Systems, Science, and Schools

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Abstract

The Systems Thinking and Curriculum Innovation Network (STACI^N) Project is a multi-year implementation and research effort intended to examine the impact of implementing and learning from a systems thinking approach to instruction and from using simulation modeling software. Systems thinking is an analytic problem solving tool that can be integrated into courses to enhance instruction. The purpose of the project is to test the potentials and effects of using the technology-based approach in precollege curricula to teach problem solving skills as well as content-specific knowledge.

Text

The Systems Thinking and Curriculum Innovation Network (STACI^N) Project attempts to address some of the pressing issues of curriculum reform in schools. STACI^N examines the impact of a technology-based curriculum innovation on teaching and learning activities. The focus is on an instructional approach that teaches subjects in new ways so that students acquire content knowledge and analytic problem solving skills. The instructional perspective espoused by the project is referred to as the systems thinking approach. The approach consists of three separate but interdependent elements: system dynamics, the theoretical perspective; STELLA (Richmond 1985), a simulation modeling software package; and the Macintosh computer. The systems approach is seen as a general problem solving tool that can be integrated into course content to provide a knowledge base that is a logical setting for the development of thinking skills.

Systems Thinking

As applied in this project, systems thinking is a scientific analysis technique that provides a means by which to understand the behavior of complex phenomena over time. In recent years greater appreciation has developed for the heuristic value of systems thinking. The creation and manipulation of models increasingly is recognized as a potentially powerful teaching technique that can result in multiple mental representations of a subject (Mathematical Science Education Board 1987, 1989; National Science Board 1983).

Based on the concept of change, system dynamics uses simulations and computer-based models to represent complex relationships among variables (Forrester 1968). By specifying rules that describe change, it is possible to understand the behavior of a system by constructing models of variables and interactions among those variables. The concept of a system is based on variables that characterize a system and change over time and the relationships among those variables that are interconnected by cause-and-effect feedback loops.

Simulations, simplified representations of real systems, are used to examine the structure of phenomena. Using simulation, characteristics of variables can be altered and their effects on other variables and the system assessed. To build a simulation, it is necessary to understand the variables that comprise the system. These variables form a dynamic feedback system, expressed in terms of simultaneous equations. Over simulated time, variables change and cause other variables and their interactions to change as well. Thus, system dynamics provides a way to understand the connections among elements in a system and how they contribute to the whole (Roberts, Andersen, Deal, Garet, & Shaffer 1983).

STELLA and the Macintosh Environment

The software environment. Until recently, the instructional use of systems thinking was constrained to environments that had powerful mainframe computers. The advent of a software product, STELLA and its HyperCard interface, StellaStacks (Structural Thinking Experimental Learning Laboratory with Animation; Richmond 1985; Richmond & Peterson 1988), has made it possible to operationalize these concepts on the Macintosh microcomputer. Capitalizing on the graphics and icon technology of the Macintosh, STELLA creates windows with structural diagrams, equations, graph pads, and tables, thus enabling learners not versed in the intricacies of computing or modeling to create their own systems By minimizing the technical and mathematical skills needed to construct models, STELLA facilitates the creation and manipulation of complex models of system phenomena.

STELLA facilitates introductions to the analytic and problem solving perspectives inherent in systems thinking through an iterative process of model construction. Modeling requires learners to formulate, test, and revise hypotheses about relations within dynamic systems. Modeling with STELLA is conceptualized as a three-step process. First, learners use the "tool kit" to create diagrams representative of the systems to be modeled. These diagrams are based on relational assumptions about the system provided by the learners. Second, learners formally specify the logic that connects the parts of the systems. Learners are provided with visual maps of the connections among the components. STELLA produces simultaneous equations based on the mathematical assumptions and the parameters supplied to define the system. Third, STELLA runs the system dynamically over hypothetical time. Results stimulate iterative sequences of hypothesis formulation, testing, and revision.

