

Some Basic Concepts in System Dynamics

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In its full development, system dynamics is a discipline with the scope of science, education, law, engineering, or medicine. On the other hand, it is becoming clear that teachers in ordinary K-12 schools can make enough progress in two or three years to achieve major improvement in students' thinking, self reliance, and enthusiasm for learning.

1. THE NATURE OF SYSTEMS

Many principles form the foundation of system dynamics and become a basis for thinking in all endeavors.

1.1. *Feedback Loops*

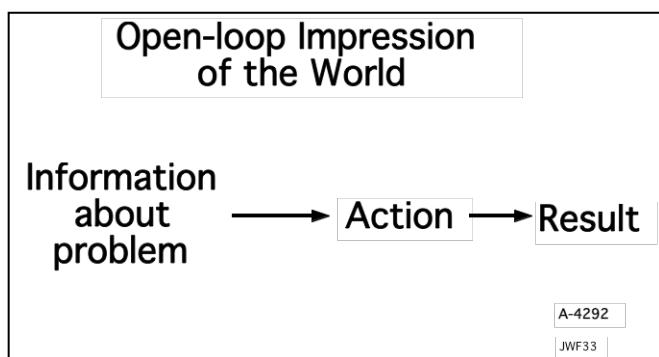


Figure 1

Here we touch on the nature of feedback loops. People seldom realize the pervasive existence of feedback loops in controlling everything that changes through time. Most people think in linear, nonfeedback terms. For example, in Figure 1, people see a problem, decide on an action, expect a result, and believe that is the end of the issue. Figure 1 illustrates the framework within which most discussions are debated in the press, business, and government.

