# System Dynamics and K-12 Teachers

a lecture at the
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# Contents

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## 1. SYSTEM DYNAMICS

System dynamics, which has been under development at MIT since 1956, and now at many other places, deals with how things change through time. That covers a great deal of what most people find important.

System dynamics first developed as a management discipline to understand how the policies of corporations produce successes and failures. What is it in decision-making policies that produce growth or decay; what policies make huge fluctuations of employment, as seen in some corporations that work seven days a week and overtime one year, and two or three years later have half the people laid off?

Later we realized that system dynamics was not limited to the field of management, and there were excursions into larger social systems. Work I did with former mayor John Collins of Boston became my *Urban Dynamics*[1] book dealing with how cities grow and then stagnate, and how national policies for dealing with cities often lie between neutral and highly detrimental, both for the city as an institution and also for the low income, unemployed residents.

Some of you may have encountered the branching of system dynamics into work with an organization called the Club of Rome that resulted in my *World Dynamics*[2] book and *The Limits to Growth*[3] by Meadows. These two books produced vastly more public reaction than any other computer modeling in the social sciences. More recently, I have applied system dynamics to better understanding of the dynamics of national economies.

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[1] Forrester, Jay W. (1969). *Urban Dynamics*. Waltham, MA: Pegasus Communications. 285 pp.

[2] Forrester, Jay W., 1973. *World Dynamics*, (2 ed.). Waltham, MA: Pegasus Communications. 144 pp.

[3] Meadows, Donella H., Dennis L. Meadows, Jørgen Randers, and William W. Behrens, III. (1972). *The Limits to Growth.* New York: Universe Books. 205 pp.

## 2. SYSTEM DYNAMICS IN EDUCATION

This morning we discuss the most recent frontier in system dynamics--its use as a foundation underlying education in kindergarten through 12th grade.

The dynamic, computer-modeling approach provides a foundation that is transferable from field to field. There are several dozen K-12 schools now doing excellent work, and several hundred doing something. Pioneering schools are scattered over the United States, extend into the Scandinavian countries and Germany, and other places from which we have little information.

System dynamics uses computer simulation models to reveal how known structures and policies often produce unexpected and troublesome behavior. The computer models are constructed from descriptive information that usually is already known. Such information relates to who is striving to do what, the information that each person has available, time delays in taking action, and what individuals will do under a variety of pressures. The same approach carries over to nonhuman systems in nature and physical change.

In K-12 education, system dynamics modeling has been applied to mathematics, physics, social studies, history, economics, biology, and literature.

## 3. LEARNER-CENTERED LEARNING

In the more successful schools, system dynamics is combined with a classroom reorganization we call “learner-centered learning.” Such a project-oriented approach goes by various names in other proposals for K-12 education, but is especially powerful when coupled with system dynamics. Learner-centered learning focuses on solving substantial problems. Teachers are no longer lecturers, no longer the source of all wisdom, not even necessarily authority figures. Teachers becomes advisors and coaches to students who are doing projects that may lie beyond the teacher’s experience. Indeed, moving to learner-centered learning can be traumatic for some teachers who feel they must be in command of all that the students are doing and learning.

A junior-high classroom can become much like a university research laboratory. Students address projects with real-world significance for which they have not been given the necessary background and techniques. They start by facing the challenge of learning what they need to know in order to accomplish the project. Such an approach departs from the highly unrealistic format of most education that is found all the way up through college.

Education in most schools could hardly be more unrealistic. Students, when they are given a problem, can usually assume they have been taught everything needed to solve the problem. How many of you in your own affairs find that challenges come pre-equipped with everything for a solution?

In the full use of learner-centered learning, if a student asks a specific question, the teacher may not know the answer, but, even if the teacher does know the answer, rather than answering, the better approach is to discuss how the student might find the answer.

## 4. THE NATURE OF SYSTEMS

In its full development, system dynamics is a profession 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.

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

### *4.1 Feedback Loops*

Here we touch on the nature of feedback loops. People seldom realize the pervasive existence of feedback loops in driving 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 framed in the press, business, and government.