Forms of models. Modeling in STELLA may be conceptualized along a continuum of cognitive complexity. One form of implementation, and the least cognitively demanding, is referred to as parameter manipulation. Here the teacher constructs a model of a system and asks students to explore the system with the use of structured worksheets which require them to change parameters. Students manipulate a parameter and observe and record subsequent changes among other variables in the system. A second form of implementation is referred to as constrained modeling. Here students construct models as a tool by which to solve traditionally assigned problems (e.g., an acceleration problem in physics). These models are generally simple and constrained in the number of variables and equations. A final, and the most cognitively demanding application, we have called epitome modeling. Students develop and construct original models that are complex and often contain many variables. Students must make decisions about which and how many variables to include in their models. Because models must be finite, the issues of boundary definition become critical in epitome modeling. An example of epitome modeling would be to construct a model to explore the epidemiology of the AIDS virus and determine the best means by which to distribute funds for containment or prevention of the disease.

The Network Project

The STACI^{N} Project is an implementation and research effort that examines the cognitive and curricular impact of using the systems thinking approach in precollege instruction (see Cline 1989; Mandinach 1988a, 1988b, 1989; Mandinach & Thorpe 1987; Mandinach, Thorpe, & Lahart 1988; Nardi 1988). The purpose of the project is to study the potentials and effects of implementing the systems approach in existing curricula to teach content-specific knowledge and problem solving skills.

Eight schools are now participating in the project. One high school in Vermont was the original site of systems activity. Two years after work began in Vermont, the project expanded to include four secondary and two middle schools in the San Francisco Bay Area. In the 1990/91 school, a high school in Tucson, Arizona will join the project. Approximately 45 teachers are implementing the systems thinking approach in their courses. Content areas include general science, biology, chemistry, physics, mathematics, social studies, economics, and humanities at the high school level, and science, mathematics, and social studies at the middle school level. The teachers are organized into content-specific task forces to facilitate curriculum development. They have formed interdisciplinary and disciplinary networks, and communication among all teachers is facilitated via the AppleLink electronic mail network.

Project Phases

Teacher support activities. STACI^N contains two phases that are intended to facilitate the implementation of new teaching and learning activities using the computer-based systems thinking approach. The first component provides the support necessary to enable teachers to develop new curriculum materials and instructional strategies. This phase focuses on inservice programs that assist teachers to develop, apply, and infuse this technology-based curriculum innovation into existing courses. The inservice programs provide teachers with a new method by which to use technology effectively to improve instruction and learning in their courses. The second phase in the research will examine learning outcomes following the implementation.

In the first phase, the primary activity is extensive inservice training. Because systems thinking and STELLA require understanding of the theory and concepts that underlie the approach, it is necessary to provide training in general systems principles. Training is ongoing, including intensive sessions during the summer and inservice days and weekends during the school year. The emphasis is on providing teachers with a new, interactive instructional tool to be used to facilitate learning rather simply the transmittal of knowledge. The training emphasizes hands-on active participation by the teachers. The model of instruction espoused is to simulate with the teachers the interactive perspective that they will apply in their own classrooms.

Another source of support for the teachers is the sharing of knowledge with others who have similar interests and instructional problems. The project is designed to make consultation and advice readily available. For this reason, the teachers and schools have been organized into a communication and resource sharing network. The promotion of effective uses of computer-based teaching innovations is enhanced greatly by providing ready access to that network. Using a variety of modes of operation, ranging from nation-wide electronic mail to face-to-face interactions, the network provides many opportunities for the teachers to share experiences concerning effective practices for computer-aided teaching with systems thinking.

Because it is critical for teachers to be able to seek assistance easily from experts and other teachers, an electronic mail network using AppleLink has been established among the schools, hardware and software producers, and Educational Testing Service. Thus, when teachers experience successes or difficulties, they can use AppleLink to seek feedback from peers, content experts, hardware and software producers, and the project management team. AppleLink also enables teachers to transmit and share models and curriculum materials. Iterations on the materials can be made by accessing the network, thereby facilitating wide dissemination and sharing of the systems modules.

A final activity is the provision for collaboration and access to expertise through disciplinary task forces. Teachers within a content area are able to garner only so much substantive assistance for curriculum development from the training sessions and network activities. Thus, another component is the substantive contributions made by content experts to each of the task forces. Distinguished scholars will work with the teachers to provide critical substantive expertise.

