

Model Facilitated Learning

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Abstract

The use of modeling and interactive simulations to represent complex subject matter is increasing due to the emergence of powerful new technologies. A promising methodology with an associated technology is system dynamics. System Dynamics is particularly well suited to provide the basis for meaningful learning experiences that involve learners in reasoning about relationships between the structure and the dynamics of such complex systems. The technology that supports system dynamics is web accessible and suitable for collaborative networked learning. Supportable experiences include the construction of interactive and web-accessible models as well as their use for hypothesis testing and experimentation. In this chapter, we develop a theoretically founded instructional design framework for the use of this technology. Key aspects of this framework include the use of modeling tools, construction kits and system dynamics simulations to provide multiple representations to help students develop an understanding of problem scenarios that are complex and dynamic. We distinguish learning by modeling from learning using models and indicate the circumstances when each approach is likely to be appropriate.

Keywords: Cognitive flexibility, Complex systems, Model-facilitated Learning, Problem-centered learning, Situated learning, Social constructivism, System dynamics

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Introduction

Technology changes. Technology changes what we do and what we can do. People change on account of technology. Technology in support of learning and instruction is no different. Instructional technology changes what teachers and learners do and can do. This is especially true when the Internet and distributed technologies are taken into consideration. Learning research has also evolved and increased our understanding of how people learn different things in different situations. There has been a trend to apply emerging instructional technologies to support learning and instruction in ever more challenging and complex domains (Spector & Anderson, 2000). Such a trend is quite natural. Once it is understood how to use technology to support mastery of simple skills, it makes good sense to explore more advanced uses of technology. We support this trend and believe, along with many others, that technology can be effectively used in distributed learning environments to support learning in and about complex systems which is the focus of the discussion in this chapter (Spector & Anderson, 2000).

Modeling and simulation tools are gaining importance as a means to explore, comprehend, learn and communicate complex ideas, especially in distributed learning and work environments (Maier & Größler, 2000). Students are building and using simulations in both guided discovery and expository learning environments (Alessi, 2000). Of particular interest is whether and when one learns by building simulations or by interacting with existing simulations (Spector, 2000). To explore this interest, we provide a framework for the integration of modeling and simulations deployable in collaborative tele-learning environments. We focus on a particular modeling and simulation approach called system dynamics (Forrester, 1985).

The system dynamics community has focused primarily on learning by creating simulation models, although some researchers are becoming more sophisticated in recognizing a variety of different learning situations and requirements (Alessi, 2000; Gibbons, 2001; Spector, 2000). The system dynamics community believes in the value of using system dynamics to improve understanding of complex, dynamic systems (Davidsen, 1996; Forrester, 1985; Sterman, 1994). This general commitment allows for both learning with models and learning by modeling.

The ability to model complex systems requires being able to define a model and use it to understand some complex phenomena - to make connections between and among parts and to analyze the model's ability to represent relevant aspects of the perceived world (Jackson et al., 2000). In the construction of models using systems dynamics tools, learners engage in cognitive and social processes that appear to promote understanding. However, it seems unreasonable to conclude that deep understanding in a complex domain always requires one to become an expert system dynamics modeler (Spector, 2000).

Considerable research has documented a variety of difficulties with learning concepts relevant to understanding complex systems in a variety of disciplines (Dörner, 1996; Kozma, 2000). For example, many people have difficulty with the following:

- understanding the effects of nonlinear relationships over time;

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- keeping the entire system in mind when trying to resolve an apparently localized problem;
- appreciating the full range of control and influence possible within a complex system; and,
- generalizing lessons learned from a particular problem context to a different problem situation.

How can learners acquire and maintain deep understanding about difficult-to-understand subject matter? How can modeling and simulation in complex domains be best used to facilitate learning? Understanding complex system behavior involves the ability to provide causal and structural explanations as well as the ability to anticipate and explain changes in underlying causes and structures. This kind of understanding is not acquired easily nor is it likely to be acquired from observations of either real or simulated behavior (Dörner, 1996). However, an appropriate methodology linked with collaborative and distributed technologies can significantly enhance such learning.

Our motivating concern is to help learners manage complexity in ways that contribute to improved learning and deep understanding. To achieve this goal, learning theory (socio-constructivism), methodology (system dynamics) and technology (collaborative tele-learning) should be suitably integrated (Spector & Anderson, 2000). We call this integration Model Facilitated Learning (MFL) (Spector & Davidsen, 2000).

