Using Cognitive Tools to Represent Problems

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Abstract

The premise of this paper is that the key to problem solving is adequately representing the problem to be solved. Most research has focused on how problems are represented to learners. The assumption that these external representations naturally map onto learners’ internal representations of problems has not been confirmed. New research has examined the role of tools for externalizing learners’ internal representations. Descriptions of how three kinds of cognitive tools—semantic networks, expert systems, and systems modeling tools—can be used to externalize learner’s internal representations are provided. Research is needed to study the efficacy of these tools for supporting problem solving. (Keywords: problem solving, problem representation, cognitive tools, systems modeling, concept mapping, expert systems)

PROBLEMS IN PROBLEM SOLVING

Problem solving is at the heart of practice in the everyday and professional contexts. Professionals are hired and retained in most contexts in order to solve problems. I believe that every secondary and tertiary education course should require students to solve problems. In order to prepare students to solve problems, many courses, especially the sciences, regularly pose problems to students. There are at least two major limitations of those problem-solving experiences. First, students are usually taught to solve well-structured problems, despite the fact that most problems in everyday and professional practice are ill-structured. Second, students are generally unable to transfer problem-solving skills that they do develop to novel problems in different contexts.

First, the kinds of problems that students solve in schools are quite different from those encountered in everyday and professional situations. Lave (1988) and Rogoff and Lave (1984) reviewed a number of field studies that showed that learners are unable to apply school-learned mathematics to everyday problems. Why is this? The reason that students are unable to transfer their classroom problem-solving experiences from the classroom to everyday and professional contexts is that in formal classes, students are usually required to solve only well-structured problems, especially story problems (Jonassen, in press). Typically found at the end of textbook chapters, these well-structured problems require the application of a finite number of concepts, rules, and principles being studied to a constrained problem situation. They consist of a well-defined initial state, a known goal state, and constrained set of logical operators. Well-structured problems present all elements of the problem to the learners: require the application of a limited number of regular and well-structured rules and principles that are organized in a predictive and prescriptive manner; and have knowable, comprehensible solutions where the relationship...
between decision choices and all problem states is known or probabilistic (Wood, 1983).

Most problems in everyday and professional practice are ill-structured. The kinds of problems that are encountered in everyday practice are typically emergent, not well-defined. Because they are not constrained by the content domains being studied in classrooms, their solutions are not predictable or convergent. Ill-structured problems appear ill-defined because one or more of the problem elements are unknown or not known with any degree of confidence (Wood, 1983). They possess multiple solutions, solution paths, or no solutions at all (Kitchner, 1983) as well as multiple criteria for evaluating solutions, so there is uncertainty about which concepts, rules, and principles are necessary for the solution and how they are organized. Solving ill-structured problems often requires learners to make judgments and express personal opinions or beliefs about the problem, so ill-structured problems are uniquely human interpersonal activities (Meacham & Emont, 1989).

Researchers have long assumed that learning to solve well-structured problems transfers positively to learning to solve ill-structured problems. Although information processing theories believed that “in general, the processes used to solve ill-structured problems are the same as those used to solve well-structured problems” (Simon, 1978, p. 287), more recent research in situated and everyday problem solving makes clear distinctions between thinking required to solve convergent problems and everyday problems. Dunkle, Schraw, and Bendixen (1995) concluded that performance in solving well-defined problems is independent of performance on ill-defined tasks, with ill-defined problems engaging a different set of epistemic beliefs. Hong, Jonassen, and McGee (in press) found that solving ill-structured problems in a simulation called on different skills than well-structured problems, including metacognition and argumentation. Other research has shown that communication patterns in teams differed when solving well-structured and ill-structured problems (Cho & Jonassen, 2002; Jonassen and Kwon, 2001). Clearly more research is needed to substantiate these findings, yet it is reasonable to conclude that well-structured and ill-structured problem solving engage different cognitive skills.

