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STORY PROBLEM SOLVER:
A schema-based system of instruction

Sandra P. Marshall
Kathryn E. Barthuli
Margaret A. Brewer
Frederic E. Rose

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Center for Research in Mathematics and Science Education

College of Sciences
San Diego State University
San Diego, CA 92182-0413

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This report describes a computer-based instructional system, the Story Problem Solver (SPS). SPS provides students with instruction about the semantic structure of story problems. It was developed to test a specific schema theory of knowledge organization in long-term memory. For this reason SPS depends explicitly upon a theory of the relationship between the form of instruction and the memory structures that develop as a result. In this report we describe the schema theory underlying SPS, the design of SPS with respect to the theory, and the system's operational features. The report concludes with a short description of ongoing extensions to the basic instructional program.

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Sandra P. Marshall
Kathryn E. Barthuli
Margaret A. Brewer
Frederic E. Rose

Department of Psychology
Center for Research in Mathematics and Science Education
San Diego State University
San Diego, California 92182

STORY PROBLEM SOLVER:
A schema-based system of instruction

This report describes a computer-based instructional system, the ***Story Problem Solver** (SPS)*. SPS provides students with instruction about the semantic structure of story problems. It was developed to test a specific schema theory of knowledge organization in long-term memory (Marshall, 1988a; 1988b). For this reason SPS depends explicitly upon a theory of the relationship between the form of instruction and the memory structures that develop as a result.

In this document we describe the schema theory underlying SPS, the design of SPS with respect to the theory, and the system's operational features. The domain of arithmetic story problems has been described in detail elsewhere (Marshall, 1987; Marshall, Pribe, & Smith, 1987) and is only briefly reviewed. The report concludes with a short description of ongoing extensions to the basic instructional program.

THEORETICAL STRUCTURE

Schema Theory

SPS is designed to develop a student's awareness and understanding of the basic relations found in arithmetic story problems. It provides instruction which will facilitate the use and organization of information in long-term memory. The instructional design derives from the theory of schema acquisition and storage described in Marshall (1988a). According to the theory there are four components or types of knowledge involved in the development of a schema: feature recognition, constraint mapping, planning/goal setting, and implementation. This architecture derives from that described in Marshall et al. (1987).

Under the theory each component develops in long-term memory as a network of nodes, representing bits of information, and links between nodes, representing memory connections among them. The presence of a particular node in a network indicates that the information it represents has been learned and can be retrieved from memory. The links to other nodes provide access to the information stored in them. A node that is isolated from others is of little use because it is accessed only on rare occasions, but a node linked to many others is accessed and used frequently. Thus, a critical element of learning is the connection of any new information to previously learned information.

The networks comprising schemas intertwine on several levels. First, within a single schema, there are connections from nodes of one component to other nodes in that component and also to nodes in other components. Second, the components of a schema are themselves linked, so that access to the information associated with one component will allow access to information associated with the other components. Finally, schemas are linked to each other within domains. At an abstract level of thinking about the whole domain one should have ready access from one schema to another.

The Domain

Marshall (1985) found that arithmetic story problems can be categorized by five distinct profiles: Change, Group, Compare, Restate, and Vary.[1] These profiles describe the semantic relations found in story problems and together comprise the common domain of story problems.

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[1] These were previously called Change, Combine, Compare, Transform, and Vary in Marshall (1985) and Marshall et al. (1987). The names of the categories were modified as a result of empirical tests with students. "Combine" suggested the operation of addition to students and was changed to "Group" to avoid the operational connection. The label of "*Transform*" was difficult for students to understand and was changed to "Restate". The labels described here have been used successfully with several groups of students and are apparently easily understood.

Each profile represents a particular relation that occurs in story form, and the story line is woven around the relation. Ordinarily one or more of the features that define the relation is unknown.

The advantages of categorizing the domain by semantic relation are (1) only a limited number are needed, (2) the relations are simple situations, deriving from individuals' experiences in daily life and easily understood even by young children, and (3) they may be combined to form complex problems reflective of situations that occur in reality. Thus, they may be used as a basis of instruction for learners of all ages.

The five semantic profiles have been described in detail elsewhere and will not be discussed at length here (c.f. Marshall et al., 1987). Table 1 contains examples of profiles in simple situations, in simple problems, and in complex problems. These are typical of the situations and problems encountered by students who use SPS.

In developing the instructional programs described here we found it necessary to reevaluate the Compare profile and the way its accompanying semantic relation is used in a story problem. The Compare profile describes the semantic relation in which two entities are examined for the purpose of deciding their relative size. As such, it requires no arithmetic computation. It does, however, require sufficient number sense to recognize when one number is larger or smaller than another. In its simplest form, the Compare relation seems almost trivial:

(1) ***Here are two numbers, 25 and 29. Which is larger?***

The complexity of the profile and the semantic component come into play when the student must interpret the descriptive statements linking the two numbers. That is, when the relation is expressed as faster, higher, cheaper, deeper, longer, and so on, should the student search for the larger or smaller number? Moreover, what are legitimate comparisons? Can any two quantities be compared or are there constraints requiring them to be of similar type (e.g., inches with inches rather than inches with yards)? The semantic requirements of Compare are sophisticated and involve an understanding of the situation represented in the problem.

Our original definition of Compare (and others' definitions as well, e.g. Riley & Greeno, 1988; Willis & Fuson, 1988) asked a different question of the Compare situation. For example, under our previous conception the following was labeled a Compare item:

(2) ***Joe walked a mile in 13 minutes. His friend Fred walked a mile in 15 minutes. How much faster did Joe walk than Fred?***

In actuality, this is not a true Compare relation in which the problem solver is asked to make a comparison because the comparison has already taken place -- it is stated in the problem that Joe walked faster than Fred. The solver does not have to decide who was faster or whether more minutes means faster or slower walking. Problem (2) is a Restate relation. It asks the student to express in a different way the information already given in the problem.

A true Compare relation would have the following form:

(3) ***Joe walked a mile in 13 minutes. His friend Fred walked a mile in 15 minutes. Who was the faster walker?***

This latter problem reflects the way that the Compare relation is taught and used in SPS. The solver needs to decide what to compare and whether to retrieve the larger or the smaller amount.

Under our new formulation, familiar problems from textbooks such as

(4) ***Sue has 30 pencils, and Joan has 20. Who has more and how much more?***

are viewed as having two different semantic relations, corresponding to the two distinct questions posed in the problem. First, the solver is asked to determine who has the larger amount (Compare), and, second, the solver is asked to compute the value of the difference (Restate).

Table 1

Examples of Situations, Simple Problems and Multi-Step Problems Used in SPS

A. Situations

CHANGE: Samantha was running a lemonade stand one day in the summer. She started out the day with twenty-five glasses of lemonade. When she closed her stand at the end of the day she had four glasses left. Samantha sold twenty-one glasses of lemonade.

GROUP: Mr. Green grows oranges, grapefruits, and avocados. If he has 3000 fruit trees in all and there are 2000 orange and grapefruit trees, then Mr. Green has 1000 avocado trees.

COMPARE: On a recent expedition two members of the hiking club climbed 5000 feet on one day and 6000 feet on the second day. They climbed further on the second day.

RESTATE: Mary budgets her money carefully. She allows herself to spend 15 percent of her weekly income on fun things like going to the movies or stopping for ice cream. Last week she earned $120, so she had $18 for fun things.

VARY: Mr. Borg's car can travel 20 miles on each gallon of gas that it uses. Since he knew that he would be driving 300 miles over the weekend, he figured that he would have to buy 15 gallons of gas for his weekend driving.

B. Simple Problems

CHANGE: Janine had 173 matchbook covers in her collection. Her aunt sent some more to her. She now has 241 matchbook covers. How many did her aunt send to her?

GROUP: Last week the Martin family took their used bottles, cans, and newspapers to the River City Recycling Center. They found that they had accumulated in one year 25 pounds of bottles, 12 pounds of cans, and 50 pounds of newspapers. How many pounds of recyclable materials did they have?

COMPARE: Anna has two jobs. Last week she earned $152 as a lab assistant in the Chemistry Lab and $93 as a cashier in the University Book Store. Which job paid better?

RESTATE: Bill and Eddie both planted tomatoes this year. Bill harvested twice as many tomatoes as Eddie did. If Bill picked 64 tomatoes, how many tomatoes did Eddie pick?

VARY: In the college football stadium there are 28 sections of seats. The stadium has a total of 2128 seats. If each section holds the same number of seats, how many seats are in each one?

C. Multi-Step Problems

1. Joe won $100 in the state lottery. He spent some of it on toys for his children. He bought a doll for Sue that cost $25 and a stuffed bear for Ellen that cost $35. How much money did he have left over after he bought the toys?

2. The electric company charges $.18 for every 3 kilowatt hours of power used. For the month of August Terry was billed for 261 kilowatt hours of electricity. During the same month his natural gas bill was $9.45. Which was higher for the month of August, his electric bill or his gas bill?

INSTRUCTIONAL DESIGN

SPS focuses on these five profiles. At the end of instruction a student should be able to:

* **Recognize the profile(s) in a story problem.**
* **Check that a problem has the required elements of the chosen profile(s).**
* **Design a solution strategy using profile information.**
* **Select the correct arithmetic operation(s).**

SPS guides the student's knowledge development and organization according to the schema theory described above. Our intention is for the student to develop a separate schema, consisting of all four components, for each of the five profiles.

SPS is designed for use by young adults under the assumption that this population shares a body of common knowledge and interests. The subject matter of examples and problems reflects this assumption. Much of the instruction about the semantic profiles is direct. Because the targeted population is adult, it is possible to present extended instruction that would overtax the attention and working memory constraints of young children.

SPS does not expect students to form appropriate schemas by trial and error. Its users are not being introduced to story problems for the first time. They have had a great deal of experience with them and typically have developed poor or incomplete strategies for solving them (evidenced by a lack of success on performance measures). SPS explains directly how and why its organization of knowledge is beneficial. It points out the advantage of using the profiles to understand and solve the problems.

SPS prefaces its instruction by drawing an analogy between understanding a story problem and understanding the real world situation of going to a restaurant. The purpose of the restaurant example and the discussion about how individuals recognize and use knowledge about restaurants is to alert students to the need for many kinds of knowledge and for many links among them. The example demonstrates how various features of the situation are used by an individual to interpret the particular instance (e.g., what makes it a restaurant and not a theatre) and to guide the individual in that setting (e.g., how to order from a menu, how to pay the bill). SPS explains that understanding and interpreting the situation in a story problem can work in the same way. Important features need to be recognized and evaluated before an arithmetic operation can be selected.

SPS addresses each of the four components of schema knowledge for every semantic profile. The student is encouraged to build a cohesive memory structure to link together all of the information that is appropriate to the profile. To do this, SPS isolates the components and focuses upon the elements of each one. It also gives the student experience in linking the components and in using two or more of them in answering questions. SPS does this in part by example and in part by asking questions relating to components and linkages.

For each component of a schema -- feature recognition, constraint mapping, goal setting, and implementation -- SPS uses the principles guiding its instruction in specific ways. These adaptations are described in the following sections.

Feature Recognition

Instruction

The feature recognition component of a schema contains the information needed to recognize that the schema fits the problem at hand. SPS's discussion of feature recognition helps the student formulate the generic case of which any problem is a special instance. The goal of feature recognition instruction is to provide a verbal label, a general description, and a simple pictorial representation for each of the five profiles. Instruction begins by using simple examples of each profile. We found in our pilot studies that students were better able to discriminate among the profiles when the initial instruction about each one was brief and when all five were discussed together. This contrasted with ability to discriminate the profiles having had a sequential, detailed description of each one (see Appendix A). Therefore, SPS begins the instruction with an overview and general discussion of all five schemas and how they differ from each other.

