SOFTWARE CRITICISM

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STELLA TEN YEARS LATER: A REVIEW OF THE LITERATURE

INTRODUCTION

Over the last decade, computer modeling and simulation for solving problems in science and engineering have become a well-established practice among the research community. Somewhat more recently, modeling and simulation have become of interest to mathematics and science educators. The availability of greater compute power at lower costs and the advent of easy to use modeling software have given impetus to this interest and provided the opportunity to address significant educational research questions. The educational research done over the past ten years on the instructional uses of computer modeling at the secondary school level serves to focus several important educational issues. In this paper, I will identify and discuss key issues that have emerged from a system dynamics approach to modeling using the software package STELLA, Structural Thinking Experimental Learning Laboratory with Animation (Richmond, 1985).

The first section of this paper is a brief introduction to system dynamics and a descriptive review of the software, including sample applications. Second, I will provide a theoretical framework for an analysis of the educational uses of computer modeling, in general, and a system dynamics approach, in particular. Third, in light of the theoretical framework, I will review and analyze the research results on student learning which have been reported to date. Fourth, I will examine some of the school-based programs which have incorporated system dynamics modeling into the curriculum. Finally, I will offer some concluding remarks on the overall lessons learned and some suggestions for topics of future research and software development.

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A BRIEF INTRODUCTION TO SYSTEM DYNAMICS

The system dynamics approach used in STELLA was pioneered by Forrester (1961, 1968) at MIT in the 1960's. The key idea underlying this approach is the notion that complex phenomena can be better understood by examining the behavior of the system and how it changes over time. Complex systems are characterized by cause being distant from effect in both space and time, by apparently influential policies having little long-term effect, by the failure of intuition in the application of policies, by the drift towards a downward spiral of collapsing goals, and by the fundamental conflict of long-term and short-term goals (Forrester, 1994). Understanding the behavior of such complex systems, Forrester argues, can only be achieved through the development and refinement of system dynamics models. An extensive discussion of the background, history and development of system dynamics can be found in Chen and Stroup (1993), Forrester (1993), and Mandinach and Cline (1994).

The modeling process is often defined as beginning by building a conceptual (or mental) model of the relationships among key variables, translating those relationships into a quantitative or mathematical model, entering that model into a computer (usually via standard computer programming languages), validating and testing the model, and then finally using the model to understand patterns of behavior or actions (Clauset, Rawley & Bodeker, 1987; Coon, 1988; Edwards & Hamson, 1990). To specify a system dynamics model requires identifying the variables that characterize the system and defining the causal relationships among the variables through inter-connected cause-and-effect feedback loops. Variables as quantities which change over time and the factors that influence that change are essential notions in a system dynamics model. For most of the past two decades, the primary tools available for any model building required students to learn programming languages and, as Coon (1988) reports, such efforts rarely got beyond programming and debugging, even for relatively simple models. The advent of STELLA, with its visually oriented structure diagram, provided a rich set of visual tools for making explicit the structural relationships that reflect the workings of a dynamic system.

Other visually oriented software for modeling dynamic systems includes PowerSim and SIMULINK, but little educational research has been reported with these packages and a comparative analysis of system dynamics software tools is beyond the scope of this paper. Even more recent developments of software to understand systems behavior include StarLogo and Model-It. Developed at MIT, the StarLogo software is based on a cellular automata approach to understanding complex systems

(Resnick, 1994; Wilensky, 1996). This approach emphasizes the rules governing the behavior of individuals rather than the causal relationships of populations governed by feedback loops, as in STELLA. The Model-It software, developed at the University of Michigan, on the other hand, is based on the same underlying structure of systems of differential equations as is STELLA, but the interface is fundamentally different. This software provides a very high level object-oriented interface, where objects can be such things as a stream or a golf course, created through digitized photographs and graphics. More importantly, Model-It supports a qualitative, verbal representation of relationships (Jackson, Stratford, Krajcik & Soloway, 1995). Both StarLogo and Model-It are learning environments, specifically designed to support the student development and exploration of models.

In much earlier work by Roberts (1981), we find a precursor to STELLA in the educational use of the software DYNAMO, which was being ported from mainframe computers to the Apple II. In 1985, the first version of STELLA was released. Descriptive reviews of the software (Clauset et al., 1987; Costanza, 1987; Heckenlively, 1987; Steed, 1992) provide useful summaries of the functionality of the package, with some applications descriptions (Choate, 1993; Coon, 1988; Kaylan, 1993; Peterson, 1985). The essential elements of the user interface in STELLA have remained largely unchanged, although numerous enhancements to the software have been made and the ease of use of the window environment has been significantly improved.

The interface to STELLA is centered in the diagram window which displays the structural elements of the model (see Figure 1). The connections among the icons in this window define the causal relationships and feedback loops among model variables and the initial conditions for the starting state of the model. One of the advantages of STELLA is the ease with which both the structure of model and its parameters can be examined and modified by the user. An equations window shows the underlying equations generated by the STELLA software and the initial constants defined by the user. There is a graph pad which displays the results of a simulation run over time and a table pad which shows the same information in table format. This design allows one to switch easily between multiple representations of the data. Most recently, the software has been extended to include an authoring version which provides a suite of tools for model developers to make their models more usable by others.

The diagram window of STELLA displays the structure of the model which is created with four basic building blocks: the stock, the flow, the converter and the connector. The stock icon represents an accumulation.