Another difficulty with school-based problem solving is that a large number of studies have documented learners’ inability to transfer problem-solving skills, even for well-structured problems. Numerous studies have shown that students are unable to solve structurally identical problems because learners focus on surface features of the problems rather than on developing adequate conceptual understanding of the problem domain (Gick & Holyoak, 1980, 1983; Reed, 1987). Even instructional programs in problem solving and critical thinking have failed to show evidence of transfer (Chipman, Segal, & Glaser, 1985; Nickerson, Perkins, & Smith, 1985). Why are students unable to transfer skills in problem solving?

The inability of students to transfer problem-solving skills to novel problems results from a number of conditions. A major hypothesis of this paper is that problem solving fails because in most educational contexts, students represent problems in only one way, typically quantitatively. This form of problem solv-
ing typically involves reading a well-structured story problem, attempting to identify the correct formula, inserting values from the problem statement into the formula, and solving for the unknown value, known as the direct translation strategy. Unfortunately, it is the unsuccessful problem solvers who base their solution plans on the numbers and keywords that they select from the problem (Hegarty, Mayer, & Monk, 1995). Relying exclusively on a quantitative (or any single) form of representation restricts student’s understanding of the problem and its relationship to domain knowledge. In order to be able to transfer problem-solving skills, students must construct conceptual understanding of how problems relate to domain knowledge, and doing so requires that students learn to represent their understanding in more than one way. How does this work? In order to develop this required conceptual understanding, it is necessary for students to understand the internal connections between problems and domain knowledge in order to transfer skills (Singly & Anderson, 1989). Well-developed mental models consist of multiple representations including structural knowledge, procedural knowledge, reflective knowledge, images and metaphors of the system of strategic knowledge as well as social/relational knowledge, conversational/discursive knowledge, and artificial knowledge (Jonassen & Henning, 1999). The more ways that learners are able to represent problems and their relations to domain knowledge, the better able they will be to transfer their skills. Evidence to support this claim is provided by Ploetzner and Spada (1998), who claim “the ability to construct and coordinate qualitative and quantitative problem representations is a precondition for successful and efficient problem solving in physics” (p. 96). Qualitative and quantitative representations are complementary. Ploetzner et al. (1999) showed that when solving physics problems, qualitative problem representations are necessary prerequisites to learning quantitative representations. Qualitative representation is a missing link in novice problem solving (Chi, Feltovich, Glaser, 1981; Larkin, 1983). When students try to understand a problem in only one way, especially when that way conveys no conceptual information about the problem, they do not understand the underlying systems in which they are working. So, it is necessary to support conceptual understanding in students before solving problems by helping them to construct a qualitative representation of the problem as well as a quantitative one. Qualitative problem representations both constrain and facilitate the construction of quantitative representations (Ploetzner & Spada, 1998).

Most failures in problem solving result from the ways that students learn how to solve problems. For the sake of efficiency, problem solving is too often proceduralized, so students’ mental models for solving problems contain only procedures. If the correct values can be identified and inserted into the correct formulas, any problem can be solved. However, such an approach does not work for well-structured problems and certainly cannot work for ill-structured problems that may be solved in a variety of ways. In order to be able to transfer the skills of solving well-structured and ill-structured problems, it is essential that students learn how to represent the problems they are solving in more than one way. Problem representation is the key to problem solving.
PROBLEM REPRESENTATION

Experts are better problem solvers than novices for several reasons. The most important reason is that they construct richer, more integrated mental representations of problems than do novices (Chi & Bassok, 1991; Chi, Feltovich, & Glaser, 1981; de Jong & Ferguson-Hessler, 1991; Larkin, 1983). Experts are better able to classify problem types (Chi & Bassok, 1991; Chi, Feltovich, & Glaser, 1981) because their representations integrate domain knowledge with problem types. However, researchers and theorists differ in their claims about the forms in which experts represent problems. Anderson (1983) claims that problems are represented as production rules, whereas Chi and Bassok (1989) and Larkin (1983) believe that they are schema-like forms. Whatever form, it is generally accepted that problem solvers need to construct some sort of internal representation (mental model) of a problem (problem space) in order to solve a problem. Personal problem representations can serve a number of functions (Savelsbergh, de Jong, & Ferguson-Hessler, 1998) such as:

- Guiding further interpretation of information about the problem.
- Simulating the behavior of the system based on knowledge about the properties of the system.
- Associating with and triggering a particular solution schema (procedure).