Research component. The second phase of the project focuses on the examination of the impact of the systems thinking approach. Much of the impact research necessarily follows the teacher support component, allowing for sufficient curriculum development and implementation to occur before examining impact. The research has three foci: learning outcomes, teacher behavior, and organizational change. The first focus examines the extent to which students acquire higher-order problem solving skills and content knowledge through interaction with the systems approach. The ultimate goal is to address the transferability of problem solving skills across content areas.

An ancillary goal of this focus is to develop new measurement techniques that are appropriate for computer-based learning systems. The systems thinking approach provides multiple pathways toward solutions and emphasizes both the process and the products of learning. Furthermore, learning often occurs in collaborative small group settings. Thus, new approaches to measurement are needed to capture group learning and cognitive processing. The project seeks to develop and implement such new measurement techniques.

The second research focus is on teacher behavior. Classroom observations and teacher interviews are documenting the ways in which teacher-student interactions are effected by the systems thinking approach. Teachers function more as the facilitators of learning experiences, rather than the distributors of facts and figures. The third research focus is more sociological in perspective, for it examines how the schools as social organizations are effected by the introduction of hardware, software, and a new teaching approach. Although research on student learning outcomes is being delayed until sufficient curriculum innovation has taken place, research activities on teacher behavior and organizational change are now underway.

Modeling Applications with the Systems Approach

As mentioned above, there are three general ways in which the systems approach has been implemented by project teachers: parameter manipulation, constrained, and epitome modeling. These forms of implementation depend on the teacher, course content, instructional objective, and targeted students. Parameter manipulation generally is used with students who are likely to be young or in less advanced classes. Parameter manipulation also might be used to introduce the concept of systems or specific content material. In contrast, constrained modeling often is found in science and mathematics courses in which students can apply systems principles to solve traditional textbook problems. Epitome modeling generally is used for open-ended and unconstrained problems in which students conduct primary research and create models to explore many possible solutions.

Teachers in the project have developed curriculum materials using these three forms of modeling and implemented them in many different courses. Applications in science and mathematics courses have been emphasized. Figure 1 lists by course or application the models developed thus far in the project. Most of these are parameter manipulation and constrained models.

Figure 1. Preliminary List of Models Created in STACI^N

Life and General Sciences:
Surface Area
Beetles
Area versus Volume
pH Equilibrium
In and Out Together
pH + HB
pH (4 versions)
Weight Loss by Exercise
Second Love
Drugs
Population

Biology:
Hormones
Industrial Melanism
Homeostasis
Sickle Cell Gene 2 (3 versions)
Diffusion/Osmosis
Yeast Population Dynamics

Chemistry:
Phase Change Diagram
Boiling Water
Periodic Table
Ideal Gas Law
Global Warming
Recycle Model
Rate Determining Step
Bridge Corrosion
Ozone
Phase Diagram 3
Acid Rain 2

Physics:
Acceleration
Spring Energy
Snell's Law
Free Fall Friction
Heat Transfer
Capacitor Charge
Cooling in Water
Charles Law
Bus/Runner Problem
Boyles Law
Density Lab-Al, Zn, Fe
Stream Velocity

Mathematics:
Area Under Curve
Related Rates
Minimum-Maximum Problem
Circumference of a Circle
Graphing Sine Curves with Different Amplitudes and Periods
Polygons and Law of Sines and Cosines
Probability Rolling 2 Die
Probability Flipping 2 Coins
Probability Flipping a Coin
Car Payments
Lottery
Compound Interest
Distance Problem
Delayed Start Time
Total Distance
Difference Times but Equal Distance
Probability
Coins
Salt Concentration
Work Problems
Same Distance
2 Coins Probability
Parabola Model

Earth Science:
Rock Cycle
Earthquake
Greenhouse Effect
Groundwater

Integrated Curricula:
Wolves
Time Management

General Applications:
Introduction to Macintosh
Population
Compound Interest
Lottery
Car Payments
Good Grades
Distance
Learning Curve

In this paper we comment only briefly on three exemplary models. The first is a parameter manipulation example. Two teachers have collaborated to develop a curriculum module for time estimation (Crawford & Molder 1988). The unit enables students to apply mathematical concepts to the evaluation of time allocation to personal experiences. Underlying the unit is practice in estimating average numbers, distinguishing between significant and insignificant quantities, approximating answers to addition and multiplication problems, knowledge of variables, and graphing concepts. The unit also reinforces small group cooperative learning and the enhancement of higher-order thinking skills. This example shows how parameter manipulation can be used to teach mathematical concepts and apply them to relevant real-world phenomena.