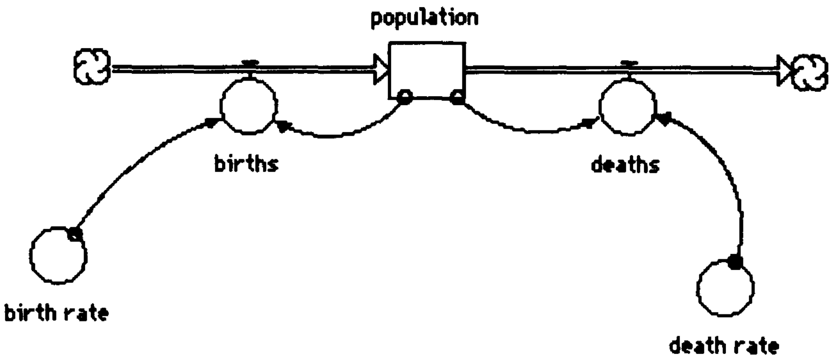

Figure 1. The diagram window for a simple population model.

population(t) = population(t - dt) + (births - deaths) * dt
INIT population = 1000
births = birth_rate*population
deaths = death_rate*population
birth_rate = .015
death_rate = .02

Figure 2. The equations generated by STELLA to govern the population model.

The default stock type is the Reservoir, which can be thought of as an undifferentiated accumulation over time of whatever is flowing into the reservoir minus the outflows. A stock can also operate as a conveyor, a queue or an oven (which processes discrete batches). The flow represents the rate at which the stock increases or decreases. Flows fill or drain stocks; the flow can be uni-directional or bi-directional and the flow within the system can be either conserved or non-conserved. Converters are used to make explicit the details of the logic that controls a flow regulator. They can hold constants, define external inputs to the model, and calculate algebraic relationships using built-in functions and graphical functions. The final building block is the connector which links the components in the model to each other. The simple population model shown in Figure 1 depicts each of these icons and their relationships. The difference equations generated by STELLA for this model are shown in Figure 2.

What is not necessarily evident from this example is *how* to move from a specific problem such as increasing population growth to the structural diagram of stocks and flows. This can require considerable time and effort, particularly if the original problem is more complex than the relatively simple population dynamics model illustrated in Figure 1.

THEORETICAL FRAMEWORK FOR MODELING

The underlying activity involved in modeling is to formulate, test and revise hypotheses about relationships within a system. In the Systems Thinking and Curriculum Innovation Network (STACI^N) project, this modeling activity is conceptualized along a continuum of cognitive complexity: from the least cognitively demanding parameter manipulation, to problems which are somewhat simplified and/or constrained, and finally to epitome modeling of original and complex problems (Mandinach & Cline, 1989, p. 193). Other authors (Clauset et al., 1987; Roberts & Barclay, 1988; Schecker, 1993; Webb & Hassell, 1988; Whitfield, 1988) simply distinguish between the activities of *running* a pre-built model and of *building* a model. In using pre-built models, students manipulate individual parameters of the model and then observe subsequent changes among other variables in the system. In building a model, students must decide which variables are important, identify the causal relationships between the variables, quantify those relationships, and test the validity of their model.

The distinction between exploring a received structure and creating one's own structure is analogous to the two categories of tools for learning defined by Bliss and Ogborn (1989): exploratory tools and expressive tools. These researchers explain the difference in the following way:

> *Exploratory* tools allow learners to investigate views of a given domain, which are different from theirs. *Expressive* tools permit pupils to represent their own models of a domain and in this way reflect upon and explore their own mental models . . . both can help to facilitate the move from the pupils' mental model of a domain, to the different or more complex conceptual model necessary for deeper understanding. (p. 41)

These authors cite microworlds as an example of exploratory tools, noting that these "provide a well-defined and yet open-ended environment in which children can experiment with and investigate rules and relationships" (Bliss & Ogborn, 1989, p. 41). Expressive tools permit students to externalize their own ideas and to formulate them in different ways. These researchers identify the critical problem of understanding the linkage between the learner's model and the expert's model and how to move students toward the expert model.

Throughout the research literature on STELLA, the argument is made that computer modeling enables teachers and researchers to focus, not just on learning outcomes, but more critically on the cognitive processes engaged in by the students. This suggests an examination of the relationships among the conceptual model, the mathematical model, the computer model, and the physical (or "real") model. The STELLA structure diagram appears to suggest a strong linkage among the first three type of models. We still need to better understand the nature of the relationship between students' concept formation and their model constructing activities. Niedderer, Schecker and Bethge (1991) advocate for a linkage between the established research tradition in physics education dealing with student conceptions and an analysis of the possibilities of computer-based dynamic modeling systems.