Problem representation is the key to problem solving among novice learners as well as experts. Instruction must help learners to construct problem representations that integrate their problem representations with domain knowledge. What characterizes good problem representations? The quality of internal problem representations is a function of the coherence (internal structure) and the integration of the different representations (qualitative and quantitative, abstract-concrete, visual-verbal). What makes experienced problem solvers more effective is their richer, more coherent, and interconnected representations of problems.

How do learners develop these representations? There are at least three different research foci that address this question. One perspective argues that mental representations depend on the ways that problems are represented to learners. Another perspective focuses on the internal mapping of problems onto qualitative as well as quantitative internal representations and the cognitive processes that are engaged. The newest perspective focuses on the distribution of cognitive activity by using tools or formalisms for externalizing problem representations. This latter method will be the recommendation of this paper.

(RE)PRESENTING PROBLEMS TO LEARNERS

The way that problems are represented to a problem solver can substantially influence how the problems are solved, according to cognitive research in the 1970s and 1980s. Well-structured (textbook) problems, for example, are typically represented to learners in text form. Learners must then interpret the text and encode problem information in whatever internal representational form that they use. At the other end of the representational spectrum, newer situated and
authentic forms of instruction, such as anchored instruction, insist on rich and realistic video for representing problems to learners (Cognition and Technology Group at Vanderbilt, 1992). Episodic information that is essential for indexing information in the narrative is best conveyed, the CTGV claims, through video.

Regardless of the method used, problem mapping is central to problem representation. The assumption is that the attributes of external problem representations will be mapped onto learners' mental representations. So, organizing and displaying problems to learners in ways that enhance their mental representations and engage appropriate problem-solving processes is the goal. There are three characteristics of problem displays: the form of information items, the organization of items into structures, and the sequences of items or groups (Kleinmuntz & Schkade, 1993). Problem information can assume three different forms: numerical, verbal, or pictorial. That information can be organized into meaningful structures, including groups, hierarchies, or patterns such as tables or matrices. There are many ways to sequence the problem information. Not all of the representation methods have been researched.

Many cognitive researchers tacitly believe that the organization of the problem representation will have the most significant effect on internal representations. Schwartz (1971) found that matrix representations of information were substantially superior to groupings, graphs, and sentences because they clearly define needed information, suggest orders of operations, and provide consistency checks for partial solutions. Schwartz and Fattah (1973) confirmed the efficacy of matrix representations except for problems stated in the negative. When given the opportunity to change the problem representation, most students chose to restructure problems in the form of matrices.

Diagrams (flowcharts) have also produced better performance than verbal representations, especially for more complex problems (Mayer, 1976). It seems that spatial reorganization of information facilitates some of the cognitive activities that are required to solve problems. Carroll, Thomas, and Malhotra (1980) found that spatial layouts of isomorphic design problems resulted in better performances and shorter solution times than temporal representations. Providing a graphic representation to both groups eliminated that difference. Mayer (1976) concluded that the more integrated the representations are, the better the learner's performance on problem-solving tasks because the degree of structural integration is an important factor in mental representation.