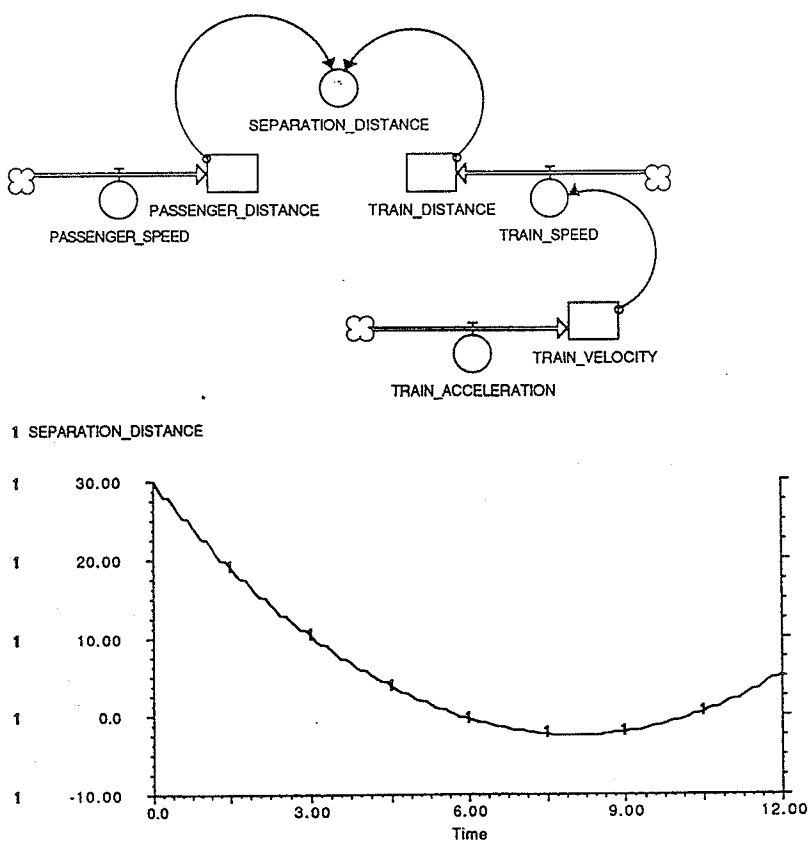
Our second example, constrained modeling, uses a common acceleration problem from high school physics (Miller, Dillon, & Smith 1980). Problems such as the following, although embedded in a particular discipline, require the application of mathematical procedures and constrained modeling techniques.

> A late passenger, sprinting at 8 m/sec, is 30 m away from the rear end of a train when it starts out of the station with an acceleration of 1 m/sec^2. Can the passenger catch the train if the platform is long enough? (Note: This problem requires

solution of a quadratic equation. Can you explain the significance of the two values you get for the time?)