SPS introduces the profiles within the common theme of a Hawaiian vacation. The situations in which the profiles are found describe activities such as buying clothes, surfing, and fishing. As noted above, we selected stories that should be of interest to our young adult students.

The SPS system uses situations instead of problems when introducing the five profiles. Situations are defined as complete stories with no missing information; problems have one or more unknowns. We focused on complete situations for two reasons. The first is logical consistency. Situations contain all parts of the profile and therefore help students understand each part in relation to the whole. Feature recognition involves all parts of the situation, but any specific problem leaves some parts out. That's what makes it a problem. To teach feature recognition, the ***whole*** situation is appropriate.

The second reason for using situations is the nature of the subject population. Most students appear to have strongly ingrained and often erroneous problem-solving strategies, and they tend to begin using them as soon as a problem is presented, often without comprehending the entire problem. This tendency interferes with the goals of SPS. SPS urges the student to understand the structure of the problem before attempting computations. If there is no problem and no unknowns, there is no computation to be made, and the student's attention can be directed to the profile structure.

SPS equips the student with specific clues for identifying each semantic profile. For example, the student learns that in the Change situation there are three different amounts -- the beginning amount, the amount of change, and the resulting amount -- and that the change occurs over time. Other clues about Change are introduced in such a way that the student should easily associate them with earlier ones. In this way SPS directs the learning of the student by presenting information that can be reasonably linked to what the student already knows.

In teaching feature recognition SPS tries to rearrange the knowledge that students already have about semantic relations and story problems and to encourage the students through instruction, example, and practice to form specific memory associations (links). We do not have to explain to students -- even very young ones -- what it means to ***change*** something. We do need to help them develop the skills to perceive when a story problem describes the Change relation. The full set of clues for a profile leads the student to a general description of the profile.

In addition to verbal clues, a simple diagram is used to represent each profile and its various parts. We refer to the diagram as the ***profile icon*** because it serves the same function that an icon serves on computer screens. The icon is a visual representation intended to call to mind several different pieces of information. Merely seeing the icon on the screen serves to remind the student of the broader entity it represents. Similarly, many trademarks and logos function to remind the viewer of a broad set of information that is associated with them (e.g., the CBS "eye" or the Apple logo). These visual representations appear to be easily learned and retrieved.

A growing body of research suggests that visual aids are very powerful learning tools (e.g., Larkin & Simon, 1988; Holmes, 1987). We use them as such. It is intended that students associate the features of a profile with the appropriate diagram. The icons also serve a second function in constraint mapping as described below.

Evaluation

Feature recognition is assessed in two ways. One way is to determine whether or not the student can correctly identify a situation by its generic name. The evaluation task presents the student with several story situations, one at a time. Below the story is a menu of the five profile names. The student's task is to select the single profile that is represented in the story. Thus, the task assesses both whether the student can identify the relevant features in the situation and also whether these features have been associated with the appropriate profile in the student's memory.

The student's responses on this task, as on all SPS tasks, are made with the mouse. The student selects the profile and buttons the menu choice. An illustration of the task is given in Figure 1.

Figure 1
A Feature Recognition Task: Verbal Components

(The student selects a response from a menu of situation names.)

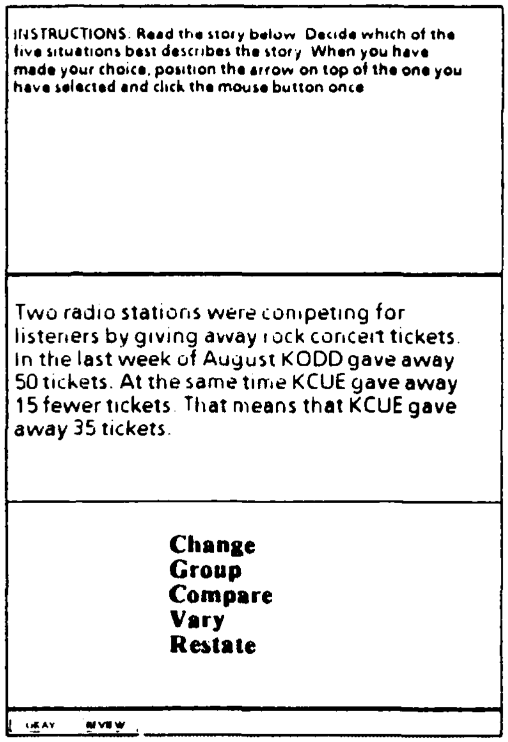
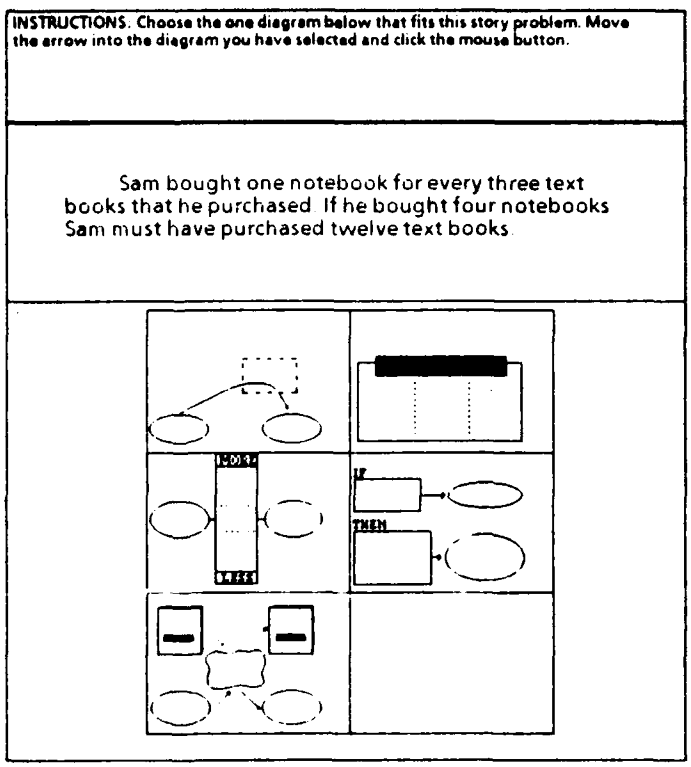


Figure 2
A Feature Recognition Task: Visual Components

(The student selects a response from a menu of diagrams.)



A second method of evaluation assesses the student's ability to associate a situation with its visual icon (diagram). The student is presented with a problem and the five icons and is asked to select the one that represents the problem. No verbal labels are used in this exercise. The task serves to assess whether the student associates individual icons with appropriate sets of features that identify the profiles. An example is given in Figure 2.

Constraint Mapping

Instruction

The goal of constraint mapping instruction is to develop systematic methods of testing whether or not hypothesized features are present. This component of schema knowledge maps the elements of the current problem to the known features of the selected profile. For instance, by using feature recognition knowledge the student might suspect that the profile describing a problem is the Change profile. This information alone is insufficient for problem solving. The student needs to ascertain that enough of the features that characterize a Change profile are present in the current problem to allow solution. In the case that the feature recognition was incorrect, the student will also find that out when important elements of the problem do not map into the Change profile.

It is useful to think of the constraint-mapping knowledge in a schema as the means by which the student constructs a working mental model of the problem being solved. The student reads a problem, calls upon feature recognition knowledge to suggest the appropriate profile structure, and then builds the model of the problem by testing whether the necessary pieces are present. When the student is *beginning* instruction, SPS displays the diagrammatic representation of the profile and visually places various parts of the problem into the diagram. As students become more expert in solving problems, SPS anticipates that they will do the matching process mentally. SPS focuses its instruction on linking parts of the story problem to the essential elements of each profile. To illustrate the instruction, we present here a discussion of the Change profile. Instruction for the remaining profiles is similar.

To develop the student's understanding of the Change profile, SPS presents a three-part figure designating beginning amount, amount of change, and resulting amount. Using a simple situation (with no unknowns) SPS leads the student through the diagram, placing the relevant numerical quantities inside the diagram and explaining why and how these quantities join together to form a Change relation. Several examples of the how one maps a Change situation follow the explanation.

After a student has had the opportunity to practice mapping situations into the Change diagram (the task itself is described below in Evaluation) SPS introduces problems in which one of the parts of the figure has no corresponding numerical value given in the story. This instruction begins with a simple situation, mapped into the three parts of the figure. SPS asks the student to consider what the situation would look like if one of these three parts were unknown. The diagram changes on the screen so that the unknown part contains a question mark. The story problem is reworded to contain a question about the unknown. The diagram then changes again so that a different part contains the question mark. The problem changes as well and the question is different. In this way SPS gives explicit instruction about the question asked in the problem and the location of the unknown in the diagram. SPS takes the student through the allowable set of unknowns and corresponding questions for each profile. The series of questions asked about a particular Change situation is illustrated in Figure 3.

Previous studies with sixth-grade students, with the pilot-study students, and with university freshmen indicate that there are two areas of confusion that instruction should address (c.f., Marshall 1987, this report, Appendix A). First, students tend to confuse Change and Group problems, especially when the arithmetic operation of addition is required. Second, students tend to confuse Restate with Compare, again in the presence of addition and subtraction. Consequently, SPS introduces the Change constraints and diagram first, going through the complete instruction, and then does the same with the Group constraints and diagram. When both have been fully covered, a special exercise calls for the student to discriminate between the two profiles (by choosing the appropriate icon from a menu containing both of them) and to make the constraint mapping once the correct diagram is selected. SPS moves on to instruction about Compare and then separately to instruction about Restate. As with Change and Group, when both Compare and Restate have been covered, the student is asked to demonstrate ability to discriminate between the two and then to map parts of the problem into the appropriate diagram. A discussion of the Vary profile concludes the constraint-mapping instruction.

Evaluation

Evaluation is in two parts: constraint mapping per se and the relation of constraint mapping and feature recognition. SPS uses two types of tasks to evaluate students' constraint-mapping knowledge. In the first SPS gives the student a set of five situations. Each of the situations is best described by a single profile. The task for the student is to match each of the five situations with the name of the appropriate profile. This task includes and extends feature recognition knowledge because it requires the student to identify a generic profile for the a situation and also requires confirmation that the profile does not more accurately describe another situation. The student must consider each profile with each situation, deciding when the elements of a situation sufficiently match the structure of a profile. This task forces the student to compare the five profiles and the five situations with each other.

In the second evaluation task used to assess constraint-mapping knowledge, SPS asks the student to use constraint-mapping knowledge to position the relevant parts of a story into a given diagram. The situation (or problem) and the correct blank diagram are presented simultaneously. The student moves the mouse cursor to the part of the situation that he or she intends to place in the diagram. When the student clicks the left mouse button, the student's selected text is printed inversely on the screen (i.e., light on dark instead of dark on light). A dotted rectangle having the same size and shape as the selected text appears on the screen, connected to the cursor. Now moving the cursor will move the rectangle. The student moves the cursor and the attached rectangle, this time to the place in the diagram in which the text is to be positioned. Another click of the mouse button drops the text into the diagram.[2]

SPS simplifies these tasks for the student as much as possible. In the constraint-mapping task it does not force the student to move parts of the story word by word. That would be tedious and unnecessary. In most instances the student needed an entire phrase (e.g., for the relation "twice as much as") rather than a single word or number. Consequently, when the situations and problems were initially entered into SPS, certain phrases were identified as ***chunks***. Some of these chunks are necessary parts of the problem solution (e.g., the number and its identifier, as in 25 cookies). Others were not necessary but typically appear together (e.g., names such as Mr. Harris). Because a student could select any part of a problem, we chunked all reasonable elements in a problem, whether or not they were required for solution. When the student buttons in any part of a chunk, the entire set of words and numbers that make up the chunk are changed to inverted print. The individual elements cannot be moved by themselves.

