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Computer-Based Assessment of Schema Knowledge in a Flexible Problem-Solving Environment

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This report describes assessment of students' schema knowledge for arithmetic word problems. The assessment takes place on-line as students interact with the computer program. The instruction that precedes the assessment, the environment in which students exhibit their knowledge, and the assessment of that knowledge all derive from one core theory of learning and memory, schema theory. This report outlines the schema theory briefly and describes the assessment environment, the student responses upon which the assessment is based, and the strategies of students observed through such assessment.

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Computer-Based Assessment of Schema Knowledge in a Flexible Problem-Solving Environment

This report describes assessment of students' schema knowledge for arithmetic word problems. The assessment takes place on-line, as students interact with the computer program. The instruction that precedes the assessment, the environment in which students exhibit their knowledge, and the assessment of that knowledge all derive from one core theory of learning and memory: schema theory. My objective here is to describe a tightly woven system of instruction, presentation, and assessment. All three parts of the system rely on computer technology, but it is particularly useful in assessment. Because all of the components of the system depend critically on schema theory, I shall begin with a brief description of the theory and how it guides them.

SCHEMA THEORY

Schema theory describes how information is stored in human memory. Broadly speaking, a schema is a collection of related pieces of information, stored in such a way that when one of the pieces is accessed, the others are also readily available for processing. Schemas are important because they offer a way to organize seemingly disparate knowledge. Thus facts, experiences, general premises, inferences, procedures, and skills may all be linked together as a schema. A number of psychologists and cognitive scientists have studied the schema, and there is general consensus on certain properties or characteristics (see, for example, Van Lehn, 1990; Kintsch & Greeno, 1985; Anderson, 1984; Rumelhart, 1980; Baddeley, 1990; Skemp, 1987; and Marshall, in press). Some of these characteristics are:

- *Schema knowledge is tightly connected, forming a network of relationships.*
- *Schemas represent knowledge of the world, not just a set of abstract rules.*
- *Schemas are internally consistent and allow inferences.*
- *A collection of schemas forms the basis of an individual's knowledge for solving problems in a given domain.*
- *Schemas function as integrative tools or building blocks.*
- *A schema is the scaffolding into which new information is assimilated.*
- *Schema organization of knowledge facilitates memory search.*

Four major types of knowledge play important roles in a schema: feature knowledge, constraint knowledge, planning knowledge, and implementation knowledge.[1] Feature knowledge contains specific details about the situations or instances governed by the schema. Located here are examples, general descriptors, and appropriate analogies. Constraint knowledge serves to test the current situation to which the schema is to be applied against the general features known to be part of the schema. Thus, it houses information about whether the current instance meets the necessary conditions of the schema. Planning knowledge guides the use of the schema. Various actions may need to be taken; subgoals may need to be attained. Planning knowledge identifies and orders these actions or subgoals. Finally, implementation knowledge contains the rules, procedures, and/or skills needed to execute the actions. Thus, this knowledge is needed to carry out the plan.

Instruction and Schema Theory

Schemas provide a useful way of looking at a subject area because they can serve as the basis for organizing much of the information pertinent to the area. Ideally, any domain would have a relatively small number of schemas that could be used to guide activity related to the domain. For instance, in the domain of arithmetic word problems, five schemas appear to be sufficient (Marshall, 1990; in press).

A number of different rationales may underlie instruction. The heart of the matter is clarification of what the instructor wants the learner to learn. On the one hand, the purpose may be for the student to learn a great many facts. Or, the goal may be the acquisition of the steps required of a particular algorithm. Neither of these objectives necessarily calls for schema-based instruction. However, when the aim is for the student to develop a body of knowledge organized in such a way that it can be used to solve real problems, then schema-based instruction is warranted.

Schema-based instruction is at least a two-tiered enterprise, focusing on different types of knowledge within one schema as well as the interrelations among several schemas. On the one hand, the learner needs to acquire the components of each schema as outlined above. On the other, the learner also needs to move among schemas, using them appropriately, and when necessary, in combination. The instruction should be designed explicitly to facilitate both needs. Sometimes this

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[1] For more elaboration of these knowledge types, the reader is referred to Marshall, forthcoming) or to a technical report available from the author (Marshall, Barthuli, Brewer, & Rose, 1989).

necessitates breaking down the subject matter into suitable chunks. For example, again in the domain of arithmetic word problems, I have developed an instructional system that focuses directly on the knowledge components described above. In the early stages of instruction, each part of the instruction and its accompanying exercise targets one of the four knowledge components. The middle stages emphasize how these come together for one problem by focusing on the situation expressed in the problem. The final stages stress the relationships among different situations (and hence different schemas) found in complex multi-step problems.[2]

The Problem-Solving Environment and Schema Theory

One desires a practice or testing environment in which the learner can use his or her schema knowledge as it develops. In order for each component to develop fully, the environment should supply a way in which each part of schema knowledge can be used independently as well as in conjunction with the others. In the word problem case, it is not sufficient to present learners with problems and ask only for a numerical solution, because they may not have the schema components sufficiently developed to access them independently. Typical students need at least a small amount of prompting to use their knowledge. Figures 1-4 illustrate the computer environment I and my research assistants have developed to study this activity. It is a flexible system in which the learner can work methodically with each part of his or her schema knowledge for one situation and/or can move globally among different situations and their associated schemas.