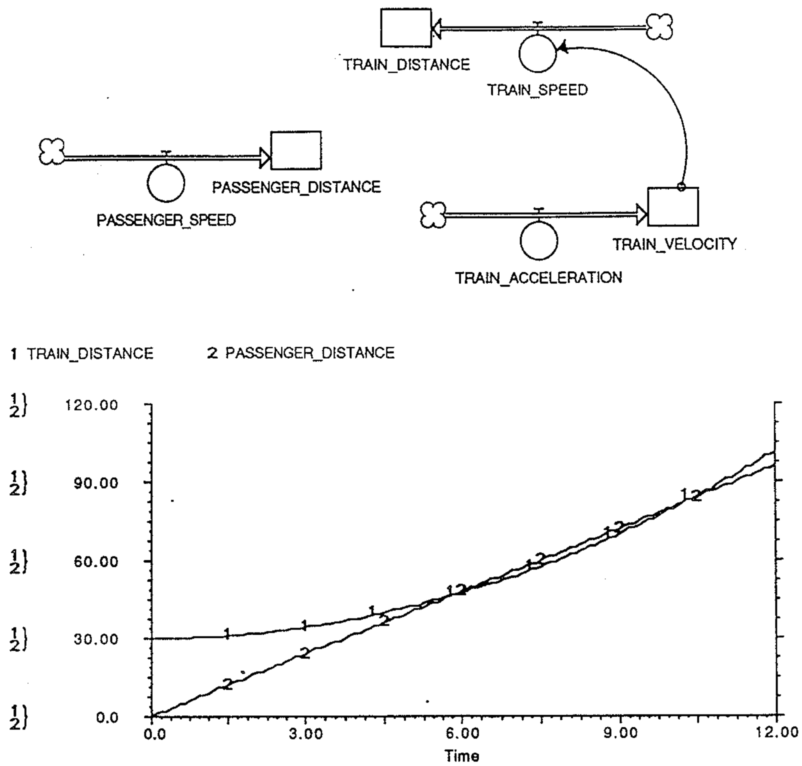
Figures 2 and 3 represent two solutions to the acceleration problem. The structural diagrams, simultaneous equations, and graphic representations are presented for both solutions. It is important to note that although the two solutions are quite similar, there are some rather subtle distinctions that indicate different approaches and conceptualizations to the problem. The basic structure of the two models are identical and reflect the students' understanding of the physics. No judgments as to correctness can or should be made between these two conceptualizations. They simply reflect how the students understood and conceptualized the physical phenomenon.

Figure 2. Acceleration Model 1



☐ PASSENGER_DISTANCE = PASSENGER_DISTANCE + dt * (PASSENGER_SPEED)
INIT(PASSENGER_DISTANCE) = 0
☐ TRAIN_DISTANCE = TRAIN_DISTANCE + dt * (TRAIN_SPEED)
INIT(TRAIN_DISTANCE) = 30
☐ TRAIN_VELOCITY = TRAIN_VELOCITY + dt * (TRAIN_ACCELERATION)
INIT(TRAIN_VELOCITY) = 0
○ PASSENGER_SPEED = 8
○ SEPARATION_DISTANCE = TRAIN_DISTANCE-PASSENGER_DISTANCE
○ TRAIN_ACCELERATION = 1
○ TRAIN_SPEED = TRAIN_VELOCITY

Figure 3. Acceleration Model II



□ PASSENGER_DISTANCE = PASSENGER_DISTANCE + dt * (PASSENGER_SPEED)
INIT(PASSENGER_DISTANCE) = 0
□ TRAIN_DISTANCE = TRAIN_DISTANCE + dt * (TRAIN_SPEED)
INIT(TRAIN_DISTANCE) = 30
□ TRAIN_VELOCITY = TRAIN_VELOCITY + dt * (TRAIN_ACCELERATION)
INIT(TRAIN_VELOCITY) = 0
○ PASSENGER_SPEED = 8
○ TRAIN_ACCELERATION = 1
○ TRAIN_SPEED = TRAIN_VELOCITY

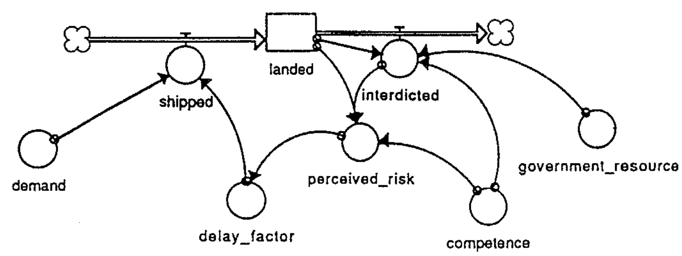
The student who constructed Solution 1 distinguished between the two main components of the problem, train distance and passenger distance and chose not the connect them in the model. Thus, the graphical output produced two separate function lines. The x-axis is time; the y-axis is distance, beginning with a zero point and increasing. The function lines intersect at two points, thereby yielding two solutions. These points of intersection indicate when the train and passenger are at the same place and the same time, allowing the passenger the chance to board the train.

