Mental Models: Knowledge in the Head and Knowledge in the World

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Abstract: Better understanding learners' mental models will help us to assess advanced knowledge and problem solving skills acquired while interacting with constructivist learning environments. Mental models are the internal, conceptual and operational representations that humans develop while interacting with complex systems. In this paper, we argue that they are also embedded in the activities engaged in by a community of practice, the social relations among members of that community, the discourse used by that community to negotiate meaning, and in the artifacts that are used and produced by the community during their activity. This paper describes two studies: one aimed at eliciting mental models in the heads of novice refrigeration technicians and the other an ethnographic study eliciting knowledge and models in the community of experienced refrigeration technicians.

Introduction

Most constructivist learning environments, including cognitive flexibility hypertexts (Spiro & Jehng, 1990), anchored instruction (Cognition & Technology Group, 1992), goal-based scenarios (Schank (1993/1994), and causally modeled diagnostic cases (Jonassen, Mann, & Ambruso, 1996), share a common goal: the construction of advanced knowledge by learners that will support complex performances, such as problem solving and transfer of learning. These environments stress situated problem solving tasks, because those are the nature of tasks that are called on and rewarded in the real world.

While advanced knowledge, higher order thinking, problem solving, and transfer of learning evoke common associations and expectations in most of us, there remains an operational inexactitude in these constructs. Just how do we know when learners have constructed advanced knowledge? How advanced or higher order does that knowledge have to be? How do we assess it? In this paper, we argue that these learning outcomes can best be operationalized and predicted by assessing and understanding mental models of the problem or content domain being learned. Why? Because solving situated, ill-structured problems in different settings requires problem solver to use complex and diverse problem representations. Problem solving performance can be at least partially explained by the quality of the mental models of the problem solvers (Gott, Benett, & Gillet, 1988). But mental models and the knowledge that they reflect exist not only in the heads of learners but also in the activity structures engaged in by learners, the identities and social relationships of the learners, the discourse they generate as problem solvers, and the artifacts employed in those processes.

The purpose of this paper is to begin to explore the utility of mental models as learning outcomes from using complex and situated learning environments. In order to provide useful recommendations, it is necessary to formulate clear and operationalizable representations of mental models and then to assess changes in those models that may result from complex interactions with learning environments.

Mental Models: Knowledge in the Head

The construct, mental models, emerged from the human computer interaction field as a metaphor for describing the conceptions that humans develop for internally describing the location, function, and structure of objects and phenomena in computer systems. The facility with which users apply and exploit the functionality of computer systems depends on the internal, conceptual models that they build for describing the components and interactions of those systems. So, mental models are the conceptions of a system that develop in the mind of the user. Mental models are representations of objects or events in systems and the structural relationships between those objects and events. Most instructional designers assume that the design of instruction controls the mental model that is developed by the user, so an ideal user's mental model would be congruent with the conceptual model of the interface as developed by the designers. However, Moray (1987) makes the argument that mental models evolve instead as homomorphs of the system's structure rather than isomorphs. Users' mental models usually vary, often significantly, from the cognitive or conceptual model promoted by the designers because of varying prior knowledge, individual abilities, and different beliefs about the purpose and functions of the system.

New, more situated conceptions of mental models must evolve if they are to be useful in the design and assessment of authentic and situated learning environments. For instance, mental models, according to Norman (1983), are the internal representations that humans develop of themselves and the objects they interact with in the world. Building mental models is an important component in accommodating to the world.

Operationalizing Mental Models

Mental models are theoretical constructs; they do not exist in any reified form. So we are not certain how they develop. A common theory for describing mental model development is analogical or metaphorical reasoning (Staggers & Norcio, 1993). That is, learners generalize existing models to new phenomena through a process known as structure-mapping, that is, mapping the old structural relations onto new (Gentner & Gentner, 1983). For example, flowing water helps most people develop a mental model for electricity. Most theories believe that mental models consist of objects and their relationships (Gentner & Gentner, 1983; Carley & Palmquist, 1992). But these conceptions define only knowledge in the head. Knowledge-in-the-head conceptions of mental models are based on a set of assumptions stated by Carley and Palmquist (1992):

- Mental models are internal representations.
- Language is the key to understanding mental models; i.e.. they are linguistically mediated.
- Mental models can be represented as networks of concepts.
- The meanings for the concepts are embedded in their relationships to other concepts.
- The social meaning of concepts is derived from the intersection of different individuals' mental models.