Grounding their work in the literature on student (mis)conceptions, alternative frameworks, matrices of understanding, and the constructivist view of learning, Niedderer et al. (1991) argue that students often have a "formal mathematical and physical knowledge without a qualitative understanding of basic concepts and relations" and that this is demonstrated by their inability to solve new problems (p. 85). They argue that formal competence (the knowledge of formulas and mathematical abilities) is subordinate to conceptual competence (a qualitative understanding of concepts and basic problem solving ability), and that the formal quantitative knowledge of science instruction hardly ever effects change at the conceptual level. Niedderer et al. (1991) focus on the need for the student to discriminate between his or her own conception and an expert ("the scientific") conception: "Unless the *conceptual* differences between the students' mental models and the scientific views are made explicit and are recognized by the students, rules and equations form a distinct layer of examination knowledge" (p. 86). Niedderer et al. do not give explicit details as to *what* constitutes and *how* conceptual change is realized, but they suggest that "conceptual awareness" is a first critical step in the teaching/learning process. Their teaching begins with a phase "which stimulates students to develop their own views of a given situation or problem, making their conception explicit" (p. 86). These researchers then argue that modeling with STELLA can achieve this aim of making explicit both student conceptions and established scientific theories. STELLA provides a conceptual map or visual structure that lays out the essential features of a problem situation. Niedderer et al. (1991) suggest that this "can help to shift the focus from learning and working with formulas to more qualitative conceptual reasoning" (p. 92).

This is a rather compelling argument when one realizes that a minor variation of the model for Newtonian mechanics (see Figure 3) can accommodate the analysis of a spring powered toy car which would result in an analytic solution such as this:

$$v(d)= SQRT\{2/0.09*[(F_{sp} - F_{fr})*d - c/2*d^{2]}\}$$

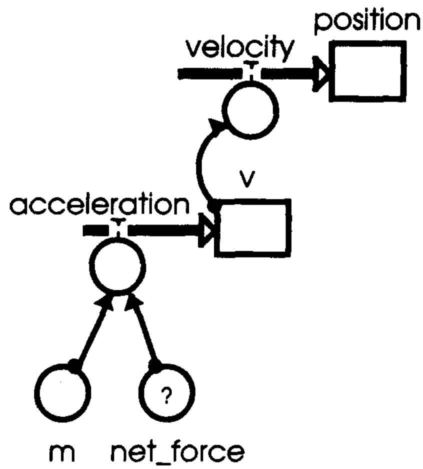

Figure 3. A STELLA model for Newtonian mechanics. From Niedderer et al. (1991) with permission.

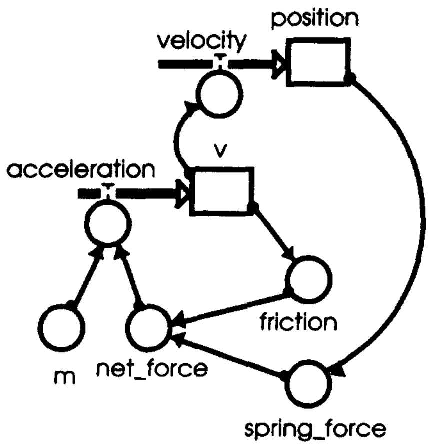

Figure 4. A modification for the analysis of a spring powered toy car. From Niedderer et al. (1991) with permission.

(Niedderer et al., 1991, p. 92). Clearly this representation focuses on symbolic manipulations rather than on the underlying relationships between quantities. The STELLA representation (see Figure 4) illuminates the fundamental relationships and similarities between these two physical situations that are obscured by the formal symbolic representation.

As Schecker (1993) argues, the model building process can engage students in the more qualitative, principle oriented analysis of the problem prior to working on an equation level. By approaching problems with a computational model, the concepts of physics can be introduced qualitatively and decoupled from the mathematical background necessary for the closed form analytic solution. Thus modeling provides an opportunity for students to express their own conceptual understanding of physical phenomena, using visual representations of both the quantities and their causal relationships.

INSIGHTS FROM MODEL BUILDING RESEARCH

The early experiences with STELLA suggest an enthusiasm for using the system dynamics approach in many areas of the curriculum. Both the National Council of Teachers of Mathematics ([NCTM],1989) and the Mathematical Sciences Education Board [MSEB] have recognized the importance of computer modeling and system dynamics for secondary education.

> Secondary school mathematics should introduce the entire spectrum of mathematical sciences. ... *Discrete mathematics*, including combinatorics, graph theory, recurrence relations, and recursion – all emphasizing algorithmic thinking. *Optimization*, including mathematical modeling, "what if" analysis, systems thinking, and network flows. (MSEB, 1990, p. 46)

Computer modeling provides an opportunity to solve problems that are not readily solved analytically or are simply impossible by any other means. A simulation also allows for the systematic control of a single variable and the running of multiple experiments in a short period of time. Others, however, make even stronger claims for the value of system dynamics modeling. Forrester (1991) argues that system dynamics can provide the framework for reversing the traditional educational sequence that progresses from learning facts, comprehending meaning, applying facts to generalizations, analyzing into component parts, and finally synthesizing the parts into a whole:

> Most students never reach that fifth step of synthesis. But, synthesis – putting it all together – can be placed near the beginning of the educational sequence. By the time students reach junior high they already possess a wealth of facts about family, interpersonal relations, community, and school. They are ready for a framework into which the facts can be fitted. ... System dynamics can provide that dynamic framework to give meaning to detailed facts. (p. 7)

The system dynamics approach, according to Forrester, provides an opportunity to engage students in more realistic and relevant problem solving much earlier in the educational process and across the disciplines. Other researchers suggest that computer modeling can be used to enhance content knowledge, improve students' problem-solving skills, promote inquiry skills, improve student abilities to interpret graphs and data, and provide students with the opportunity to formulate, test and revise hypotheses (Coon, 1988; Mandinach & Cline, 1989; Roberts, 1981; Steed, 1992).

