretary: Hmm, I'd call the vendor, they mostly have an 800 number, and ask for the current price...
Interviewer: Hmhm...
Secretary: I'd put the price down on the purchase order, too ... , hmm, and then I'd mail the purchase order to the propriety department ... and I'd have to file a copy of the purchase order in our own books.

In this interview, units of grouped operations can be observed. These units fit very much what is called *Handlung* by german psychologists and philosophers. *Handlung* is a central concept for philosophers like Boesch [Boe80]. In the psychology of sport [Tho78] and the psychology of labor [HR80] it is the basis for human knowledge and activity. A *Handlung* is a *conscious, goal-directed act of a human being, controlled by will, directed towards shaping reality. It contains three aspects: an intended goal, an analysis of means for its achievement and the decision to do so.*[1] A *Handlung* contains operations, conducted by a human, which transform states of reality into other states, serving a certain purpose [KB72]. The sequence of *Handlungen, i.e. Handlungskette* is what is recalled in the above interview. In the remainder of this report we will use the English term *act* instead of the german *Handlung*. The reader should be aware though that the word act is only a weak substitute for a concept as complex as *Handlung*.

The act is the smallest coherent unit in the description of a task. Persons describing a task do this on a level of abstraction that seems appropriate to them. The single unit on this self-perceived level of appropriateness is the act. Therefore acts are readily recalled. This individually perceived appropriateness as smallest unit, varying from person to person and from task to task, makes the concept very suitable for our purpose. It also distinguishes the act from GPS-operators [NS72]. While operators are "the rules of the game" as found by a methodological or task analysis, acts are the representation of the human's perception of these rules. This makes them closer to GOMS methods. Both the act and the GOMS/GPS operator share the property of producing new states from old ones in the problem domain, but the evidence for the entity, its appropriateness and its structure differ. GOMS methods and operators are not derived only by an analysis of the domain, like GPS-operators, but also by observation and interpretation of the subjects behavior. This makes them already more psychologically valid than their GPS counterparts. Acts and GOMS methods share a very close relationship. Both are sequences of operators. Both are at a unit task level of the individual. But the act is more than a method. The act also incorporates goals and preconditions. This is not the case in GOMS because there independent goals and selection rules exist. For the individual reporting its own task behavior, a process derived from self-observation, the goal has no separated existence but it is tied into the task performed. The recall of a method or an operator will also result in the recall of the goal and the precondition tied to it. Acts model this phenomenon by representing goals, preconditions and lists of operators in one unit.

[1] Definition from: Der grosse Brockhaus; 17th Edition. Translation by the authors.

As acts are performed with an intention to transform states of reality into other states, the effect of the operations in the operator list of an act is also present in the act. This is another difference to the GOMS-method, which does not deal with the change of the current situation to a resultant situation after the application of the operators.

3.2 Operationalization of Act

As the above definition of acts does not lend itself to immediate operationalization, we try to formalize its aspects in information processing terms [SA77]. The first aspect of an act is, by the above definition, the conscious goal; in our case the intention to complete a certain task. This intention is equivalent to the goal in the GOMS model or the intention in the UCSD model. The goal can be regarded as a slot of a larger structure. During work on one task, this goal remains the same, only situations change, not intention. People consciously know about this goal and should be ready to report it without difficulty.

The current state of reality is captured in a second slot. We call this slot the pre-situation. It corresponds to the second aspect of the definition of acts. During execution of the same task (same goal) the situation determines which operators are to be applied. Norman and Draper call this the orientation in their UCSD model. Only when the task is completed or interrupted does the goal change. When people are actually performing a task, they directly perceive the pre-situation. In the case of mental simulation, or recall, the content of the working memory mirrors this state. People who are imagining working on a certain task are able to report what the current state of affairs is by simply reporting the content of their working memory.

The third aspect of the definition is the decision to generate behavior, which in turn is observable. We represent this as a third slot holding names of the operations to be generated. This is the same idea as the method definition of GOMS. Because we are not concerned with the actual execution of tasks, but only the part of them that can be reported, we are satisfied with the name the person ascribes to a certain operation. The mapping of the names to primitives of the system will be accomplished by decomposition, explained later in this chapter.

The effects are also available in the recalled act. We call this fourth slot, describing the situation after the application of operations, the post-situation. The post-situation is described in the same terms as the pre-situation but it includes the changes caused by the operations. This defini-

Goal: Intention of the Whole Act
Pre-Situation: List of Properties
Operations: List of Operations
Post-Situation: List of Properties

Figure 4: Operationalization for acts

tion is similar to the specification of GPS operators by lists of effects. The justification for this slot comes form the explanation that acts transform states of reality into other states of reality. The difference to GPS operators is rooted in the psychological reality.

The complete representation of a formal act is given by the structure in figure 4. We are aware that the operationalization of such a complex concept as an act can not be complete. The structure we present here will certainly have to be amended. We assume that results from the research in situated actions will be of importance to this issue.

We assume that acts are not directly stored in human memory. Acts are temporarily generated when humans recall tasks. Lower level cognitive structures, which themselves are not reportable, are processed and form acts. This property of acts leads us to the assumption that they can be sequentialized and decomposed.

Decomposition is the conscious process of recalling the operations of an act as acts in their own rights. Instead of just reporting the name of an operation, subjects would report the pre-situation for this operation in general, the goal of the operation, the post-situation and other operations used, making this operation an act.

