LEARNING THROUGH SYSTEM DYNAMICS
AS PREPARATION FOR THE 21ST CENTURY

by Jay W. Forrester

This article is excerpted from the Keynote address given by Dr. Jay Forrester at the June, 1994 Systems Thinking and Dynamic Modeling Conference held in Concord, Massachuetts. The whole text of the paper is available from the Creative Learning Exchange.

We do not expect most students to spend their lives in front of a computer building system dynamics models. What should be the outcome of a systems education beyond the subjects in this week's program?

I believe we should give students a more effective way of interpreting the world around them. They should gain a greater and well-founded confidence for managing their lives and the situations they encounter.

The objectives of a system dynamics education might be grouped under three headings:

1. Developing personal skills,
2. Shaping an outlook and personality to fit the 21st century, and
3. Understanding the nature of systems in which we work and live.

DEVELOPING PERSONAL SKILLS

A system dynamics education should sharpen clarity of thought and provide a basis for improved communication. It should build courage for holding unconventional opinions. It should instill a personal philosophy that is consistent with the complex world in which we live.

Basis for Clear Thought and Communication

The ordinary spoken and written language allows a person to hide behind ambiguous, incomplete, and even illogical statements. Language, within itself, does not impose a discipline for clarity and consistency. By contrast, computer modeling requires clear, rigorous statements.

In ordinary discussion, a general statement like, "How people respond depends on the situation," might be accepted. But, if this were to become an input for a model, one would be forced to specify which people, what response, dependence on what specific aspect of the situation, and what precise action would to be taken under various conditions.

Students must struggle to achieve the precision of expression required to go from language to explicit statements in a simulation model. Even a process as simple as filling a bathtub with water, or describing the cooling of a cup of coffee, can be surprisingly demanding. Such clarity is not achieved after only a few exercises. Learning precision in thinking requires years of reinforcement.

Translating from descriptive language to model language is only half of the story. One can then make the reverse translation. From a simulation model, reverse translation to descriptive language yields clear statements that embody the precision that came from building and using the model.

Students should come out of a systems education convinced that a much better understanding is possible in the present puzzling behavior of personal, social, economic, and business situations. They should realize that any debate about policies for the future can be clarified and made more meaningful if someone will make the underlying assumptions explicit and show which assumptions lead to behavior that best fits the knowledge we have of the real world.

Students in kindergarten through 12th grade should have the repeated experience of using modeling to resolve debates, misunderstandings, and differences of opinion. One discovers that the most intense disagreements usually arise, not because of differences about underlying assumptions, but from different and incorrect intuitive solutions for the behavior implied

UPDATES. . .

Systems Thinking and Dynamic Modeling Conference

The System Thinking and Dynamic Modeling conference held at Concord Academy in June was attended by more than 260 people from all over the country and overseas. The conference filled by the middle of May and we were, unfortunately, unable to accommodate quite a number of interested people. Hopefully, those unable to attend will keep in touch with us and use our resources to get started. The keynote speakers, Peter Senge and Jay Forrester, gave their usual thought-provoking comments. Dr. Forrester's paper is excerpted in this issue.

Current curricular ideas and techniques were presented by teachers who are practitioners of the use of system dynamics in the curriculum . The areas covered ranged widely. Topics varied from interdisciplinary middle school curricula from the Glynn County Systems Thinking project in Georgia, through English and science at Catalina Foothills in Arizona, to math, science and social science from the CC-Stadus project in Oregon, as well as many more.

The commitment of time and energy of these educators both in their work and in their zeal to share it with others at the conference was impressive. Teachers showing other teachers what they are actually doing is perhaps the most effective way we have of disseminating the ideas and techniques involved.

The curricular piece at the conference was reinforced by an active organizational strand. Such people as Bill Issacs from the Dialogue project in the Organizational Learning Center at MIT, as well as David Kreutzer from Gould-Kreutzer Associates joined us to contribute their expertise and insight. Administrators from the Catalina Foothills district in Arizona, the Ann Arbor district in Michigan and the Ridgewood district in New Jersey lent their own particular brands of experience on the organizational front lines.