Many papers cite specific advantages to using STELLA for computer modeling. The barrier of using high level computer languages for the development of a simulation is eliminated with STELLA. As Costanza (1987) observes, this reduces model development time by at least an order of magnitude. STELLA's visual interface allows for the easy addition of elements to the model and the modification of the relationships among existing elements. Not only can parameters be varied, but also the basic structure of model can be easily changed or enhanced. The visual interface allows for ease of use by non-computer specialists (Clauset et al., 1987; Whitfield, 1988).

The visual interface of the diagram window has particular importance as a "conceptual representation of the model" that supports the expression of students' own ideas and at the same time allows them to experiment with those ideas (Coon, 1988, p. 67). Students must make explicit their own understanding of the structure of the system and the underlying causal relationships. Webb and Hassell (1988) claim that learning can be enhanced by giving students the opportunity to "construct, test, and evaluate concrete representations of their own mental models" (p. 271). The process of converting internal mental models to external ones, allows students to become "active builders of their own intellectual structures" and leads to better understanding by:

(1) raising the level of cognitive processes
(2) encouraging pupils to define their ideas more precisely
(3) providing pupils with opportunities to test their own cognitive models and detect and correct inconsistencies (p. 271).

STELLA is described by Steed (1992) as "a construction site where systems can be build piece by piece through the explicit expression of assumptions. . . . The structural diagram on the screen in some respects becomes a mirror of internal structures. If this is true then setting them forth in this way may help confront potential misconceptions and analyze how certain things are thought about" (p. 50). Unfortunately, the linkages between students' concepts and the structural diagrams that they create are largely unexamined in the current research. Little evidence is given that shows how and to what extent the diagram mirrors students' ideas.

The visual interface of STELLA can significantly ease the mathematical demands for manipulating symbols and solving equations. Whitfield (1988) notes that this can shift the emphasis from the manipulation of models to the creation of a model: "Using STELLA, the necessity for subsidiary skills, such as mathematical manipulation and computational knowledge, is minimised and a proper emphasis can be placed on the creation of mathematical models rather than on their subsequent manipulation which is, after all, relatively meaningless if the student cannot produce a viable model in the first instance" (p. 300). This argument for by-passing the formalisms of the symbolic representations in favor of focusing on the structural and causal relationships among variables needs to be examined more carefully. The work of Niedderer et al. (1991) clearly illustrates in the case of the spring-powered car (see Figures 3 and 4) the potential for representations on an iconic level to help students gain insight into situations that are similar in principle, but whose formalisms have little apparent similarity. Several researchers have found that STELLA provided students with an environment where they could reason qualitatively and intuitively about systems (Clauset et al., 1987; Coon, 1988; Mandinach, 1989). But little work has been done to examine the potential for students to develop insights into the phenomena being modeled through a coordination across both the symbolic and iconic representations available in STELLA.

The graphing capabilities of STELLA provide yet another representation of the dynamics of the model. Steed (1992) notes that "inferring behavior from graphs is a major way of interpreting results. Being able to analyze data plotted against time is vital to understanding continuous simulations and helping to interpret and refine models" (p. 45). Understanding the relationship of the graph to the structural diagrams of the model could potentially improve student abilities in the interpretation of graphs. But Steed doesn't address the conceptual difficulties students often have in interpreting graphs and, perhaps more importantly, how the linkage between the graph and the structural diagram is established and understood. Student difficulties in interpreting graphs are well-known (Leinhardt, Zaslavsky, & Stein, 1990). But none of the research to date with STELLA has systematically addressed its impact on how students interpret graphs or, more importantly, on students' abilities to understand the relationship between the graph and the structural diagram.

While STELLA does require explicit links for causal relationships and the quantification of those relationships, it does not (and cannot) solve the "garbage in, garbage out" problem. Even though all relevant inputs must be initialized, the model will run, regardless of the validity or meaningfulness of that input. Although Heckenlively (1987) notes this problem, the only research on it is found in Whitfield (1988), who directly addresses the issue of the validation of the student's model. In his work, as part of a tutorial, the results of a simulation model are locked into a graph pad page for verification by comparison. Establishing the connection between the results of the model and experimental data are crucial steps in the overall modeling process, but these steps are not necessarily easily taken. Coon (1988), in the modeling of fishery management, clearly points to the need for students to "test their understanding by asking questions of their model using a structured, experimental approach" (p. 66). However, no research has been done which examines how students would go about systematically testing their simulation models. What aspects of the model's representations contribute to students' understanding of the relationship between their own concepts and the model's outputs and behaviors? The relative advantages and disadvantages of the various representations (graph, table, equations, and structure diagram) in different types of modeling situations and across the entire cycle of the development of the model have yet to be examined.

In refining their models, students need to develop criteria for making judgments about their model and to test the validity of the predictions generated by the model in light of that criteria. Steed (1992) argues that "a model is neither true nor false, but more or less useful" (p. 47). He thus neatly avoids the problem of the correctness of the model by giving internal consistency, equilibrium and effectiveness as the criteria for a *useful* model. Forrester (1993) also argues that models are to be judged on their usefulness and that refinements can be bought about by resolving discrepancies between the simulation results and the behavior in the system being represented. However, this leaves unexamined how students come to understand that some features are intentionally excluded from a model or are modified in some significant way, while other model features may be artifacts of the computing environment or invalid assumptions about the relationships among quantities. In testing their theories, students need to determine if their model is consistent with their own beliefs and with other data and descriptions of behavior about the system being modeled. Students also need to understand the assumptions underlying the model itself.