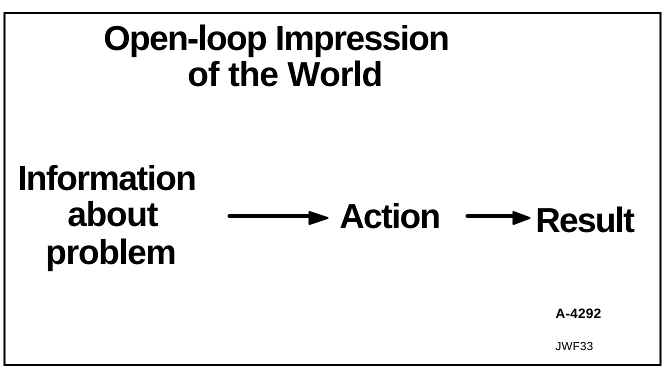


Figure 1.

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.

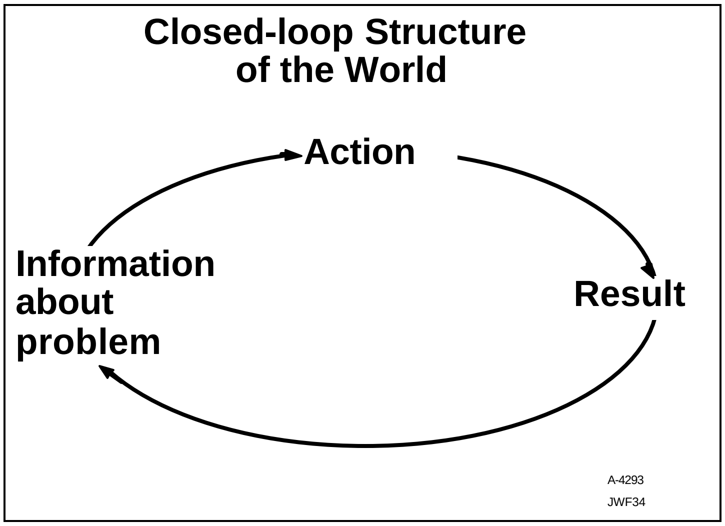


Figure 2.

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.

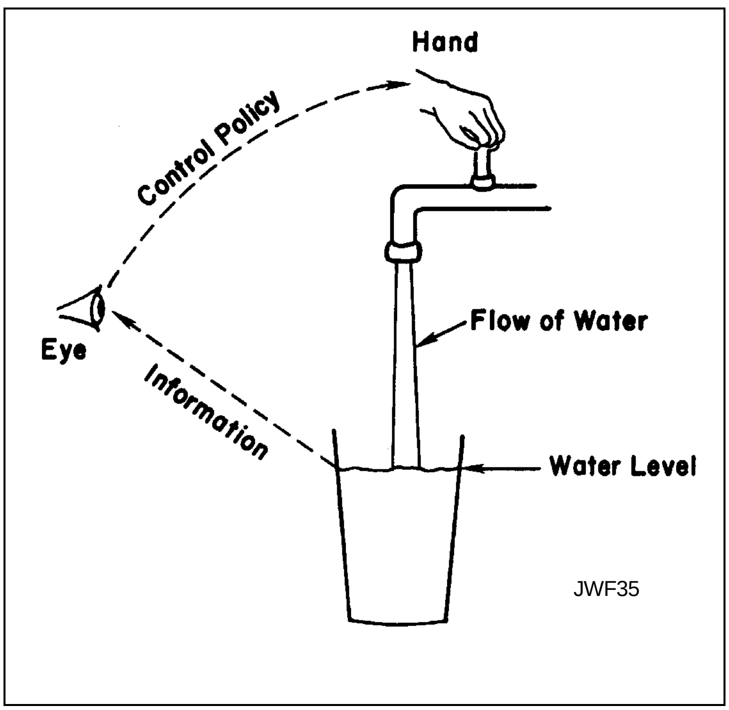


Figure 3.

