FEATURE

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LEARNING THROUGH SYSTEM DYNAMICS AS PREPARATION FOR THE 21ST CENTURY

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What should be the outcome of a systems education? We do not expect most students to spend their lives in front of a computer building system dynamics models, so what should system dynamics modeling accomplish?

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. 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 concepts and 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 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 conventionally 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. 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. 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.

We can hope that students will develop caution about jumping to premature conclusions and will search for a wider range of alternatives. Even if individual students do not construct models in later life, they should expect that system dynamics models will be constructed by those who are proposing changes in economic and social policies. Moreover, in the 21st century, citizens should expect that such models will be made available for public inspection. From their K through 12th grade experiences, they will know that they can read, understand, and evaluate such models. More and more, computer models will be used as the basis for determining social and economic policies. In order to participate, the public will need to know the nature of such models, to evaluate the assumptions in models, and to feel comfortable in pushing the proponents of policy models to reveal their assumptions and to justify their conclusions.

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. 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.

System dynamics provides a foundation underlying all subjects. When that foundation is mastered, an individual will have mobility to move from field to field. An MIT undergraduate in electrical engineering demonstrated such mobility. He studied system dynamics during his junior and senior years. When he continued for a master of science degree in electrical engineering, he did his thesis on the way the body handles insulin and glucose in various aspects of diabetes. He immediately developed a working-colleague relationship with doctors in Boston's research clinic for diabetes because for the first time they were able to put together their fragments of medical knowledge into a meaningful system (Richard O. Foster. *The Dynamics of Blood-Sugar Regulation*. M.Sc. thesis, MIT, 1970). He next worked with me in extending the Urban Dynamics model (Jay W. Forrester. *Urban Dynamics.* Pegasus Communications, 1969). For a year, he led discussions with a group from Boston's black community to incorporate many aspects of education into the model. Later he went to work with a corporation. He could move from one setting to another because his fundamental understanding of systems allowed him to provide a dynamic organizing framework to any activity.

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 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 ability to deal better with one's environment starts with even very simple systems. One of our MIT doctoral students in system dynamics went to work for the Department of Energy. Two years later he told me he was amazed by the amount of influence he could have on governmental thinking with a two-level simulation model. Even such a simple system is often beyond what people in important policy positions are taking into account.

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* (Dorsey Press, 1962). 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. 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 continually 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.

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.

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. 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 these 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.

When I talk to a group of business executives, I ask how many have ever had the experience of facing a serious problem, devising policies to correct the situation, and five years later find there has been no improvement. Most will hold up their hands. Perhaps you have experienced the same in education. The quality of education has been severely criticized, many educators have tried remedies, and often there is little change.

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 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 percent 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 have several times had the experience of going into a company with a serious difficulty where intended policies were causing the problem. It might be low profitability, or falling market share, or severe instability with the company working overtime one year and having half the people laid off two years later. One carries on extensive interviews to determine the policies (decision-making rules) that people are using in different positions in the company. People justify their policies as intended to solve the major problem. One then puts the expressed policies into a system dynamics simulation model and finds that the model generates the same difficulty that the company is experiencing. In other words, the policies that people know they are following are the cause of their trouble. Local interpretation of symptoms leads to local actions that combine to produce detrimental results. This is a treacherous situation. If people believe their actions will reduce the problem, but do not know those actions are making it worse, then as matters become worse there is growing incentive to take the presumed corrections that are actually causing further decline.

One sees this spiral of system deterioration at all levels in society. Individuals in a family in serious psychiatric difficulty know they are in trouble, each wants to do something to help, yet everything that everyone does makes matters worse. In the Urban Dynamics model, we saw that governmental policies about low-cost housing do not improve cities but cause more decay. In the same way, we might suspect that our national foreign trade policies lead to importing goods made by low-skilled labor while our own low-skilled population loses the jobs that could provide an employment and training ladder to higher skills.

Students should have many experiences working with models that reveal the multitude of policies 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. When Detroit was losing market share to Japanese automobiles, executives of American companies blamed Japan for dumping at low prices, when the real cause was Detroit's own declining quality. Parents blame schools for low competence of students, when perhaps the deficiency

arises more from preschool home life and failure in parental guidance. A company is more inclined to blame falling sales on unfair competition or fickle consumers than on its own poor products and service.

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 of an inventory manager may be to maintain a given level of inventory. 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.

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 own 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. Under pressure from voters, the U.S. Congress is borrowing money to provide ever-increasing goodies to constituents, with the probable future consequence that government becomes insolvent and may not be able to provide basic public services. Over a much longer time horizon, improved public health and modern agriculture raised the standard of living and reduced death rates, resulting now in the threat of an unsustainable population explosion.

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. A company that forgoes higher dividends and increased executive salaries can invest in research on new products and increase future income.

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.

Changing the Nature of Education

System dynamics, if introduced most advantageously, can change the nature of education. It becomes a foundation under most subjects, it unifies learning, it is interdisciplinary, and it gives a student confidence to move between subjects and professions. Traditional education crams the student with facts without the excitement of tackling important real problems; a problem is assigned only when the student has been given the material to reach a solution. That is contrary to real life. In a system dynamics–oriented school, students engage issues of importance to their families, the city, their school, or the outside world. Then they have the motivation to learn what they need to know to address an exciting problem. A teacher is no longer the source of all wisdom but becomes a coach to suggest directions for students who hit dead ends or become frustrated. High school students can attack problems that the adult world is afraid to try. ◘

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