The success of the conference was due to the time and energy exerted by all who participated, both presenters and participants. We wish to thank everyone who took the time to come and learn together.

Although the Creative Learning Exchange will not sponsor another national conference the summer of 1995, we will do our best to keep you informed about learning opportunities in the field during the next year.

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FROM THE EDITOR. . .

This school year is starting on an enthusiastic note in many school systems across the country. Many teachers and administrators feel that there was a momentum generated by the Systems Thinking and Dynamic Modeling Conference held in Concord, Massachusetts this past June. The challenge for this school year is to keep the interest high and the learning progressing throughout the school year, in the midst of the myriad demands which are placed on educators.

A focus for this year for the Creative Learning Exchange will be establishing a regular electronic communication system. The System Dynamics in Education Project will be heading up a push to get a server with both K-12 materials and system dynamics materials for all levels on line with in the next few months. They can be contacted at: echoi@mit.edu.

In the interest of getting all our materials available electronically, we will be putting everything we have on disk. If you have sent us materials, you should have received a request for a disk copy of it. Thank you for your cooperation. The more channels we can use to disseminate our materials, the more people will use it.

I am available through e-mail, and would be happy to receive any materials requests or inquiries through that source. My address is: **stuntzln@tiac.net**. I hope to hear from you.

Lees Stuntz

GORDON STANLEY BROWN FUND ESTABLISHED

To support preparation for distribution of materials for using system dynamics in K through 12 education

The Gordon Brown Fund can support teachers for:
- Released time or summer time to put into usable form materials and methods that have already been used in schools and that could be of help to others,
- Communicating experiences that did not meet expectations so that others can be forewarned.

The Gordon Stanley Brown Fund has been established to promote system dynamics and an understanding of dynamic behavior in feedback systems in kindergarten through 12th grade schools.

The Fund will focus on making teaching experiences available to others. The financial assistance can be used for released time and summer time for putting into transmittable and usable form materials and experiences that have already had classroom exposure. Small and medium sized proposals are encouraged.

Work supported by the Fund is to be available for distribution through the Creative Learning Exchange and any other channels that the author arranges.

The Fund honors Gordon Brown who pioneered the theory and practice of feedback dynamics and engineering control systems at the Massachusetts Institute of Technology in the 1940s. Brown went on to be head of the Electrical Engineering Department and Dean of Engineering at MIT. During retirement, he has devoted energy and skillful leadership to bringing system dynamics into the Catalina Foothills school system in Tucson, Arizona.

Address applications, with an outline of the proposed project, to:

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by the assumptions. In building a system dynamics model, one starts from the structure and the decision-making rules in a system. Usually there is little debate about structure and the major considerations in decisions. When a model has been constructed from the accepted structure and policies, the behavior will often be unexpected. As the reasons for that behavior become understood, I have often seen extreme differences of opinion converge into agreement.

Students should see modeling and an understanding of systems as a way to reduce social and political conflict.

Building Courage

A strong background in modeling should show students that con-

ventionally accepted opinions about social and economic policies are often actually the causes of our most serious problems. If they realize that popular opinions are not necessarily correct, they should develop courage to think more deeply, look beyond the immediate situation, and stand against majority opinion that is ill founded and short sighted.

Working with models should not only enhance skill in making precise statements, but also bolster the courage to do so. Very often people take refuge in statements that are so general, so incomplete, and so superficial that they cannot be proved wrong. On the other hand, such vague statements can not be effective.

Making precise statements opens one to being wrong. By a precise

statement I mean one that is unambiguous. A precise statement has a unique meaning; it is clear. However, a precise statement is not necessarily accurate or correct. Precise statements are necessary for clear communication. If such statements are wrong, that will be more quickly discovered if communication is clear. In model building, students will many times have the experience of making assertions that model simulations demonstrate to be incorrect. Students should develop the courage to be precise, even if wrong, in the process of learning and improving understanding.

Personal Philosophy

Experience in computer simulation should change the way students respond to the world around them.

Jay Forrester's Keynote Speech, *continued from previous page*

From simulation models, students should appreciate the complexity of social and economic systems, whether those systems be at the level of families, communities, corporations, nations, or international relationships. They should have seen many times the counterintuitive nature of such systems. They should understand that "obvious" solutions to problems are not always correct, and that apparently correct actions are often the causes of the very problems that are being addressed.