Sequentialization is the process of finding a sequence of acts that leads from one state of the world (possibly the start state) to another one (possibly the end state). The post-situation of an act becomes the pre-situation for the next one. The goal for these acts always remains the same: Completion of a certain task.

It is necessary to remember that the specification of subject performed tasks is not a problem solving process for the experienced subject because the subject knows the answer already. It is a process of recalling pieces of information that are relevant to planning. Therefore we are satisfied with the mere existence and description of the processes above and need not investigate their underlying mechanisms.

In addition to the recall of tasks, we assume the recallability of objects, relations and states of the world. As these entities comply to a certain degree with those items usually encountered in recall experiments, we need to make no additional assumptions.

The proposed framework of long term memory recall of subject performed tasks fulfills the requirements posed on the function $\mathcal{F}$ in equation 2. Let us consider every construct in S_{aip} and how our framework maps S_{de} and P_{de} into it. Goals are a part of the act and are recalled with it. The same is true for preconditions. The Pre-situation of the act may be more general than the precondition, but the precondition is always part of it. We will at worst elicit redundant information in addition to the precondition. The decomposition of goals into subgoals is achieved by the decomposition process on acts in our framework. Side effects are captured in the post-situation. The ordering is the sequence in which the operations of an act are recalled.

3.3 Set of Hypotheses

With the operationalization of acts and the proposed subprocesses, we are able to state the following hypotheses about the recall of subject performed tasks from long term memory. It is important to realize that these hypotheses are only one of many possible descriptions for the phenomena occurring but that they seem to be a reasonable one for our purpose.

1. A general task (goal) and a specific situation (pre-situation) will result in the recall of a specific set of operations.

2. Changing the pre-situation or the general task (goal) will result in the recall of different operations.

3. A goal, a start situation and an end situation will result in the recall of a sequence of acts. This sequence leads over intermediate situations from the start state to the end state.

4. An operation may itself be composed of acts and those acts are recallable (*decomposition*).

5. An alternative act can often be produced if the post-situation of another act is not achievable.

6. Operations can be distinguished from the post-situation created by these operations, by identifying properties of their physical or mental environment that have changed.

4 Pilot Study

The experiments in this section mark the beginning of our efforts in the research of task structure and recall. They ought to be regarded as a first, cautious exploration of the problem. We started these experiments with no preconceptions about human task and activity representation. The framework in section 4 is based on the interviews conducted in this pilot study and the results of the review in section 2. We conducted the exploration in three phases:

- unstructured interview phase to gather raw observations.
- forming hypotheses (section 4 on the basis of the observations and the models from section 2).
- testing the hypothesis in structured problems (reported in this section).

In the first phase we asked three secretaries in the department of computer science to describe a task they perform frequently. The tasks involved forms, interaction with other people and activities of the secretary . A copy of the questionnaire given to the secretaries is shown in appendix A.

From the answers and observations we formed hypotheses about the way secretaries think about their work and the way they report it. We extracted the acts the secretaries perform in order to complete the task they described to us (see Appendix B for a transcript of those extractions). This might seem odd, as acts are by definition what subjects report. The explanation is that our theory was not formed when we conducted the exploratory interviews. We modeled the state of the world (pre-situation) after the application of each of the acts in terms of which documents and information would be accessible to the secretary.

In the third phase, we presented each of the secretaries with very specific question, based on the previous interviews. As the interviews gave us a part of the secretaries activity representation, we could test our theory on a very detailed level and ask very specific questions. These experiments were held six months after the interviews, to exclude ceiling effects.

4.1 Existence of Acts

This experiment is intended to show that the recall of procedural tasks results in distinct acts which are different from declarative knowledge. The following task was given to the subject:

You come back from a vacation and want to resume the work your temporary replacement had started in the meantime. Unfortunately you do not have a chance to talk to the person when you come back, but you know he was doing things exactly as you would have done them. You know he was working on purchasing an item. You find the following items and notes on your desk:

- *a note from R. requesting 10 ribbons for typewriters;*
- *a note with the item number and its price;*
- *an open supply catalog;*
- *a list of graduate students;*
- *a note with a vendor phone number;*
- *a note with object code and vendor code;*

What do you do next?

From the interviews we conducted earlier with this subject, we expected the following answer: ***get a purchase order and fill it out with the information provided by the notes.*** This answer, or a semantically equivalent answer would support our model because the secretary would recall the same act as in the interview. Now we can try to elicit the recall of this act, by cueing with the situation.

The answer given by the subject was:

> I check if the item has already been ordered, if a purchase order has been filled out...then I check if we have enough funds...(you cannot find a purchase order for this process-experimenter)...well, I have to fill one out, all the information I need is given... .

Analysis of the answer leads to the following conclusion: the situation is correctly identified, there are adjustments to ensure the validity of the data because of the artificiality of the situation (mistrust in temporary replacement), after an integrity check of the situation the expected act is recalled by its procedural name.

4.2 Decomposability of acts

This experiment is to test if acts are decomposable and if the constituent acts are easily recallable by the subject. We picked one act the subject mentioned in the interview and asked the subject to break it down into constituent acts. We embedded this into the experimental context in the following way:

For a change, let's say you get to meet the person before you leave. You are explaining to him how you work on purchasing items.

You just explained that you file a copy of the purchase order in your own books for bookkeeping. He has never done that before. Please explain to him how you file the purchase order.