An example may clarify how this works. First, the student receives instruction about the different situations, learns to recognize a set of icons associated with them, and practices manipulating the icons. The icons are a central part of the instruction. Previous studies have indicated their importance in schema development (Marshall, 1990; Marshall & Brewer, 1990). When the student has developed the facility for identifying the situations and for understanding howaspects of a given situation map onto specific parts of the appropriate icon, he or she is introduced to the computer environment shown in Figures1-4.

A problem-solving session starts with the display of a complex word problem requiring at least two steps for solution. Figure 1 illustrates the computer screen as it appears to the student. Five icons are displayed immediately above the problem, in the upper left corner. To begin to solve the problem, the student selects one of the icons as representative of a situation in the problem. When selected, the

[2] Details of the system are available in Marshall et al., (1989).

Figure 1: The Initial Screen

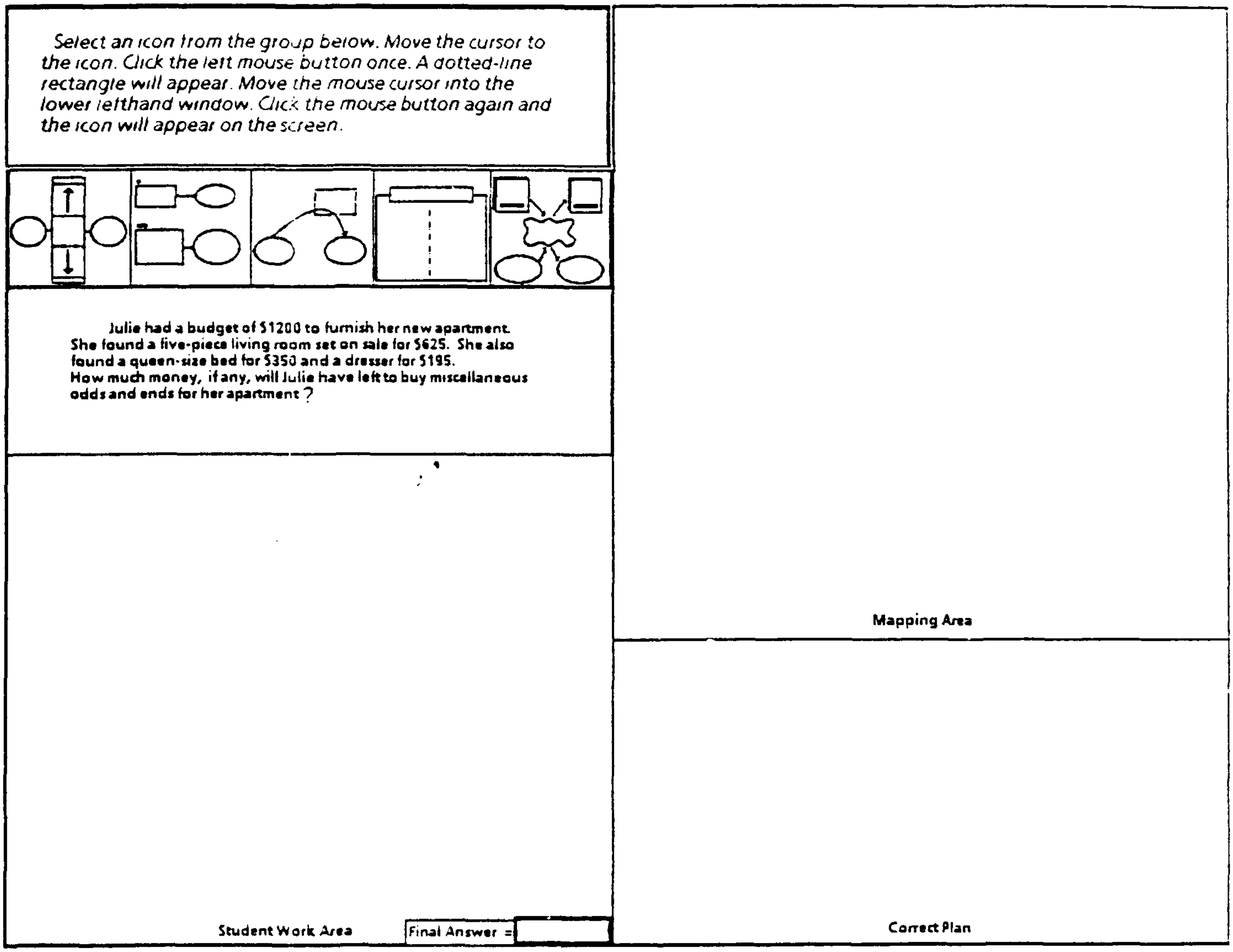


Figure 2: Screen After Icon Selection

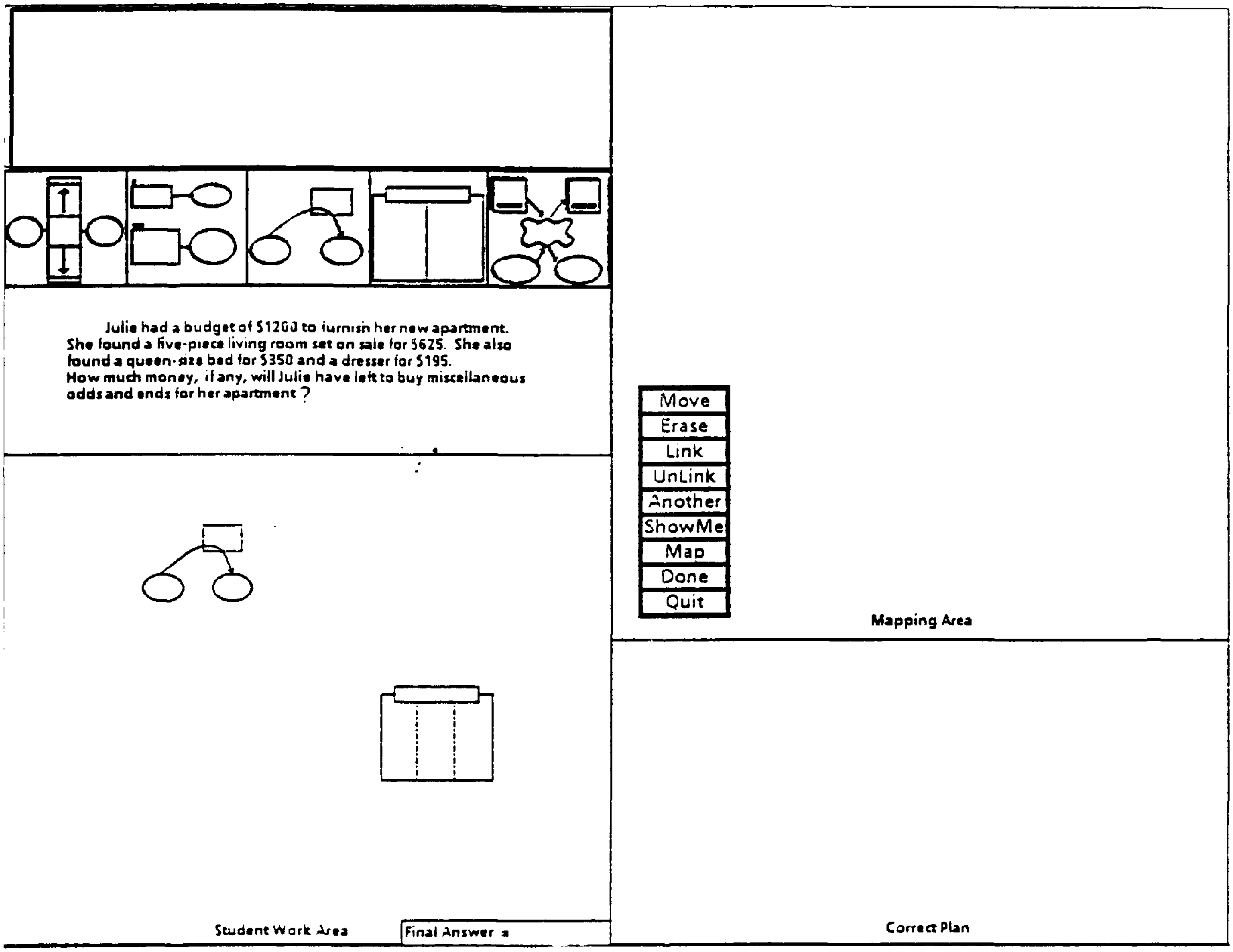


Figure 3: The Mapping Option

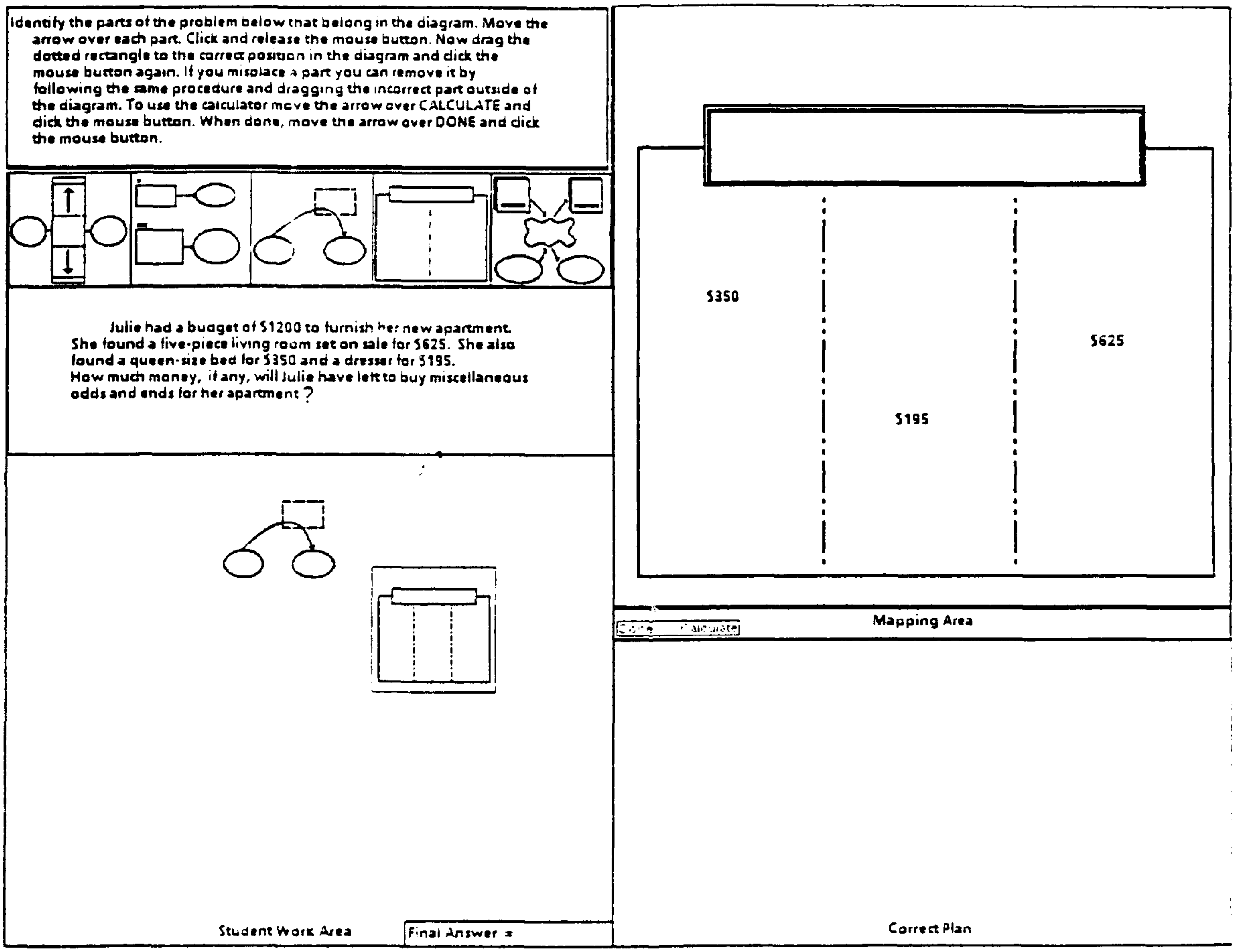
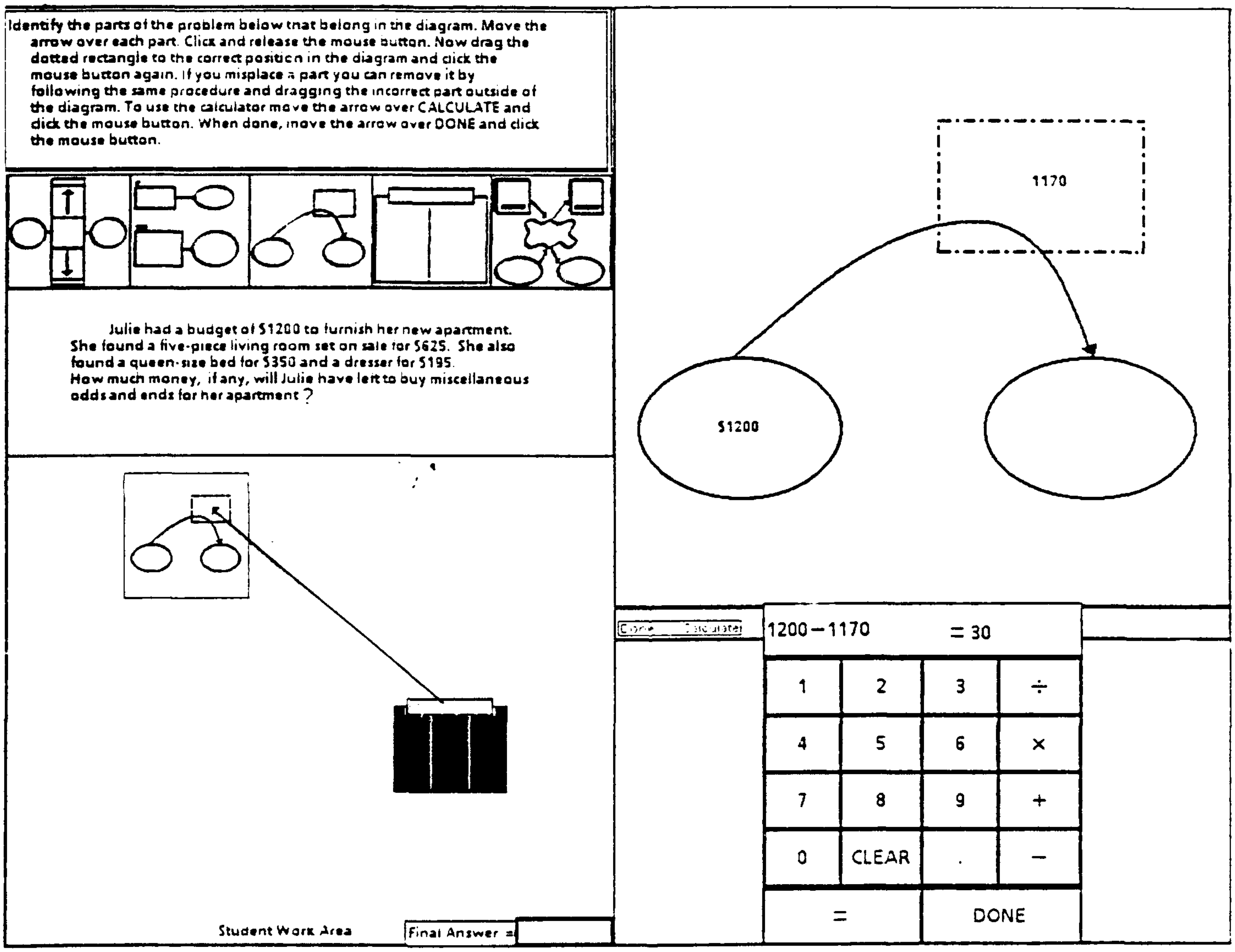