Seeing Interrelatedness

Interrelationships in systems are far more interesting and important than separate details. The interrelationships reveal how the feedback loops are organized that produce behavior. Students with a strong background in systems modeling should be sensitized to the importance of how the world is organized. They should want to search for interconnecting structure that gives meaning to the parts.

One sees the significance of modeling in a discussion I had with a student who had graduated from MIT several years before. I asked him what his system dynamics study had done for him. His answer: "It gives me an entirely different way of reading the newspapers." He meant that he sees the relationships between different things that are happening today, he understands the relationships between today's news and what happened last week and last year, and he reads between the lines to know what must have been part of the story but was not reported.

"Renaissance Man," Unifying Knowledge, Mobility

The 21st century will exhibit rapid changes in societies. We already see turmoil in the former Soviet Union and in Africa. In the past century, change came from new technologies. In the next century I believe change will be driven mostly by population growth, crowding, environmental degradation, pollution, and shortages of food, water, and resources. In other words, societies will be continually reshaped and, as a consequence, the roles of individuals will continually change. Today's students should be prepared for unexpected change.

Education must reverse the trends of the last century toward more and more specialization. A specialization interest can start early in life and lead to a professional training in college that will often become obsolete within an individual's working career. Education should provide a foundation that gives a student mobility to shift with changing demands and opportunities.

A person with an understanding of systems sees the common elements in diverse settings rather than focusing on differences. For example, communities may have identical basic structures but behave quite differently because of different policies that are followed at crucial places. Systems with the same structure show the same range of behaviors. For example, a simple two-level model for a swinging pendulum can be relabeled and it becomes oscillating employment and inventories at the core of economic business cycles.

Transferability of structure and behavior should create a bridge between science and the humanities. Feedback-loop structures are common to both. An understanding of systems creates a common language. Science, economics, and human behavior rest on the same kinds of dynamic structures.

I see a reversal of the trend toward specialization. As the underlying unity between fields becomes teachable, we can move back toward that concept of the "Renaissance Man," who has broad intellectual interests and is accomplished in areas of both the arts and the sciences.

OUTLOOK AND PERSONALITY

A systems education should give students confidence that they can shape their own futures. A systems education should help mold a personality that looks for causes and solutions. Working with systems should reveal the strengths and weaknesses of mental models and show how mental models and computer models can reinforce one another.

Confidence in Creating the Future

Many of the stresses in modern life arise because people feel buffeted by forces they neither understand nor know how to control. Such sense of helplessness can be traced to not understanding the systems of which we are a part. Events that seem capricious when viewed locally are often understandable when seen from a broader systems perspective.

I hope that a system dynamics thread in K through 12 education would leave individuals willing and able to appreciate the nature of complexity. They should want to look beyond their immediate setting in search of the fundamental causes of problems. They should develop optimism about understanding those problems of society that earlier generations have found so baffling. Inflation, wars, unfavorable balance of trade, and destruction of the environment have persisted for hundreds of years without public understanding of the causes. Such problems are too serious to be left to the self-appointed experts; the public must acquire the insights that permit participation in debates of such importance.

Such better understanding comes in small steps. I am reminded of the story told by a television producer who was taking video pictures in a group of parents, teachers, and students at a school where the systems approach is making excellent progress. The producer turned to a junior high school boy

and asked, "What have these systems studies meant to you?" His immediate answer: "I am much better able to deal with my mother."

Authoritarian vs. Innovative Personality

A systems education should mold the personality of students by enhancing innovative tendencies in children and counteracting the forces in society that convert an innovative personality into an authoritarian one. I am here using authoritarian and innovative personalities in the sense described by Everett Hagen in his book, *On the Theory of Social Change* Hagen contrasts two opposite extremes of personality.

The authoritarian personality fits into a rigid hierarchy. Life is capricious. One does as ordered by those of higher status. There are no reasons for such orders. Capricious orders fit the old army saying borrowed from Tennyson, "Yours not to reason why, yours but to do and die." The reward for yielding to higher authority comes from the individual having authority over someone of lower rank. The pure authoritarian personality expects no reasons for why things happen and has no will to search for reasons.