The answer given by the subject, *when all is signed I take out the department copy of the purchase order, punch it, go to the book for the appropriate account number, look up the category (supply, ...), I enter the information to the master sheet in the right category and I put the copy right behind the master sheet into the book*, shows that the subject is easily able to decompose the given act. The existence of lower level acts, serving a lower level goal which was not appropriate in the original sequence, is obvious. New objects like master sheet, local to the lower level act, are mentioned.

4.3 Difference between Post-Situation and Operations

This experiment is designed to show that the post-situation created by the operations can be recalled separately form other parts of the act. The post-situation is the set of expected effects and information redundant to the but important to the person. We tried to elicit a description of the post-situation in the following way:

How does the action you took effect the collection of items, notes and forms that were previously on your desk?
What changes?
What appears and what disappears?

The given answer,...*everything else would be removed from the desk...I'd put the catalog back...a card with the vendor information is created...I put that in a file listed by vendor and by item...I toss away the note to buy the item...I hold on to the purchase order until R. has signed it*, confirms our hypothesis. Items are created and deleted as expected. Effects of operations are described without executing the operations themselves or simulating them mentally.

4.4 Goal and Pre-situation Determine Recall

This experiment is to show that there are acts in a distinct memory and that the recall of a specific act is elicited by a goal and a pre-situation. The goal

and the start situation are given, it is asked for the next act. We gave the subject the following question: *Now imagine instead of finding those items just mentioned, finding the following items instead. By now you know that the intention is to work on a proposal for a grant.*
You find the following items and notes on your desk:

- *request for a proposal*
- *a copy of a budget*
- *an supply catalog*
- *a draft of a proposal from B.*

What do you do next?
The expected answer, we deducted form the earlier interview, ***either go through the rewrite cycle or, if everything is correct, send it out***, matches the one given by the subject: ***I put the budget into the draft, look at the request and see if I can make any input...I write up a new draft and give it to B.***

The subject identifies the pre-situation correctly, sets bindings and gives the two next expected acts.

4.5 Evaluation of the Results of the Experiments

We only tested our theory on three subjects. The interview and the results from the experiment helped us to understand the recall of tasks in terms of planning. Our framework is based on these simple observations. Having assessed the knowledge structure of the subjects, we were able to test our framework in a detailed form.

We can summarize the following: Subjects could recall distinct acts, given goals and pre-situation. Subjects distinguished between operations and their effects. Acts were successfully decomposed. Due to the small number of subjects and the highly individual experimental procedures, we dispense with testing and statistical analysis. Three computer science secretaries are hardly a representative sample of the work force.

The scatter in the experiments is particular to the experimental setting. Good secretaries do not trust their temporary replacements. This technicality can be avoided by a different experimental design. This is done in the next chapter.

5 Act Framework Experiments

This section reports a large scale experiment testing the framework we developed in section 3. This experiment was designed to avoid the technical problems encountered in the pilot study and to provide statistically more valid data by using a larger group of subjects. Our subjects were 134 college freshmen at the University of Massachusetts. They were computer science and non-computer science majors enrolled in the computer science department and in the school of education. As it was impossible to interview every single one of them, as we did in the pilot study, to obtain a subset of their particular act memory, we decided on a task domain that would probably be known by all students. In addition this task domain had to be restricted enough to only a few sequences of acts and on the other hand it had to allow for enough variation in the possible sequences of acts. We eventually decided on the general tasks of "checking out a book from the main library" and "studying in the library". These general tasks involve various situations and actions, enough to allow for a number of different sequences of acts to achieve the goal. Figure 5 shows a directed graph of acts possible to achieve the goal "have book". Every path from the start situation to the final situation is considered a valid sequence of acts.

5.1 Goal and Pre-situation determine Recall of Act

To see whether subjects would be able to recall one act of the set of acts, we told them that they had just entered the library tower with the intention to check out a certain book. This means that we put them at the top state in figure 5. We then asked them for the next thing they would do, expecting one of the of the following answers:

- ask librarian for location of book;
- go to card catalog;
- know already where book is;
- search randomly through stacks.

The answer distribution was the following:

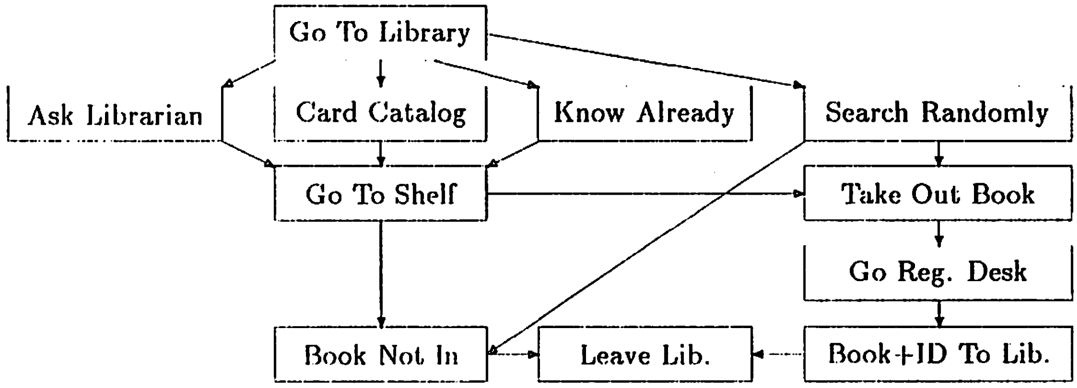
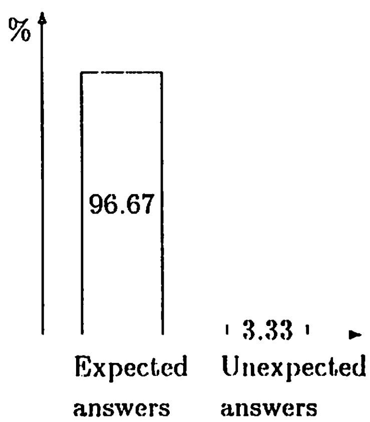