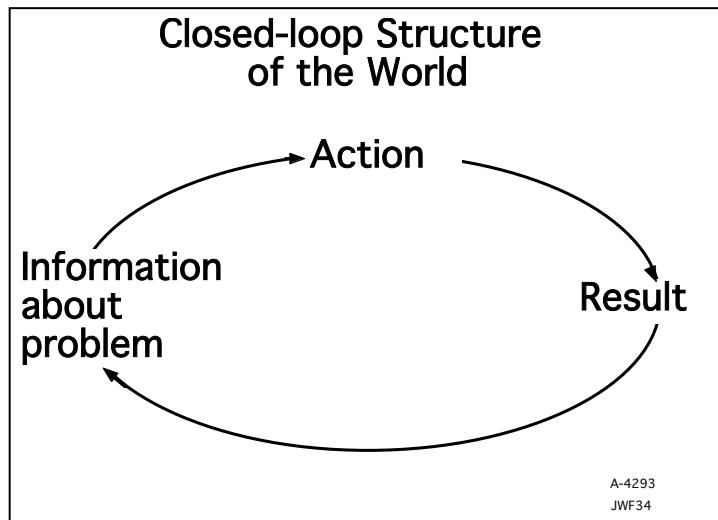


Figure 2

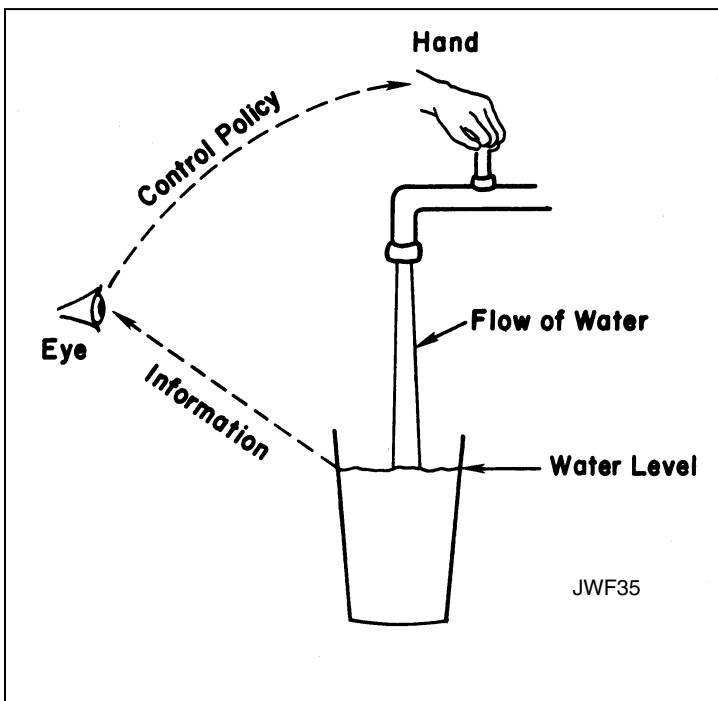


Figure 3

However, a far more realistic perception would be Figure 2 in which a problem leads to action that produces a result that creates future problems and actions. There is no beginning or end.

We live in a complex of nested feedback loops. Every action, every change in nature, is set within a network of feedback loops. Feedback loops are the structures within which all changes occur.

Filling a glass of water is not merely a matter of water flowing into the glass. There is a control of how much water. That control is the feedback loop from water level to eye to hand to faucet to water flow and back to water level. Such closed loops control all action everywhere.