By contrast, the innovative personality believes there are reasons for why things happen. Even if the reasons are unknown, there is still the assumption that reasons exist. Also, it is worth looking for the reasons because, if one understands, then one can probably change and improve what is happening. The innovative personality looks for causes and works toward beneficial advances.

I believe that babies are born as innovative personalities. They want to explore, to understand, and to see how things work and how to master their environments. But our social processes work to stamp out exploration and questioning. The child is continu-

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ally confronted with, "Do as you are told," or "Stop asking questions and just mind me," or "Study this because it is good for you." Repeated restraint of innovative inclinations gradually forces personalities into the authoritarian mold.

A system dynamics modeling curriculum, by letting students formulate the structure and policies causing behavior under study, will help preserve and rebuild the innovative outlook. Simulation emphasizes reasons for consequences. To be innovative, one must be willing to make mistakes while searching for reasons and improvement. Computer simulation modeling is a repeating process of trial and error. One learns that progress is made through exploration and by learning from mistakes. An authoritarian personality fears mistakes and does not try the unknown. An innovative personality knows that mistakes are stepping stones to better understanding.

Mental Models and Computer Models

Students should learn that all decisions are made on the basis of models. Most models are in our heads. Mental models are not true and accurate images of our surroundings, but are only sets of assumptions and observations gained from experience.

Mental models control nearly all social and economic activities. Mental models have great strengths, but also serious weaknesses. From a systems

education, students should learn how mental models can be useful and when they are unreliable. Furthermore, they should appreciate how computer simulation models can compensate for weaknesses in mental models.

Mental models contain a vast wealth of information that is available no where else. Mental models contain information about the structure and policies in systems. By structure I mean the elements in a system and the connections between the elements—who has what information, who is connected to whom, and, what decisions are made and where. By policies I mean the rules that govern decision making—what factors influence decisions, what is a particular decision point trying to accomplish, and what goals are sought. At this detailed level of structure and policies, mental models are rich and reasonably reliable sources of information.

However, mental models have serious shortcomings. Partly, the weaknesses in mental models arise from incompleteness, and internal contradictions. But more serious is our mental inability to draw correct dynamic conclusions from the structural and policy information in our mental models.

System dynamics computer simulation goes a long way toward compensating for deficiencies in mental models. In model building, one must remedy incompleteness and internal contradictions before the system dynamics software will even allow simulation. After a logically complete model has been created, one can be certain that the computer is correctly simulating the system based on the assumptions that were incorporated in the model. It is in simulation, or determining consequences of the structural and policy assumptions, that mental models are unreliable, but computer models are completely dependable.

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Students should also realize that there are no possible proofs of the validity of any models, whether they are mental or computer models. Models are to be judged by their comparative usefulness. Assumptions about structure and policies should be compared with any available information. Computer simulation results should be compared with behavior in the real system being represented. Discrepancies lead to improving both mental and computer models.

A two-way street runs between mental models and computer models. Mental models contribute much of the input for computer models. Creating a computer model requires that the mental models be clarified, unified, and extended. From the computer simulations come new insights about behavior that give new meaning to mental models. Mental models will continue to be the basis for most decisions, but those mental models can be made more relevant and more useful by interacting with computer models.

UNDERSTANDING THE NATURE OF SYSTEMS

We live in a network of complex systems. Yet few people realize the extent to which those systems control human actions. In fact, few people realize the extent to which complex systems actively mislead people into making counterproductive decisions. Students, after a 12-year encounter with systems, should be on guard against the deceptive nature of systems.

Cause and Effect Not Closely Related in Time or Space

Most understandable experiences teach us that cause and effect are closely related in time and space. However, the idea that the cause of a symptom must lie nearby and must have occurred shortly before the symptom is true only in simple systems. In the more realistic complex systems, causes may be far removed in both timing and location from their observed effects.

