Computer-Based Simulations as Learning Tools: Changing Student Mental Models of Real-World Dynamical Systems

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The evolution of the World Wide Web (WWW), recent developments in interactive software, and the emergence of systems thinking provide a unique opportunity to create interactive, web-based simulations that address student learning. This paper explores current theory of mental model formation and its role in student understanding. It describes the potential of computer simulation to enhance student learning, here defined as a change in a student's mental model(s). As web-based simulations are newly emerging, an example will be provided in hopes the reader will take the opportunity to explore. The author's work involves the use of STELLA modeling program. High Performance Systems, Inc., producer of this software, has yet to deliver on a promised "web-runnable" version (now proposed for a Summer 2001 release), therefore this aspect of the proposed study had to be abandoned.

The Mental Model

If you understand inflation, a mathematical proof, the way a computer works, DNA, divorce, then you have a mental representation that serves as a model of an entity in much the same way as, say, a clock functions as a model of the earth's rotation (Johnson-Laird, 1987). "A mental model is a network of facts and concepts…that contains our understanding of social and physical phenomena." (Morecroft and Sterman, 1994).

Mental models are naturally evolving models. Through an interaction with a target system (area of interest) people formulate mental models of that system. These models need not be technically accurate (and often are not), but they must be functional. A person, through interaction with the system, will continue to modify the model in order to get a workable result. Mental models will be constrained by such things as the user's technical background, previous experience with similar systems, and the structure of the human information processing system. The scientist's conceptualization of a mental model is, therefore, a model of a model (Gentner and Stevens, 1983).

Don Norman's (1983) observations on a variety of tasks, with a wide variety of people, led him to a few general observations about mental models:

1. mental models are incomplete
2. people's ability to "run" their models can be severely limited
3. mental models are unstable...people can forget details of the system especially when those details have not been utilized for a while
4. mental models do not have firm boundaries
5. mental models are unscientific, and often include "superstitious" behavior and/or distrust of technology as a factor...sometimes superstitious behavior persists even when people are aware of their faulty thinking...(they seek) to avoid a void and/or to maintain as easier model
6. mental models are parsimonious...people often do excess physical operations rather than the mental planning necessary ...they trade off physical action for reduced mental complexity, especially when reduction of complexity can be applied to multiple systems thus avoiding confusion.

Norman (1983) cites typical use of hand-held calculators as examples of the latter observations. As a classroom teacher I often see similar behavior. Students, especially those less comfortable with the technology, will persistently and repeatedly hit the clear key, often 3-4 times, before beginning a new calculation. It is a mistrust of the technology but it resides in a faulty mental model, one that cannot accommodate to the capacity and precision of the device. Students are reluctant to use more complex functions, for example the memory registers, despite my having shown them (more than once). Upon completing a problem in physics, their first assumption is that the error lies in the calculation (the "device") and not in their conceptual thinking. This drives them to re-calculate, sometimes repeatedly, assuming the "calculator system" did not behave. Similar reiterative behavior is observed in students in physics lab exercises where video analyses or graphical functions are repeated in hopes of correctness. Students who have internalized a sufficient mental image of the calculator or computer functioning do not seem to exhibit this behavior.

Functional factors apply to mental models as well. If we seek to engage students to both think systematically and employ the learning potential inherent in simulations, we must instruct students as to their purposes. Norman (1983) cites these factors:

1. belief system: the mental model is a reflection of the person's belief about the system
2. observability: correspondence between parameters/states of the mental model and the physical system (observed or able to be observed)
3. predictive power: purpose of mental model is to understand and anticipate the behavior of the system.

Mental models, therefore, serve a number of purposes related to what one believes, what one sees, and what one thinks (or hopes) might transpire. Thus the persistence of mental models, even when challenged, must be accounted for in any educational effort to foster learning.

So the mental models which students bring to class are resistant, boundless, incomplete, and unscientific. The educational process must first become aware of the existence of resident mental models, their components and functions, and then provide suitable and powerful educational experiences to allow students to engage in the process of changing their mental models (learning).