Student construction and testing of theories led Tinker (1993) to investigate the interplay of theory and experimentation through the synergy of system dynamics modeling and micro-computer based laboratories (MBLs). The use of STELLA for the system dynamics would eliminate the need for the formalisms of calculus, while at the same time reduce the use of algebra by providing graphical interconnections as representations. The use of micro-computer based laboratories would provide a means to generate data that would be concrete, meaningful and accessible to students.

In his study, Tinker (1993) found that the flow diagrams of STELLA were not easily grasped by students. The distinctions between rates and levels were not easily distinguished by naive students and the importance of the conservation of the quantity flowing through the pipes, regulated by the valves and accumulating in the reservoirs was not grasped by the students. In particular, Tinker (1993) notes the strange sense in which velocity and acceleration are represented in a flow diagram: "What does it mean to have acceleration flow through a valve controlled by force and mass and accumulate in a reservoir called velocity?" (p. 98). In his analysis of quantitative modeling tools, Boohan (1994) similarly suggests that while the metaphor of stocks and flows may be suitable for money in an economic system or chemicals in a reaction, it is difficult to think of quantities like velocity in this way.

Furthermore the flow diagram has additional difficulties: two valves cannot be placed in series in the model; the flowing quantity can be discrete; negative accumulations can be generated; a rate in one part of the diagram can appear as a level in another part. Despite these difficulties, Tinker suspected that concrete experience with water, pipes and tanks might make the STELLA flow metaphor more meaningful. Tinker and his colleagues developed an MBL interface to the flow of water between beakers and cylinders, but found that the combination was of limited value to the students.

Tinker then shifted his focus from STELLA to spreadsheet modeling. He found that while many science teachers and students preferred the use of STELLA, the spreadsheet approach was "definitely more appealing to the mathematics teachers and probably the more mathematical students" (1993, p. 101). Tinker concluded that "spreadsheets gave the most accessible representation of dynamic systems and that the 'flow' representation had weaknesses and needed additional research" (p. 101). The preference for more traditional solutions on the part of some students was also found by Mandinach and Cline (1989) and by Schecker (1994). These students felt that the software overcomplicated problems which they perceived as simple. In her work on semi-quantitative reasoning, Bliss (1994) found that while the concept of a variable changing was not problematic, the representation of the rate of change of a variable as itself another variable was difficult for students. Bliss (1994) found that "STELLA's structure worked as a 'straight jacket', obliging the student to use the idea of rates of change. When not confident of this idea, students could not express themselves with this tool" (p. 126). In their work with students aged 14 to

18, Cox and Webb (1994) found that the structural diagram was helpful in identifying variables and their causal relationships, but "deciding what type of variable was required and specifying the mathematical relationships was too difficult for most students" (p. 189). These results suggest that the easy by-pass of the mathematical symbolism suggested by other researchers is limited only to a by-pass of the difference equations or of a closed form symbolic representation of the system. Students must still identify quantities, their rates of change, and their relationships in order to create a meaningful mathematical model of a system. It would appear that the stocks and flows metaphor and the dominance of the idea of rate of change would make the expression of some student ideas simply too difficult.

As a result of his work with physics students (ages 16–19) in upper level secondary courses, Schecker (1993) suggests that while it may be initially unlikely to use the plumbing (flow and reservoir) metaphor to think of the relationship between acceleration and velocity, that the basic structural relationship between these quantities and the flexibility of STELLA allow for the expression of student ideas and the modeling of complex phenomena. While acknowledging Tinker's (1993) results that the flow metaphor for acceleration and velocity is not helpful to students, Schecker (1993) found that students worked with STELLA's icons on a more abstract level, using the pipes for successive accumulation over time and the single arrows for direct algebraic relationships. Figure 5 compares a Newtonian model for motion with two student-generated expressions for the phenomena. These alternative student models could be evaluated by the students as they examined the consequences of their assumptions about the behavior of the system. Schecker (1993) notes that the model building forces students to make their vague, imprecise ideas into explicit causal relationships.

Schecker found that modeling complex, realistic problems helped students explicate their own ideas and supported individual problem solving along multiple paths. Through a series of examples, Schecker makes a clear and compelling argument that STELLA models allow for the qualitative structure of the relationship among force, acceleration, velocity and position (Newton's second law) to be seen in a full range of complex and realistic situations about which students can reason. The STELLA model for uniform motion has only to be slightly modified to include the force of friction, which is proportional to the velocity squared, whereas the analytic equations appear to have nothing in common (see Figure 6).