1.2. Simplest Feedback Loop

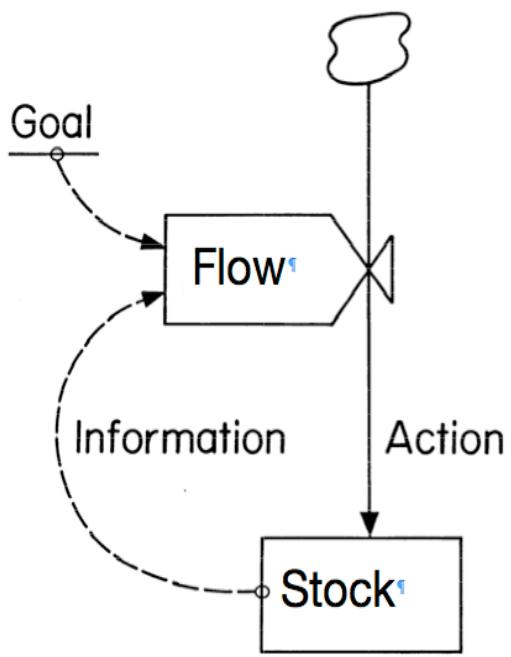


Figure 4

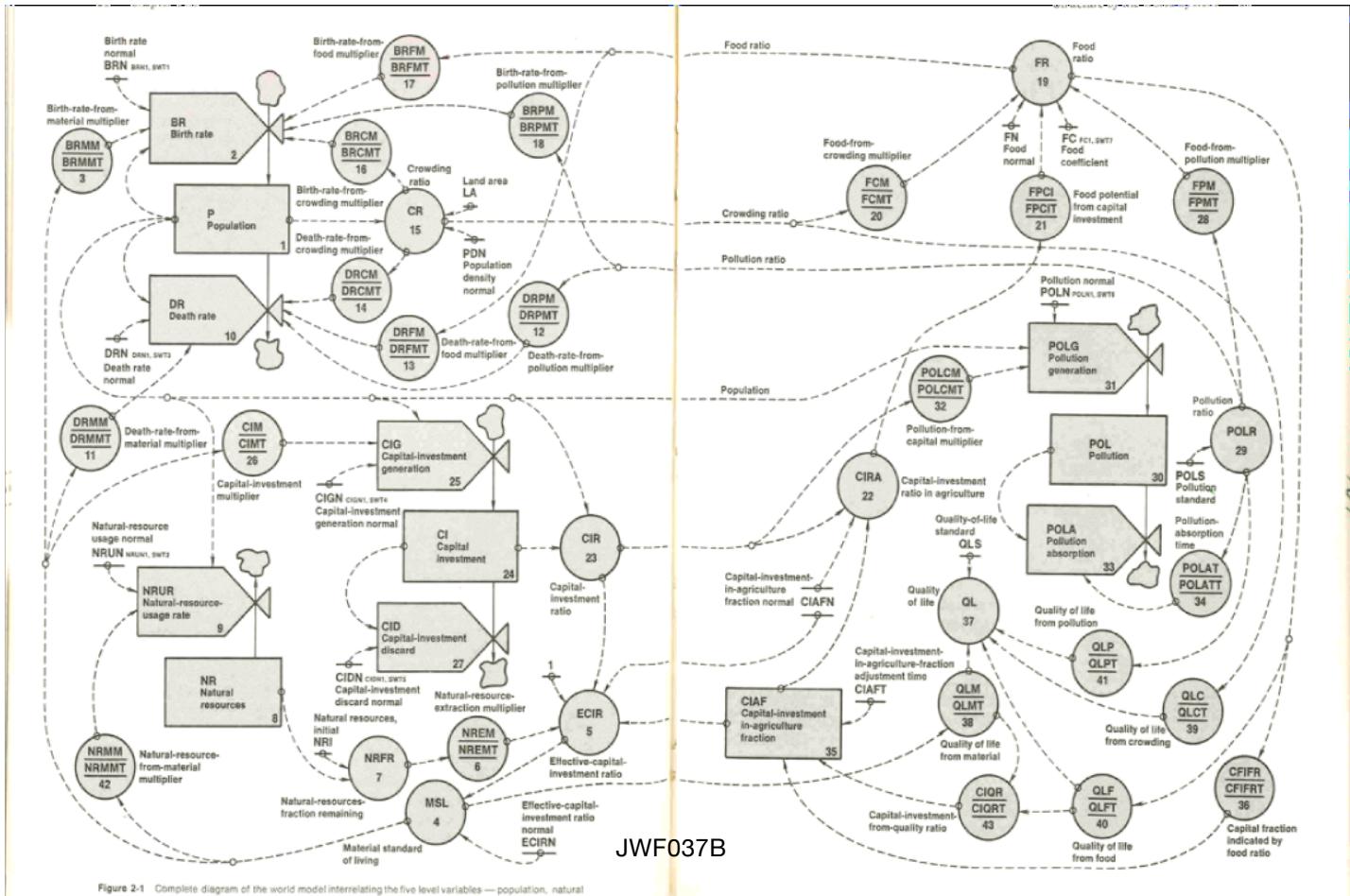
Figure 4 shows the simplest possible feedback system. In the figure are two symbols—a stock, and a flow. The stock is an accumulation, or integration, or level, to choose terminology from different fields. The flow changes the amount in the stock. The flow is determined by a statement that tells how the flow is controlled by the value of the stock in comparison to a goal. All systems, everywhere, consist of these two kinds of concepts—stocks and flows—and none other. Such a statement, that there are two and only two kinds of variables in a system, is powerful in simplifying our view of the world. People familiar with accounting statements, as in annual reports of corporations, will recognize the two classes of variables. A financial report is presented on two different pages—the

balance sheet and the profit and loss statement. All numbers on the balance sheet are stocks representing accumulations that have evolved over time. The profit and loss statement represents the flows that cause the stocks to change. There is no comparably important third page, only the page representing stocks and the page representing flows. That structure of an accounting statement represents a fundamental truth about all systems. Water in a bathtub is a stock; the flow of water changes the stock. A person's reputation is a stock that is changed by the flow of good and bad actions by that person. The degree of frustration in a group is a stock that gradually changes in response to surrounding pressures.

2. FROM SIMPLE TO COMPLEX SYSTEMS

The basic feedback loop in Figure 4 is too simple to represent real-world situations. But simple loops have more serious shortcomings—they are misleading and teach the wrong lessons. Most of our intuitive learning comes from very simple systems. The truths learned from simple systems are often completely

opposite from the behavior of more complex systems. A person understands filling a water glass, as in Figure 3. But, if we go to a system that is only five times as



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complicated, as in Figure 5, intuition fails. A person cannot look at Figure 5 and anticipate the behavior of the pictured system.

Figure 5 from *World Dynamics* is five times more complicated than Figure 4 in the sense that it has five stocks—the rectangles in the figure. The figure shows how rapidly apparent complexity increases as more system stocks are added.

Mathematicians would describe Figure 5 as a fifth-order, nonlinear, dynamic system. No one can predict the behavior by studying the diagram or its underlying

equations. Only by using computer simulation can the implied behavior be revealed.