Systems Thinking

Despite the traditional educational predominance of reductionism, current brain research indicates that a more holistic approach to learning is preferable. Many students are unable to sequentially build concepts and skills from parts to whole, the basic "pathway" of reductionism. These students often stop trying to see the wholes before all the parts are presented to them. We need to see the "whole before we are able to make sense of the parts." (Brooks and Brooks, 1993) "Systems thinking" is an emergent field that sees knowledge systematically, as a "whole", and provides a set of tools and a methodology for understanding both simple and complex systems. Russell Ackoff (Johnson, 1997) describes the present dawn of "Systems Age" thinking following the decline of "Machine Age" thinking. The basic tenets of the Machine Age Ackoff cites are:

1. the universe is completely understandable
2. analysis is inquiry
3. cause-effect relationships as key mechanism

These tenets, especially the third, carry some consequences: God must be the eventual cause of all things, that environment is irrelevant, and that all is predetermined, leaving nothing to probability. Merely deconstruct the system of interest and all will be understood. Isaac Newton embodies this approach to knowledge. This way of thinking began to decline with the development of new ideas in the physical sciences: uncertainty, quantum mechanics and chaos theory. A new view of the universe was needed. A vision was provided by Norbert Weiner in *Cybernetics* (1947) and by Ludwig von Bertalanffy in *General Systems Theory* (1954). These two works introduced the concept of "systems" and began a revolution in thinking.

A system is a whole that consists of sets of two or more parts. Each part effects the behavior of the whole, depending on the part's interaction with other parts of the system (Johnson, 1997). The properties of the system reside in the whole and not in the parts; remove a part and it does not behave as the whole. Remove the heart from the circulatory system and the heart behavior changes and the system behavior changes. The heart cannot adopt the function of the system nor the system respond to compensate for the lack of a heart. The circulatory system is not the sum of its parts, but the sum of its interactions. "Analysis" of a system is futile. To understand systems requires the use of synthesis (Johnson, 1997). Synthesis looks at the holistic "why" of system function as opposed to the "how." Context is as important (if not more so) than content.

Cain and Cain (1991) state, "..most real systems are non-linear, complex, and highly interactive. Their functioning is normally counter-intuitive." They site the characteristics of "experts":

1. experts see larger chunks, bigger patterns, the system at hand
2. experts grasp context; where the important patterns exist in the world
3. experts remember via a specific framework (similar to "local" system)

Systems thinkers operate to see the larger "chunks," the context, and have a systematic framework to "store" their understanding (deeper knowledge). Even physiological research on rat brains supports the notion that a natural, complex environment results in the greatest brain functioning. The brain also exhibits the capacity to process parts and wholes together (Cain and Cain, 1991). Systems thinkers simultaneously see the "forest" and the "trees," looking through complexity to see and understand the underlying system structure generating change (Senge, 1994).

Mental Models and Conceptual Models

Shawn Glynn and Reinders Duit (1995) extend the mental model concept further to include the mental models teachers evolve over years of study, called "conceptual models." The notion is that teachers address their students within a framework of their own conceptual model(s). Conceptual models are devised as tools for teaching/understanding physical and natural systems while mental models are what people really have in their heads. Ideally, there should be a direct and simple relationship between the two. When the two are in dissonance is when learning opportunities arrive. As the teacher possesses the correct conceptual model, his task is to elicit the mental models of his students and decrease the dissonance via "teaching." So teaching becomes the task of eliciting student mental models and providing sufficient experience to allow students to adapt, modify, reject, and enhance their own mental models (again, here defined as "learning").

"For …instruction to be effective it is important for teachers … to be aware that significant differences often exist between their conceptual models and the mental models of students and that students' mental models often contain a variety of misconceptions that can be resistant to change." (Glynn and Duit, 1995)

Eliciting Mental Models

The initial task, then, is to develop strategies for allowing and encouraging children to "expose" their mental models. A variety of strategies exist for use in the business community (see Richardson (1996), Morecroft and Sterman (1994)). If systems education and the use of simulations are to succeed in education, we must first develop and employ techniques by which students can describe their current mental model of the situation or system under study. Requesting students to provide a written and/or artistic representation of what they believe is effective. Even more useful are visual tools that provide scaffolding for students to elicit their mental models. Hyerle (1996) groups visual tools into three broad categories based upon their purpose:

1) brainstorming for fostering individual and group creativity
2) task-specific organizers for fostering basic skills and deep content learning
3) thinking-process maps for fostering cognitive development and critical thinking

It is these second and third categories that have the most impact upon eliciting student models. These include mind mapping tools, flowcharts, annotated concept maps, Venn diagrams, causal loop diagrams, stock/flow maps, and numerous visual organizers. Beyond identifying the components or variables in the system, task-specific organizers and thinking-process maps include relational or behavioral connections among and between the variables. Maps and webs can point out "cloudy" thinking. (This is where opportunities for learning exist.) Visual maps and webs provide a bird's-eye view of patterns, interrelationships, and interdependencies—all aspects of mental models (Hyerle, 1996).

When visual tools are coupled with in-class discussion and map presentations, the learning is further enhanced. Thinking and discussion begets more thinking, and thinking and problem solving capacities are enhanced when students think aloud, discuss, and communicate their thought processes to others—when students make their implicit thought processes explicit. Simulations can then be employed to permit students to "explore" the systems that their mental models propose to explain.

Simulations and Learning

In this context, "simulation" refers to the use of computer-based, dynamic modeling simulations. Other simulations, from "role-playing" to "virtual reality" have valid application but are not included in this discussion.

A classroom simulation is a method of teaching/learning or evaluating learning of curricular content that is based on an actual situation. The simulation, designed to replicate a real-life situation as closely as desired, has students assume roles as they analyze data, make decisions, and solve the problems inherent in the situation. As the simulation proceeds, students respond to the changes within the situation by studying the consequences of their decisions and subsequent actions and predicting future problems/solutions. During the simulation, students perform tasks that enable them to learn or have their learning evaluated. A well-designed simulation simplifies a real world system while heightening awareness of the complexity of that system. Students can participate in the simplified system and learn how the real system operates without spending the days, weeks, or years it would take to undergo this experience in the real world (Chilcott, 1996).

Classroom simulations motivate students by keeping them actively engaged in the learning process through requiring that problem-solving and decision-making skills be used to make the simulation run. As the simulation runs, it is modeling a dynamic system in which the learner is involved (plays a role). Thus, participation in simulations enables students to engage in systems thinking and enhances their understanding of systems as well as of social science and/or science concepts (Chilcott, 1996).

Since student mental models are built upon assumptions that evolve over time as a result of experiences and prior learning, the simulation environment gives students a chance for "playing" with their assumptions, testing various beliefs, and seeing the response of the system to their inputs. In the "Soda Game Simulation" (Glass-Hussein, 1995), a supply and demand simulation, students test their understanding of basic business concepts: the impact of advertising, and the notion of supply/demand equilibria. In this interactive environment, students act as retailers and make decisions regarding advertising expenditures, purchases from wholesalers, and pricing policy. Work with a group of 100 students indicated that their initial mental model had a firm grounding in supply and demand schedules (from in-class learning), but a weak understanding of supply/demand equilibria. Their text (as do most classical economics texts) portrays a static picture of the interplay of price, supply, and demand. By working with the simulator, students can use a set price to eventually establish an equilibria, and then perturbate the system by introducing a price "slash" or price "hike," and observe the behavior of supply/demand dynamics as a new equilibrium point is sought by the system over 26 weeks. Moreover, in the space of 2 class periods, students can manipulate the system over 15 times, establishing new equilibria under different constraints. Post-testing indicates a significant increase in understanding of supply/demand dynamics. "Students have, for the first time, a real understanding of the equilibrium point and how changing price or advertising causes pressures to shift the equilibrium." (Lord, 1999) Students also developed an appreciation for the structure and behavior of the real-world system: that equilibria are dynamic, time dependent, impacted by information and material delays, and prone to oscillations (in part driven by the students' inputs). The students' increased depth of understanding was quite apparent and striking (Lord, 1999).