Schecker found positive results with group work for open-ended, complex problems and that STELLA supported the students in qualitative

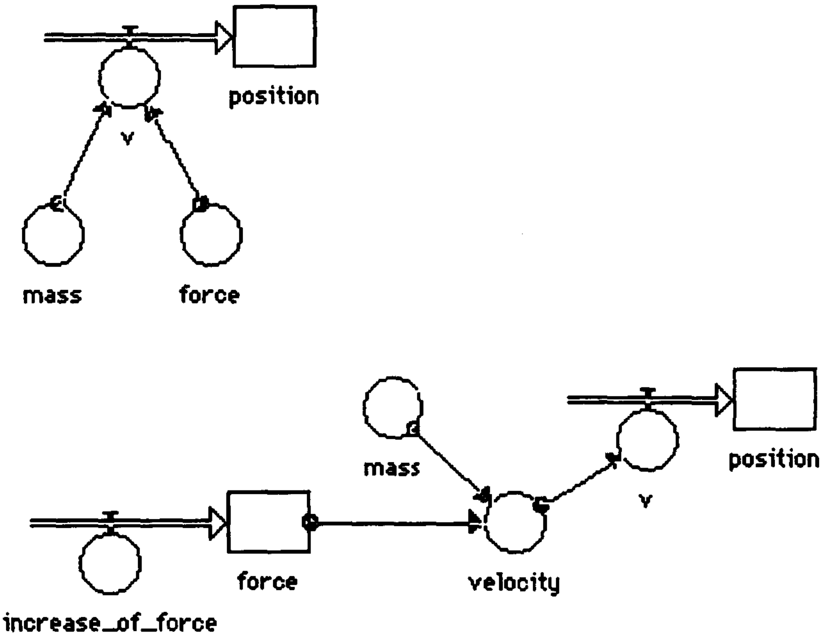

Figure 5. Two alternative student conceptualizations of the Newtonian model for accelerated motion. From Schecker (1993) with permission.

reasoning and discussion about physical systems. He is positive, though cautious, about his results for the positive effect of model building with system dynamics software on the development of physical competence and deeper insights on the part of students.

SCHOOL-BASED PROJECTS AND IMPLEMENTATION ISSUES

There have been several school-based projects to integrate systems thinking into the curriculum. The oldest and largest of these is the Systems Thinking and Curriculum Innovation Network (STACI^N) Project, which began as a two year project in 1986–87, with Brattleboro Union High School, Brattleboro, Vermont. This effort is a multi-year research project "intended to examine the cognitive demands and consequences of learning from a systems thinking approach to instruction and from using simulation-modeling software. The purpose of the study is to test the potentials and effects of integrating the systems approach into science and history courses to teach content knowledge as well as general problem solving skills" (Mandinach, 1988, p. 2). Content areas included general physical science, biology, chemistry, physics, and a history course. The project reports focus on the curriculum development, teaching activities, and

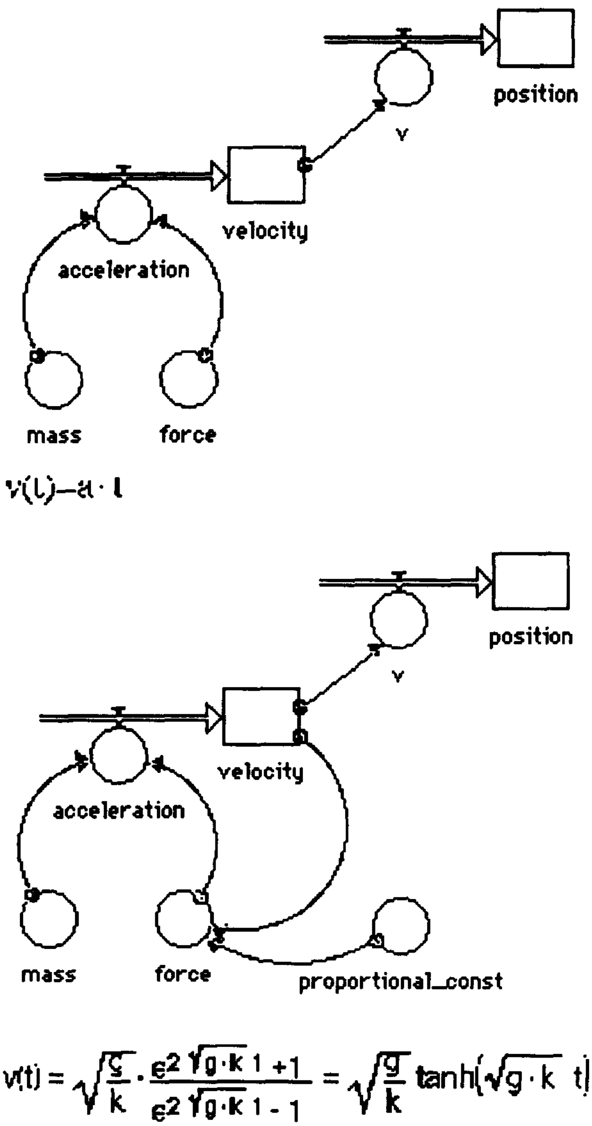

Figure 6. The STELLA model for uniform motion has only to be slightly modified to include the force of friction. From Schecker (1993) with permission.

learning outcomes (Mandinach, 1987, 1988; Mandinach & Thorpe, 1987, 1988; Mandinach, Thorpe & Lahart, 1988). The project later expanded to include eight schools in California and Arizona and continued in its purpose "to test the potential and effects of using the technology-based approach in precollege curricula to teach problem solving-skills as well as content-specific knowledge" (Mandinach & Cline, 1989, p. 189). The expanded project consisted of three phases: teacher support for curriculum development and implementation, educational research, and dissemination. The first phase provided in-service training, both in general systems principles and hands-on activities; electronic mail networks; and disciplinary task forces with content experts. The primary research goal was to address the transferability of skills across content areas. An ancillary goal was to develop measurement techniques that were appropriate for computer based learning systems. The approach was to teach concepts already mandated in the curriculum, primarily those topics that have been problematic and in courses that reach a range of students and "at-risk" learners (Mandinach & Cline, 1989). Specific examples used in the STACI^N project include a model in calculus to simulate areas under curves; models of dice rolling and coin flipping to understand probability and statistics; time-estimation; a model for a related rate problem in calculus; and a relative motion problem from physics.