During this task the student has considerable flexibility. If the student desires to modify a previous response, it can be done simply by buttoning on the selected text, moving the cursor (and attached rectangle) out of the diagram, and buttoning again. The student then returns to the problem, selects another part, and drags it into position. Like all exercises in SPS, this one is under student control. SPS will not continue with problem presentation or with additional instruction until cued. For the mapping exercises, the student indicates that the diagram is filled and ready for SPS to check by selecting "OKAY" from a control menu printed at the bottom of the screen. At that point SPS evaluates the response and gives feedback. If the student has made correct selections, the feedback is positive and SPS asks the student to indicate readiness for another exercise. If the student has erred, SPS informs the student of a mistake and gives the student a second change to map. If the student is incorrect a second time, SPS displays both the student's choices and the correct responses. Again, the student indicates when to continue by making a selection from the control menu.

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[2] SPS teaches these moves in a tutorial before initial instruction begins and also reviews them at the start of the exercise. Our subjects had no difficulty in learning the mechanical steps.

Figure 3

The Multiple Questions of Change

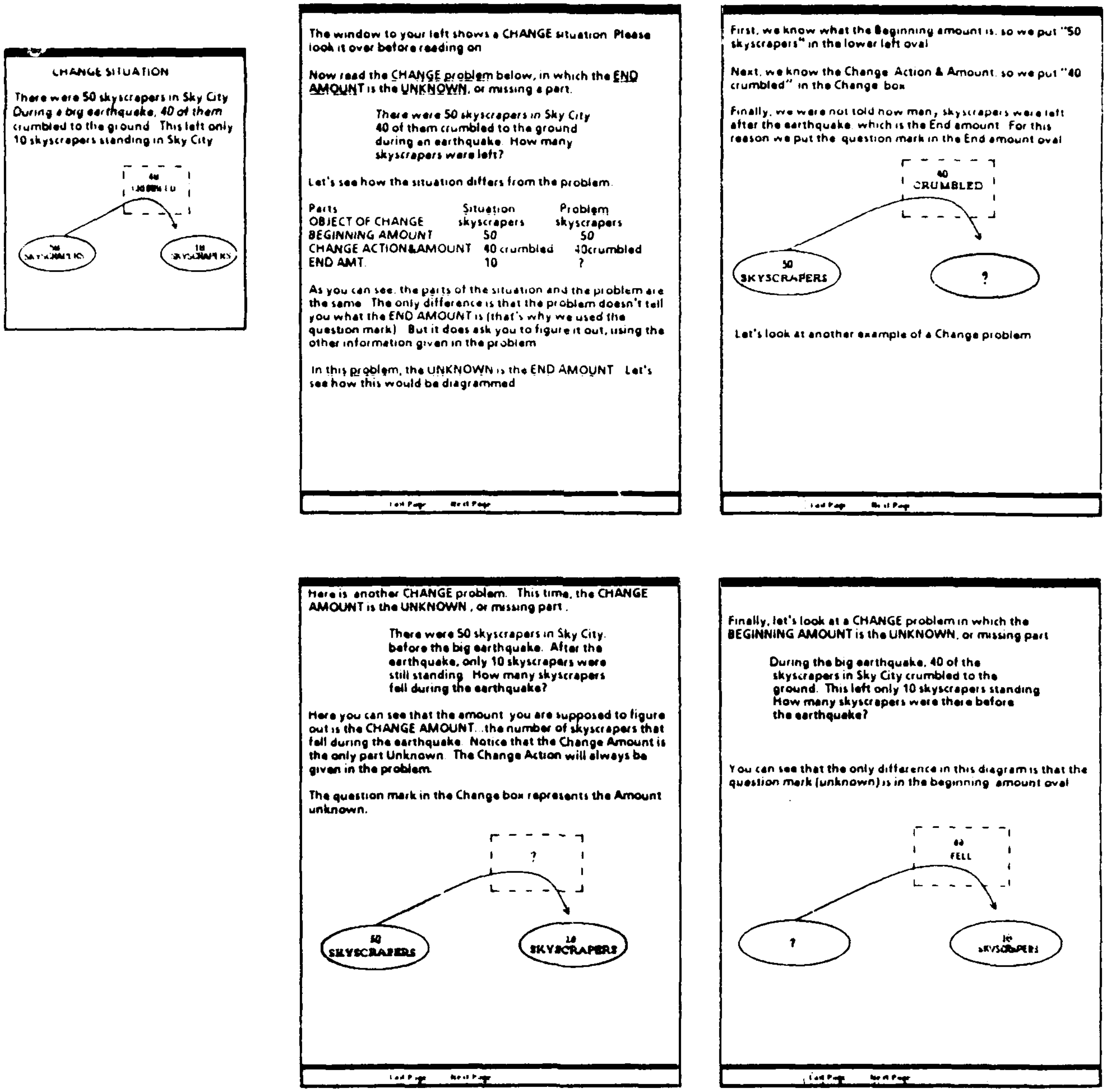
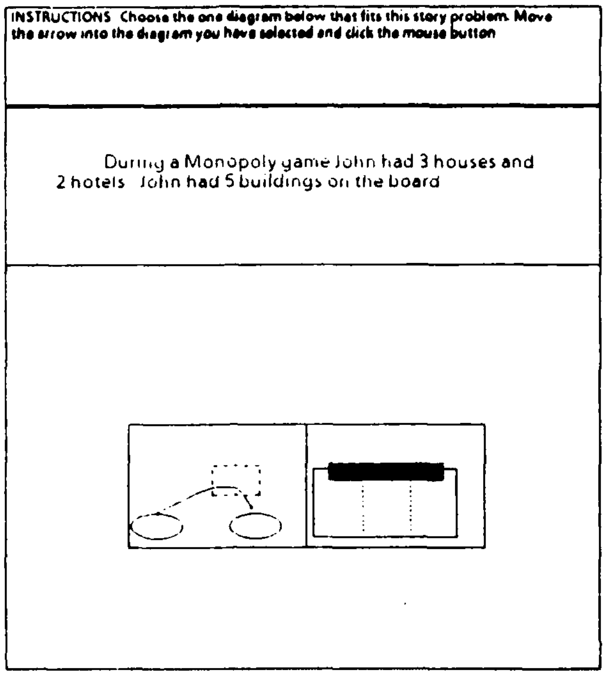


Figure 4

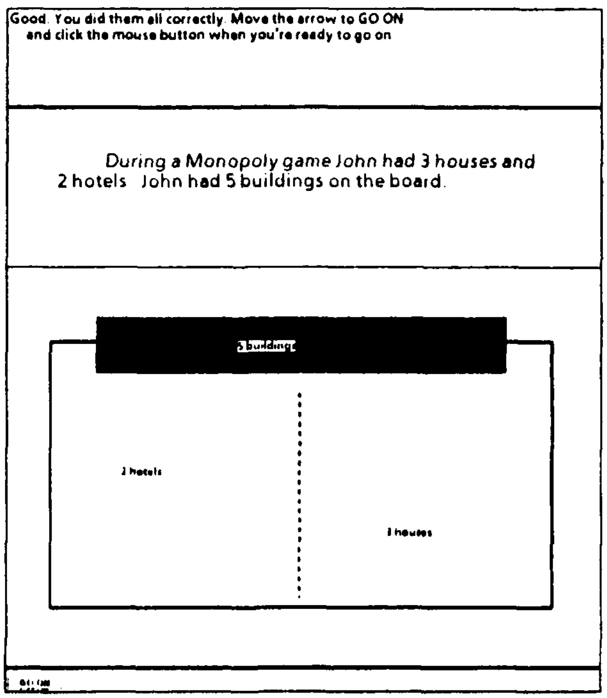
A. Feature Recognition

(The student first selects the appropriate diagram from a menu.)



B. Constraint Mapping

(The selected diagram is enlarged, and the student maps the elements of the problem into the diagram.)



The task which assesses the link between feature recognition and constraint mapping elicits two responses from the student, a discrimination among types of profiles and a mapping from the problem to the profile. In the task students are presented with a mixed set of problems and situations. Each problem or situation is displayed with a menu of icons. The student's first response is to select the appropriate icon (a feature-recognition test). If the student makes the correct choice, SPS gives appropriate feedback and replaces the icon menu with the profile diagram which is an enlarged version of the selected icon. The student's second response is to map the problem into the diagram (a constraint-mapping evaluation). If the initial selection from the icon menu is incorrect, SPS provides feedback about the choice and then displays the correct enlarged diagram.

SPS has three versions of this task. One of the versions follows instruction about Change and Group, and offers a choice only of these two profiles. A second, similar version follows instruction about Compare and Restate and allows choice of these two. The third version follows instruction and practice with the Vary profile. In the last one they choose from all five profiles. Figure 4 illustrates one of the two-choice evaluation items.

Planning/Goal-Setting

Instruction

Planning is quite simple in problems involving only one profile (i.e., one-step problems). SPS does not teach planning at this level. It deals with planning in problems involving two or more profiles (i.e., multi-step problems). To solve a multi-step problem, the student must recognize the different profiles in the story and order them in such a way that the correct solution can be obtained. This entails recognizing the overall profile of the situation and determining how the subsequent profile or profiles are subordinated to it.

SPS's instruction on planning has three parts. Part one is recognizing which profiles are primary and which are secondary. Part two teaches mapping what is known about the problem into the overall or primary profile. Part three develops links between components of two or more profiles. All three emphases are important in developing a plan. Ideally, a student should ask himself or herself a sequence of questions about them such as the following:

> ***PROBLEM:*** *Sarah had $1575 in her checking account at the end of March. She deposited a payroll check of $870, a gift from her parents for $200, and a refund check from IRS for $315. How much was in her account after she made the deposit?*

Q: Do I know the overall profile? *(feature recognition)*
A: Yes, it's a Change.

Q: Can I solve it yet? *(constraints)*
A: No, there are two missing parts.

Q: Is there a second profile? *(feature recognition)*
A: Yes, it's a Group.

Q: Can I solve this one yet? *(constraints)*
A: Yes, it has three subgroups and I know all of them.

Q: Will the solution help me solve the first one? *(goal-setting)*
A: Yes, the Group result is the amount of change required in the Change problem.

Q: What will my goals look like?
A: The top goal is Change followed by Group.

Q: How shall I proceed to solve the problem?
A: Take the lower goal (Group) first. Solve for it.
Then take the next goal (Change) and solve for it.

In teaching students to recognize primary and secondary profiles SPS stresses the difference between top-down and bottom-up problem solving. It advocates a top-down strategy for planning and a bottom-up strategy for carrying out computations. The relationship between these two strategies is made explicit through one of SPS's extended examples.[3] The example centers on going to medical school. SPS develops a plan that outlines the requirements for getting accepted, such as having a satisfactory GPA, having letters of recommendation, and so on. The plan is developed graphically on the screen, with the goal (going to medical school) positioned at the top center and with subgoals branching below it. These subgoals are themselves developed further by outlining what each entails (such as scoring well on tests, going to class, etc. for having a satisfactory GPA). When complete, the full plan has the goal at the top, and it extends downward through subgoals to their constituent parts at the bottom.

SPS then discusses how the goal might be achieved and points out the need to carry out all the steps at the bottom of the plan in order to move up to the next level of subgoals. The plan development has arrows flowing from the overall goal down to the subgoals. The plan execution reverses the arrows: They begin at the lowest part of the figure and point up to the next subgoal.