From earliest childhood we learn that cause and effect are closely associated. If one touches a hot stove, the hand is burned here and now. When one stumbles over a threshold, the cause is immediately seen as not picking the foot high enough, and the resulting fall is immediate. All simple feedback processes that we fully understand reinforce the same lesson of close association of cause and effect. However, those lessons are aggressively misleading in more complex systems.

In systems composed of many interacting feedback loops and long time delays, causes of an observed symptom may come from an entirely different part of the system and lie far back in time.

To make matters even more misleading, such systems present the kind of evidence that one has been conditioned to expect. There will be apparent causes that meet the test of being closely associated in time and in location. However, those apparent causes are usually coincident symptoms arising from the distant cause. People are thereby drawn to actions that are not relevant to the problem at hand.

Comments such as I have just made about cause and effect carry little conviction from being stated in a lecture. Only after a student has repeatedly worked with models that demonstrate such behavior, and has had time to observe the same kinds of behavior in real life, will the idea be internalized and become part of normal thinking.

Low-Leverage Policies

Complex systems differ from simple systems in another way. In simple systems, the policies to yield better results are obvious and they work. To avoid burning your fingers on a hot stove, you keep away from the stove. But in complex systems, the apparently influential policies often have very little effect.

In complex systems, there are many interconnecting feedback loops. A new policy, which is intended to solve a problem, causes reactions in other parts of the system that counteract the new policy. In education that reaction may come from administrators, from school boards, from parents who do not want new experimental ideas tried on their children, or from budget pressures.

I believe that a very high percentage, say 98%, of the policies in a system have very little leverage to create change. They do not matter. However, most of the heated debates in communities, companies, and governments are about policies that are not influential. Such debates are a waste of time and energy. Debates about low-leverage policies divert attention from the few policies that could lead to improvement.

Students must have experience working with models of complex systems to appreciate how often proposed policies fail to produce results.

High Leverage Policies, Often Wrongly Applied

Fortunately, a few high-leverage policies exist that can alter the behavior of a system. However, high-leverage policies lay another trap for the unwary. One occasionally finds a person who is working with a high-leverage policy. However, I estimate that more than 90% of the time that person is pushing the high-leverage policy in the opposite direction relative to what that person wants to accomplish. In complicated systems, intuition provides no reliable guide even to the direction that a high-leverage policy should be changed.

I do not know of any way to determine which are high-leverage policies and which direction to apply them except to do a systems dynamics simulation of the situation. Students should have many experiences working with models that reveal the multitude of poli-

cies having little effect, that allow them to search for high-leverage policies, and that show them the danger of intuitively judging even the direction of effect of high-leverage policies. Students should come out of a systems education with an appreciation for how mental models alone can lead one astray in multiple-loop systems. They should demand that important issues be modeled, and that the models be made available to the public. They should have confidence that they can read and evaluate such models. Models then become a powerful and explicit means of communication.

We Cause Our Own Problems

The often quoted line from the comic strips, "We have met the enemy, and he is us," has more than a grain of truth. Usually, problems exhibited by a social system are caused by the people in that system. However, people naturally tend to blame others. Parents blame schools for low competence of students, when perhaps the deficiency arises more from preschool home life and failure in parental guidance.

In preparation for the 21st century, a systems education should condition students to look for the source of their troubles first in their own actions before blaming others.

Drift to Low Performance, Collapse of Goals

One component of any feedback loop is the goal toward which the feedback process is striving. In simple models, goals are usually given as constants, for example, the goal of a pendulum is to seek the vertical as it swings from one side to the other. The goal that determines the amount of sleep we get is to maintain a certain degree of restfulness. But in a more complete representation of systems, the goals themselves are properly shown as variables. We may be striving toward a certain goal, but, failing to reach the goal, we may readjust our goal to something that seems more achievable.

There is a strong tendency for goals of all kinds—personal, community, corporate, or national—to drift downward. Pressures tend to cause performance to fall short of goals. But failing to meet goals is uncomfortable. The response is often to let the goals adjust downward toward the actual performance. As goals fall, the incentives for high achievement decline. Performance continues to fall short of the new lower goals and the downward spiral continues.