These assumptions, we believe, are probably necessary but not sufficient for describing knowledge in the head. We shall briefly examine and illustrate additional components.

Components of Mental Models

Mental models have been traditionally thought to consist of an awareness of the structural components of the system and their descriptions and functions, knowledge of the structural interrelatedness of those components, a causal model describing and predicting the performance of the system (often formalized by production rules), and a runnable model of how the system functions (Gott, Benett, & Gillet, 1988; deKleer & Brown, 1988). So they have been assessed using a variety of methods, including think-alouds and verbal protocols, online protocols (audit trails), problem solving and troubleshooting performance, information retention over time, observations of system use, users' explanations of systems, and users' predictions about system performance (Sasse, 1991). These data are often collected while users interact with experimental versions of systems, causing Sasse to conclude that such findings are often flawed because the experimental scenarios are too restrictive and artificial, an insufficient range of information is collected, and samples are too small and too often reflect only novice users.

Mental models are more than structural maps of components. They are dynamic constructions. They are multimodal as well as multi-dimensional. Mental models are complex and inherently epistemic, that is, they form the basis for expressing how we know what we know. Because mental models are epistemic, they are not readily known to others and, in fact, not necessarily comprehended by the knower. However, we believe that they can be represented in the following ways.

Structural Knowledge. Structural knowledge is the knowledge of the structure of concepts in a knowledge domain and can be measured in a variety of ways (Jonassen et al, 1993). A number of researchers have used structural knowledge methods to develop representations of mental models. For example, Pathfinder nets generated from relatedness data were generated to depict mental model (Kraiger & Salas, 1993). Carley and Palmquist (1992) use their own software for constructing interlinked concept circles (maps) based upon text analysis or interviews. These methods all rest on the assumptions that cognitive structure can modeled using symbols (Carley & Palmquist, 1992) and that semantic proximity can be represented in terms of geometric space (Jonassen et al, 1993). Using structural knowledge methods to model mental models further assumes that they can be represented as networks. In this study, we will use Pathfinder nets to analyze the structural knowledge using a constrained set of 20 refrigeration systems concepts. While we believe that networks of interconnected knowledge underlay mental models, they cannot function adequately as the sole means of representation.

Performance/Procedural Knowledge. It is essential that learners be required to perform problem solving tasks. Kyllonen and Shute (1989) recommend process outcome predictions for assessing mental models, that is, performing some task, such as troubleshooting a simulated task or "walking through" a performance test. "Running" the model has received limited investigation of simple concepts to qualitatively test the visual images in their heads (diSessa, 1983). These will be assessed using think-aloud protocol analysis while solving the problem provided. In addition to providing performance problems that need to be solved, learners should be required to articulate their plan for solving the problem, and they should be observed on how well they adhere to the plan, what strategies they use for dealing with discrepant data and events, and finally what kinds of generalizable conclusion they can draw from the solution. These data can probably best be gathered by having learners think aloud while solving the problem. We propose to intervene and prompt the learner at various stages with questions requiring them to explain or infer why certain results occurred and to make predictions about what will happen next.

Reflective Procedural Knowledge. An increasingly common method for assessing mental models is the teach-back procedure, in which learners or users are asked to teach another learner (typically a novice) how to perform certain tasks or how to use a system. Students often produce a variety of representations, such as a list of commands, verbal descriptions of task components, flow charts of semantic components, descriptions of keystrokes (van der Veer, 1989).

Image of System. Wittgenstein (1922) described propositions as imaginal models of reality. Most humans generate mental images of verbal representations. The statement, "The stone gained speed as it rolled down the steep slope" is meaningful only when an image of a mountain with a stone descending along its side is generated. Mental models definitely include mental images of the application of domain knowledge. So, it is important to elicit the learner's mental image of a prototype of the system s/he is constructing. Some learning environments accommodate this need by providing an "envisioning machine" that displays system objects in different views (Roschelle, 1987). However, such envisioning tools map representations or views of the world that may not be consonant with the learners'. So, in this study, we require learners to articulate and visualize their "runnable" physical models or the physical devices or processes (Gott et al, 1986) using interviews

Metaphors. In addition to imaginal representations, humans naturally tend to relate new systems to existing knowledge, often by associating them with other physical objects. A recent interview with an engineer produced a "marshmallow" metaphor for molecules. While most metaphors are not as distinctive, they are important means for understanding peoples' mental models. We will therefore require the participants to generate metaphors or analogies of the system involved in the performance, asking them to explain the similarities between the refrigeration system and the metaphor.