SPS draws an analogy between the medical school scenario and a multi-step problem, showing the student that the identity of the primary profile dictates the overall goal. At each step in solving a problem the student should evaluate whether the overall goal has been reached or whether the pursuit of a subgoal is needed. Subgoals correspond to secondary profiles embedded in the problem. Thus, SPS encourages the student to develop a system for representing the story problem abstractly in terms of its constituent profiles and to use that representation as a plan for problem solving. Further SPS instruction on planning centers on knowledge about semantic profiles. SPS frequently refers to the icons of feature recognition and the diagrams introduced in constraint mapping. For simple one-step problems, all but one of the parts of a profile diagram can be filled directly with information given in the problem. The single unknown corresponds to the question posed in the problem. Multi-step problems have more than one unknown in the overall profile. One of these corresponds to the question posed in the problem, just as it does in a one-step problem. The unknown associated with the stated question represents the primary goal, and the overall profile is the primary profile. The other unknown quantities, while not answering the primary question, must nevertheless be found before the problem can be solved. SPS calls these secondary problems. Each secondary problem is solved by recognizing the semantic profile and using information from the associated schema. These associated profiles are called secondary profiles. SPS uses only two-step problems in instruction, and, consequently, it focuses on a primary profile and a single secondary one.

As part of its instruction SPS maps simple one-step problems into their respective profile diagrams by placing the numerical quantities into the parts of the diagrams. The mapping at the multi-step level is more complex. To help students understand what is known or already given in a problem, SPS makes an abstract mapping into the overall profile diagram. It uses the terms ***Given*** for information that is explicitly stated in the problem, ***Partial Answer*** for information that can be derived immediately from the Given information, and ***Final Answer*** for the value of the primary unknown. Final Answer will require having the solution for Partial Answer. This language promotes the maintenance of an abstract mental model of the entire problem. The advantage of the abstract model is that it is easier to maintain in short-term memory when the student begins solving the problem. As the student attempts to solve the

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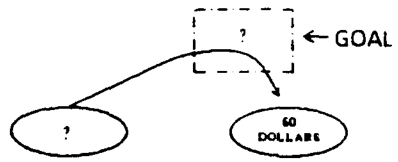
[3] As with the other extended examples in SPS, this one was developed to be of particular interest to our adult population. It would not be appropriate for elementary or middle school students.

Figure 5

A Multi-Step Plan in SPS

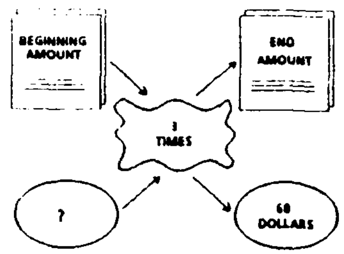
THE PROBLEM

Eric arrived at the horse race track with three times as much money as he left with. He left with $60.00. How much did he lose at the track?



What's missing in this diagram?

You can see that the **BEGINNING AMOUNT** (the amount of money Eric arrived at the track with), and the **CHANGE AMOUNT** (the amount of money Eric lost at the track) are **UNKNOWN**. The goal of the problem is to find out what the **CHANGE AMOUNT** is. Obviously we can't do this without finding out what the **BEGINNING AMOUNT** is. How can we do this?



You can see that by solving the RESTATE situation, you get the information needed to solve the main CHANGE situation.

Since the answer to the RESTATE situation helps you find the answer to the main CHANGE situation, we call this the partial answer.

We call the answer to the CHANGE situation the final answer, since it is the answer to the problem.

THE PLAN

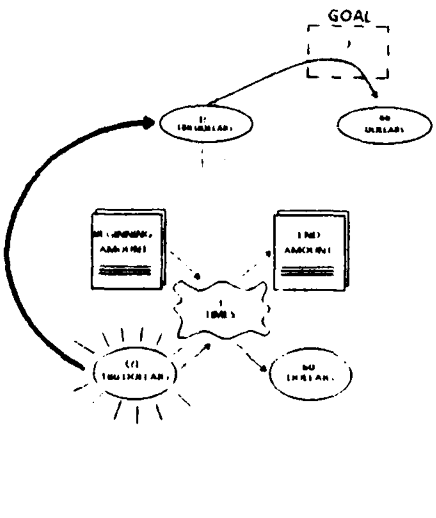
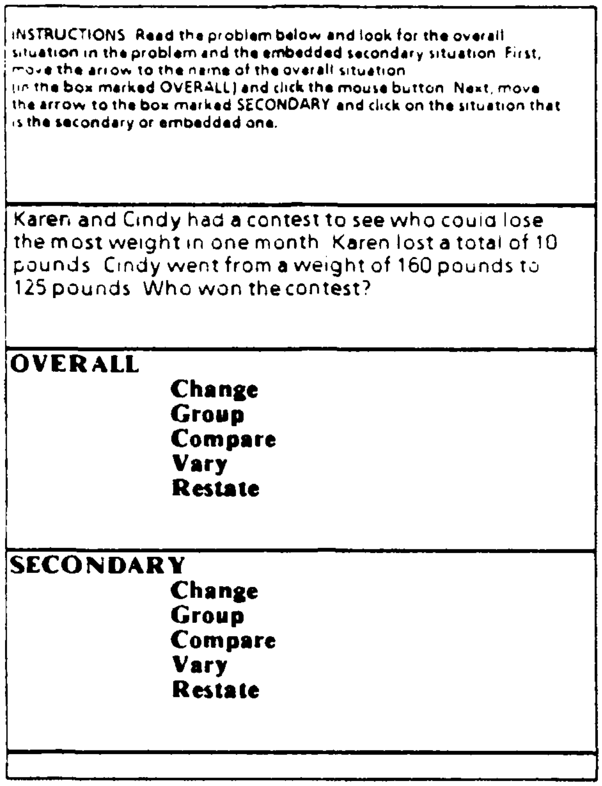
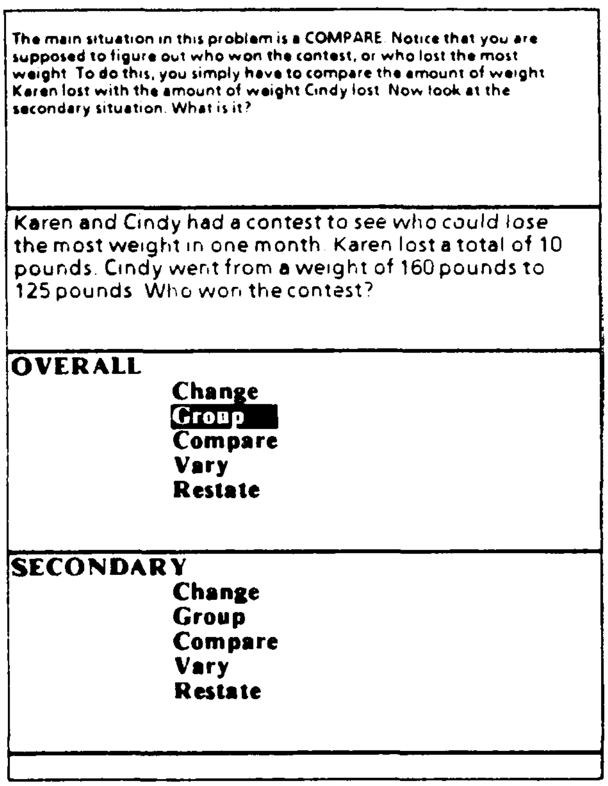


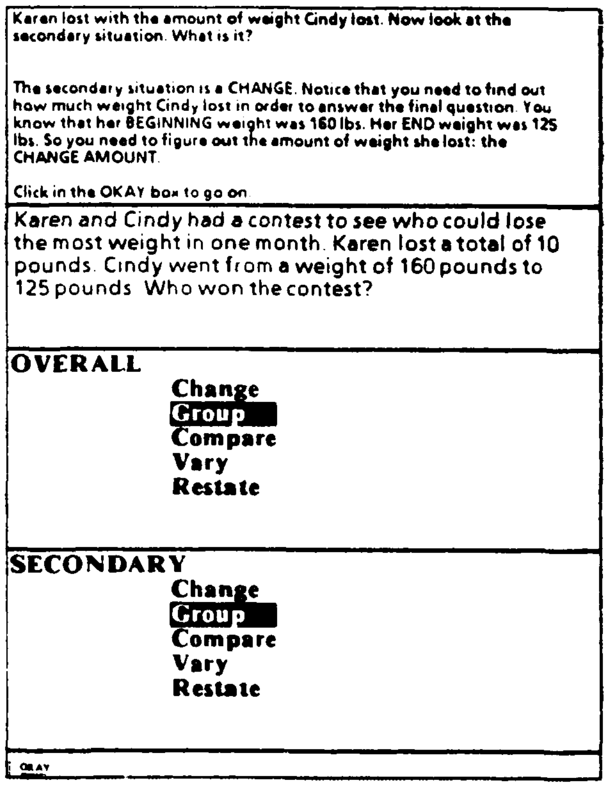
Figure 6
Exercise in Recognizing the Primary and Secondary Profiles



(The problem as presented to the student.)



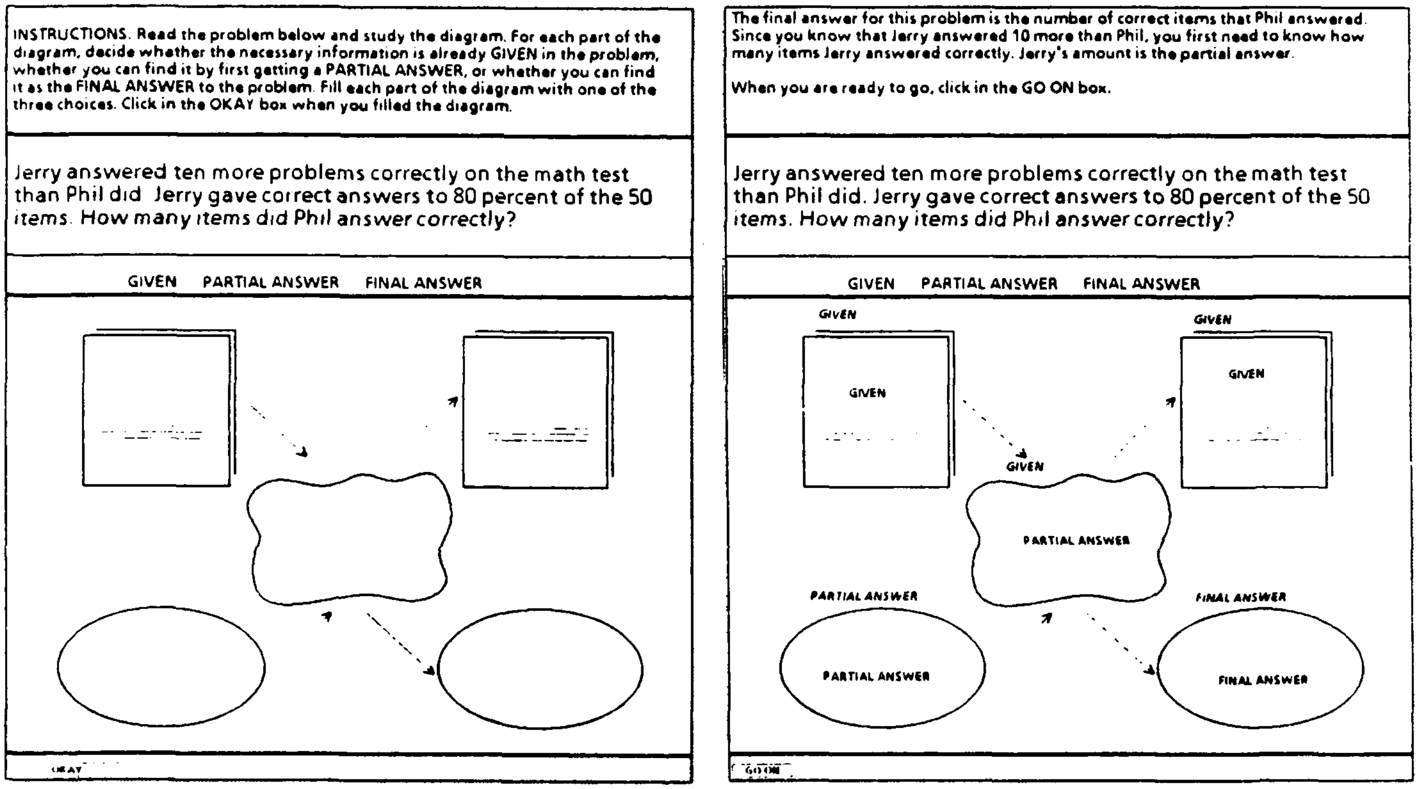
(The student responds to the first question by selecting an item from the OVERALL menu and receives feedback.)