The difficulties of integrating new approaches into traditional curricula are well illustrated by the following anecdote:

> ETS staff spoke at length with one of the project teachers who had prepared a model of a generic class of problems taught in advanced placement calculus. He described how the model fit into the curriculum and how it would be used instructionally. He then mentioned that the model would not be introduced until the latter part of May, after the Advanced Placement (AP) Calculus Examination was given. Although this model was directly relevant to the course content, the pressure to adhere to the specified AP course did not easily allow for the implementation of an alternative pedagogical approach. (Mandinach & Cline, 1994, p. 88)

The major curriculum issues encountered in STACI^N were: introducing the theoretical foundation into the curriculum, topic selection and sequencing, individual differences and specific sub-populations of students, motivational factors, and the changing role of the teacher.

The Orange Grove Middle School in Tucson, Arizona, became a longitudinal research site for the Apple Classrooms of Tomorrow program. During the 1989–90 and the 1990–91 school years, Orange Grove developed STELLA models for use in the science curriculum, drawing applications from world population, ozone depletion, water models, speed and acceleration, genetics, planning a state park, nutrition, chemical reaction rates and others. Preliminary results showed improved motivation and success for at-risk students (Draper, 1990). In 1993, a three-year National Science Foundation (NSF) project, Cross-Curricular Systems Thinking and Dynamics Using STELLA, was funded in Oregon to provide training and software for teachers interested in using system dynamics within their current high school curriculum. One outcome of this project has been the creation of a network site for sharing models developed and used by teachers (e.g., Littleton & Meskimen (1994)). System dynamics models and the sharing of these models over the internet has become part of the Maryland Virtual High School project, also funded by the NSF (see http://www.mbhs.edu/mvhs.html).

Research and development on both practical and theoretical issues are just beginning on overall curriculum and appropriate sequences and activities for students in elementary through secondary school (see, for example, Mandinach and Cline (1994), Draper (1993), and Road Maps, developed by the MIT System Dynamics Education project and distributed through the Creative Learning Exchange).

In addition to the numerous open questions with regard to the curriculum (selection of topics, sequencing, integration, development of materials, student assessment), there are difficult issues with regard to the teachers. Building on their earlier successes and enthusiasms with students, Roberts and Barclay (1988) reported on their efforts to introduce model-building and simulation into the high school curriculum. After a successful summer workshop with high school students, the project staff decided to pilot the materials in two high schools and to prepare the teachers for using these materials with a four-day summer workshop. "We used many of the same activities and approaches that had been successful with the students the previous summer. But teachers are not high school students and there were many problems that stubbornly resisted solution" (Roberts & Barclay, 1988, p. 15). The teachers wanted much more complete instructions than the students had; they resisted problems outside their discipline; they were concerned about finding time to incorporate examples into existing curriculum; the teachers indicated they would not want to introduce modeling unless they felt completely confident with all aspects of the subject (Roberts & Barclay, 1988). The teachers did very little after the first workshop, but they did request a second in-service course to help develop classroom lessons. But even at the end of the second workshop, it was clear to the staff that their expectations were unreasonable. Given that the materials were demonstrably successful with students, why then were the broader-based trials a failure? Four reasons for the difficulties are given:

(1) Model-building is hard to teach because it requires teachers to: make a paradigm shift in they way they think about their discipline; look at their discipline's material in a much deeper way; learn new mathematics or apply mathematics initially learned by rote; make a pedagogic shift from fact-and-formula to exploration, uncertainty, and willingness to learn with their students;

(2) The school environment seems critical. The teachers who had success were from schools that support and provide time for teachers to revise and create curriculum

(3) The use of commercial software that was unnecessarily complex

(4) Given that the project staff did not have either completed curriculum or software, their expectations were unrealistic (Roberts & Barclay, 1988, p. 16).

Given these results, Roberts and Barclay suggest three strategies to provide large numbers of students with the opportunity to learn from model-building and simulation: (1) software development, (2) on-going teacher education and support, and (3) materials development based on new teaching strategies. Webb and Hassell (1988) confirm these strategies by suggesting the design of new software tools for modeling, the importance of the development of curriculum materials, and the need for in-service teacher training. The provision of teacher training and support is clearly a critical issue. Much more fundamental than mastering STELLA is mastering the theoretical foundation which underlies system dynamics. As a teacher in one project noted, "deciding which elements of prototypes in the real-world are to be presented as stores and which as flows is not as simple as it appears" (Riley, 1990, p. 258).

In earlier work, Mandinach (1989) suggests that "perhaps most exciting is how the approach is changing the role of the teacher in fundamental ways. The teacher takes on the role of facilitator, working interactively with students who also can supply knowledge in the classroom setting. This is in direct contrast to the teacher who is the sole expert, one who imparts knowledge to a class of passively receptive students" (p. 235). One can not take lightly the difficulties inherent in shifting the role of the teacher. Further research needs to be done to identify effective strategies for enabling teachers to take on new roles and for shifting greater portions of the responsibility for the teaching/learning process to the learners.