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Falling goals will in time lead to crisis, but by then recovery may be impossible. One sees erosion of goals in attitudes toward the national deficit. Thirty years ago, the present size of the national deficit would have been unthinkable. But as the deficit rose, people came to accept each new rise and adjusted to the higher deficit. Eventually such goal erosion can lead to disaster. Successful people, successful corporations, and successful countries have leadership or deeply held beliefs that stop such goal erosion.

Students should be exposed to the dynamics of goal collapse in models and have an opportunity to relate the process to their own lives. Goal collapse, that is, becoming accustomed to and accepting falling standards, may be the greatest threat to the future of individuals and countries.

Long-Term vs Short-Term Goals

A fundamental conflict exists between short-term and long-term goals. Students should observe this conflict between the present and the future in system dynamics models and then relate the lessons to their lives. Actions that yield immediate rewards almost always exact punishment in the long run, and vice versa. Quick gratification is the enemy of future well-being. It is hard to find exceptions where actions with an immediate reward do not extract a price in the more distant future.

A person who steals may benefit immediately, but usually suffers later. A person who works all night to finish an important task pays by being inefficient for the next several days. Taking mind-altering drugs may give an immediate sense of well being at the expense of future ill health or poverty. Borrowing on credit cards allows an immediate increase in standard of living but the consequence in the longer term is a lower standard of living while paying back the loan and interest.

Conversely, accepting a short-term disadvantage can often yield rewards in the longer-term. For example, saving now, rather than spending all one's income, can increase the future standard of living.

The conflict between short-term and long-term goals bears directly on what should be considered ethical and humanitarian. Humanitarian impulses are usually based on short-term considerations but often lead to worsening the situation in the more distant future. Food aid to starving populations seems humanitarian in the short run, but may well encourage population growth and greater starvation of even more people in the future.

Students should study the fundamental conflicts between short-term and long-term goals in the context of system dynamics models and have the opportunity to relate the lessons to their families, communities, and nation.

ACHIEVING THE BENEFITS OF A SYSTEMS EDUCATION

A systems thinking and systems modeling curriculum will not automatically yield the lifetime insights and personal guidance that I have been discussing. A student might easily go through the motions of working with models without gaining the understanding that is potentially available.

Jay Forrester's Keynote Speech *, continued from previous page*

Experience and Participation

Students will not internalize their understanding of systems merely from being told. Nor will discussion and debate be effective. Coming to an understanding of systems must be a participative activity. Learning about systems in not a spectator sport, such learning comes from active involvement. One does not learn to ride a bicycle or play basketball from lectures alone; one must practice. A person learns from experience. Computer modeling allows an accelerated vicarious experience.

The Deeper Lessons

A student can work with computer simulation models without realizing the deeper lessons that should be absorbed. Most learning for the 21st century that I have discussed can be missed by students unless the right guidance is provided. Students must create their own models and learn from trial and error. They must be led toward models that can teach the lessons that I have been discussing. Even with models that contain the lessons, students can miss the most important implica-

tions, so they should be encouraged to see the deeper consequences of what they are doing. They should relate what they are learning to systems they already know in families, community, and school.

To appreciate the nature of systems, students must have extensive personal experience in working with systems. This means creating system dynamics models on a computer, simulating their behavior, exploring how the models respond to changes in structure and policies, and comparing model behavior to the real systems being represented. Such active modeling should extend at least throughout the several years of middle school and high school. As early as possible, schools should move away from canned models that have been previously prepared for student use. Instead, students should create models, examine their short comings, and learn from discovering improvements.

Students should gain experience in modeling systems in which they have a personal interest. Such systems can be drawn from family and community situations. Items from the newspa-

pers should be converted to formal models to reveal student understanding of current events, to detect omissions and contradictions in the news items, and to provide practice in moving in both directions between mental and computer models. History and literature likewise provide material that can be made more explicit and understandable through modeling.

Throughout student work with models, more should be learned than just the details of the models themselves. Beneath such models are the underlying principles of systems. Beyond such models are the kinds of learning discussed in this talk. Students probably will not see such general and transferable insights merely from exposure to models. The larger and more enduring lessons must be pointed out. Students should work with examples of the broader implications. Such active use of the insights will thereby become part of their thinking and the way they look at the world around them.

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