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 and water flow. Such closed loops control all action everywhere.

*4.2 Simplest Feedback Loop*

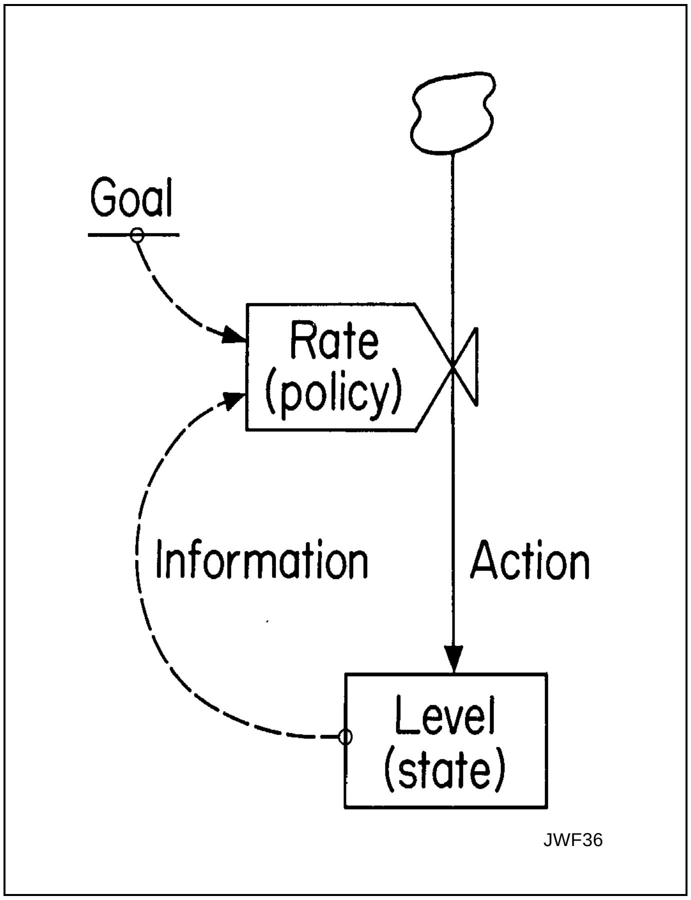


Figure 4.

Figure 4 shows the simplest possible feedback system. In spite of its simplicity, many universal truths are evident:[4]

a. In the figure are two symbols--a level, and a rate. The level is an accumulation, or integration, or stock, to choose terminology from different fields. The rate is a flow that changes the amount in the level. The rate is defined by a "policy" statement that tells how the rate is controlled by the value of the level in comparison to a goal. All systems, everywhere, consist of these two kinds of concepts --levels and rates--and none other. Such a statement, that there 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 levels representing accumulations that have evolved over time. The profit and loss statement represents the flows that cause the levels to change. There is no third page, only the page representing levels and the page representing rates. That structure of an accounting statement represents a fundamental truth about all systems. Water in a bathtub is a level, the flow of water is the rate that changes the level. A person's reputation is a level that is changed by the flow of good and bad actions by that person. The degree of frustration in a group is a level that gradually changes in response to surrounding pressures.

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[4] Forrester, Jay W. (1968). *Principles of Systems.* (2nd ed.). Waltham, MA: Pegasus Communications. 391 pp.

b. As in Figure 4, levels are changed only by rates of flow, never directly by other levels.

c. Rates of flow are controlled only by levels, never directly by other rates of flow.

d. At the point where a rate of flow is being determined, the condition of the system, as indicated by the values of the levels, is compared with a goal to determine control of the flow.

## 5. QUOTATIONS FROM TEACHERS

When I discuss K-12 education, you might be justified in feeling that, because I have not taught pre-college students, I lack credibility. So, in preparing this talk, I sent out email messages to some 20 teachers asking each for a quotable paragraph that captures how system dynamics is being used in their schools. I will read some of the responses to illustrate my message.