More recent research has focused on the types of processing that are affected by form, organization, and sequencing of problem information. It appears that form, organization, and sequence of problem representation differentially affect cognitive processes. Mayer (1976) showed that examples were more effective than various jump (go-to) organizations of material. McGuinness (1986) compared the organizational characteristics of spatial arrays. She compared information that was organized into matrices with hierarchical representations and found the matrix superior for some problems but not for others. Why? Mapping differences engaged by different representations affected the number of mental steps needed to solve some questions, but not others. In one of the most comprehensive studies of external problem representations, Schkade and
Kleinmuntz (1994) compared the organization of individual items of information into patterns or structures (matrices vs. list-by-attribute or list-by-alternative), form (numbers vs. words), and sequence in which items appear in the organization (sorted vs. random) on decision-making problems. They found that organization strongly influenced information acquisition, form strongly influenced information combination and evaluation, and sequence had limited effects overall.

Zhang (1997) referred to the conceptual rationale for these findings as representational determinism. He argued that the form of the external representation of problems determines what information can be perceived, what processes can be activated, and what structures can be discovered from the representation. He believed that, based on principles of ecological psychology, information from problem representations can be perceived directly from the problem without mediation from memory, inference, or other cognitive processes. External problem representations have different affordances. External representations are more than merely inputs (e.g., memory aids) to an internal representation process during problem solving, so care must be exercised in how we represent problems to learners. More systematic research is needed to clarify the relations between problem elements and problem mapping process.

INTERNAL, MENTAL PROBLEM REPRESENTATIONS

Although it is widely assumed that problem solvers usually perform a task by using the external representation of the problem as given, other researchers have focused on the processes of mapping problem elements in the construction of personal, mental problem representations. "Problem solving must begin with the conversion of the problem statement into an internal representation" (Reimann & Chi, 1989, p. 165). Most psychologists believe that "...there exists an early holistic or gestalt stage in problem solving in which students must disembody relevant information from the question and restructure the problem" (Bodner & McMillen, 1986, p. 735) and that "representation, by definition, is the specification of these objects, operators, and constraints, as well as the initial and final states" (Reimann & Chi, 1989, p. 165).

Why is problem representation construction so important? Meaningful problem solving is impossible without connecting the problem to domain understanding. In order to do so, learners must relate the original problem presentation to construct a meaningful internal representation that can be manipulated (Larkin, 1985). In a series of experiments, Kotovsky and Fallside (1989) demonstrated that problem-solving transfer depends on the internal representation of problems. Internal representations can then function, they believe, independently of the stimulus features of the problem, which contradicts the assumptions of researchers focusing on the external problem representations. By evoking particular internal problem representations, we can increase the likelihood that those representations will produce positive transfer.

Mental problem representation is also important because individuals choose to represent problems in ways that make more sense to them. For instance, Jones and Schkade (1995) found that a substantial proportion of analysts use
representations of problems different than those presented to them. That is, they translate problems from the given external representation to one that is more familiar or convenient. Rather than uniformly identifying and representing core issues in design problems, Goldschmidt (1989) found that architectural designers interpreted and attended to remote and diverse issues and generated very idiosyncratic problem representations.

Problem spaces are mentally constructed by selecting and mapping specific relations from a problem domain onto the problem (McGuinness, 1986). These mappings may facilitate or impede different kinds of processing. When mapping certain structures onto cognitive representation reduces the number of mental steps, it facilitates problem solving. For example, spatial mappings are most effective when memory load is greatest (Potts & Scholz, 1975). Spatial reasoning supports problem solving when used to visually disambiguate problem elements. Unfortunately, people do not always use the most efficient representations of problems, so their representations may impede problem solving. That is why learning how to effectively represent problems is so important to problem-solving performance. As the complexity of the problem increases, producing efficient representations becomes more important, and efficiency of representations is a function of organization, integration, or coherence (McGuinness, 1986).

There are three kinds of knowledge represented in mental problem representations: naïve, qualitative scientific, and quantitative scientific (Ploetzner & Spada, 1993). Naïve representations are replete with misconceptions, and so should not be considered further. Qualitative knowledge specifies the concepts and abstractions in a problem situation, the conditions under which concepts and abstractions can be applied, the physical objects referred to, the attributes and values objects possess, and other concepts to which objects are related. Quantitative representations are those that make use of mathematical formalisms to represent the problem. Because problem representations are the crux of the problem-solving process, I will review each of the forms next.