Figure 4: Illustration of Calculator Option and Link



icon becomes highlighted, and the student can move it into the *Student Work Area* in the lower left part of the screen. At this point, a pop-up menu appears near the center of the screen (see Figure 2). The student will use this menu to make most of his or her choices during the session. Each choice may be used to characterize the student's skill or ineptitude and will serve as a basis for the assessment described later. For the moment, I will simply describe the choices open to the student.

In solving the problem, the student makes several decisions. Among his options are to select other icons, to examine the already-selected icon more closely, or to ask for help. Thus, if the student so wishes, he may select other icons that he considers pertinent to the problem. Any number may be selected. The system does not force the student to make particular choices, nor does it correct incorrect selections. A second alternative is to examine the chosen icon more closely. Under this option, the selected icon is highlighted in the workspace and an enlarged version of it (called a diagram here) appears in the *Mapping Area* in the upper right quadrant of the screen (see Figure 3). Again, the student has several choices. He can "map" the problem into the diagram (as partially shown in Figures 3-4). To do this, he goes to the problem display on the left side of the screen and uses the mouse to move different phrases, numbers, or expressions into the parts of the enlarged diagram. (In earlier instruction, the student has developed expertise in making this mapping.)

At this point the student may elect to carry out a calculation. By selecting the calculation option in the middle of the right-hand side of the screen (as shown in Figure 3), the student gains access to a calculator which appears in the lower portion (see Figure 4). Calculations may be made with or without mappings. The results of calculations are movable and may themselves be placed into the diagram. If the learner believes the correct solution has now been obtained, he may enter his solution in the *Final Answer* box at the bottom of the screen. Or, he may return to the work area and examine other icons. When the diagram is closed, all mapped elements are remembered by the system, so that if the learner selects the corresponding icon again, the diagram automatically displays the pieces of the problem and the calculations that were previously entered. At all times, the system reminds the student which parts of the icons have been mapped by displaying them as shaded areas (see the lower icon displayed in Figure 4).

Upon return to the *Student Work Area*, the learner will now need to select another icon if only one has been previously chosen. At this point, he can build an explicit link between the two icons, as shown in Figure 4. This linkage indicates that the contents of a specific part of one diagram are also the contents of a specific part of a second diagram. Values are automatically transferred and will appear in the diagram for the second icon.

The learner thus moves back and forth in the environment, looking at the various situations represented by the icons, and developing a plan for solving the problem. A fully developed plan would have a set of completely filled icons with correct linkages. Computations would have been made at different points of the plan, with a final computation yielding the answer. When the correct answer is entered in the *Final Answer* box, the system informs the student that his response is correct.