Executive Knowledge. It is not enough to have a runnable model of a domain or process, but in order to solve ill-structured problems it is essential to know when to run which model. Knowing when to activate mental models allows the learner to allocate and apply necessary cognitive resources to various applications. This can only be assessed by presenting a variety of problems to solve. That is not possible in this initial study.

Method

In this study, we studied the internal mental models of refrigeration technicians. A group of six novices (students in the final semester of a two-year, technical college program in refrigeration technology. All of the participants were male between 20 and 38 years of age. The situation for validating internal components of mental models was a laboratory activity for 3rd semester students in a 2-year program in refrigeration technology. The problem was a 3-phase motor simulation controlled by 3-pole motor starter which is controlled by a 208 v coil which is switched by a line voltage cooling thermostat & switch. The context was a troubleshooting exercise in which students using visual cues and voltmeter had to determine what caused load to be energized. Students' think alouds were used to assess their runnable models of the system. They also provided pairwise similarity ratings between 12 concepts defining the simulation, from which Pathfinder Nets (Schvanenveldt, 1989) were generated. Images of the system were provided by written protocols of a survey or tour of system (Tversky, 1994).

Results and Discussion

Because of space restrictions, we shall compare only two of the participants, the individual who was slowest in completing the troubleshooting task and the individual who was fastest. The slowest troubleshooter indicated in the think-aloud that he "couldn't see the problem." He required consistent instructor prompting to complete the required tests, and his testing sequence was less goal-oriented and systematic. He randomly tested different parts of the system. He required almost five minutes to find the fault.

The Pathfinder net produced from the ratings of the slowest performer had fewer links, fewer levels, and was less integrated than the fastest performer. The primary component of the system, the starter coil, is on the fringe and relatively disconnected from the other components.

When asked to provide a tour of the system, he described: "Coming out of L1 you go to a terminal block and through a H.P. switch and then through a cold control. Coming out of the cold control L1 goes through the relay 1 and out 3. Then it goes to the overload on the motor starter and back to L2." This description is very literal and sequential. The metaphor that he generated to describe the system was :"Motor starter is like an Army protecting its country from being taken down by a higher power."

The fastest troubleshooter tested system systematically. He checked power first and then proceeded to check each set of connections with his voltmeter until he found the fault 45 seconds later.

The Pathfinder Net of the fastest troubleshooter produced more links on more levels. Important system components, the coil, breaker, and pressure switch, are all interconnected as a set of system controls.

When asked to provide an overview tour of the system, he provided a more hierarchical description of the system: "The three phase system was a detailed version of a typical three phase motor starter. The motor starter was controlled by a single 208v control circuit. Line voltage power was fed through a cold control and high pressure switch and if both were closed would energize the coil or the motor starter relay. When the coil on the relay was energized the normally open contacts were closed thus energizing the motor starter. The motor starter then sends three phase power to ..." The metaphor that the fastest troubleshooter provided: "Motor starter is like a job foreman. It works to ensure important tasks are carried out." The regulatory function of the starter is evident even in his metaphor.

These measures clearly show that differences in troubleshooting ability (requiring a runnable model of the systems) were evidenced by differences in knowledge structures, differences in visualization, and differences in the metaphors generated by the individual. It was clear from only a few data points that individuals build significantly different mental models of even a simple refrigeration system, and that those models affect their ability to perform problem solving activities.

Mental Models: Knowledge in the World

Social constructivism and situated learning perspectives make different claims about the nature understanding and knowledge. The view of situated learning that Lave (1988) favors is situated social practice. Rather than being shaped by social factors, she believes that cognition and thinking are shaped by activity, and that learning is represented as the centripetal movement toward the center of a community of practice. That results from the dynamic interplay between the activities that people engage in and the sense of that activity that they socially negotiate. Knowledge in this view is not an object that is possessed by individuals. Rather, knowledge, at least in an epistemic sense, is also embedded in the activities and processes that people engage in, the social relations and identities of the actors, and in the conversations or social discourse they use to make meaning of the activities and events. Finally, we believe that knowledge is embedded in physical artifacts that are the objects of activity and used to construct meaning.