Glynn and Duit (1995) indicate five conditions for learning meaningfully:

1. existing knowledge is activated (source of motivation)
2. existing knowledge is related to educational experiences
3. intrinsic motivation is developed
4. new knowledge is constructed
5. new knowledge is applied, evaluated, and revised

The use of a simulation addresses each of these conditions. Engaging in the simulation activates existing knowledge. This speaks to the need to develop significant background information and prior learning before running the simulation.

Chilcott (1996) indicates that the authentic nature of many simulations can be highly motivating. The teacher's enthusiasm can be contagious, especially if the role-playing is presented to students as a wonderful opportunity to change their identities. Students are actively engaged in the learning process as they solve problems and make decisions as it is done in the adult world. Simulations provide a forum in which creative, divergent thinking is legitimized and valued. Because simulations are much more like the "real world" than many classroom methods, students do not stop learning when the class period is over. Their interest carries over into informal out-of-class discussions with other students and adults in which experiences and ideas are shared and evaluated. Enthusiasm bubbles and school attendance is high. Students become educational ambassadors as they continue their discussions at home. Students describe this kind of learning as authentic and not boring.

Conditions 4 and 5 (above) are evident in the learning that occurs as students play with, test, and revise the simulation while simultaneously doing the same with their mental models. This requires, however, that there be supportive materials that focus the students on what they are doing, how their thinking is being changed, and what is their final mental model of the system. Supportive materials might be process guides, reflective pieces, or directed worksheets. Without sufficient supportive materials, students often lapse strictly into "play" mode without any mechanism for assessing the impacts upon their mental models. Glynn and Duit, (1995), state that guided discovery is vital for students "in post-preschool environs…a situation, question, or experiment is exposed for students and leading questions provided to 'guide' student thinking." Feedback is provided to students immediately where it can support appropriate change in students' understanding.

In simulation environments, students explore by doing, often begin by failing, and then move incrementally to success, and come away with rich stories (war stories). The power of learning by doing is well supported in the literature. The importance of failing in a non-threatening environment (a non-judgmental machine) cannot be stressed too much. Research supports the concept that learning opportunities arise at points when failure occurs. The simulation provides immediate feedback regarding the failure, as well as an immediate opportunity to try again. If the student moves toward success, then we would assume that the student has acquired new knowledge and adjusted the mental model(s) being employed. The "war stories" add to student engagement and enthusiasm.

Research has also pointed out the performance differences in group vs. individual simulation scenarios (Richardson, (1996), Morecroft and Sterman, (1994), Schoen (1983), Argyris, (1983)). In effect, [simulations] are "practice fields" for managers and teams. Little learning would be possible for the sports team without regular practice, or for the symphony orchestra or theatre troupe without rehearsal. The continuous movement between practice and performance enhances individual skills, group understanding…" (Issacs and Senge, (n.d.). Learning in teams is well documented. Having someone else to "bounce" your thinking off, and with whom to reflect upon performance, is a valuable component to increasing understanding.

At this time, little systematic, formal assessment of the impact of simulations has been published. Work within 28 school districts in the Waters Consortium, a group whose mission is to introduce systems thinking and dynamic modeling into the K-12 arena, indicates the need for formalized assessment. This work remains to be done.

Conclusion

Our increasing understanding of mental structures, brain-based learning, and the role of mental models in concept formation leads to the potential for utilizing computer-based simulations to increase student learning. The ability to approximate real-world behavior and structure, compress time horizons, provide "play" with decisions and the decision-making processes, and foster holistic, systematic thinking support the use of simulations for increasing student understanding.

Afterword: Web-Based Simulations

Interactive, web-based dynamic simulations are just being to appear on web-sites. Powersim Corporation (www.powersim.com) has several demonstration "web-sims" at their site. These are based on the Powersim modeling software, and can be run individually, or "players" can log into a continuing simulation with other players. The well-known simulation, "Beer

Game," a supply/demand simulation (the basis for Sodagame cited above) developed at MIT, places the player in one of several possible roles: wholesaler, producer, or retailer. High Performance Systems has just released "Otterville," an urban policy web-based simulation in STELLA (see http://www2.hps-inc.com/otterville/). Widespread use of interactive web-based simulations, however, has yet to become a reality.

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