A Theoretically Grounded Framework

Our understanding of the developmental, cognitive, and social dimensions of learning improved in the last half of the 20th century. Research inspired by Vygotsky and others suggests that recognizing the need for learners to engage peers in dialogue concerning challenging new concepts and to work in collaboration with colleagues on difficult tasks produces desirable and persisting improvements in understanding (Jonassen et al., 2000; Rouwette et al., 2000; Spector et al., 1999; Wells, 1999). Distributed technologies (e.g., networked learning communities) are well-suited to support such collaboration.

Learning in complex and ill-structured domains places significant cognitive demands on learners, as appropriately recognized by the medical community. Feltovich et al. (1996) note that one of the difficulties involves the misunderstanding of situations in which there are multiple, co-occurring processes or dimensions of interaction. In these kind of situations, learners often confine their understanding to one or a small number of the operative dimensions rather than the many that are pertinent (see also Dörner, 1996). Technology that depicts dynamic interactions can be of particular help in this area. The learning perspective we find most appropriate is based on notions derived from situated and problem-based learning (Lave & Wenger, 1990), especially as informed by cognitive flexibility theory (Spiro et al., 1988). Instructional design methods and principles consistent with this learning perspective can be derived from elaboration theory (Reigeluth & Stein, 1983) and from cognitive apprenticeship (Collins et al., 1989). MFL is derived from these learning and instructional theories. That these theories are reasonably well established but not embraced by the system dynamics learning community is somewhat disturbing.

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Situated learning (Lave & Wenger, 1988) is a general theory of knowledge acquisition based on the notion that learning (stable, persisting changes in knowledge, skills and behavior) occurs in the context of activities that typically involve a problem, others, and a culture. This perspective is based on observations indicating that learners gradually move from newcomer status (operating on the periphery of a community of practitioners) to more advanced status (operating at the center of the community of practitioners). As learners become more advanced in a domain, they typically become more engaged with the central and challenging problems that occupy a particular group of practitioners.

Cognitive Flexibility Theory (CFT) (Spiro et al., 1988) shares with situated and problem-based learning the view that learning is context dependent, with the associated need to provide multiple representations and varied examples so as to promote generalization and abstraction processes. Feltovich et al. (1996) argue that CFT and related approaches can help learners develop skills for thinking and learning about complex subject matter. Multiple representations naturally emerge in collaborative and group work. When learners are distributed in various settings and circumstances, it is essential to support multiple representations; CFT suggests this is important even for individual learners. Moreover, learning should be supported with a variety of problems and cases, which is especially important in distributed learning environments. However, people seem to prefer single and simple models. These restricted perspectives may be detrimental to learning (Feltovich et al., 1996; Kozma, 2000). As knowledge is used and represented in many ways it becomes more meaningful and more powerful. Towards this end, CFT advocates multiple types of models, multiple representations, alternative conceptualizations, varying levels of representational granularity, and so on. Additionally, CFT places particular emphasis on the importance of learner-constructed and learner-modifiable representations.

MFL, as a realization of CFT through system dynamics and distributed technology, provides learners with the opportunity and challenge to become model builders, to exchange and discuss models with peers, and to experiment with models to test hypotheses and explore alternative explanations for various phenomena. We believe that such modeling activities are often appropriate activity for advanced learners, but model building and construction is not always required in order to understand some aspects of a complex and dynamic system. Moreover, we believe that other activities, including interacting with existing models and simulations, are often appropriate pre-cursors to model building activities. MFL advocates a sequence of learning activities that begins with some kind of concrete operation, manipulating tangible objects in order to solve specific problems (Milrad, Spector & Davidsen, 2000). As these operations are mastered, learners can then progress to more abstract representations and solve increasingly complex problems. A set of principles to guide an MFL elaboration sequence is:

1. Situate the learning experience. Provide an opening scenario or a concrete case to familiarize learners with the complexity of the domain and with typical problems encountered in that domain.
2. Present problems and challenges of increasing complexity related to the opening scenario. For instance, suppose the initial situation involves managing a production plant. A problem sequence might be to determine existing inventory, predict future orders, and provide a plan for maintaining a stable inventory. As participants gain expertise, other aspects of the enterprise can be brought into consideration, such as the

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effect of overtime on workers as they try to keep up with orders or the effect of backlogged orders on future orders and so on.