Figure 5 displays interactions between population, capital equipment, agriculture, resources, and pollution. The diagram links multiple disciplines. A proper study of systems must usually break down the boundaries between academic disciplines. As stated by Gordon S. Brown, former dean of engineering at MIT, “The message is in the feedback, and the feedback is inherently interdisciplinary.”

3. EVERYONE USES MODELS

I sometimes ask an audience how many use models for all their decisions. No one responds. How then, I ask, do they make decisions? They quickly see that all decisions are made on the basis of mental models. No one's head contains a family, city, school, country, or business. Decisions are based only on assumptions about separate parts of real systems, and trying by intuition to fit those fragments of knowledge into an estimate of how things change and what will be the consequences of a proposed action.

Models	3.1.
<p>All actions based on models</p> <p>Mental models Basis of human activity.</p> <p>Major strength: Tremendous store of information</p> <p>Major weakness: Unreliable in handling complexity and dynamic change.</p> <p style="text-align: right;">JWF12</p>	<p><i>Computer Models and Mental Models</i></p> <p>System dynamics builds two-way communication between mental models and simulation models. Mental models are the basis for everyday decisions. Mental models contain tremendous stores of information. But the human mind is unreliable in understanding what the available information means in terms of behavior. Computer simulation meshes nicely with mental models by taking the mentally stored information and then displaying the dynamic consequences.</p>

Figure 6

Such mental models belong to the same class as the computer models used in system dynamics. In fact a system dynamics model is often built from assumptions in the mental models. Mental models are rich and often sufficiently

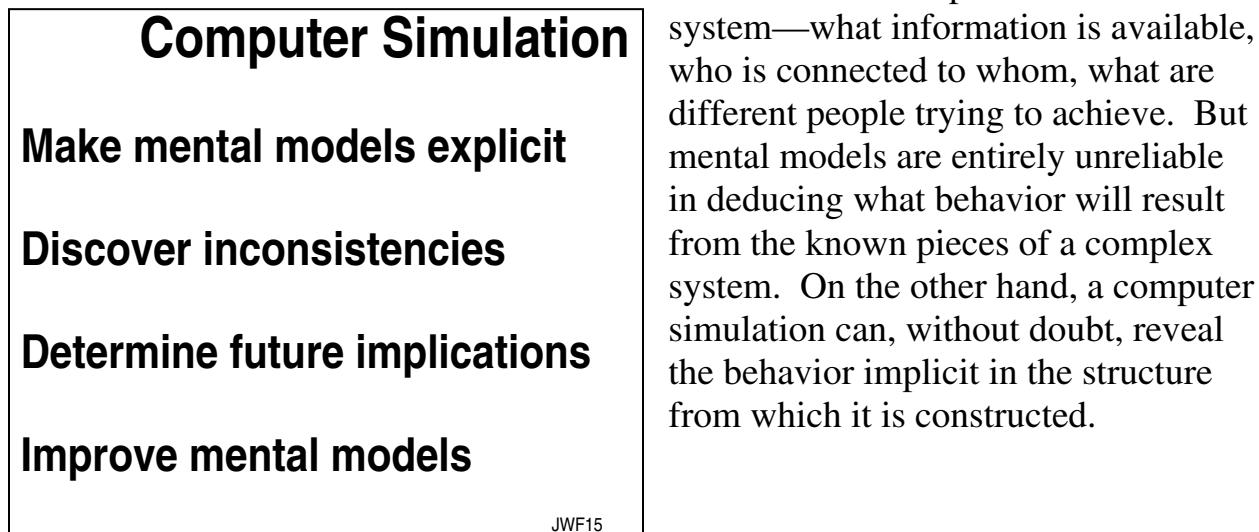


Figure 7

4. WORKING WITH COMPUTER MODELS

The translation of a mental model to a system dynamics simulation model moves through several stages.