(The student responds to the second question by selecting an item from the SECONDARY menu and receives feedback.)

Figure 7

Exercise in Abstract Mapping
of a Multi-Step Problem



(The student is asked to identify the parts of the problem.)

(The student's responses appear within the diagram. Correct answers are given in italics above each component.)

problem, of course, he or she will need specific information about the parts of the model and more detailed mapping. The abstract model is then developed more completely profile by profile.

An important feature of SPS's instruction is the explanation of how two or more profiles fit together within a single problem. This is done abstractly, as described above, using the terms Given, Partial Answer, and Final Answer. It is also done more concretely by focusing on the profiles, their constituent parts, and the way these parts are related. SPS takes the student through the planning and linking of profiles for several examples. With each example SPS points out the overall profile and displays the appropriate diagram. Two parts of the diagram contain question marks, indicating that they are both unknown. One of the unknown parts can be found by looking at a second profile that is also present in the problem. SPS displays a second diagram, linking it to the first (see Figure 5). SPS emphasizes that the solution found with the second diagram will have a place in the first. Thus, the two profiles are linked through specific components of the diagrams.

One strength of using icons to represent the semantic profiles is that they can be easily and clearly linked to each other. These connections are important in solving multi-step problems. Students need to visualize how the profiles can be joined together to form a complex problem. With the icons SPS can show them directly.

Evaluation

Two of the instructional goals described above are evaluated directly in the current implementation of SPS. A third form of evaluation is under development and will be incorporated into the system this year. The two that are now in use evaluate whether the student is able to recognize the primary profile in a multi-step problem and whether the student is able to complete an abstract model of a problem. The third task involves linking the icons and is described at the end of this document under *System Extensions*.

Students identify main and secondary profiles in several exercises. The first of these exercises involves reading a multi-step problem and selecting one of two choices for the main situation. As with the constraint mapping instruction, SPS develops the concept first with only two of the profiles (Change and Group) and allows the student to master them. Two others are then studied (Compare and Restate) with accompanying exercises. After the full set of profiles has been reviewed, SPS presents a series of problems involving a random mixture of all five.

After the student has become proficient in finding the primary profile, SPS assigns tasks involving the identification of both the main and the secondary situations. In this case the student gives two responses by making a choice from a menu of primary situations and a choice from a menu of secondary situations. Figure 6 illustrates this exercise.

SPS also evaluates the student's ability to map multi-step problems abstractly. Rather than having students move text from the problem into the appropriate diagram, SPS asks the student to locate the words ***Given, Partial Answer,*** and ***Final Answer*** within it. As before, the student is given the opportunity to change a response if it is incorrect. After two failing attempts to make the abstract map, SPS shows the student the correct mapping, as shown in Figure 7.

Implementation

Instruction

The last segment of SPS instruction addresses the selection of an appropriate arithmetic operation for solving a story problem. This is the first time arithmetic computation is mentioned. At this point SPS cautions that relying only on key words such as "have left" or "altogether" in choosing an appropriate arithmetic operation often results in errors. It stresses instead that choice of operation is dependent upon profile identification and upon awareness of which part of the profile model is missing. This is an important aspect of schema-based instruction: The use of key words and set equations is ***not*** a satisfactory method for solving problems. Unfortunately, it is sufficient for many simple one-step problems, and a large number of students apparently have developed key-word strategies (c.f., Marshall, 1982, Sowder, 1987).

The following example illustrates the instructional methods employed in SPS. Consider this Change problem:

> ***Jim added 20 more baseball cards to his collection. He then had 68 cards altogether. How many cards did he have to begin with?***

SPS explains that, although this situation clearly reflects the addition of the new cards to the existing ones, the arithmetic operation needed to solve the problem as stated is not addition. SPS points out that in this case the initial amount is unknown. To find it the student needs to subtract the amount of change from the total rather than add the two. In this problem SPS encourages the student to identify the profile (Change), to use constraint knowledge and feature recognition knowledge to develop the appropriate diagram (either mentally or on paper), and to determine where the unknown occurs within the profile.

Students using SPS already have strong knowledge of arithmetic operations -- including algorithms, usages, and requirements. SPS augments the student's operational knowledge and helps create schemas that incorporate the existing knowledge with new knowledge about semantic profiles.

SPS implementation instruction consists of a brief review of the important parts of each profile, examples of profile-specific problems with each part missing, and the appropriate operation to be used in each example. Diagrams are used to show the student how to determine which part is missing and how to consider which operation to use in finding it. This section of instruction refers directly to the recognition, constraint mapping, and planning components of SPS and links them with the implementation component.

Evaluation

An exercise follows the computation discussion about each profile. In each exercise SPS presents a problem and asks the student to select an arithmetic expression that will solve it. The arithmetic expression does not require the student to make a computation. The expression has the form "Subtract 250 from 375" or "add 5 and 8". Following instruction and exercises for each profile is a task in which problems representing all five profiles are randomly presented. Figure 8 shows this task.

The Synthesis

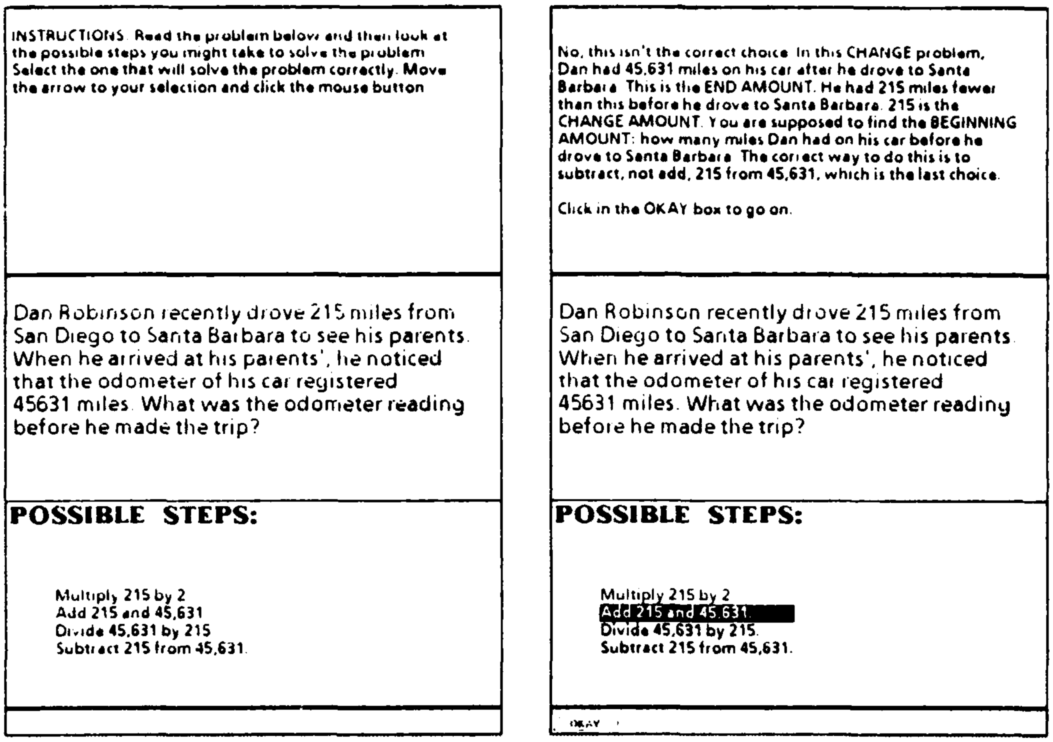
Two assessments are made at the end of instruction, an on-line test and a traditional paper-and-pencil evaluation. The on-line task requires the student to recognize, diagram, and plan a solution strategy for problems which contain various combinations of the five profiles. This exercise tests whether all of the knowledge is successfully linked together. It also gives students practice in using the components simultaneously. The student makes two responses in this task. The first response is the choice of the appropriate icon (feature recognition). The second response is to indicate the unknown in the selected icon. Knowledge of constraint mapping and planning are required here but are not specifically and separately cued. The student must make the mental mapping (either specific or abstract) to locate the overall unknown of the problem.

The paper-and-pencil evaluation consists of a set of multi-step problems. For the first time students are asked to solve the problems, carrying out the operations and answering the questions posed in the problems. They are also asked to indicate which of the profiles are present in each problem.

The two forms of evaluation provide data about which parts of the schemas are well learned. In aggregation these data provide information about the efficacy of the system and give clues about where instruction might be expanded, compressed, or otherwise improved.

Figure 8

An Example of an Implementation Exercise



(The student makes a selection from a menu of responses.)

(The student's response is inverted. Feedback is situation-specific.)

SYSTEM DETAILS

Equipment. SPS was developed in Lisp on Xerox 1186 AI work stations with 40 megabytes of memory. Each work station is equipped with a Xerox 6085 series keyboard, floppy drive, 19-inch display, and a three-button optical mouse.

The Instructional/Experimental Setting. In field tests and in experimental laboratory studies students worked independently. Typically, four students were present at the same time, each interacting with SPS at a stand-alone work station. Students participated in 5-8 instructional sessions, with most sessions lasting 45-60 minutes.

Student Responses. Students interact with SPS by means of the optical mouse. A special tutorial instructs them in the use of the mouse prior to the onset of SPS instruction about the profiles. Students move into the SPS instruction only when they have mastered use of the mouse. The mouse tutorial shows the students how to move the cursor on the screen by moving the mouse, and it gives students practice in making menu selections and in moving items around on the screen. At the end of the tutorial students complete a short exercise using the skills they had just learned. When students appear to have trouble manipulating objects on the screen, the system provides them with more practice.

In SPS students respond to items in one of two ways. The first way allows students to make a menu selection. Typically the menu contains two to five items, and the student need only move the cursor to the item selected in the menu and press the left or middle mouse button. See Figures 1, 4b, and 6 as examples.

The second response mode involves repositioning items on the screen. For this response the student aligns the cursor and the item to be moved (usually text) and presses the left button. The selected item changes to inverse print on the screen and a dotted box having the shape and size of the selected item appears. When the cursor is moved, the dotted box moves with it. The student positions the dotted box in the desired new location and again presses the mouse button. The inverted region returns to normal, the dotted box disappears, the selected item is copied onto the new location. Figures 2, 4b, and 7 illustrate this response type.

Screen Design of Instruction. SPS presents much of its instruction through a central 6 1/2" x 9" window on the 11" x 15" screen. Attached to the window is a menu with the options "Next Page" and "Last Page", allowing students to proceed at their own pace, moving to the next page or returning to previously displayed instruction if desired. Other windows, up to three at once, appear at various times during instruction. These windows are of differing sizes and locations. They allow simultaneous presentation of an example problem, a description of its structure, and a graphical illustration. Control of the display passes from window to window. Some of them remain on the screen as others change or vanish.