3. Involve learners in responding to a set of increasingly complex inquiries about the problem situation. For example, suppose that the sales force has predicted a seasonal increase in orders. A number of inquiries about the effect on existing inventories can be constructed and used to stimulate individual and small group discussion and experimentation in order to provide answers about predicted system behavior.
4. Challenge learners to develop decision-making rules and guidelines for a variety of anticipated situations. In this case, a great deal of experimentation with models and simulations is appropriate. As the challenges increase in complexity, it is at this stage of learning that it is appropriate to provide opportunities for learners to modify models or create new models.

To summarize, we accept the notion that concepts are best learned in context – a problem setting in which the learner must apply and use the relevant concepts and knowledge to solve meaningful problems. Such learning should improve both retention (by providing a relevant context) and transfer (by providing multiple representations). The principle of graduated complexity (Spector & Davidsen, 2000) is used to guide the design of learning sequences. In addition, the notion of socially-situated learning experiences threads throughout such a sequence. Such learning principles suggest that the coupling of system dynamics with collaborative and distributed technologies has strong potential. Next we examine the role of models in learning.

The Potentials of Models in Learning

In this section, we illustrate how models can be used to represent complex subject matter. It is worth emphasizing that the steps in a graduated complexity model should not be considered fixed or rigid. The model we advocate recognizes individual and group differences and supports the notion of iterative development of learning, understanding and expertise.

Learning with models and learning by modeling are discussed separately here, but in a learning or problem-solving environment it is conceivable that both might be involved (albeit for different purposes and in different ways). In MFL, there are three stages of learner development with associated instructional approaches (Spector & Davidsen, 2000):

1. **problem-orientation** (problem confronting and problem solving), in which learners are presented typical problem situations and asked to solve relatively simple problems;
2. **inquiry-exploration** (hypothesis formulation and experimentation), in which learners are challenged to explore a complex domain and asked to identify and elaborate causal relationships and dominant underlying structures; and,
3. **policy-development** (decision making rule and global system elaboration), in which learners are immersed in the full complex system and asked to develop rules and heuristics to guide decision making in order to create stability or avoid undesirable situations.

The stages and principles of MFL correspond with major components of van Merriënboer's (1997) 4C/ID model and Dreyfus and Dryefus (1986) (see Table 1). Interestingly, the

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methods in the 4C/ID model are primarily focused on an analysis of the subject domain whereas Dreyfus and Dreyfus focus primarily on the learner. Naturally, both are important considerations for an instructional designer.

| Major Activity | MFL | 4C/ID | Dreyfus & Dreyfus |
|---|--|---|------------------------------------|
| Introduction to the domain | Problem-orientation and learning with models | Whole task introduction and prerequisite knowledge | Absolute beginner |
| Familiarization with the situation/system | Problem-orientation and learning with models | Part- or whole-task practice with prerequisite and supportive knowledge | Apprentice |
| Identification of causal relationships | From problem-orientation to inquiry-exploration | Part-task practice and algorithmic methods | Competent performer |
| Elaboration of causal relationships | Inquiry-exploration with learning with models and by modeling | Whole-task practice and heuristic methods | Competent and proficient performer |
| Reflection on the whole situation or system | From inquiry-exploration to policy-development with learning with models and by modeling | Heuristic methods | Competent and proficient performer |
| Understanding and solving new problems | Policy-development and learning by modeling | Whole-task practice and heuristic methods | Proficient performer |

Table 1. MFL, learning development and related models.

The principle of graduated complexity in MFL suggests a sequence of learner challenges:

1. Challenge learners to characterize the standard behavior of the complex system (how the system behaves over time with an indication of how components are interrelated).
2. Challenge learners to identify key variables and points of leverage with respect to a desired outcome.
3. Challenge learners to identify and explain the causes for observed system behavior, especially in terms of key influence factors that might be subject to control and manipulation.
4. Challenge learners to reflect on the dynamic aspects of the system in the context of decision and policy guides to achieve desired outcomes.
5. Challenge learners to encapsulate learning in terms of a rationale for system structure, decision-making guidelines, and an elaborated strategy for policy formulation.
6. Challenge learners to diversify and generalize to new problem situations. (To assess deep understanding one might ask learners to create a dynamic model relevant to an apparently new problem situation that is likely to have an underlying structure similar to a problem situation already resolved by the learner).