Figure 5: State-Action graph for "checking-out-a-book"

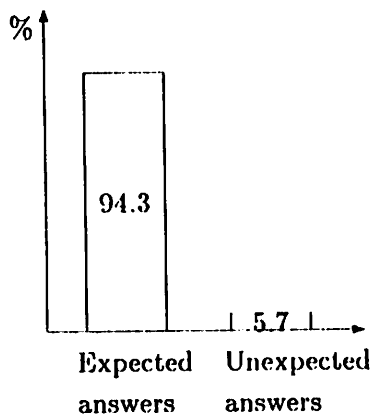


Only one out of 31 tested subjects gave an unexpected answer. Assuming that this was due to our framework rather than the experimental set up or our supposed knowledge structure about student library behavior, it still means that at least 96% of the population behave according to our framework.

In a different group of students we presented the same situation but altered the goal. Now the students were not to check out a book, but to go to the library to study. We asked them for the next thing they did once they entered the lobby. Again we devised a set of expected answers:

- take the elevator to one of the study floors;
- go down the stairs to a study area.

The answer distribution with this different goal was the following:



Two out of 35 subjects gave unexpected answers. This means that at least 94% of the tested subjects are in support of our framework, assuming no other factors biasing the results.

The variable we manipulated in the previous experiments was the goal of the act. One of our claims is that a different goal will result in the recall of a different action, even in the same situation. This is the major distinguishing factor between our framework and traditional *Stimulus-Reaction* theories [2] and "cognitive" *Stimulus-Reaction* theories [3] We now want to test if the manipulation of the goal from the first to the second experiment has a considerable effect on the subjects behavior. The goal in the first experiment was to check out a book, in the second experiment it was to study in the library. Dropping the subjects that did not behave according to our framework in the first place, we have 30 subjects under the first goal who gave

[2]Orthodox Stimulus-Reaction theory rejects all cognitive processes and tries to explain observable behavior (reaction) only in terms of stimuli which should preferably be controllable and measurable [Ski74].

[3]These theories try to identify cognitive processes that accomplish the connection between environmental, proprioreceptive or mental stimuli and mental or observable reactions. Most theories model those processes by IF-THEN rules. [And83].

	Responses fitting Goal 1	Responses fitting Goal 2	Other Responses	Number of Subjects
Goal 1 and Pre-situation 1	30	0	1	31
Goal 2 and Pre-situation 1	0	33	2	35
Number of Subjects	30	33	3	66

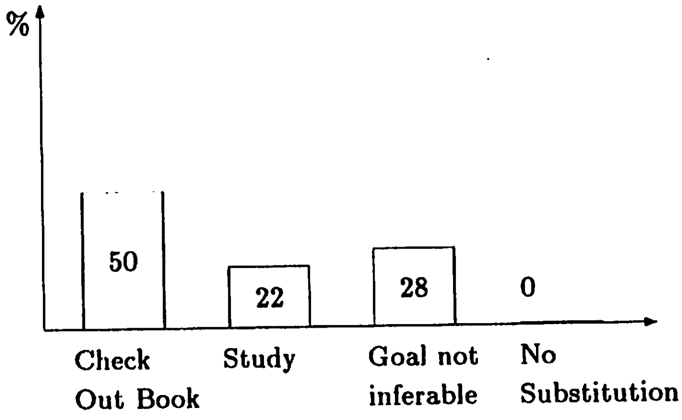
Table 2: Same situation, different goal.

an answer from the set expected for goal "check out book" and 33 subjects who gave an answer expected for the second goal-condition "study". Table 2 summarizes these numbers and conditions. The null hypothesis would be that each row-cell in the table should have the same number of subjects in it as the other row cells, meaning changing goals has no effect. Clearly this is not the case. We can reject the null hypothesis at a .01 level.

In a third experiment concerning the effect of the goal of the general task on the act recalled, was conducted with a third group of students. Different groups had to be used to guarantee the independence of the experiments. In this case, the subjects were given no goal at all, just the situation. We expected that in the absence of a goal, the subjects would generate a substitute goal in order to do anything at all. We expected the following set of substitute goals:

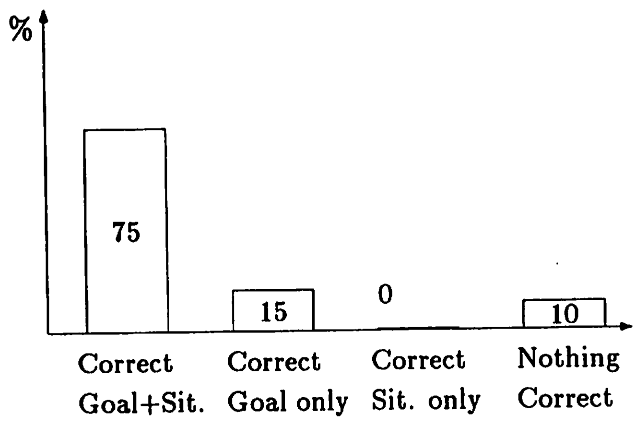
- check out book;
- study;

These are the only reasonable things a student could do in this library. The following diagram shows the answer distribution:



The results show that the subjects substituted goals as we expected. Those subjects whose goals were not inferable gave an answer that could have either of the two aforementioned tasks (check out book, go study) as goal. To explore this issue deeper, we would have to devise a different experimental setting. We do not intend to do this this as the issue of inferring and generating goals is only of minor interest to our framework and the system we intend to build.