Quantitative Problem Representations

When learning how to solve problems, especially in mathematics and the sciences, students come to understand the process as extracting values from the problem presentation and plugging them into the appropriate algorithm, which is then solved for the answer. If they have selected the appropriate algorithm to represent the phenomena, their answer is likely to be correct. However, more often than not, the students have failed to learn the underlying principles of the problem and are therefore unable to transfer their ability. For example, students in a physics class at Harvard who were competently solving physics problems that were represented mathematically failed a test of conceptual understanding of the problems and their underlying principles (Mazur, 1997). Students could apply equation-based, quantitative problem-solving procedures without understanding the physics concepts they were representing mathematically, so they were unable to transfer their skills because of their limited conceptual understanding. The over-emphasis on exclusively teaching procedural, quantitative
models of how to solve problems necessarily limits students' understanding of the problems. They represent the problem mentally as a series of solution steps. More emphasis on learning to qualitatively represent problems is needed. As indicated before, Ploetzner, Felse, Kneser, and Spada (1999) showed that when solving physics problems, qualitative problem representations are necessary prerequisites to learning quantitative representations. When students try to understand a problem in only one way, they do not understand the underlying systems they are working in.

**Qualitative Problem Representations**

Qualitative representations assume many different forms and organizations. They may be spatial or verbal, and they may be organized in many different ways. Qualitative representations are more physical than numerical. Physical representations of problems consist of entities that are embedded in particular domains (e.g., physics), and the inferencing rules that connect them and give them meaning are qualitative (Larkin, 1983). Qualitative representations function to:

- explicate information that is stated only implicitly in problem descriptions but is important to problem solution,
- provide preconditions on which quantitative knowledge can be applied,
- qualitative reasoning supports construction of quantitative knowledge not available initially, and
- yield a set of constraints that provide guidelines for quantitative reasoning (Ploetzner & Spada, 1993).


It is important to note that qualitative representations support the solution of quantitative problems. Successful mathematical problem solving requires both qualitative and quantitative reasoning. Instruction in mathematical problem solving should focus on the development of qualitative reasoning skills (how to build a mental model of a problem situation) (Mayer, Lewis, & Hegarty, 1992). In order to apply quantitative operators, it is necessary to transform the problem into a form that includes the problem objects—direct physical references translated into physics entities that are related by physics principles. Only then can a meaningful mathematical solution be derived. Training students to recognize and qualitatively represent problems improves students' problem-solving performance. Because most problems in mathematics, the sciences, and engineering are ultimately solved quantitatively, it is important to teach students how to represent problems qualitatively.

What kinds of qualitative representations best support quantitative problem solving? That varies according to experience and, of course, the kind of problem. Experts and novices tend to represent problems differently. Reimann and
Chi (1989) found that novice problem categories are characterized by literal objects and entities that are included in the problem statement, while experts classify problems by abstract principles of mechanics. Experts' cognitive representations of problems are more abstract representations, while novices use more concrete representations (Lamberti & Newson, 1989). When information was represented in an expert system knowledge base to scaffold diagnostic reasoning, highly skilled employees answered questions faster and more accurately and solved problems more efficiently when using abstract representations than when using concrete representations. However, low-skilled employees performed faster and more accurately using concrete representations of the problem. They made more errors when using abstract information.

If we agree with the research that qualitative representation of the problem is essential and should be prerequisite to quantitative representations, we need to conduct research on what forms those qualitative representations should take. That is, which kind of representation best supports different kinds of problem solving. If we agree with Anderson (1983) that problem schemas are best represented as production rules, then instruction needs to help learners to construct production-rule representations of their problems. If we agree with Chi and Bassok (1989) and Larkin (1983) that problem representations are schematic-like, then instruction needs to help learners construct schema-like representations of their problems. If we assume that problem representation must integrate qualitative and quantitative representations, then instruction needs to help learners construct dynamic system model representations of their problems. By providing tools that scaffold the representation of problems in different ways, we can have learners externalize their internal representations, which is described next.