Throughout the various stages learners are challenged to start meaningful discussions with peers about problems, models and proposed solutions, all of which are well supported by available web-based technologies. Such discussions help learners reflect about the subject matter and encourage peer-peer learning and group collaboration.

Next we shall provide examples. We follow Alessi (2000) in distinguishing learning with models from learning by modeling. We believe that learning with models is generally well

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suited for the earlier learning stages that often involve simple procedural tasks and simpler conceptual foundations (similar to algorithmic-based learning in 4C/ID), whereas learning by modeling is generally better suited for more advanced stages of development targeted at causal understanding and mastery of complex procedures not amenable to formulaic or standard solution (similar to heuristic-based learning in 4C/ID).

MFL emphasizes socially-situated learning processes. A suggestion of how to support collaboration with modeling tools in a discovery setting has been made by van Joolingen (2000). In the construction of models using systems dynamics tools, learners engage in cognitive and social processes that promote collaborative knowledge building. Rouwette et al. (2000) argue that a collaborative approach to model and policy design is effective for learning and understanding. In these cases, we see theory, methodology and technology all coming together.

Learning with models

MFL advocates learning with models as an instructional approach to introduce learners to a new domain or problem situation and to promote learning simpler procedures and associated concepts. Causal loop diagrams (also called causal influence diagrams) are quite good at providing a representation of an entire system (see Figure 1). Such diagrams can be used to support an elaboration of a problem scenario, knowledge elicitation, and assessment of understanding (Davidsen et al., 1999).

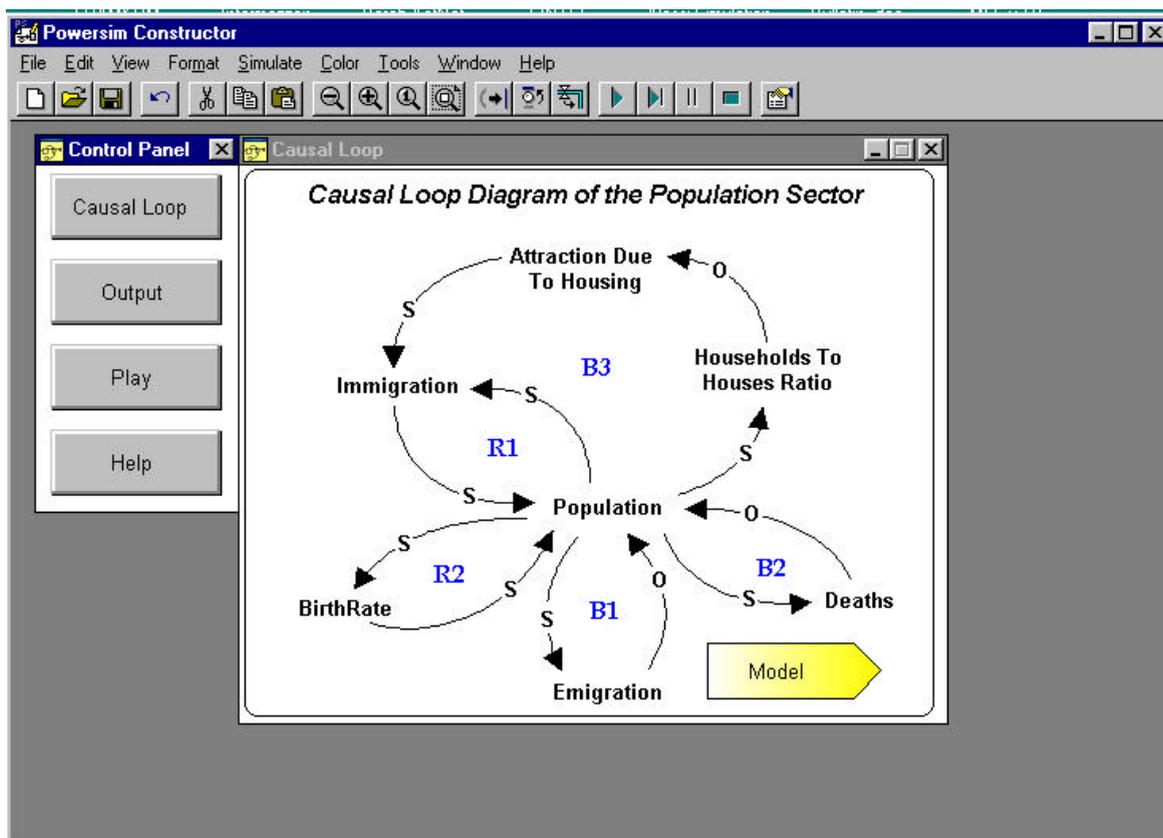


Figure 1. Causal loop diagram (Powersim Constructor Sample Application).