The adequacy of school resources, a history of active involvement of teachers in curriculum planning, support for teacher professional development, and administrative support are key factors identified in numerous schools where system dynamics approaches are being pioneered by enthusiastic teachers (Stuntz, 1994). As a result of their work with the $STACI^N$ project, Mandinach and Cline (1994) identified several key implementation issues: school district motives for participating in the project, the need for administrative support, physical resources and facilities, hardware and laboratory configurations, dedicated computers for the teachers, on-site technical expertise, and software. However, it is an unanswered question as to the extent of teacher involvement and administrative support necessary for the changes to become self-sustaining over the long term.

The earlier reports on STACI^N discuss the systems thinking instrument which was a 76 item test used to assess a range of skills underlying systems thinking. This was a traditional paper and pencil testing for a very fundamentally different instructional approach. In their more recent work, however, Mandinach and Cline (1994) argue that the notion of using pretest/posttest comparisons of control and treatment groups was fundamentally inappropriate to capture the complexity of a major technology-based curriculum innovation. An open research question is how to develop appropriate assessments for the kind of learning which takes place in a model-building, learning environment. Forrester (1991) notes that "little is known about how to evaluate students coming out of this different kind of education" (p. 14). Assessments of student cognitive processes will need to recognize that for many problems multiple solution paths usually exist.

CONCLUSIONS

There is some evidence that the use of STELLA for system dynamics modeling may lead to improvements in students' abilities to qualitatively reason about problem situations, particularly in the domain of introductory physics. Despite the difficulties with the plumbing metaphor of flows and accumulators, STELLA provides a means for discerning the structural similarities among problems whose symbolic algebraic representations appear to have little in common. Some students prefer not to use the STELLA structure diagrams, but find the analytic equations to be a more straightforward solution to certain problems. The complexity of some problems was clearly beyond closed form analytic solution and students were able to successfully model such problem situations using STELLA. Thus, there is some evidence to support the claim that system dynamics software such as STELLA can support students in solving more complex, realistic problems.

The software also supported multiple approaches to problems and the expression of student conceptions. When built on the existing research base of student pre-conceptions in physics, the students' qualitative reasoning using principles of physics is impressive. Nonetheless, one must be cautious about any broad conclusions concerning students' learning given the limited scope and extent of educational research to date.

The introduction of STELLA into various school settings has highlighted several key issues: the necessity for a changed role for the teacher from that of central knowledge authority to one of guide and facilitator; the need for both technical support and teacher education; and, perhaps most importantly, the need to develop, implement and support new teaching strategies. As an incremental change in schooling, the introduction of modeling activities (whether using pre-built models or engaging in model-building) with STELLA is likely to be ineffective. More fundamental changes, such as can be brought about with a technology-based curriculum revision using STELLA, are set in the context of the entire complexity of schools and are thus likely to proceed slowly.

While the impact of STELLA on student learning has been largely in a positive direction, much of what is reported is anecdotal and unsystematic. Issues such as how do the students determine the validity of their models and how do they go about making changes and refinements are largely unexamined. Furthermore, in some studies, familiar content goals were left unchanged but other studies shifted their goals for student learning to higher order cognitive processes and problem solving skills. In both cases, assessing student learning by conventional paper and pencil tests is problematic. The development of alternative assessment techniques and their systematic application across a broad range of re-conceived and traditional content areas with a diversity of students remains to be done.

Current program efforts to train and support in-service teachers in system dynamics will provide settings within which it will be possible to more closely examine the changes in teachers' roles and effective strategies to accomplish and support such changes. Along with those changed pedagogies, it will be necessary to examine classroom interactions among students and to investigate from both a theoretical and practical perspective the social construction of models. The classroom interactions and the relationship of these interactions to the larger social context in terms of the modeling activity itself, its assumptions and its outcomes are largely unexamined.

The theoretical perspective on modeling suggested by the research on STELLA is built on the distinction between running a pre-built model versus building one's own model and on the relationship between the model (and its representations) and the student's conceptual model. Important theoretical work remains to be accomplished. In particular, the distinction between model application and model development may be too simplistic. The STELLA diagram window, for example, makes manipulating the structural elements of the model as easy as varying the parameters. As is illustrated by the physics examples, a basic structural relationship can be used and re-used in numerous models. Thus, it may be more useful to conceive of a continuum of modeling activities from model application to the development of original models. This could then lead to a fuller definition of the nature and range of student learning and the kinds of supporting software tools for that learning. The development of re-formulated curricula in light of such software tools is a critical next step; the examples from introductory physics are promising, but we need other fully developed examples in a range of content areas and coordinated across age levels. Just as importantly, we need to more fully understand how it is that students move along such a continuum of modeling activities and what teaching strategies best support such movement. The nature of the relationship between students' models and students' conceptual knowledge and how model building can promote conceptual change needs to be examined. Finally, the relationship between computer models and experiment needs to be more fully explicated. How are student models validated? What are the assumptions about the experimental data that are built into the model in the first place? Research using micro-computer based laboratories and system dynamics modeling tools would appear particularly promising in this regard. Although system dynamics education is still in its infancy, it has already served to focus our attention on these issues.

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