1. A model must be created with no logical inconsistencies. All variables must be defined. None can be defined more than once. Equations must be unambiguous. Units of measure should be the same on both sides of an equation. Most system dynamics software applications check for and find such logical errors.
2. When a model is first simulated, the results may be absurd. Simulated behavior may be impossible. Inventories, or water in a bathtub, or students in the school may go negative; negative values often have no real-world meaning. One goes back to refine the model and make the structure more realistic and more robust.
3. As a model becomes better, surprising behavior often does not reveal model errors but instead begins to tell something about real life that was not previously realized. I have usually had such new insights from models. One example arose from the model in my *Urban Dynamics* book dealing with the growth and stagnation in cities. One weekend I added a job-training program to the model. It was a perfect job-training program in the sense that it simply took people out of the unskilled and underemployed category and put them

accurate about the pieces of a system—what information is available, who is connected to whom, what are different people trying to achieve. But mental models are entirely unreliable in deducing what behavior will result from the known pieces of a complex system. On the other hand, a computer simulation can, without doubt, reveal the behavior implicit in the structure from which it is constructed.

in skilled labor; and, furthermore, no charge was assigned so it cost nothing.

The perfect job-training program caused unemployment in the model to go up. The increase in unemployment surprised me until I spent a day discovering what the model was doing, after which the result seemed plausible. I took the computer runs back to former mayor John Collins and the several people from Boston business and politics that had been working with me. They looked at the rising unemployment as a result of introducing job training in silence for several minutes until one said, "Oh, Detroit has the best job-training program in the country and the most rapidly rising unemployment rate!" Later I went to people in the business of running job-training programs and asked if they had ever heard of a situation where job training could increase unemployment. Their answer, "Of course, when that happens we go to another city."

The job-training program in the model was defeated by three forces: 1) before the program, businesses had been dipping into the unskilled and unemployed pool as necessary to obtain employees. The job-training program substituted for the training that businesses would have done, so training by businesses stopped. About half of the training program was neutralized by such substitution; 2) the program increased the number of skilled workers thereby increasing unemployment among skilled workers and resulted in increased downward flow back to the unskilled-unemployed pool. Nearly another half of the training was lost through the increased downward mobility; 3) and last, the training program had high public visibility and attracted unemployed from other cities, even though the program had not created significant new jobs. Forces within the system neutralized the training program and the public visibility of the program attracted additional people who would increase unemployed.

Another situation of first learning about real life from a simulation model arose when a student modeled the behavior of insulin and glucose in various aspects of diabetes. In response to an experiment simulated within the model, he got a result from his computer patient that had never been reported in the medical literature. Was there something wrong with the model? He showed the results to doctors doing diabetes research. After studying what was happening in the model, their response was, "We had a patient like that once, but always thought there was

a mistake in the measurements.” This process had identified a new medical syndrome.

5. SOURCES OF INFORMATION

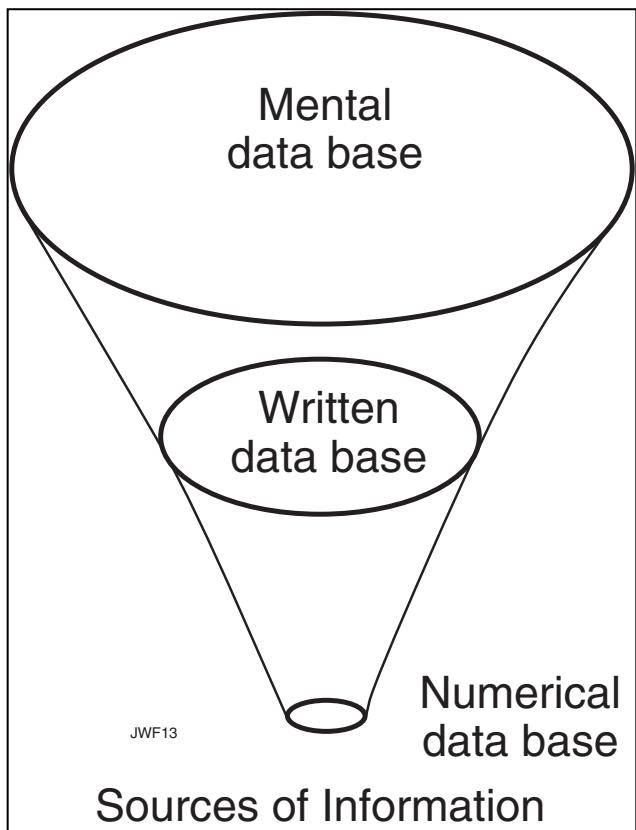


Figure 8

Consider the available databases, or sources of information from which we can build computer simulation models.