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A meaningful learning activity consistent with MFL is to present learners with a problem scenario and ask them to construct an annotated causal loop diagram. Such an activity serves to center thinking around meaningful problems and is typically effective in facilitating small group collaboration. This activity can also be used to assess progress of learning and predict how well a learner will perform in future complex situations (Christensen et al., 2000). A sample scenario that we have used in our research follows:

The Kaibab Plateau is situated on the north side of the Grand Canyon in Arizona in the USA and consists of some 727,000 acres. Prior to 1907 the deer herd there numbered about 4,000. In 1907, a law was passed banning all hunting of deer from the area. By 1918 the deer population increased tenfold, and by 1924 the herd had reached 100,000. Then it started to decrease and by 1936 to 1940 it was around 10,000. The deer feed on grass. Their natural predators in the region are primarily cougars (mountain lions).

Causal loop diagrams can be used to represent the problem situation and help facilitate problem solving. A simple problem might be to indicate how a hunting policy effects the deer population over time. A more complex problem is to develop a hunting policy that achieves a particular goal over a sustained period of time. Causal loop diagrams can also be used to initially determine how people think about a complex domain in comparison with domain experts and used for assessment of progress through a sequence of learning activities.

Figure 2 represents how relatively advanced learners may think about this problem domain. Much discussion can occur around such a representation and system behavior.

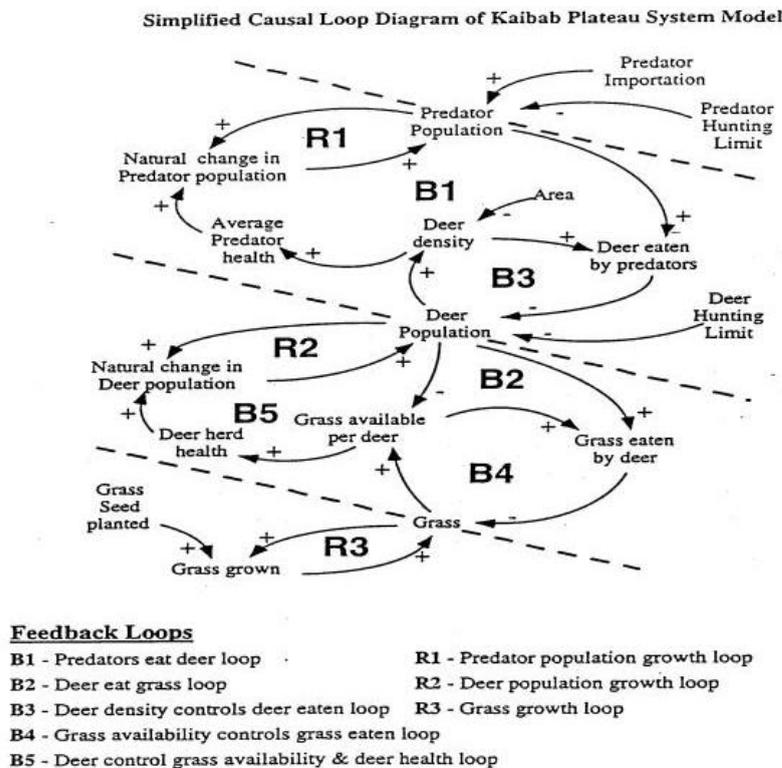


Figure 2. Causal loop diagram created by learners for the deer population scenario.

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For example, learners discuss how an increase in deer created by a restrictive hunting policy might lead to competition for a limited source of food (e.g., grass) and eventually result in overgrazing and elimination that source of food. This could then lead to starvation of a significant portion of the deer population in spite of well-intentioned attempts to help deer thrive. It is useful in the early stages of learning development to challenge learners to identify what they believe to be the most influential factor, perturb the system with a slight change and then predict the outcome. This technique is especially effective when the outcome is counterintuitive as this begins to instill in learners an appreciation for the complexity of the situation, generates much discussion, and initiates a search for an explanation. Such cognitive dissonance can promote learning. In the terminology of MFL, learner-recognized and learner-generated knowledge gaps in the problem-orientation stage provide an effective stepping stone for the inquiry-exploration stage of learner development.