Exercise Design. Exercises drill the particular features of problem solving covered by SPS instruction. Many of these concepts are intermediate problem-solving steps that may be rarely observed in ordinary instruction. SPS contains thirty different exercises. The individual student may encounter all of them or a subset, depending upon the time limitations for instruction. Typically, whenever a new concept is introduced through instruction, it is followed by a simple exercise that further demonstrates the concept and allows the student to use it directly.

The exercises are designed to allow explicit evaluation of the four components of schema knowledge as described above. Some of them have only a single response from one menu, some contain multiple menus and hence multiple responses, and still others necessitate making selections and moving elements around on the screen. When the response is a menu selection, SPS evaluates the student's response and makes appropriate feedback (as described below). The student has only one opportunity to respond to an item and SPS evaluates that response as soon as the menu selection is made.

Evaluation is delayed in tasks requiring the student to move items. This design is most often used in the diagramming exercises. Such tasks generally have several items to be moved. SPS gives the student several opportunities to respond and delays evaluation of the response until the student signals completion by buttoning in a control menu window. SPS assesses the accuracy of each item that has been positioned in a diagram and allows the student a second attempt if any of the items is incorrectly located. The student first buttons on the "FIX" option in the control menu window, clearing the screen of the previous response. The student then repositions the items as desired. Once the student is satisfied with the new response, he or she buttons on the "OKAY" option. SPS evaluates the response and gives feedback. To continue the student buttons on "GO ON" in the control menu window.

Item Banks. SPS requires three item banks: situations, one-step problems, and multi-step problems. Each bank contains a large number of items, and each item has a set of properties associated with it. SPS uses these properties to assess correct responses to the various exercises and to provide relevant feedback to students. Each item may be used in a variety of exercises, and there is no single correct answer associated with each one. Depending upon the exercise, the appropriate answer might be the identification of the underlying profile(s), the correct mapping of the specific elements of the item, an abstract mapping, or an arithmetic expression.

SPS uses problems and situations that were created for it and that conform to the following criteria: Traditional key words and phrases are avoided whenever possible. themes and story lines are appropriate for young adults. Items are worded for clear mapping into the profile diagrams, and numbers used in the problems are simple.

Feedback. SPS provides feedback to students who answer an exercise question incorrectly. The nature of the feedback depends upon the particular exercise. In the feature recognition tasks, SPS's response to the student depends upon how the student is doing in the particular exercise. If the student makes two errors in identifying a particular profile, SPS gives supplemental review about that profile. If the student has erred on three consecutive items, SPS provides a general review of all profiles. If the student is generally doing well but makes an occasional error, SPS gives a short message indicating why the student's answer is incorrect.

Feedback on the mapping tasks is brief. When a student first errs on an item, SPS indicates that the response is incorrect and asks the student to try again. After a second error on the item, SPS simply shows the student the correct mapping. The student's own attempt remains on the screen together with the correct response so that the student can see how his or her answer differs from the correct assignment.

The planning exercises demand a different type of feedback. When the student selects an incorrect primary or secondary profile, SPS gives problem-specific feedback, indicating why the student's selection is in error and identifying specific characteristics of the problem to which the student should attend. The implementation exercises also incorporate problem-specific feedback.

Each instructional session ends with a task for which no feedback is given. Sessions are typically 50 minutes in duration (similar to a class period in high school or university). SPS monitors the time and ends the instructional session at an appropriate juncture, usually at the conclusion of a set of instruction and related exercises. Before the student leaves the work station, he or she is asked to respond to an end-of-session task which functions as a daily quiz. In early sessions, the task involves matching the five profile names to five story situations. In later sessions, the student identifies the location of the unknown in the problem. On both of these tasks, the student makes his or her responses to a small number of items and then exits the program.

Record Keeping. SPS keeps a continuous log of each student's activity. It records the date, the time required for each exercise, the specific problems used in the exercise, the student's responses to each problem, and SPS's rejoinder. During each exercise SPS refers to the log and to the student's current responses to develop a model of how the student is performing. At various points in the exercises, SPS will stop the student and will provide additional instruction if the student appears to need it. This supplement may take the form of a quick review or may be an extensive remediation.

System Implementation

SPS has been used in a four-week remedial course for community college students enrolled in basic mathematics or beginning algebra courses. The course met twice a week for a total of eight class sessions. Approximately twenty-five students completed the program of instruction. This course served as a field test and led to several important system modifications.

SPS has also been the basis of laboratory experiments in which college freshmen participated. These students attended five sessions and were individually interviewed following each session. Some of them also participated in a follow-up study two to three months after the original study. Data from these implementations are currently being analyzed and will be reported in a separate report. Initial indications are that students can easily learn the semantic profiles, they can carry out the constraint mapping and planning tasks, and they find the icons useful.

System Extensions

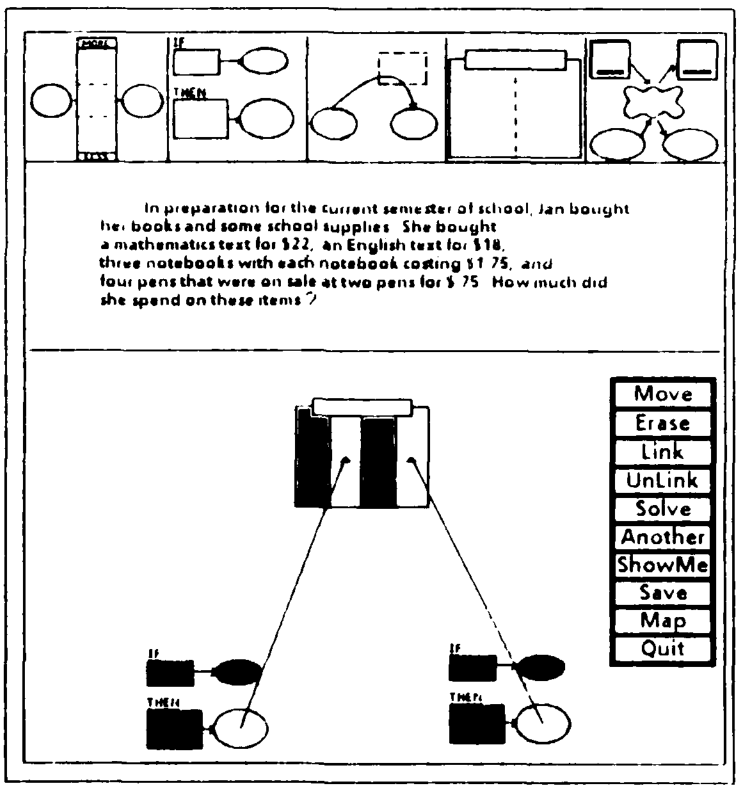
Once the students have developed semantic schemas for story problems it is desirable to have an environment in which they can instantiate them and in which SPS can monitor the usage of them. To this end we have developed a problem environment (PE) in which the student has the capability of selecting icons to represent parts of a multi-step problem and of manipulating them to model the problem.[4] Figure 9 illustrates the environment.

The problem environment is student-controlled. The student can select which icons to use, can link and unlink them, can enlarge and map the various parts of them, and can ask for confirmation or help from SPS at any point. SPS will not direct the order in which any of the problem-solving steps are carried out by the student. SPS provides advice when asked and will test for the student whether a representation leads to a successful solution of the problem.

[4] We acknowledge J. P. Marshall for his programming assistance in building the problem environment.

Figure 9

The Problem Environment



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APPENDIX A

Prior to the development of SPS we carried out experiments to evaluate specific design features for SPS. Described here is one experimental study of the effects of sequential versus all-at-once presentation of the situations.

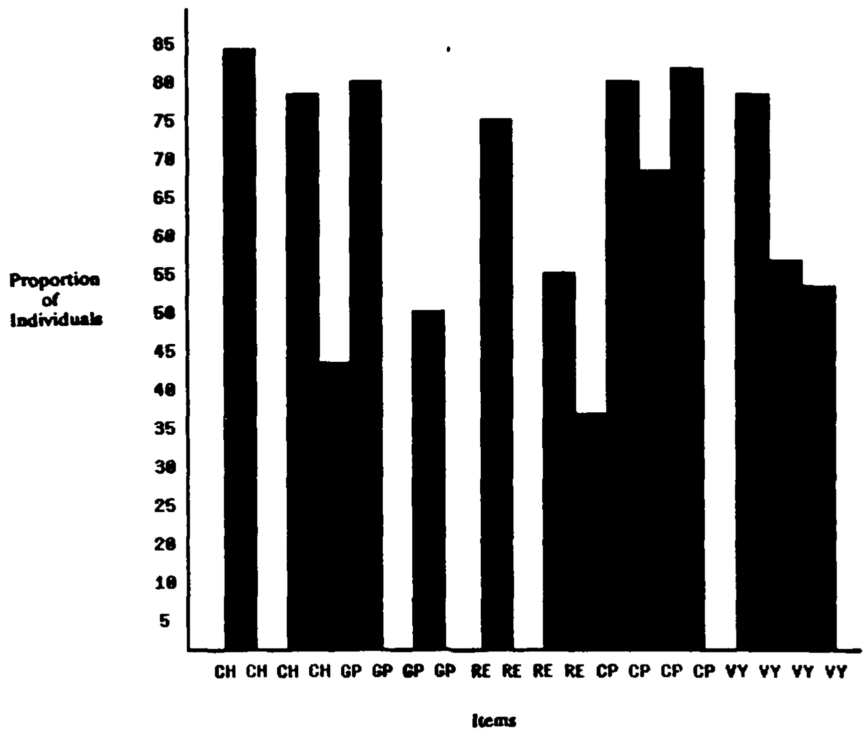
The Experimental Question: The issue is whether students will be more successful in learning when each situation is described individually and in detail, one at a time, or whether students will be more successful in learning when all five situations are introduced broadly and then described in relation to each other. The former should cause greater depth of feature recognition information but perhaps be weaker in constraint (and discrimination) knowledge. The latter should build a knowledge base that allows easy discrimination among the situations but may lack adequate feature knowledge.

Procedure: 126 San Diego State University students participated in the study. Half of them received Sequential Instruction (with each type of situation developed fully before the presentation of another one) and the remaining half received Parallel Instruction (with all types presented at once and discussed together). Each student worked through a paper-and-pencil exercise booklet. At the conclusion of the experiment, the students were asked to sort 20 problems according to the situations they had just studied. The sorting task was used to evaluate the students' understanding and recognition of the five situations.

Results: Cluster analyses of the sorting task are given in Figures A.1 and A.2. All students learned something about the situations, and they were able to sort more than half of the problems correctly. The students in the Parallel group performed better on this task. They were more successful in forming appropriate clusters of the problems, and their clusters were more tightly linked (as can be seen by the shape of the clusters in the figures). Moreover, the Sequential Group had difficulty in distinguishing between Compare and Restate. The largest cluster formed by this group contained problems of both types.