The basic concepts about systems, illustrated in Figure 4, can be introduced as early as kindergarten, as described by Tim Lucas, elementary school principal, Ridgewood, NJ:

> "We are introducing kindergartners to the concepts of stocks and flows and the idea that behaviors can be graphed over time. Beginning in first grade students are mapping larger sets of information and working with causal loops to explain cycles in nature and everyday events. Students continue working across the curriculum, strengthening their understandings of behaviors over time, causal loops, and simulations mediated through a systems approach. By fifth grade, students are manipulating simple computer models that integrate into their curriculum.
>
> "Every one of the 40 Macintosh computers in the building has STELLA, SemNet, and Inspiration on the hard drive. We introduce the software across the curriculum starting with Inspiration in grade 2."

STELLA is the system dynamics software most commonly used in schools, although Powersim and Vensim are also being adopted.[5]

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[5] STELLA from High Performance Systems, Hanover, NH; Powersim from the PowerSim Corporation, Reston, VA; and Vensim from Ventana Systems, Belmont, MA.

In the above quote from Lucas, kindergarten students go through their environments identifying levels and rates (that is, stocks and flows). They are beginning to see the fundamental structure of all systems in their surrounding world.

## 6. FROM SIMPLE TO COMPLEX SYSTEMS

The basic feedback loops in Figures 3 and 4 appear too simple to represent real-world situations. They are indeed simple, but they have a more serious shortcoming--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 complicated, as in Figure 5, intuition fails. A person can not look at Figure 5 and anticipate the behavior of the pictured system.

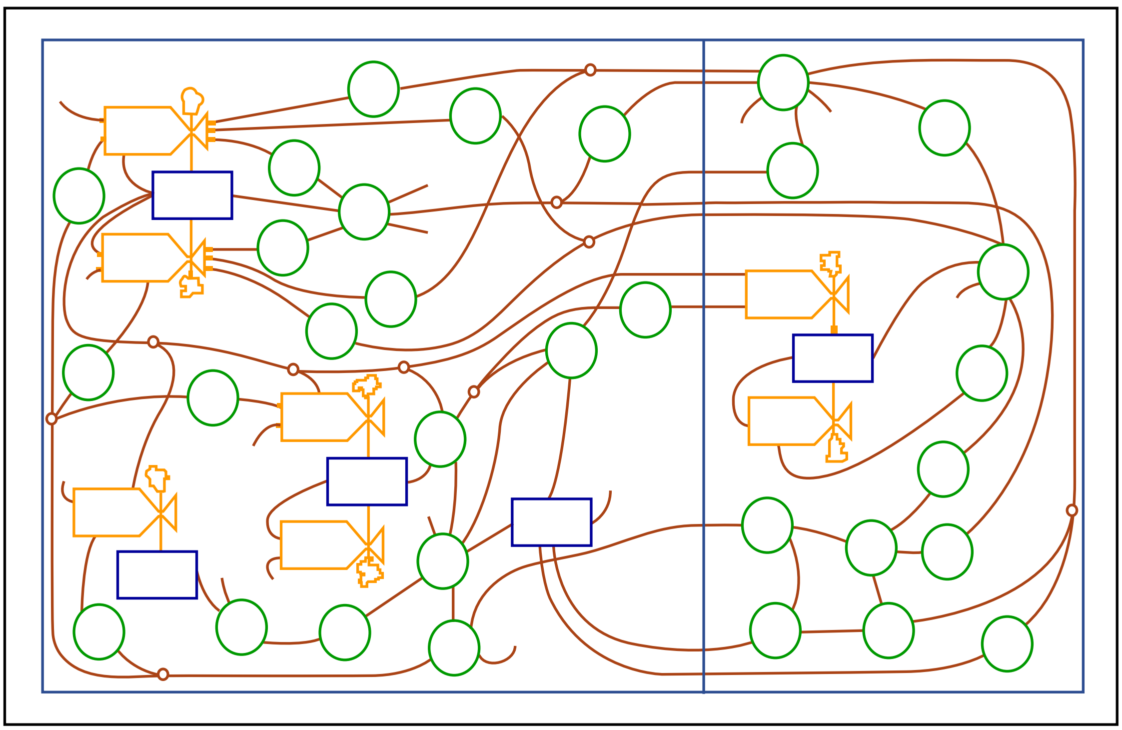

Figure 5.