To finish the part of the experimental series that concerns goals, we were interested if subjects could do the reverse to generate actions: Recognize goals and situations by partial action sequences. We described a sequence of two actions (take spare tire out of trunk, jack up car) and asked the subjects to identify the general task (change a flat tire) and the specific situation (car jacked up, flat still on car, spare tire in stand by position). The diagram shows how many subjects could identify the general task correctly and how many could identify the specific situation correctly:

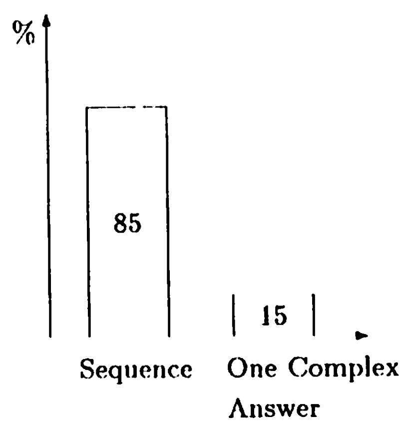


The results show that subjects can infer goals and situations.

5.2 Sequencing and Decomposing Acts

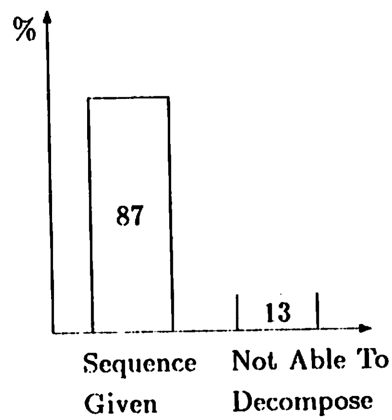
The second major component of our framework is the decomposability of acts. Subjects should be able to break a act into its lower level constituent acts. This applies only to acts subjects generated themselves, as only they know what their "standard granularity" for a certain goal is. Related to decomposability is sequencing. According to our framework subjects should be able to start at a certain situation, mentally execute the operations of the act and produce a new situation. Continuing from this new situation subjects should be able to generate a sequence of acts, all with the same goal, until the goal is achieved.

The next experiment concerned the sequencing of acts. A goal (checking out a book from the library) and a pre-situation (found the book on the shelf) were given. Then a second situation was given (being outside the library with the book). The subjects were asked to provide the actions that led from the first to the second situation. We expected that subjects could give such a sequence that would conform with the local library procedures. The diagram shows how many subjects could give such a sequence and how many gave a complex answer (e.g. *just check it out*) that would bring them from the given situation immediately to the desired one:



This result does not support our framework in general. We expected much more subjects to be able to generate a sequence than the 85%. The case is not too serious though, as we still have decomposition to acquire a sequence of actions. For the plan specification system this means that sequencing and decomposition techniques have to be used side by side.

The next experiment concerns decomposition. A high level, abstract act has to be broken down into constituent acts. We asked subjects to explain how they accomplish actions they had given as answer to previous questions. We expected these explanations to be sequences of lower level actions. The subjects answered in the following way:

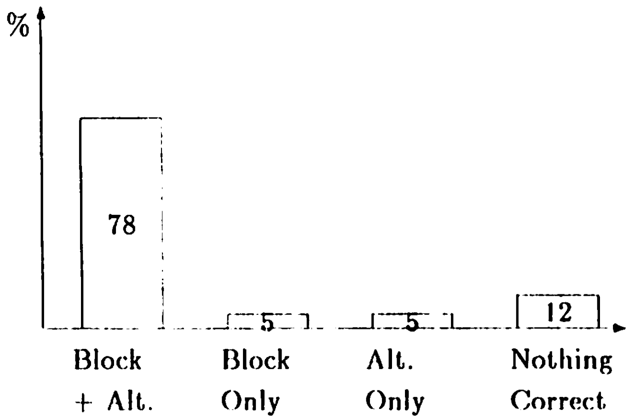


We found that 87% of the subjects were able to do the task. Though most of the subjects can decompose and sequence we have to be very careful in drawing conclusions from these two experiments for plan specification systems.

5.3 Unanticipated Effects of Operations

The third major aspect of our framework concerns unanticipated effects. The occurrence of effects not anticipated by the subjects results in a situation different from the post-situation of the act. Thus the subjects have to generate an act different from the one anticipated in the post-situation as shown in the sequencing experiments. The subjects should still be able though to generate a act because acts are only dependent on the goal and the current pre-situation. Expectation may play a role, but our framework makes no statements about it. Eventually the act associated with the current pre-situation and the current goal should be activated.