This environment is an ideal arena for assessing schema knowledge. Selection of the appropriate icon demonstrates constraint knowledge. The learner recognizes which of the icons are appropriate for the situations expressed in the problem. Mapping the parts of the problem into the diagram uses feature recognition knowledge. Each diagram corresponds to a particular situation and has different features. For example, there are three characteristics of a change situation: the quantity available before the change occurs, the amount by which it changes, and the resulting quantity after the change. Each of these is represented by a separate part of the change diagram. Planning knowledge shows up in the linkages among the icons as well as in the order in which the icons are accessed. And, finally, implementation knowledge is evident through the learner's computations and designation of the final answer.

Assessment and Schema Theory

Schema-based assessment has the same focus as the instruction: the set of desired schemas and their individual knowledge components. The goal is to examine the extent to which learners have developed and can use the schemas which guided the instruction.

Schema assessment presents some difficulties that do not occur in other types of assessment. A central one is that schemas are highly individualized. Schemas are created and tailored by individuals to reflect their own experiences and understandings of the world. No two individuals will form identical schemas because no two individuals can experience the world identically, but both of them may have well-formed and useful schemas. This contrasts sharply with the knowledge of a fact or a computational procedure which all learners may be expected to know in the same way. While it is possible to assess knowledge of a fact with a single question that elicits the identical response from all individuals, it is not reasonable to apply the same technique in assessing schema knowledge.

Nevertheless, through schema-based instruction, individuals are provided with common experiences that facilitate the development of targeted schemas. Some of the elements of any schema will undoubtedly be unique to each learner, because each one will bring his or her own prior experiences, but other pieces of the schema should come from the common ground of instruction.

The impact of this individualization is that the focus should not be too narrow in schema assessment. Whereas an individual may not have a specific piece of information stored in memory as part of the schema, he may nonetheless have a great deal of interrelated schema knowledge. Thus, satisfactory assessment will have a broader scope and will look at patterns of elements rather than single elements of knowledge. The exception is the case in which a specific piece of information is an essential ingredient of a particular schema. One might want to evaluate first that the individual does indeed know this piece of information and second that he associates it with the correct schema and in correct relation to other requisite schema knowledge.

A second unique characteristic of schema assessment is that it is multi-layered. One can assess components within a schema, assess the relationships among components of a single schema, or assess the interactions among a set of schemas. All three layers are considered in a full assessment.

On-Line Assessment

To date, most assessments of schema knowledge have been through interviews or thinking-aloud protocols (e.g., Chi, Glaser, Feltovich, 1981; Marshall, 1990). One reason that these procedures have been widely utilized is that schema assessment requires a great deal of flexibility. Rarely can a single question tap the richness of schema knowledge possessed by an individual. Usually one begins with a standardized question and then allows a variety of different follow-up questions to probe each individual's schema knowledge.

The system described in this paper is one alternative to assessment by interview for the domain of arithmetic word problems. It was created in part to provide the means of evaluating students' schemas and in part to give students a tolerant environment in which to practice their schema understanding. The environment was described above. This section outlines its capabilities for assessment.

Perhaps surprisingly, a simple history of the student's interaction with the system offers extremely valuable information that can be used to assess schema knowledge. The system records all students requests, responses, and mouse clicks. Its record-keeping does not require a great deal of translation and is immediately readable. By recording the student's every action, the system follows the student's path through the environment. The history of that path provides a great deal of information about how the student perceived the problem, about any misunderstandings the student had about the problem and whether these were self-corrected, and about how the student went about the business of finding a solution.

Example of Student Responses

To illustrate how the word-problem environment may be used for assessment, Table 1 contains the computer record for one student solving one problem. The system output is unedited except for the insertion of blank lines to separate segments for the accompanying explanations in the table.

As shown in Table 1, the record of student activity consists of a list of events. Each event corresponds to some action taken by the student. The record is a history of all events in the order in which they occurred. The primary events that are contained in a student record are *IconSelected, Map, LiftWord, CalculatorSolve, Link,* and *ShowMe.* Brief descriptions of each one follow.

IconSelected. This event indicates that the student selected one of the five icons and placed it in the *Student Work Area.* The name of the corresponding situation and its position in the window are recorded as well as its rank order in the set of selected icons.

Map. Whenever the student requests that an icon be enlarged, this event is recorded, together with the name of the diagram and its ranking.

LiftWord. This event is recorded whenever the student selects a part of the problem or a result of a calculation for placement in a diagram or in the final answer slot. The record contains the activity, the words or numbers that have been lifted, and the destination in which they are placed. Only one map is available at any time, so there is no confusion about which diagram is designated. The final integer values in the event indicate the part of the diagram used. Each component of the diagram has its own identification number.

CalculatorSolve. This event indicates that the student requested a calculation. The expression to be calculated and its result are recorded.

Link. The link event has four parts: the rank order of the icon from which the link emanates, the numbered part of that icon, the rank order of the icon in which the link terminates, and the numbered part of it.