Interaction with a simulation is useful in determining if predicted outcomes occur. If historical data exists, then those data are relevant as well. In short, the inquiry-exploration stage is well supported with learner interactions with simulation models. This type of learning has a reasonably well-developed history within the system dynamics educational community in the form of 'management flight simulators' (Sterman, 1988). There exist popular simulations to support such interactions, such as SimCity™ and related simulation models (Alessi, 2000). Typically these simulations are run in cycles. After each cycle, small groups of learners are asked to indicate the current state of the system, provided an opportunity to change a few key factors and asked to predict what the state of the system will be at the end of the next cycle. Spector & Davidsen (1997) report that this black-box approach has certain advantages and disadvantages. The advantages are that peer-peer discussion and collaboration are effectively supported. Indeed, most of the learning appears to occur in the small group discussions and not in direct interaction with the simulation model. This type of activity is suitable for networked learning environments where learners can collaborate in this discussion process, and it is consistent with evidence presented by Van Joolingen (2000) that discovery behavior displayed by learners may improve under the influence of collaboration.

The disadvantage is that without access to the underlying simulation model, learners are unable to develop deep causal understanding of a complex system. As learners become more proficient in using the simulation, they require access to the underlying simulation model in order to advance their understanding (Davidsen & Spector, 1997; Spector & Davidsen, 1997).

Learning by modeling

As learners gain confidence in a complex system, it is appropriate and productive to provide opportunities to modify existing simulation models and to create alternative representations. There are two principles that provide a foundation for making the transition from learning with models to learning by modeling. First, learners need to appreciate that there exist connections between underlying system structure and observed outcomes (system behavior). There are a number of ways to support this transition requirement. Including multiple representations (e.g., causal loop diagrams, stock and flow diagrams, and behavioral diagrams) appears to be an effective technique based on the earlier discussion of cognitive flexibility theory (Spiro et al., 1988) (see Figure 3).

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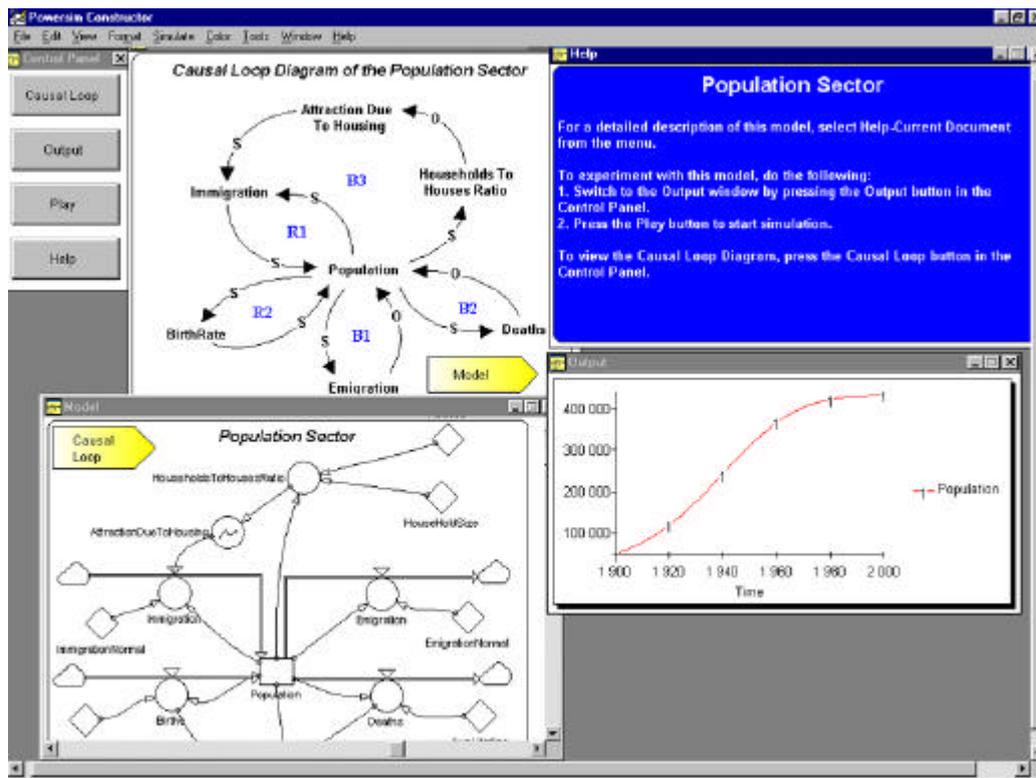


Figure 3. Linking multiple representations (Powersim[®] sample application).