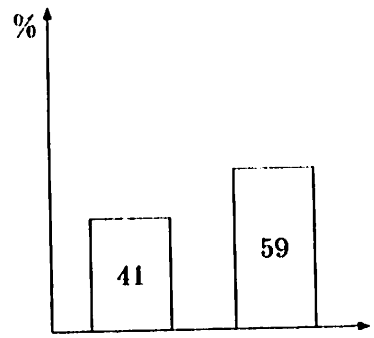
In the experiment we first asked the subjects to give an action for a certain goal and pre-situation. Then we told them that this action was blocked. We asked if they could think of any reasons why this action could be blocked and asked for an alternative action. The diagram shows how many subjects were able to provide a reason for the block and how many gave alternative action to proceed in their tasks:



These results show that 83% of the subjects could at least provide an alternative action to proceed in the execution of their task. Even subjects who could not think of a block were able to provide an alternate action.

5.4 Distinguishing Post-Situations from Operations

The fourth and last major aspect of our framework is the distinguishability of operations from post-situations. We assume that subjects can easily tell what their operations result in, i.e. which effects they have. Once the subjects had generated a act, as answer to a question, we asked them to give us properties of their world that had changed ("How does the action you mentioned change the whereabouts or the information you have available?"). We counted an answer to this question as "correct", if the subjects gave a list of properties for location or possession. The following results are surprising:



These results do not fit our framework. The subjects were generally not able to distinguish between their operations and the effects of those operations. This is especially surprising as the secretaries in the pilot study had no problems identifying the effects of their operations. We will review this problem, explanations to it and a possible remedy in section 6.

5.5 Comprehensive Results

1. Goal and pre-situation determine the recalled act; true on a 94% level of confidence.
2. Changing goals changes operations recalled; true on 99% level.
3. Changing pre-situation changes operations recalled; true on 99% level.
4. acts can be sequenced; true on 85% level.
5. acts can be decomposed; true on 87% level.
6. subjects are able to report alternative acts if the default one is blocked; true on 80% level of confidence.
7. Post-situation can be distinguished from operations; failed at 41% level.

6 Post-Situation Reexamined

The experiments reported in section 5 suggested that our assumptions about the recall of the post-situation were not completely correct. Most subjects were not able to specify the post-situation. Subjects could not relate to the topic and did not understand our questions. To solve this problem, we started experiments concerning exclusively the effects of actions.

We were interested in the subject's ability to relate to the effects of an activity in terms of the primitives of a given knowledge base. We asked questions about the post-situation and the subjects had to say if those statements were true or not. For example: In the book-task in the library experiment, we asked students who said they would go down to the card catalog, if they were any longer in the lobby of the library. Students denied this. We asked if they were next to the card catalog and if they had information as to what the books call number was. All subjects were able to answer these these directly phrased questions correctly.

We concluded that the problem of specifying effects does not arise from a lack in the subject's knowledge. We detected two causes that might have been responsible for the problem. The first cause concerns the communicational background and the level of primitives. In human communication we assume certain primitives that are operationally defined and need no further explanation, e.g. it seems strange to say: *I put the book in the drawer and now the book is in the drawer and is no longer on the table.* The sentence contains redundant information because it explains a primitive of the human language. The second cause is the way of eliciting the knowledge, the way of asking.

Considering these possible causes we designed a new experiment. This new experiment was designed to address the two cardinal questions of the specification of effects:

- can subjects specify effects operationally when prompted in an adequate way;
- do subjects recall all effects of an action.

Our subjects were thirty students enrolled in introductory computer science classes at Smith College, Massachusetts. We gave the subjects a short story, consisting of only a few sentences. The story was a semantic paraphrase of the state of the knowledge base.

Example:
Jill wants to buy a car. She has enough money in her account. She shops around. She decides on a red YUGO.

Then we gave a stimulus sentence that contained an action verb.

Jill buys the YUGO.

We asked the subjects to specify all the resultant effects of that sentence on the story, using as many as possible words from a list given after the sentence. The list of word would correspond to the primitives of a given knowledgebase of a system. Example:

(have, less, more, dealer, father, happy).

Subjects were expected to give short sentenced answers like:

```
Jill has the YUGO.
Jill has less money.
The dealer has more money.
The dealer has a YUGO less.
```

Although we described the state of the knowledge base in a short story and gave a list of primitives (with some distractor items), subjects were not able to describe the post-situation. Subjects either continued the story, using the primitives given in the list, or they gave incomplete and generally useless long answers describing the goal of the activity.

We concluded that the verbal character of the story and the list of items confused the subjects. We resorted to the "form approach" which had proven advantageous in knowledge acquisition for expert systems (see section 2). Instead of telling a short story, we gave the subjects a description of the situation by means of some forms (see appendix C). Then we presented the subjects with the stimulus sentence, as in the previous experiment. Subjects were given the same forms as in the description of the situation (but with no values) to fill their answers in.

The questionnaire in section C consists of three tasks. The first task used the same forms in specifying the pre-situation and gave those forms without any values so that the subject could fill in the values of the post-situation. Some of those values might have changed (effects and goal) most stayed the same. We expected the subjects to notice that the "number of exposures left in the camera" after a new roll of film is inserted (stimulus sentence) change. We also expected the subjects to notice that the number of films in the camera-bag changes.

- 93% of the subjects noticed that the exposure slot is affected.
- 93% of the subjects noticed that the number of unused films in the camera-bag decreases to 2.
- 74% noticed that the number of used films increases to 5.
- None of the subjects tried to change an attribute that was not affected.