EXTERNALIZING MENTAL PROBLEM REPRESENTATIONS

As described before, there have been two types of research on problem representations: (1) how we as instructors represent problems to learners in the problem statement, and (2) how we as problem solvers cognitively represent problems we are trying to solve. The goal of both types of research has been to determine how problem solvers should cognitively represent problems and how their internal representations affect their problem-solving ability. The assumption of the latter type of research is that the way that we represent problems to learners affects the learner's cognitive representation of the problem. A third type of research needs to develop; how to directly affect learners' problem representations by providing them with tools that model different kinds of qualitative representations. Tools that constrain and scaffold students' problem representation performance are more likely to affect the cognitive representations they develop than the ways in which the problems are represented to the learners. The rationale for using tools to scaffold problem representations is artificial intelligence in reverse; rather than having the computer simulate human intelligence, require the human to simulate the computer's unique intelligence and come to use it as part of their cognitive apparatus (Salomon, 1988). When learners internalize the tool, they begin to think in terms of it. So, this paper
proposes that we examine the use of three different tools for qualitatively representing problems in the sciences and engineering.

Another rationale for using tools to scaffold problem representations is the distribution of cognitive responsibility. Zhang and Norman (1994) developed a theoretical framework for distributing representations internally and externally. They consider the internal and external representations as equal partners in a representation system, each with separate functions. For example, external representations, Zhang and Norman claim, activate perceptual processes while internal representations activate cognitive processes. Together, the representations are symbiotic. A key assumption of problem solving, according to Zhang (1997) is that external representations need not necessarily be re-represented as an internal representation in order to be used for problem solving. They can directly activate perceptual operations and cognitive activities provided by the problem solver. These external representations cannot function independently without the support of internal perceptions or cognitions.

There is some empirical evidence to support this distributed, tool-mediated conception of problem representation. Though focusing on problem representations to learners, Polich and Schwartz (1974) observed this distributed-representations perspective when their matrix representations of problems were especially effective for larger, more complex problems because of the ease of applying and storing the results of logical operations in such a problem space. That is, matrices off-load some of the memory tasks. Their previous assumption was that such matrices were superior because they facilitated the encoding process. Jones and Schkade (1995) found that when learners were provided with diagrammatic or table-like tools for representing problems, many of them chose to restructure the problem representations into their preferred mode, diagrams. Externalizing problem representations supports memory as well as providing information that can be directly perceived and used without being interpreted (Zhang & Norman, 1994) — because they anchor and structure cognitive behavior of the learner, they alter the nature of the task.

USING TOOLS FOR EXTERNALIZING PROBLEMS

If external representations function as affordances that constrain different kinds of cognitive activity, then interacting with those representations should afford even greater cognitive benefits. However, affordances depend on properties of the environment and the properties of the perceiver. They are mutually constraining and complimentary. If the perceiver is tuned to attend to environmental affordances, they will be able to use them. It will be necessary to practice the use of these tools to represent problems during class time, to support the tuning of students to the affordances of these different tools. Because there is no research on the interaction of individual differences and tool use, it is impossible to predict which, if any, of the properties of the perceiver will affect their use.

It is also important to note that using formalisms and tools to represent both the external problem representation as well as the problem solver's internal representation goes beyond distributing cognitive tasks. Using problem-representa-
tion tools begins to integrate internal and external problem representations into a continuous form of representation. The functions of those separate representations begin to blur. How seamless that representation becomes probably depends on the problem solver's comfort and facility with the tool to represent different classes of problems.