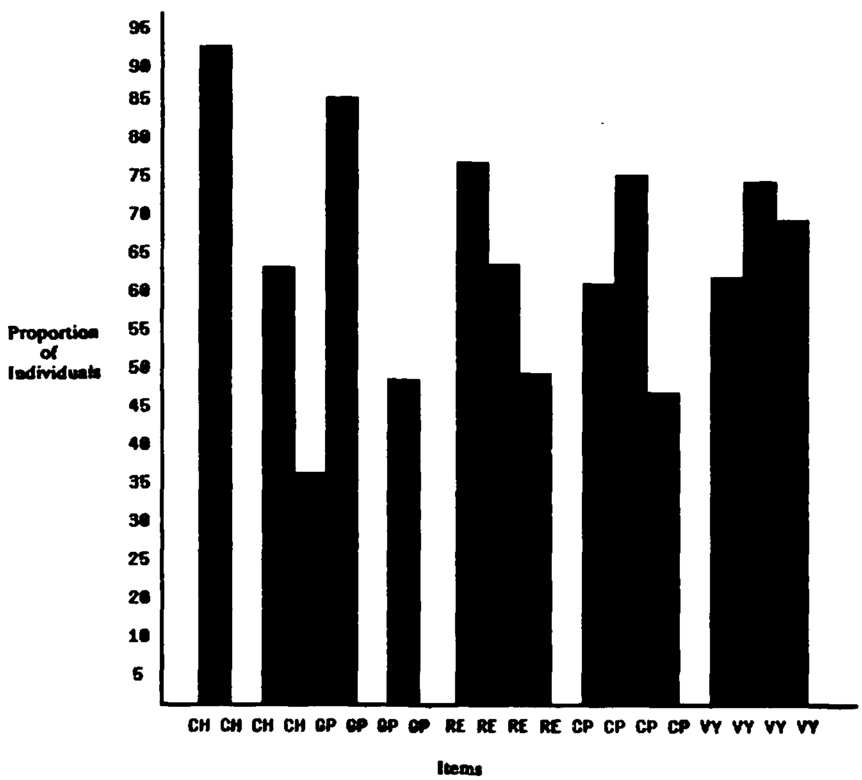
Both groups had difficulty in distinguishing between certain Change and Group items. There was also some confusion in both groups among some of the Restate and Compare items, although this was much more prominent in the Sequential Group.

Figure A.1
Results of the Sorting Task: Sequential Group



Sequential Group

Figure A.2
Results of the Sorting Task: Parallel Group



Parallel Group

ONR Distribution List - S. Marshall -

Dr. Beth Adelson
Department of Computer Science
Tufts University
Medford, MA 02155

Air Force Human Resources Lab
AFHRL/MPD
Brooks, AFB, TX 78235

AFOSR, Life Sciences Directorate
Bolling Air Force Base
Washington, DC 20332

Dr. Robert Ahlers
Code N711
Human Factors Laboratory
Naval Training Systems Center
Orlando, FL 32813

Dr. John R. Anderson
Department of Psychology
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Dr. Nancy S. Anderson
Department of Psychology
University of Maryland
College Park, MD 20742

Technical Director, ARI
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Patricia Baggett
School of Education
610 E. University, Rm 1302D
University of Michigan
Ann Arbor, MI 48109-1259

Dr. Eva L. Baker
UCLA
Ctr for the Study of Evaluation
145 Moore Hall
University of California
Los Angeles, CA 90024

Dr. William M. Bart
University of Minnesota
Dept. of Educ. Psychology
330 Burton Hall
178 Pillsbury Dr., S.E.
Minneapolis, MN 55455

Dr. Lee Roy Beach
Dept. of Psychology (NI-25)
University of Washington
Seattle, WA 98195

Dr. Isaac Bejar
Mail Stop: 10-R
Educational Testing Service
Rosedale Road
Princeton, NJ 08541

Dr. John Black
Teachers College, Box 8
Columbia University
525 West 120th Street
New York, NY 10027

Dr. R. Darrell Bock
University of Chicago
NORC
6030 South Ellis
Chicago, IL 60637

Dr. Jeff Bonar
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

Dr. J. C. Boudreaux
Ctr for Manufacturing Eng
National Bureau of Standards
Gaithersburg, MD 20899

Dr. Robert Breaux
Code 7B
Naval Training Systems Ctr
Orlando, FL 32813-7100

Dr. John S. Brown
XEROX Palo Alto Research Ctr
3333 Coyote Road
Palo Alto, CA 94304

Dr. John T. Bruer
James S. McDonnell Foundation
Suite 1610
1034 South Brentwood Blvd.
St. Louis, MO 63117

Dr. Joanne Capper, Director
Ctr for Research into Practice
1718 Connecticut Ave., N.W.
Washington, DC 20009

Dr. Susan Carey
Dept of Cognitive & Neural Science
MIT
Cambridge, MA 02139

Dr. Pat Carpenter
Carnegie-Mellon University
Department of Psychology
Pittsburgh, PA 15213

Dr. John B. Carroll
409 Elliott Rd., North
Chapel Hill, NC 27514

CDR Robert Carter
Office of Chief of Naval Operations
OP-933D4
Washington, DC 20350-2000

Dr. Davida Charney
English Department
Penn State University
University Park, PA 16802

Dr. Michelene Chi
Learning R & D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15260

Dr. William Clancey
Institute for Research on Learning
3333 Coyote Hill Road
Palo Alto, CA 94304

Asst Chief of Staff for Research
Development, Test, and Evaluation
Naval Education and
Training Command (N-5)
NAS Pensacola, FL 32508

Dr. Paul Cobb
Purdue University
Education Building
W. Lafayette, IN 47907

Dr. Allan M. Collins
Bolt Beranek & Newman, Inc.
10 Moulton Street
Cambridge, MA 02238

Dr. Stanley Collyer, Code 222
Office of Naval Technology
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. Jere Confrey
Cornell University
Dept. of Education
Room 490 Roberts
Ithaca, NY 14853

Dr. William Crano
Department of Psychology
Texas A&M University
College Station, TX 77843

Dr. Cary Czichon
Intelligent Instructional System
Texas Instruments AI Lab
P.O. Box 660246
Dallas, TX 75266

Brian Dallman
Training Technology Branch
3400 TCHTW/TTGXC
Lowry AFB, CO 80230-5000

Dr. Robert B. Davis
Curriculum Laboratory (Education
University of Illinois
Urbana, IL 61801

Dr. Sharon Derry
Florida State University
Department of Psychology
Tallahassee, FL 32306

Dr. J. Stuart Donn
Faculty of Education
University of British Columbia
2125 Main Mall
Vancouver, BC CANADA V6T 1Z5

Defense Technical Information Ct
Cameron Station, Bldg 5
Alexandria, VA 22314
Attn: TC
(12 Copies)

Dr. Richard Duran
Graduate School of Education
University of California
Santa Barbara, CA 93106

Dr. Susan Embretson
University of Kansas
Psychology Department
426 Fraser
Lawrence, KS 66045

ERIC Facility-Acquisitions
4350 East-West Hwy.
Suite 1100
Bethesda, MD 20814-4475

Dr. Beatrice J. Farr
Army Research Institute
PERI-IC
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Marshall J. Farr
Consultant
Cognitive & Instructional
Sciences
2520 North Vernon Street
Arlington, VA 22207

Dr. P-A. Federico
Code 51
NPRDC
San Diego, CA 92152-6800

Dr. Paul Feltovich
Southern Illinois University
School of Medicine
Medical Education Department
P.O. Box 3926
Springfield, IL 62708

Mr. Wallace Feurzeig
Educational Technology
Bolt Beranek & Newman
10 Moulton St.
Cambridge, MA 02238

Dr. Gerhard Fischer
Liebiggasse 5/3
A 1010 Vienna
AUSTRIA

Dr. Gerhard Fischer
University of Colorado
Dept of Computer Science
Boulder, CO 80309

Dr. Linda Flower
Carnegie-Mellon University
Department of English
Pittsburgh, PA 15213

Dr. Barbara A. Fox
University of Colorado
Department of Linguistics
Boulder, CO 80309

Dr. Carl H. Frederiksen
Dept. of Educational Psych.
McGill University
3700 McTavish Street
Montreal, Quebec
CANADA H3A 1Y2

Dr. John R. Frederiksen
BBN Laboratories
10 Moulton Street
Cambridge, MA 02238

Dr. Norman Frederiksen
Educational Testing Service
(05-R)
Princeton, NJ 08541

Dr. Michael Friendly
Psychology Department
York University
Toronto ONT
CANADA M3J 1P3

Dr. Robert M. Gagne
1456 Mitchell Avenue
Tallahassee, FL 32303

Dr. Dedre Gentner
University of Illinois
Department of Psychology
603 E. Daniel St.
Champaign, IL 61820

Psychology Department
George Mason University
4400 University Drive
Fairfax, VA 22030

Dr. Robert D. Gibbons
IL State Psychiatric Inst.
Rm 529W
1601 W. Taylor Street
Chicago, IL 60612

Dr. C. Lee Giles
AFOSR/NE, Bldg. 410
Bolling AFB
Washington, DC 20332

Dr. Herbert Ginsburg
Box 184
Teachers College
Columbia University
525 West 121st Street
New York, NY 10027

Dr. Robert Glaser
LRDC
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15260

Dr. Arthur M. Glenberg
University of Wisconsin
W. J. Brogden Psych. Bldg.
1202 W. Johnson Street
Madison, WI 53706

Dr. Marvin D. Glock
101 Homestead Terrace
Ithaca, NY 14856

Dr. Sam Glucksberg
Department of Psychology
Princeton University
Princeton, NJ 08540

Dr. Susan R. Goldman
Dept. of Education
University of California
Santa Barbara, CA 93106

Dr. Sherrie Gott
AFHRL/MOMJ
Brooks AFB, TX 78235-5601

Dr. T. Govindaraj
GA Institute of Technology
School of Industrial
and Systems Engineering
Atlanta, GA 30332-0205

Dr. Wayne Gray
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Bert Green
Johns Hopkins University
Department of Psychology
Charles & 34th Street
Baltimore, MD 21218

Dr. James G. Greeno
School of Education
Stanford University
Room 311
Stanford, CA 94305

Prof. Edward Haertel
School of Education
Stanford University
Stanford, CA 94305

Dr. Henry M. Halff
Halff Resources, Inc.
4918 33rd Road, North
Arlington, VA 22207

Dr. Ronald K. Hambleton
University of Massachusetts
Laboratory of Psychometric
and Evaluative Research
Hills South, Room 152
Amherst, MA 01003

Dr. Ray Hannapel
Scientific and Engineering
Personnel and Education
National Science Foundation
Washington, DC 20550

Dr. John R. Hayes
Carnegie-Mellon University
Department of Psychology
Schenley Park
Pittsburgh, PA 15213

Dr. Barbara Hayes-Roth
Knowledge Systems Lab
Stanford University
701 Welch Road
Palo Alto, CA 94304

Dr. Melissa Holland
Army Research Institute
for the Behavioral and
Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Keith Holyoak
Department of Psychology
University of California
Los Angeles, CA 90024

Ms. Julia S. Hough
Lawrence Erlbaum Associates
110 W. Harvey Street
Philadelphia, PA 19144

Dr. Lloyd Humphreys
University of Illinois
Department of Psychology
603 East Daniel Street
Champaign, IL 61820

Dr. Ed Hutchins
Intelligent Systems Group
Inst. for Cognitive Science
UCSD
La Jolla, CA 92093

Dr. Huynh Huynh
College of Education
Univ. of South Carolina
Columbia, SC 29208

Dr. Alice M. Isen
Department of Psychology
University of Maryland
Catonsville, MD 21228

Dr. Janet Jackson
Rijksuniversiteit Groningen
Biologisch Centrum, Vleugel D
Kerklaan 30, 9751 NN Haren
The NETHERLANDS

Dr. Robert Jannarone
Elec. and Computer Eng. Dept.
University of South Carolina
Columbia, SC 29208

Dr. Claude Janvier
Universite' du Quebec
a Montreal
P.O. Box 8888, succ: A"
Montreal, Quebec H3C 3P8
CANADA

Dr. Robin Jeffries
Hewlett-Packard Laboratories
3L
P.O. Box 10490
Palo Alto, CA 94303-0971

Dr. Douglas H. Jones
Thatcher Jones Associates
P.O. Box 6640
10 Trafalgar Court
Lawrenceville, NJ 08648