These results show that subjects can specify effects with given forms in primitive terms of a knowledge base.

The second task was similar to the first task but one of the forms was incomplete. A major attribute describing the spare tire in the trunk was missing. This attribute was the status of the tire in the trunk. Is it flat or is it usable? We wanted to test if subjects could remember all attributes of objects that are affected by the activity.

- 74% of the subjects recognized the missing attribute.

These subjects noticed that it is important to distinguish between the usable spare tire in the trunk of the car and the changed flat tire that takes the place of the spare tire. This result shows that subjects are able to augment objects of the knowledge base.

In the third task we withheld a complete form from the subjects. We tested if the subjects would be able to recall all objects that would be affected by the activity. In the situation presented to the subjects (a car sale) the account of the buyer would have less money after the transaction. A form for the account of the buyer was missing. We expected subjects to notice that and therefore produce a form that resembled the account-form of the seller.

- 70% of the subjects were able to produce the missing form.
- The same subjects completed that form correctly.
- More than 94% of the subjects noticed the effects of the sentence on the forms given.

The problem of specifying effects can be viewed as an instance of what is known in artificial intelligence as the *frame problem*. This problem will be encountered when an action has taken place and changed certain aspects of a knowledge base. It is not always obvious which aspects of the domain remain the same and which change their values due to the action. The subjects in our experiments had to deal with this very problem: Which aspects of the world are affected, which remain unaltered.. In all three tasks subjects dealt with the frame problem in an expected way. Everything that was not explicitly mentioned in the stimulus sentence was perceived as remaining the same. Objects not mentioned but essential to the activity (like the buyer account in the "car-sales task") were easily recalled and updated.

The results show that we had taken the right approach to ask questions about effects. Subjects are able to specify the effects of an activity in terms of primitives of the system when given forms. Subjects are able to augment forms to accommodate more complex situations. Objects not mentioned in the activity but essential to it are recalled and can be specified as a form.

7 Implications for Plan Specification Systems

Our theoretical framework and the experiments show that humans, even if not familiar with computer science, can specify all elements of a plan. The experiments show that most of the components of a plan are easily specified but that effects need special consideration. The answer to the question posed in equation 5 is therefore "yes", humans can specify plans.

The most important implication from our framework and experiments derives from the fact that humans react to a situation differently with different intentions and that they do not set up conscious goal stacks but go step by step. People are guided by context and fine tuned by situation. The basic knowledge representation unit is the act triggered by goal and situation. This gives us a powerful criterion for designing the interactive structure of the plan specification system's interface. It shows that it is not foreign to people to recall in goal/pre-situation terms, which is very important for a goal based system like POLYMER. The human description of a plan consists of a sequence of activities. A plan definition system should therefore allow the stepwise specification of these "acts". The decomposition of acts into primitive plans and subgoals follows as a consequence of the primitives of the system. The act is either a primitive plan the system understands, or it has to be explained in terms of those primitive plans, then the act is a subgoal to the system.

The problem of breaking a plan down into hierarchies of goals and subgoals should therefore not be forced on the user but evolve from the user's perspective. Decomposition and sequentialization are the processes to employ in this situation. The experiments show, that a complex act can be decomposed. People can also give a sequence of acts from a start state to an end state. A combination of both techniques, decomposition and sequencing, seems to be most appropriate.

The concept of act has another implication for the plan specification system. Human agents go from one act to the next. They do not have a detailed layout of how to tackle a task. The system should therefore not force the user to specify the sequence of acts as a whole, but piecewise, i.e. stepwise. The specification of a new act should only begin when the last one is completely defined. This guarantees consistency and supports the human desire for closure.

Unanticipated or non-default effects can be handled by people. This finding supports the first point about goals and situations. It shows that non-default effects are not particularly hard. This fact is important for the completeness and versatility of planning systems. An implementation of a plan specification interface based on these results is currently under way.

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A The Questionnaire

Questionnaire

I want you to think of a procedure you encounter rather frequently in your work. The procedure should not be too complicated, too lengthy, too complex or too prone to exceptions. On the other hand it should not be too easy, like filing a record. It should be a standard procedure consisting of some steps you have to take, some forms you have to fill, some information you have to gather, people you have to talk to (either for information or approval) in order to get on .{The procedure for hiring graduate students is a nice example of such a procedure}.

Let me stress that this only for my research project and that there is no such thing as 'good' or 'bad' answers. I just need to know about office work in order to understand how things are done.

O.K. now that you have decided on your procedure, please try to explain the procedure to me. To let you know what I am mostly interested in, I have noted some key questions:

What is the procedure about ?

Which single actions make up the procedure?
Which action do you take first?
Which action next? And so on until the procedure is done.

How is the procedure initiated ?

How is it ended, when do you know it is over ?

Which forms do you need ? (please attach a copy of those)

What do you have to fill in there ?

Where do you get the information you fill in the forms ?

Who do you need to communicate with (people and institutions) to accomplish the procedure ?

Are there certain steps in the procedure which cannot be done without checking for something (funds, approval, etc.)? If so which steps are these and what has to be checked?

steps:

to be checked:

What could make you cancel the procedure ? Why ?

Thank you very much for your help and cooperation.