TOOLS FOR EXTERNALIZING PROBLEM SPACES

A fundamental conclusion of this paper is that successful problem solving requires learners to qualitatively as well as quantitatively represent problems that they are attempting to solve. The most effective way to support different problem representations by learners is to require them to use different knowledge representation formalisms (i.e., knowledge representation tools, a.k.a. cognitive tools) to represent problem spaces (the specific problem embedded in domain knowledge).

Cognitive tools are any technologies that engage and facilitate specific cognitive activities. They amplify the learners' thinking by enabling learners to represent what they know using different representational formalisms. As knowledge representation formalisms, cognitive tools are premised on the idea that humans learn more from constructing and justifying their own models of systems than from studying someone else's (Jonassen, 1990; 2000).

Semantic Networks for Modeling Conceptual Knowledge

Semantic networks, also known as concept maps or cognitive maps, are spatial representations of concepts and their interrelationships that are intended to represent the knowledge structures that humans store in their minds (Jonassen, Beissner, & Yacci, 1993). These knowledge structures are also known as cognitive structures, conceptual knowledge, structural knowledge, and systemic knowledge. They are useful for our purpose because internal problem representations can be represented as semantic nets (Larkin, 1985).

Semantic networks are graphs consisting of nodes representing concepts and labeled lines representing relationships among them. Figure 1 illustrates a semantic network about stoichiometry problems that are solved in introductory chemistry courses. When students construct semantic nets, they are required to isolate the most important concepts in a problem domain, assemble those concepts into nodes, and link the nodes and determine the semantic nature of the link between the nodes. Why is it important to externalize structural knowledge? Meaningful learning requires that learners connect new ideas to prior knowledge. Semantic networks help in organizing learners' knowledge by integrating information into a progressively more complex conceptual framework. When learners construct concept maps for representing their understanding in a domain, they reconceptualize the content domain by constantly using new propositions to elaborate and refine the concepts that they already know. More importantly, concept maps help in increasing the total quantity of formal content knowledge because they facilitate the skill of searching for patterns and relationships among concepts (Slack & Stewart, 1990). Research has shown that well-organized and integrated domain knowledge (as evidenced by integrated semantic networks) is essential for problem solving. It is
necessary to understand the conceptual relationships among the concepts in any problem domain in order to be able to transfer any problem-solving skills developed. How much effect the construction of semantic networks will have on problem solving needs to be examined. There are a number of software tools available for constructing semantic networks. The most powerful is Semantics from Semantic Research. More popular, though much weaker, tools are Inspiration and Axon Idea Processor. These tools can be mastered in less than one hour.

Expert Systems for Representing Procedural Knowledge

Expert systems are artificial intelligence programs designed to simulate expert reasoning in support of decision making for any kind of problem. Like a human expert, an expert system (computer program) is approached by an individual (novice) with a problem. The system queries the individual about the current status of the problem, searches its knowledge base (which contains previously stored expert knowledge) for pertinent facts and rules, processes the information, arrives at a decision, and reports the solution to the user.

Building expert systems is a knowledge-modeling process that enables experts and knowledge engineers to construct models of causal reasoning processes.

![Figure 1. Semantic network of stoichiometry problem](image-url)
Context: 'This knowledge base is intended to cognitively simulate the processes of calculating molar conversions.'

D1: 'You know the mass of one mole of sample.'
D2: 'You need to determine molar (formula) mass.'
D3: 'Divide sample mass by molar mass.'
D4: 'Multiply number of moles by molar mass.'
D5: 'You know atomic mass units.'
D6: 'You know molar mass.'
D7: 'Divide mass of sample by molar mass and multiply by Avogadro's number.'
D8: 'Divide number of particles by Avogadro's number.'
D9: 'Convert number of particles to moles, then convert moles to mass.'
D10: 'Convert mass to moles using molar mass, and then convert moles to molecules using Avogadro's number.'
D11: 'Convert from volume to moles (divide volume by volume/mole), and then convert moles to moles by multiplying by Avogadro's number.'