CAPT Tom Jones
ONR Code 121D
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. Marcel Just
Carnegie-Mellon University
Department of Psychology
Schenley Park
Pittsburgh, PA 15213

Dr. Ruth Kanfer
University of Minnesota
Department of Psychology
Elliott Hall
75 E. River Road
Minneapolis, MN 55455

Dr. Milton S. Katz
European Science Coordination
Office
U.S. Army Research Institute
Box 65
FPO New York 09510-1500

Dr. Frank Keil
Department of Psychology
228 Uris Hall
Cornell University
Ithaca, NY 14850

Dr. Wendy Kellogg
IBM T. J. Watson Research Ctr.
P.O. Box 704
Yorktown Heights, NY 10598

Dr. Dennis Kibler
University of California
Department of Information
and Computer Science
Irvine, CA 92717

Dr. David Kieras
Tech.Communication Program
TIDAL Bldg.
2360 Bonisteel Blvd.
University of Michigan
Ann Arbor, MI 48109-2108

Dr. Kenneth Kotovsky
Community College of
Allegheny Co.
808 Ridge Avenue
Pittsburgh, PA 15212

Dr. Pat Langley
University of California
Department of Information
and Computer Science
Irvine, CA 92717

Dr. Jill Larkin
Carnegie-Mellon University
Department of Psychology
Pittsburgh, PA 15213

Dr. Jean Lave
Institute for Research
on Learning
3333 Coyote Hill Road
Palo Alto, CA 92304

Dr. Robert W. Lawler
Matthews 118
Purdue University
West Lafayette, IN 47907

Dr. Alan M. Lesgold
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

Dr. John Levine
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

Dr. Michael Levine
Educational Psychology
210 Education Bldg.
University of Illinois
Champaign, IL 61801

Dr. Clayton Lewis
University of Colorado
Dept of Computer Science
Campus Box 430
Boulder, CO 80309

Matthew Lewis
Rand Corporation
P.O. Box 2138
Santa Monica, CA 90406-2138

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Dr. Marcia C. Linn
Graduate School of Education
EMST
Tolman Hall
University of California
Berkeley, CA 9472[illegible]

Dr. Robert L. Linn
Campus Box 249
University of Colorado
Boulder, CO 80309-0249

Dr. Richard E. Mayer
Department of Psychology
University of California
Santa Barbara, CA 93106

Dr. James R. McBride
The Psychological Corporation
1250 Sixth Avenue
San Diego, CA 92101

Dr. Joseph C. McLachlan
Code 52
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. James McMichael
Technical Director
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Barbara Means
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

Dr. Douglas L. Medin
Department of Psychology
University of Illinois
603 E. Daniel Street
Champaign, IL 61820

Dr. George A. Miller
Dept. of Psychology
Green Hall
Princeton University
Princeton, NJ 08540

Dr. Andrew R. Molnar
Applications of Advanced
Technology
Science and Engr. Education
National Science Foundation
Washington, DC 20550

Dr. William Montague
NPRDC Code 13
San Diego, CA 92152-6800

Dr. Randy Mumaw
Training Research Division
HumRRO
1100 S. Washington
Alexandria, VA 22314

Dr. Allen Munro
Behavioral Technology Labs
USC
1845 S. Elena Ave., 4th Floor
Redondo Beach, CA 90277

Dr. Richard E. Nisbett
University of Michigan
Institute for Social Research
Room 5261
Ann Arbor, MI 48109

Dr. Donald A. Norman
C-015
Inst. for Cognitive Science
University of California
La Jolla, CA 92093

Deputy Technical Director
NPRDC Code 01A
San Diego, CA 92152-6800

Director
Training Laboratory
NPRDC (Code 05)
San Diego, CA 92152-6800

Director
Manpower and Personnel Lab
NPRDC (Code 06)
San Diego, CA 92152-6800

Director
Human Factors & Organizational
Systems Lab
NPRDC (Code 07)
San Diego, CA 92152-6800

Library, NPRDC
Code P201L
San Diego, CA 92152-6800

Technical Director
Navy Personnel R&D Center
San Diego, CA 92152-6800

Commanding Officer,
Naval Research Laboratory
Code 2627
Washington, DC 20390

Dr. Harold F. O'Neil, Jr.
School of Education - WPH 801
Department of Educational
Psychology & Technology
USC
Los Angeles, CA 90089-0031

Dr. Stellan Ohlsson
Learning R & D Center
University of Pittsburgh
Pittsburgh, PA 15260

Office of Naval Research
Code 1142
800 N. Quincy St.
Arlington, VA 22217-5000

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Arlington, VA 22217-5000

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Arlington, VA 22217-5000

Office of Naval Research
Code 125
800 N. Quincy Street
Arlington, VA 22217-5000

Psychologist
Office of Naval Research
Branch Office, London
Box 39
FPO New York, NY 09510

Special Assistant for Marine
Corps Matters,
ONR Code 00MC
800 N. Quincy St.
Arlington, VA 22217-5000

Dr. Judith Orasanu
Basic Research Office
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Military Assistant for Training
and Personnel Technology,
OUSD (R & E)
Room 3D129, The Pentagon
Washington, DC 20301-3080

Dr. Ray S. Perez
ARI (PERI-II)
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. David N. Perkins
Project Zero
Harvard
Graduate School of Education
7 Appian Way
Cambridge, MA 02138

Dr. Tjeerd Plomp
Twente University of Technology
Department of Education
P.O. Box 217
7500 AE ENSCHEDE
THE NETHERLANDS

Dr. Martha Polson
Department of Psychology
University of Colorado
Boulder, CO 80309-0345

Dr. Harry E. Pople
University of Pittsburgh
Decision Systems Laboratory
1360 Scaife Hall
Pittsburgh, PA 15261

Dr. Joseph Psotka
ATTN: PERI-IC
Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333-5600

Dr. Lynne Reder
Department of Psychology
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Dr. Steve Reder
Northwest Regional
Educational Laboratory
400 Lindsay Bldg.
710 S.W. Second Ave.
Portland, OR 97204

Dr. James A. Reggia
University of Maryland
School of Medicine
Department of Neurology
22 South Greene Street
Baltimore, MD 21201

Dr. J. Wesley Regian
AFHRL/IDI
Brooks AFB, TX 78235

Dr. Fred Reif
Physics Department
University of California
Berkeley, CA 94720

Dr. Lauren Resnick
Learning R & D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

Dr. Gilbert Ricard
Mail Stop K02-14
Grumman Aircraft Systems
Bethpage, NY 11787

Dr. Linda G. Roberts
Science, Education, and
Transportation Program
Office of Technology Assessment
Congress of the United States
Washington, DC 20510

Dr. William B. Rouse
Search Technology, Inc.
4725 Peachtree Corners Circle
Suite 200
Norcross, GA 30092

Dr. Fumiko Samejima
Department of Psychology
University of Tennessee
310B Austin Peay Bldg.
Knoxville, TN 37916-0900

Dr. Robert Sasmor
HQDA DAMA-ARL
Pentagon, Room 3E516
Washington, DC 20310-0631

Dr. Walter Schneider
Learning R&D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15260

Dr. Alan H. Schoenfeld
University of California
Department of Education
Berkeley, CA 94720

Dr. Janet W. Schofield
816 LRDC Building
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15260

Dr. Judith W. Segal
OERI
555 New Jersey Ave., NW
Washington, DC 20208

Dr. Colleen M. Seifert
Inst. for Cognitive Science
Mail Code C-015
University of California
La Jolla, CA 92093

Dr. Lee S. Shulman
School of Education
507 Ceras
Stanford University
Stanford, CA 94305-3084

Dr. Randall Shumaker
Naval Research Laboratory
Code 5510
4555 Overlook Avenue, S.W.
Washington, DC 20375-5000

Dr. Robert S. Siegler
Carnegie-Mellon University
Department of Psychology
Schenley Park
Pittsburgh, PA 15213

Dr. Edward Silver
LRDC
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15260

Robert L. Simpson, Jr.
DARPA/ISTO
1400 Wilson Blvd.
Arlington, VA 22209-2308

Dr. Zita M. Simutis
Chief
Technologies for Skill
Acquisition and Retention
ARI
5001 Eisenhower Avenue
Alexandria, VA 22333

Dr. Derek Sleeman
Computing Science Department
King's College
Old Aberdeen AB9 2UB
Scotland
UNITED KINGDOM

Dr. Richard E. Snow
School of Education
Stanford University
Stanford, CA 94305

Dr. Elliot Soloway
Yale University
Computer Science Department
P.O. Box 2158
New Haven, CT 06520

Dr. Richard C. Sorensen
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. Paul Speckman
University of Missouri
Department of Statistics
Columbia, MO 65201

Dr. Robert J. Sternberg
Department of Psychology
Yale University
Box 11A, Yale Station
New Haven, CT 06520

Dr. Thomas Sticht
Applied Behavioral and
Cognitive Sciences, Inc.
P.O. Box 6640
San Diego, CA 92106

Mr. Brad Sympson
Navy Personnel R&D Center
Code-62
San Diego, CA 92152-6800

Dr. John Tangney
AFOSR/NL, Bldg. 410
Bolling AFB, DC 20332-6448

Dr. Kikumi Tatsuoka
CERL
252 Engineering Research
Laboratory
103 S. Mathews Avenue
Urbana, IL 61801

Dr. M. Martin Taylor
DCIEM
Box 2000
Downsview, Ontario
CANADA M3M 3B9

Dr. Perry W. Thorndke
FMC Corporation
Central Engineering Labs
1205 Coleman Avenue, Box 580
Santa Clara, CA 95052

Dr. Martin A. Tolcott
3001 Veazey Terr., N.W.
Apt. 1617
Washington, DC 20008

Dr. Douglas Towne
Behavioral Technology Labs
USC
1845 S. Elena Ave.
Redondo Beach, CA 90277

Dr. Robert Tsutakawa
University of Missouri
Department of Statistics
222 Math. Sciences Bldg.
Columbia, MO 65211

Dr. Zita E. Tyer
Department of Psychology
George Mason University
4400 University Drive
Fairfax, VA 22030

Headquarters,
U. S. Marine Corps
Code MPI-20
Washington, DC 20380

Dr. Kurt Van Lehn
Department of Psychology
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Dr. Jerry Vogt
Navy Personnel R&D Center
Code 51
San Diego, CA 92152-6800

Dr. Ming-Mei Wang
Lindquist Center for
Measurement
University of Iowa
Iowa City, IA 52242

Dr. Beth Warren
BBN Laboratories, Inc.
10 Moulton Street
Cambridge, MA 02238

Dr. Kent E. Williams
Inst. for Simulation
and Training
University of Central Fla
P.O. Box 25000
Orlando, FL 32816-0544

Dr. Hilda Wing
NRC MH-176
2101 Constitution Ave.
Washington, DC 20418

Ms. Marilyn Wingersky
Educational Testing Service
Princeton, NJ 08541

Dr. Robert A. Wisher
U.S. Army Institute for the
Behavioral & Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

Dr. Martin F. Wiskoff
Defense Manpower Data Center
550 Camino El Estero, Suite 200
Monterey, CA 93943-3231

Mr. John H. Wolfe
Navy Personnel R&D Center
San Diego, CA 92152-6800

Dr. George Wong
Biostatistics Laboratory
Memorial Sloan-Kettering
Cancer Center
1275 York Avenue
New York, NY 10021

Dr. Wallace Wulfeck, III
Navy Personnel R&D Center
Code 51
San Diego, CA 92152-6800

Dr. Masoud Yazdani
Dept. of Computer Science
University of Exeter
Prince of Wales Road
Exeter EX44PT
ENGLAND

Dr. Joseph L. Young
National Science Foundation
Room 320
1800 G Street, N.W.
Washington, DC 20550