The second principle that lays the foundation for learning by modeling is a direct application of graduated complexity. The notion is that the learner should first establish the ability to fill in parts of an existing model in a way that is consistent with observed system behavior. This principle is closely linked with the previous principle and contributes to the learner's understanding of structure (cause) and behavior (effect). Davidsen (1996) suggests that linking structure to behavior and creating structures to account for behavior are important building blocks of deep understanding. In a more general sense, hypothesizing about potential causal relationships and then testing those hypotheses is important to building up understanding in a complex domain.

An interesting technique used by Davidsen (1996) to facilitate progress in the policy-development stage is to start with what might be characterized as simpler complex system behavior and ask learners to create models that account for system behavior. Learners are then given a goal (e.g., stabilize the deer population in the Kaibab Plateau) and asked to develop a decision-making guideline to achieve that goal. The policy is then tested in an arbitrarily wide variety of situations that might conceivably arise with regard to such a system (e.g., drought conditions, diseases among the predator population, etc.). Learners are asked to reflect on their understanding of the situation along the way.

Moreover, the process of constructing such simulation models requires a person to do all of the kinds of activities typically associated with experts: representing causal relationships, formulating hypotheses about those relationships, creating experimental settings to test hypotheses, identifying key leverage points and influence factors in a system, developing policies to guide decision making with regard to those factors subject to human control, and

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so on. These in fact represent patterns of expert behavior that are generally desirable to engender in advanced learners.

Learning by modeling and learning with models

In this particular section we will illustrate how these two approaches can be combined for the design of meaningful learning activities to support complex learning. An example used in our research consists of giving learners the opportunity to understand the behavior and underlying structure of a complex problem in an ecological system (Ford, 1999). Learners should also be able to understand the dynamics of the decision-making process with regard to a complex system; in this case it is in the domain of water quality.

To learn about acid rain, learners build and test a dynamic model or portions a model. Relevant situated learning takes place as learners build a device with sensors and a software tool for collecting and analyzing data, and then hypothesize about relationships and test those hypotheses. Learners have access to a number of interactive tools supporting different aspects of complex learning, including a modeling tool, a construction and programmable kit and a simulation environment, all of which are open for student use and manipulation. The specific tools provided to learners are: Model Builder, the LEGO-DACTA Robotics System, the ROBOLAB™ programming language, and Powersim™. Following the design principles of MFL, learners are challenged to solve a variety of complex problems (See Table 2) according to the three stages of learner development: (1) Problem-orientation, (2) Inquiry-exploration; and (3) Policy- development .

| Task/Complex thinking component | Cognitive/Social skills | Learning tools and strategies | Computational-support |
|--|--|---|---|
| Which are the factors that influence the PH level of a lake? Problem-Orientation | <i>Identifying main ideas</i> <i>Inferring</i> <i>Hypothesizing</i> <i>Reflection</i> | <i>Mental Models</i> <i>Concept Mapping</i> <i>Modeling</i> Problem Based Learning | <i>Inspiration</i> <i>Model Builder</i> |
| Putting the problem in a context. Build a device that can monitor the ph and the temperature of the lake? Inquiry-Exploration | <i>Planning</i> <i>Determining criteria</i> <i>Concretizing</i> <i>Inventing a product</i> <i>Group discussion</i> <i>Collaboration</i> | <i>Construction</i> <i>Manipulation</i> <i>Visualization</i> <i>Situated Learning</i> <i>Constructionism</i> Inquiry Based Learning | <i>Lego Robotics</i> <i>Robolab Software</i> |
| Giving the problem a time perspective and a new context. What will happen with the fish population of the lake in 5 years from now? Policy-Development | <i>Hypothesis formulation</i> <i>Identifying causal relationships</i> <i>Inferring</i> <i>Synthesis</i> <i>Predicting</i> <i>Group discussion</i> | <i>Casual Loops</i> <i>Model building</i> <i>Simulation</i> Decision-Based Learning | <i>PowerSim</i> <i>Web Based Simulations</i> |

Table 2: Computational Media to support learning about complex domains.