B Extraction of procedural steps from office procedures obtained via interviews

B.1 Procedural Steps for purchasing items

- generating purchase order
- professor comes says he wants item [e.g. paper holder]
- find most appropriate office supply catalog
- determine vendor, part#, telephone number
- call 800 number vendor for current price
- get purchase order
- if do not know vendor code call propriement office for vendor code for this company
- fill out whole purchase order form: vendor, address, item, price [check if funds are available], part # for the item, quantity, vendor code, object code
- put purchase order in mail to propriement office
- file order in bookkeeping books
- (propriement sends order out to the vendor)
- (propriement office sends copy to accounting)
- once item received vendor sends invoice
- check invoice amount against original purchase order (amounts are the same?)
- fill out imbursement schedule (invoice #, purchase order #, vendor code, vendor, object code of purchased object)
- (report comes back from accounting on monthly basis)
- check report from accounting against own books

B.2 Procedural Steps for grant application

- request for proposal comes to coins from a funding agency (not in M.'s field of responsibility)
- if it is in the area of V. or somebody in his group they write a proposal
- proposal includes budget
- now M. comes: helps find figures for the budget (fringe benefits)
- type and edit proposal, follow guidelines of the agency = formal (how many pages, budget page, table of contents, etc.)
- go through rewrite cycle with proposal writer
- proposal for grant funding gets approved by the sponsor (unofficially)
- form from office of grants and contracts comes to M.
- that forms says what actual allocation is (may not be what was asked for) comes together with request for internal processing form
- put down budget there again
- have department head sign it
- incorporate changes (shift figures and categories)
- investigator and department head sign it
- send back to office of grants and contracts
- they inform accounting, gets account number, shows on monthly print-out
- wait that accounting has processed it, shows on next months printout

C Dedicated Effect Experiment Questionnaire

Please help us to make a human factors design decision by filling out this questionnaire. Your participation is absolutely voluntarily. There will be three questions. It should take you only a short time to answer them.

First we give you a set of forms that describe some objects. Here is a form that describes a house and a form that describes paint for the house:

HOUSE	
Owner:	J. Miller
Bedrooms:	4
Color:	blue

HOUSE-PAINT	
Hue:	white
Owner:	J. Miller
Producer:	Quast Inc.
Gallons:	30

Then we give you a sentence that effects these objects, for example:

J. Miller paints her house with 25 gallons of white paint.

Now we want you to fill out blank forms for the house and the paint. You have to be careful, as some properties change, e.g. the color of the house or the amount of color that is left, while others remain the same like the owner or the number of bedrooms. Your answer in this case would look like this:

HOUSE	
Owner:	J. Miller
Bedrooms:	4
Color:	white

HOUSE-PAINT	
Hue:	white
Owner:	J. Miller
Producer:	Quast Inc.
Gallons:	5

note the chan…

Now it is your turn. Here is the first set of forms:

CAMERA	
Make:	Minox
Model:	Klick-o
Owner:	J. Miller
Value:	$500
Exposures left:	0
Battery stat.:	fair
Lens:	zoom
Winder:	yes

CAMERA-BAG	
For Camera:	Minox
Owner:	J. Miller
Color:	blue
# of unused films:	3
# of used films:	4

This is the sentence: **J. Miller puts film in her Minox-Camera.**

Here are the blank forms for your answers. Make sure you reflect all the changes of the sentence and the effects it has on the two objects.

CAMERA	
Make:	
Model:	
Owner:	
Value:	
Exposures left:	
Battery stat.:	
Lens:	
Winder:	

CAMERA-BAG	
For Camera:	
Owner:	
Color:	
# of unused films:	
# of used films:	

Now we give you a set of forms but the second form is not complete. One important aspect is missing. When you read the sentence you will probably know which aspect that is. Here are the forms:

CAR-TIRES	
On car:	my Ford
# of tires:	4
Front Pressure:	25
Rear Pressure:	33

TIRE-IN-TRUNK	
Type:	Spare
Make:	Continent Rubber
:	

The sentence is: **He changes a flat tire on his car.**

Now complete the forms and add the one aspect in the TIRE-IN-TRUNK form that was left out. Don't forget to add that aspect in the TIRE-IN-TRUNK form above!

CAR-TIRES	
On car:	
# of tires:	
Front Pressure:	
Rear Pressure:	

TIRE-IN-TRUNK	
Type:	
Make:	
:	

Now we have "forgotten" a whole form! Once you know which form it is, add it to the other forms above and below the sentence. Try to add all the details to that form too. Here are the forms and a blank space for the missing one:

CAR	
Make:	Nickel
Model:	Burrito
Owner:	Car Sales Co.
Value:	$3500
HP:	112
Year:	1985
cu.inches:	350
Color:	red

BANK-ACCOUNT	
Acct.#:	144 j 2232 k
Balance:	$34,189.21
Owner:	Car Sales Co.

CAR-INVENTORY	
Dealer:	Car Sales Co.
# of new cars:	22
# of used cars:	34

The sentence is: **J. Miller buys a brand new "Nickel Burrito" from the dealer for $3500.**

Here are the forms for you to fill out. Make sure you capture all the effects of the transaction described in the sentence. Add the missing form.

CAR	
Make:	
Model:	
Owner:	
Value:	
HP:	
Year:	
cu.inches:	
Color:	

BANK-ACCOUNT	
Acct.#:	
Balance:	
Owner:	

CAR-INVENTORY	
Dealer:	
# of new cars:	
# of used cars:	