Solution 2 is identical except that the student connected the two main components of the model. Train distance and passenger distance are linked, defining as a new variable, separation distance. According to the equations, separation distance is defined as the difference between train distance and passenger distance. Thus, when separation distance equals zero, the train and the passenger are in the same place, allowing the passenger the opportunity to board the train. Here, the graphical output produces one function line, separation distance. Again the x-axis is time. Although the y-axis is distance, there is a subtle difference. Here the zero point becomes critical. Prior to the first instance when the function line crosses the zero point, the distance between the passenger and train is decreasing. They then are at the same place at the same time until a few seconds later, after which the separation distance begins to increase. Note that the only difference in the equations produced between Solutions 1 and 2 is the inclusion of separation distance.

Results from the students' solutions to such constrained problems indicate differences in the extent to which students apply and benefit from the use of the systems approach. Many students report that the mathematical solutions fail to provide concrete representations of the problems and physical concepts. Instead, the numbers have only abstract meaning that they cannot link to real-world phenomena. In contrast, these students are able to model the problems, revise parameters, and demonstrate theoretically and practically what the problem and solution meant. A minority of the students express a preference for the mathematical solutions. Some of these students are confounded by the structure of STELLA in what they perceived as simple problems are made overly complicated. The traditional solutions are more straightforward for some of the mathematically sophisticated students. On the whole, most of the students agree that they achieve a better and more thorough conceptual understanding of the physical phenomena and the processes by which they obtain those solutions through the use of systems analysis.

The example of epitome modeling was provided by a mathematics teacher who has collaborated with but formally is not part of the STACI^{N} Project. One of her students obtained a copy of a federal agency research report on drug interdiction and translated the document into a systems model. The student first had to identify the most critical variables reflected in the report, then determine how they interrelated to form a system. The student's interpretation of the report resulted in a fairly simple model depicted in Figure 4. According to the student's interpretation, the amount of drugs landed depends on the amounts shipped and interdicted. The amounts shipped and interdicted are dependent on such factors as the demand for drugs, perceived risks on the part of the drug runners, the competence of the drug runners, and governmental resources expended to deter drugs. The mathematics underlying the model were based on data presented in the report, the results of which are illustrated in the STELLA graphical representation of the model. The student took primary research materials, imposed on them an intellectual structure, then constructed a systems model based on the logic and structure of the phenomenon of interest.

Figure 4. Drug Runner Model



Model provided by G. Mountcastle, Thomas Jefferson High School for Science and Technology, Alexandria, Virginia

Conclusions and Implications

These models and applications are examples of how the systems approach has been implemented in courses to enhance teaching and learning activities. The pedagogical perspective espoused in the systems approach may facilitate educational reform and change fundamentally the ways in which teaching and learning activities occur in schools and colleges. The STACI^{N} Project is examining some of these changes. Furthermore, STACI^{N} provides the opportunity to implement and address directly the recent curriculum standards espoused by the National Council of Teachers of Mathematics (1989). The Council stresses active participation and problem solving rather than passive rote learning and teacher-directed lecturing. It also recommends that the teaching of mathematics should be applied to real-life activities in order to make it more relevant, interesting, and engaging for a greater proportion of the student population.

The systems approach addresses these recommendations by making accessible to students and teachers modeling capabilities, which until very recently were found only on powerful mainframe computers. Modeling broadens the range of cognitive representations and instructional strategies students and teachers can bring to bear in solving problems. The systems approach allows students and teachers to develop and implement dynamic models of systems by using a variety of abstract representations to explore and make concrete many phenomena. The integration of this learning environment into curricula has the potential to produce students who have a greater capacity to understand the interrelated and complex nature of phenomena they encounter in daily life. Technology-based curriculum innovations such as the systems thinking approach will provide opportunities to examine how technology impacts on the fundamental nature of teaching, learning, and assessment activities.

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