Table 1
Example of System Assessment Record*

SYSTEM OUTPUT	EXPLANATION OF OUTPUT
(Problem M16)	*System randomly selects problem 16 for presentation.*
(IconSelected CHsmall 1 (78 . 285)) (IconSelected GR3small 2 (252 . 248))	*S selects the Change icon first (1) -- which is the overall situation of the problem. (The numbers in parentheses at the end of the statement indicate the location on the screen at which S positioned the icon). S then selects the Group icon (2) -- which is an embedded subproblem.*
Map GR3small 2) (LiftWord $1200 NIL) (LiftWord $625 4) (LiftWord $350 3) (LiftWord $195 2) (CalculatorCalled) (CalculatorSolve (625+350+195) 1170) (LiftWord (Calculation 1170) 1)	*S elects to map the parts of the Group icon. (At this point the enlarged diagram would appear on the upper right portion of the screen.)* *S first erroneously picks up the number $1200 and then releases it -- presumably realizing that it was not needed. S then maps as subgroups the values $625, $350, and $195. S calculates their sum and places it in the supergroup position of the diagram. S closes the enlarged diagram and returns to the Student Work Area.*

Table 1: continued

SYSTEM OUTPUT	EXPLANATION OF OUTPUT
(Link 2 1 1 2)	*S realizes that the supergroup value calculated for the Group diagram is also a value needed in the Change diagram. S uses the link command to connect the "supergroup box" of the Group icon and the "amount of change box" of the Change icon.*
(Map CHsmall 1) (LiftWord $1200 1) (CalculatorCalled) (CalculatorClear (1170 - 12)) (CalculatorSolve (12) 12) (CalculatorClear NIL) (CalculatorSolve (1200 - 1170) 30) (LiftWord (Calculation 30) 3) (LiftWord (Calculation 30) NIL) (LiftWord (Calculation 30) AnswerWindow)	*S then maps the Change icon, placing the previously rejected value of $1200 into the initial position of the enlarged diagram. The value $1170 already appears in the map because of the explicit link made by S. S does several calculations at this point, mostly incorrect. S then correctly calculates the value $30 and places it first in the diagram and then in the Answer Box.*
(RightAnswer)	*System records that S answered the problem correctly.*

*This is an actual output from one of the students in the study. The output appears here exactly as it is recorded by the system. Blank lines are inserted to illustrate the different segments of the problem solving.

ShowMe. Whenever a student asks for the full display of the solution, this event is recorded. A student may request the display more than once. Every time it is requested, the event is recorded.

Several other events also may be included in the record. These are found less frequently and are not described here.

Some Results: Problem-Solving Strategies

Students using the system have displayed a number of different strategies, each suggesting a different schema development.[3] The most frequent ones are described below.

Before doing anything else, a student may select all icons that will be needed. When this is the initial behavior, we know that the student is using his schema knowledge to construct a plan. A set of subproblems is identified, and one infers that the student has mentally linked them together in some way. There is useful information in the order with which the student selects these icons. The student may begin by selecting the first situation that arises in the problem, moving sequentially through all necessary ones, and culminating with the selection of the overall situation that governs the problem. Such behavior represents a rather groping approach and may be contrasted with the selection first of the overall situation followed by the necessary subproblem situations, an approach that indicates awareness of the general structure of the problem. These two selection strategies show differences that are roughly analogous to those of bottom-up or top-down processing. Generally, from the small number of subjects we have observed, we find that students who engage in the top-down approach (i.e., select the icon for the overall situation first) have a better understanding of the problem and appear to have more coherent schemas.

Students who were well on their way to having coherent schemas and using them as a related set tended to begin their problem solving sessions in similar ways. They made an initial selection of one icon and attempted to map it. If the mapping was unsuccessful, they closed the diagram and selected another icon, attempting to map the same problem elements as before. Thus, they demonstrated self-monitoring. Very rarely did any student incorrectly map part of a problem and then continue as if the mapping were correct. If successful in the initial mapping or revised mapping, the students returned to the menu of icons and selected a second

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[3] To date, the system has been used by a total of 31 college students with weak problem solving skills.

icon with which to work. At this point we observed two strategies indicating variations in students' understanding. Some of the students already knew which part of the second icon contained an unknown quantity that corresponded to a part of the first icon. Students generally tried to link the two icons together if they were aware of how the components fit together. If they were uncertain, they mapped the second diagram and then carried out the linking. Only after all mapping and linkages were complete did students using these strategies enter the answer in the *Final Answer* window at the bottom of the screen. They carefully went through every step and linkage. After solving several problems in this way, they frequently switched to the strategy described below in which only the first diagram was complete filled. This switch suggests that students' use of the schema knowledge was becoming more routinized.