I suggest that the world's store of information lies primarily in people's heads—the mental database. As a test of that statement, consider any institution, for example, your corporation or your school system. Imagine that at 10 o'clock some morning every person suddenly leaves and is replaced by a person who can read but has no experience in the system. You instruct your replacement to follow the instructions and policy statements in your office and carry on for you. Chaos would result. Our families, schools, businesses and countries operate on the information in

people's heads gained from participation, apprenticeship, and on-the-job learning. The mental database is vastly richer than the written database in the form of books, magazines, and newspapers. In turn, the written database is far more informative about how society operates than the numerically recorded information.

System dynamics modeling should build on all available information, including the voluminous mental database. By contrast, most analyses in the social sciences have been limited to information that has been numerically recorded. The numerical information is an extremely small part of all the information that is available.

6. GENERIC OR TRANSFERABLE STRUCTURES

Generic Structures	
Transferable between:	Many structures of levels and rates are found repeatedly.
Past and present	They are “generic structures”
From one setting to another	because they are found in many different situations, even in entirely different fields of application. If a particular structure is understood in one setting, it is understood in all settings. Generic structures provide a person with power to move between situations with the learning in one area being applied to other situations.
A small number cover a wide range of situations	
When understood in one setting they are understood in all settings	
Basis for effective education	

Figure 9

In education, after understanding a collection of basic dynamic structures, a student can quickly draw on one to understand a new situation if its structure has been encountered previously.

6.1. Generic Structure of a Clock and Economic Business Cycle

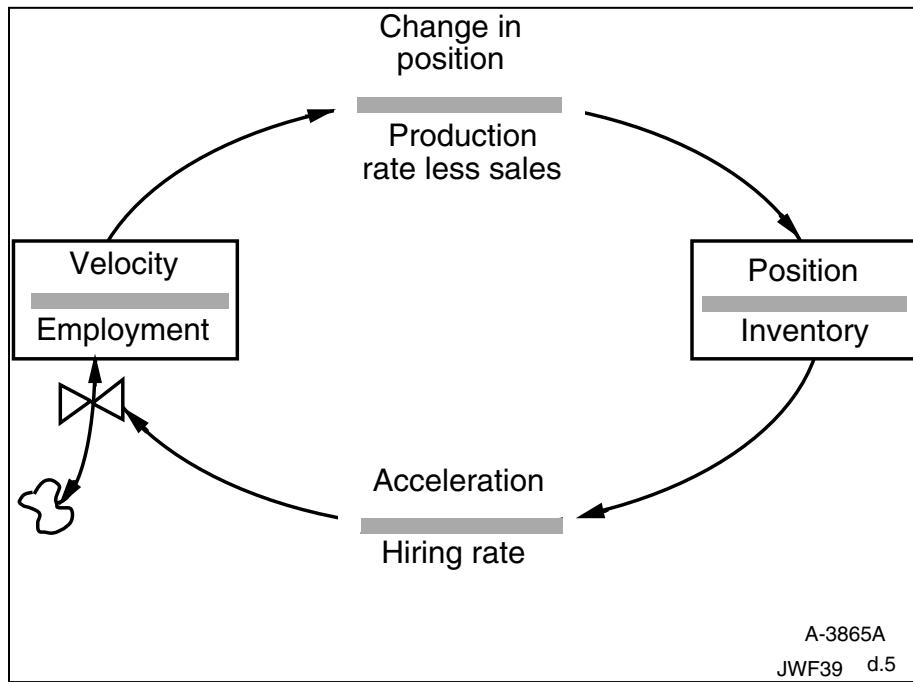


Figure 10

Figure 10 shows two sets of nomenclature. The labels above the bars relate to the swinging pendulum of a clock. The labels below the bars describe inventory and employment in manufacturing. With appropriate choices of parameter values, the structure will exhibit the oscillation of a one-second clock pendulum, or alternatively the several-year interval between peaks of a business cycle. The single loop with two levels as in Figure 10 results in only a sustained oscillation. Additional structure is necessary to represent friction in a pendulum or the forces that might change the amplitude of business cycles. A swinging pendulum and the central core of the production-inventory business cycle have the same oscillatory structure.