Figure 4 shows results obtained at different learning stages while learning by modeling and with models in the particular domain of water quality.

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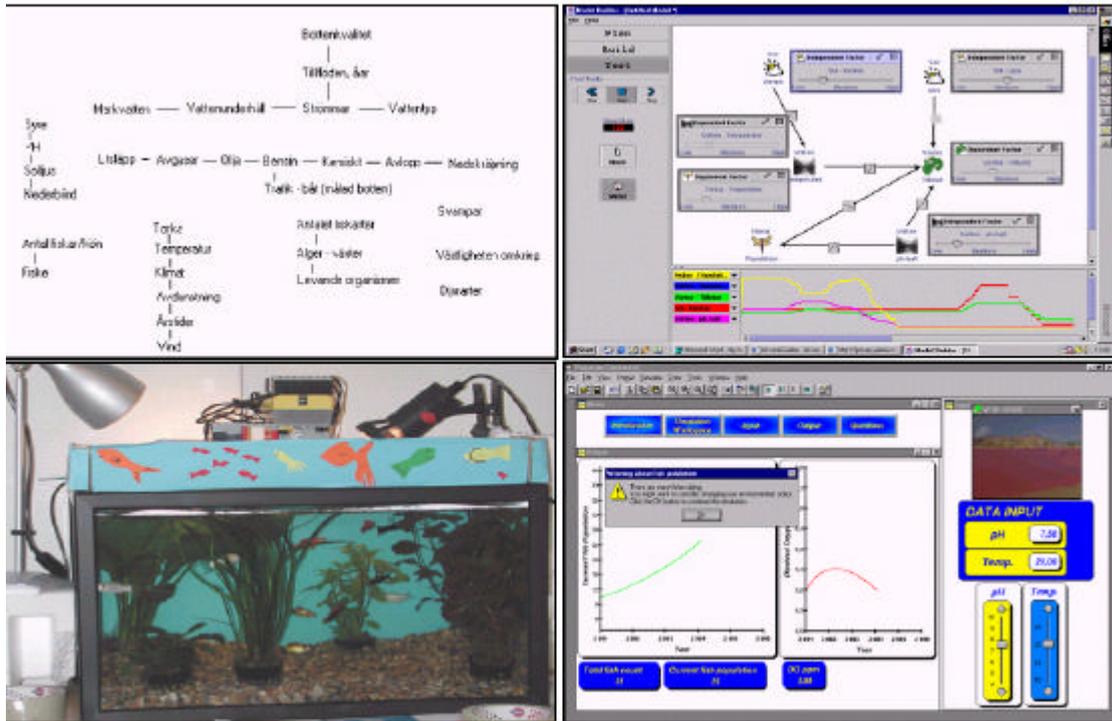


Figure 4. From a concept map to a system dynamic simulation through modeling and construction.

In this particular example, we see theory, methodology and technology all coming together. Preliminary results suggest that the MFL approach is effective in the sense that this learning environment engages learners in solving complex problems through collaborative knowledge building and through interactive modeling, design, and construction of system dynamics simulations (Milrad, 2001).

Conclusions

We conclude with a few comments about evaluating MFL and recommendations for future development and exploration. MFL should be held to established instructional design principles. Merrill (2001) provides a set of first principles for instruction:

1. Principle of Problem Centeredness: Learning is effective when learners are engaged in solving real-world problems.
2. Principle of Learner Activation: Learning is effective when existing learner knowledge is activated as a foundation for new knowledge and skills.
3. Principle of Demonstration: Learning is effective when desired knowledge applications and skills are demonstrated for learners.
4. Principle of Application: Learning is effective when learners are required to apply new knowledge and skills.
5. Principle of Integration: Learning is effective when new knowledge and skills are integrated into the learner's world.

Does MFL satisfy these principles? The MFL problem-orientation stage satisfies Merrill's principle of problem centeredness, and the inquiry-exploration stage satisfies Merrill's principle of application. We accept all of Merrill's principles and believe that MFL provides

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an appropriate guide for application of these principles in complex domains using models and simulations.

Our work suggests that the following deserve further exploration:

- Support for representing multiple perspectives of complex , dynamic problems;
- Technology support for learning as a shared, collaborative activity-particularly in the context of bridging multiple perspectives in distributed settings;
- Simulation and model-centered support in terms of interactions, collaborations and reflections “around the simulation” and “beyond the simulation”.

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