Other strategies are also revealing. Some students selected only the icon for the overall situation and turned immediately to the mapping of the problem into the expanded diagram. They mapped the appropriate quantities from the problem to the diagram and also mapped the full description of the subproblem (as stated in the problem) directly into the diagram. They then made the necessary calculation for the subproblem without needing to map its corresponding diagram. Students displaying this strategy,usually had a good grasp of the overall and subproblem icons and did not need to have all diagrams displayed. They selected the correct quantities for calculation and showed a high level of confidence in what they are doing. Moreover, in follow-up interviews they indicated that they were indeed using mental models corresponding to the omitted icons and diagrams.

Another strategy was to select a single initial icon, either the same one for all problems or perhaps a random choice; in both cases, the selected icon was usually incorrect. Students using this strategy went immediately to the calculator without attempting to map the problem. Usually, they made an incorrect calculation, either reversing the position of the quantities in the calculation or selecting incorrect quantities for the calculation. In our sample, they also almost always overlooked one of the subproblems required for solution. These students displayed relatively weak schema knowledge. Although they had developed the facility of identifying icons and mapping problems into the diagrams in previous instructional sessions, they elected not to use their knowledge of the icons and/or diagrams and relied instead upon previously learned (and frequently incorrect) problem-solving strategies. [4]

[4] They admitted this freely in followup interviews. Most said that they liked the diagrams but already knew how to solve the problems and just used their own procedures.

One feature of the system as currently implemented is a *Show Me* option. At any point in the problem solving, the student can ask for a display of the full solution. This appears in the lower right-hand portion of the screen (in the same location as the calculator). The system begins by displaying the icon for the overall situation and then any other needed ones. Necessary links are drawn. The icon corresponding to the most embedded subproblem is then enlarged, displayed as a diagram, and fully mapped. However, no calculations are carried out. *Show Me* simply displays the necessary icons and linkages. After it disappears from the screen, the student may elect to carry out the solution or may choose another problem. Most of the students in our sample elected to complete the solution.

Scoring

A last point about schema assessment is that it is unlikely to yield a numerical score. It does not really matter how many problems the student solved. We are much more concerned with the way in which the student went about it and the changes in strategies that emerge over time. We take this to be indicative of the knowledge structure the student is developing. Alone, of course, the computer assessment is not conclusive. To check its validity, we interviewed 16 of the 31 students following each session to determine whether our assessment of their knowledge based on performance in the computer environment matches our evaluation of schema development made during the interview. Thus far, we find strong agreement between the results of the computer assessment and the interview assessment.

Conclusions

There are several important reasons for employing computer-based assessment as it is presented here. First, it is appropriate for the computer-based instruction it assesses. Students are familiar with the types of required responses and understand the idiosyncrasies of the system. Second, it is unobtrusive. Students may expect that their responses are being recorded, but they do not seem to think much about it. They are free to pursue their problem solving without interruptions, without being asked to write down a particular step, or without being stopped to clarify what they are now doing and why. Third, a system such as this is economical because it serves a dual purpose. On the one hand, it can be an instructional aid, providing a practice ground for individuals to hone their understanding of the structure of word problems. On the other, it functions as an assessment tool, allowing us to determine which aspects of schema knowledge are well developed in an individual and which are weak.

A final advantage of this system of assessment is that it can provide both diagnostic information for the individual and summative information for a group of students. Of interest in the individual evaluation are questions such as which strategy is employed or whether the individual has difficulty with one or more of the diagrams. At the group level of assessment we are concerned with questions such as determining whether the group as a whole is successful in solving complex problems or whether most (or all) of them demonstrate a sufficient level of competency in organizing their problem solving. Thus, at the group level, we are much less concerned with the fine-grained details. Both types of assessment are typically needed, and this system easily provides them.

The three issues of any assessment are *what, why,* and *how.* What is being assessed and why it is to be done are the driving forces behind the assessment. The issue of how is not the first question or issue to be addressed, although it is clearly an important one. One of the lessons learned from multiple choice tests is that we should not carry out a particular assessment just because we have a well-developed technique. We are very good at developing multiple choice tests. We know the psychometric theory of the testing situation, we know how to build certain estimates, and we can score tests quickly and accurately. However, one of the main problems facing assessment leaders today is that these procedures are being used in too many instances because of the third question--"how"--and not because of the first two questions just posed--"what" and "why". It is now widely argued in assessment circles that a multiple choice test does not reflect what an individual understands and is in fact a poor vehicle in many areas.

Several alternatives to multiple-choice tests are under investigation by a number of test developers. Among them are things such as portfolios, performance assessments, and free-response items. Unfortunately, these are viewed simply as alternatives to the "how" question, and little attention has been given to any theory of learning or understanding that should underlie them. As demonstrated here, the explicit linkage between instruction, learning, and assessment is crucial. The common underlying theory provides the basis for interpreting the assessment. Without it, one is left only with a collection of isolated student responses. Thus, schema-based assessment puts the "what" and the "why" of assessment first, and it does so by supplying an integrated picture of memory, learning, and assessment. The assessment eventually made is dictated by the model of memory and learning and not by convenience of data collection.

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