Q1: 'Do you know the number of molecules?'
Q2: 'Do you know the mass of the sample in grams?'
Q3: 'Do you know the molar mass of the element or compound?'
Q4: 'Do you know the number of moles of the sample?'
Q5: 'Do you want to know the number of molecules?'
Q6: 'Do you want to know the mass of the sample in grams?'
Q7: 'Do you want to know the molar mass of the compound?'
Q8: 'Do you want to know the number of moles of the sample?'
Q9: 'Do you know atomic mass units?'
Q10: 'Do you know the volume of a gas?'
Q11: 'You need to determine molar (formula) mass.'

Rule1: IF q2a1 AND q8a1 THEN D2
Rule2: IF (d1 OR q3a1) AND q2a1 AND q8a1 THEN D3
Rule3: IF q4a1 AND q3a1 AND q6a1 THEN D4
Rule4: IF q3a1 THEN D1
Rule5: IF q3a1 THEN D5
Rule6: IF q9a1 THEN D6
Rule7: IF q3a1 AND q2a1 AND q5a1 THEN D7
Rule8: IF q1a1 AND q8a1 THEN D8
Rule9: IF q1a1 AND q6a1 THEN D9
Rule10: IF q2a1 AND q5a1 THEN d10
Rule11: IF q10a1 AND q1a1 THEN d11

Figure 2. Excerpt from expert system rule base on stoichiometry.
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assessing the viability and comprehensiveness of learners’ knowledge. System-modeling tools are very probably the most powerful cognitive tools available.

There is a small base of literature that describes experiences with systems modeling in high school and college. However, no empirical research has ever focused on the use of systems modeling to support problem solving or higher-order thinking. It is obvious from any form of cognitive task analysis that systems modeling necessarily engages causal reasoning about dynamic systems. Because systems modeling supports strategic understanding of a problem, we believe that building systems models of problem types will support problem solving and transfer better than any other kind of tool. How much effect the construction of systems models will have on problem solving needs to be examined.

Systems modeling tools are readily available. My preferred tool is Stella from High Performance Systems. Equally powerful are PowerSim and VenSim. Although they are incredibly powerful tools, there is a steeper learning curve associated with them. Several hours to several days are required for competence. The Highly Interactive Computing Group at the University of Michigan has designed a simpler tool called Model It, designed for use by middle school students. What it loses in power, it gains in ease of use.

Figure 3. Systems dynamics model of stoichiometry problem in Stella.
RATIONALE FOR USING TECHNOLOGY TOOLS FOR EXTERNALIZING PROBLEM REPRESENTATIONS

Although no empirical research has examined the effects of using technology tools for representing problems on problem-solving performance, there are several good reasons for predicting their efficacy.

First, Simon (1981, p. 153) claimed that “solving a problem simply means representing it so as to make the solution transparent.” The centrality of problem representation to problem solving is inherent in all of the research reported in this paper. Representing the problem in a coherent way is key to solving problems.

Externally representing problems will also decrease cognitive load in learners, especially while solving complex problems. Sweller and Chandler (1994) showed that limited working memory makes it difficult to assimilate multiple elements of information simultaneously, and multiple elements must be assimilated when the problem components interact, especially when solving complex problems. Providing an external representation of the problem components scaffolds working memory by off-loading the need to simultaneously model multiple problem components.

External problem representations, especially those in the form of dynamic models, enable learners to manipulate and test their models. That is, learners can test predictions of their models as a way of confirming the validity of their assumptions. The problem arises when learners can test the assumptions that are conveyed by their model.

Finally, building models of problems is at the heart of scientific thinking and requires diverse mental activities such as planning, data collecting, collaborating and accessing information, data visualizing, modeling, and reporting (Soloway, Krajcik, & Finkel, 1995). The potential for research confirming positive relationships between modeling and problem solving is great.

Contributors

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References