In my own experience with transferability of structure, I was meeting with a group of medical doctors and pharmacologists in Palo Alto one day. A topic came up that was not on the agenda. They began to talk about a doctor who was doing an experimental treatment, which clearly those present did not approve. They had described the experiment but had said nothing of the results when I suggested an outcome. I told them that if I were to judge that medical experiment on the basis of the kind of behavior that we had seen in the *Urban Dynamics* model of cities, I would guess the treatment would cause atrophy of the pancreas. They said, “You’re right. That’s exactly what’s happening.” There was enough

transferability of structure between the two systems to justify suggesting the medical outcome.

For dramatic, personal-experience learning, computer structures can be converted into games with people making the decisions that would control the flows in a model. A distribution system from manufacturer, through distributor and retailer, to customers has been played by hundreds of thousands of people around the world to drive home the way in which people can interact to create instability. Other games show the dynamics of producing great depressions some 45 to 80 years apart, and still others show how companies can grow so rapidly that they cause their own failure.

7. DIFFERENTIAL EQUATIONS VS. INTEGRATION

One might ask how it is now possible to teach behavior of complex dynamic systems in K-12 when the subject has usually been reserved for college and graduate schools. The answer lies in having realized that the mathematics of differential equations has been standing in the way.

Differential equations are difficult, confusing, weak, and unrealistic. They often mislead students as to the nature of systems. Mathematicians have had difficulty defining a derivative and there is a reason. Derivatives do not exist except in a mathematician's imagination. Nowhere in nature does nature take a derivative. Nature only integrates, that is, accumulates in stocks. Casting behavior in terms of differential equations leaves many students with an ambiguous or even reversed sense of the direction of causality. I have had MIT students argue that water flows out of the faucet because the level of water in the glass is rising; that seems natural to them if the flow has been defined as the derivative of the water level in the glass.

Any child who can fill a water glass or take toys from a playmate knows what accumulation means. The stocks in a system dynamics model (the rectangles in Figures 4 and 5) are the integrations (accumulations). By approaching dynamics through the window of accumulation, students can deal with high-order dynamic systems without ever discovering that their elders consider such to be very difficult.

An MIT undergraduate working to develop system dynamics materials for K-12 education observed:

In my differential equations class we used calculus to figure out the behavior of populations. I realized just how much simpler system dynamics made that thought process. Whereas only college students can understand such phenomena using math, elementary scholars can understand the same things by using system dynamics modeling. It's really amazing."

This paper has given only a glimpse of the principles and concepts that make up an understanding of complex social and economic systems. Furthermore, an understanding of systems will not be internalized just by reading about them. We look forward to the time when an education from kindergarten through college will create citizens and leaders who can create far more satisfactory human and environmental systems.

8. MORE ON SYSTEM DYNAMICS

Study materials are available from the Creative Learning Exchange. Many downloads of the K-12 information come from corporations that use the material for internal training. Exactly the same material can be used anywhere from the 5th grade to chief executive officers; it is new to all.

Creative Learning Exchange

<http://clexchange.org>

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Acton, MA 01720

tel: 978-635-9797

fax: 978-635-3737

email: stuntzln@clexchange.org

Look on the web site or ask about the list of available materials to be downloaded and the "Road Maps," which is a self-study introduction to system dynamics. Also go to:

sysdyn.clexchange.org

for the assignments and solutions for the Guided Study Program in System Dynamics

Internet discussion group: Send a message to
listserv@sysdyn.clexchange.org with the line "subscribe k-12sd first-name last-

name” as the only thing in the message’s body (no footer, no signature, etc.) The subject line is immaterial. “First-name” and “last-name” are your first and last names.

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