Method

One of the authors conducted an ethnographic study of supermarket refrigeration service technicians for a seven month period in 1995. Service technicians are ideal for studying from a situated perspective because the consequences of failure are obvious and immediate and because supermarkets are complex social, technical, and cultural spaces all of which impinge on the job. Clearly, technicians must interact with physical objects and processes, but they must also negotiate with a variety of other actors on the complex milieu, and they constantly struggle to form an identity within that milieu.

The technicians studied worked for a medium-sized supermarket chain. Each was responsible for maintaining the refrigeration equipment in nine stores. The participants included seven technicians, with whom the researcher rode with one 10-hour day per week for seven months.

Data gathering methods included participant observation, document and artifact analysis, unstructured interviews while riding to jobs, video recordings of work activities, and a journal. Field notes, videotape logs, and journal entries were logged, annotated, and categorized.

Results and Discussion

Analysis of the ethnographic data showed four kinds of knowledge that emerged from their practice.

Activity Based Knowledge. The technicians maintained considerable autonomy in setting their work schedules, so long as the equipment in their stores was adequately maintained. Their work involved getting dirty as they changed compressors but also involved a major analytical components as they solved complex refrigeration problems. Their function is primarily care for the refrigeration systems that are so integral to a modern supermarket. However, in order to accomplish that role, they must garner the cooperation of other store personnel. So, their jobs also required widely different social relationships in dealing with other technicians and refrigeration specialists but also with store personnel. The success the technicians was a function of the kinds of social relations they maintained with store managers and other personnel.

Social/Relational Knowledge. The modern supermarket is both technically and socially complex, which caused refrigeration technician their greatest identity problems, as they are regarded as external to the functioning of the supermarket, even though their expertise and services are so essential. This ambiguity about status has been found in other studies of technicians (Barley & Bechty, 1994). However, there exists a very strong identity among service technicians, who are members of a well-defined community of practice. This definition is accomplished through extensive social negotiation (Orr, 1990).

Conversational/Discursive Knowledge. Social negotiation of meaning was a primary means of solving problems, building personal knowledge, establishing an identity, and most other functions of the technicians. In solving problems, technicians used the question as a means of stating possible solutions or causes for a problem. The "What do you think?" style initiated extensive conversations among the technicians, supervisors, and factory representatives. Not only did it form a bond among the technicians, but it also led to solutions.

The primary medium of discourse were stories, which is consistent with other studies of technicians (Orr, 1990). These stories provided contextual information, worked as a format for diagnosis, and also expressed an identity of being a technician. They provided a natural flow of conversation among the technicians. Interestingly, the stories always contained strong emotional overtones about the experiences , especially about first experiences. The stories often reaffirmed their pride in being service technicians.

Artifactual Knowledge. Refrigeration technicians regularly converse with machines and tools as well as with store personnel. The person-machine conversation is carried out by placing hands on the piping to sense temperatures, listening to the sound of a compressor, looking for oil stains on the floor, or interacting with the computer screen. The objects all possess a means for direct communication with the technicians through sense impressions. One of the technicians referred to this as "touchy-feely" knowledge.

The artifacts also served as discourse markers. Empty parts boxes and failed parts or dead batteries were often left at a scene as markers of previous attempts to solve problems, despite the generally neat nature of the compressor rooms maintained by the technicians. These marker served as important lessons to others.

Conclusion

The knowledge that is reflected in mental models is both internal and external to the individual. Clearly, we naturally construct internal models of activities and systems tat we interact with. Yet those internal models are inadequate for accomplishing many tasks. In order to function in a community of practice, we call on the collective knowledge, experience, stories, and wisdom of other members of that community. So, there is a community mental model that is socially negotiated. That model defines the identity of its members as well as defining the activities of that community. In short, knowledge exists in the head, but it also exists in the world -- in the social relationships, in the artifacts, and most especially in the discourse of that community.

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