Figure by MIT OpenCourseWare.

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

*Dynamics* book, each level is controlled by more than a single flow. Each flow can be influenced by several of the system levels. The circles in the diagram do not contradict the earlier statement that there are only two kinds of variables: the circles are subdivisions of the equations (policies) for the rates of flow; such subdivisions define separately identifiable concepts within the control of rates.

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.”

Complex systems behave in ways entirely different from our expectations derived from experience with simple systems. Because intuition is based on simple systems, people are misled when making decisions about complex systems. Six examples show the dangers in judging real-life systems based on a lifetime of conditioning from simple systems:

### *6.1 Cause and Effect not Closely Related*

From simple systems we learn that cause and effect are closely related in time and space. When we touch a hot stove, we are burned here and now. Experiences that are understandable almost always drive home the lesson that the cause of a symptom is to be found nearby and immediately before the observed consequence. But in complex systems the cause of a symptom is usually far back in time and arises from an entirely different part of the system. To make matters even more misleading, complex systems usually present what appear to be causes that are close in time and space to the immediate problem, but those apparent causes are only coincident symptoms. Learning ever since childhood teaches lessons that cause people to misjudge and mismanage complex systems.

*6.2 Long-Term vs. Short-Term tradeoffs*

In a simple system, a goal can be accomplished and a task finished. When the water glass is full we turn off the water, the objective has been met, and there are probably no direct unpleasant consequences. However, in complex systems there is nearly always a tradeoff. If the short-term goal is maximized, the result is a longer-term undesirable consequence. A child takes a toy from a playmate, the goal of having another toy is achieved, but a fight is likely to ensue. Borrowing on credit cards enhances the short-term standard of living with the longer consequence that the standard of living must be lowered to pay interest and refund the loan. Excessive welfare programs in many countries relieved immediate social pressures but led to mounting governmental debt and severe political consequences as expenditures had to be curtailed. Gratification of immediate desires may lead some to stealing with the later consequence of jail.

*6.3 Ineffective Actions*

In simple systems, it is clear what must be done to achieve a goal. One turns the steering wheel in the right direction to keep a car on the road. But in complex systems, the obvious decisions are often ineffective. An exceedingly large fraction of policies in complex systems have very little effect. Nevertheless those low-leverage policies receive most of the attention in business and government. Debate centers around decisions that will be defeated by consequences emerging from other feedback loops in the system. Taxes may be raised to balance the budget, but the extra governmental income can become an excuse for more expenditure and the budget remains in deficit. Experience from simple systems misguides people to take actions that the system itself can defeat.

*6.4 Wrong Directions for Effective Actions*

In simple systems, the direction of action to achieve a goal is obvious. Diligent work and longer hours will increase income. In complex systems, even when a rare high-leverage policy has been chosen, the desirable direction to change that policy is often unclear, or worse, may usually be misjudged and the policy moved in the wrong direction. In the *Urban Dynamics* model, low-cost housing was found to be a high-leverage policy for affecting the vitality of a city and well being of its residents. Governments had been constructing low-cost housing, but that is the wrong direction. Old and decaying housing, which is the principal stock of low-cost housing, should be removed, not augmented. Low-income housing uses land space that could instead be used for job-creating industrial structures, while the housing draws in people who need jobs. The additional housing reduces jobs while increasing the number of people who need jobs. Additional housing is not a way to alleviate poverty but instead is an active force for increasing poverty. The validity of the model has been verified by urban trends. It is only through comprehensive modeling of complex systems that we can hope to overcome the policy errors that arise from a lifetime of learning the wrong lessons from simple systems.

### *6.5 Blaming Others*

In simple systems, the cause of a failure is clear. One trips over a rock because the foot was not raised high enough; it is obvious that the fault was our own. In complex systems, causes are more obscure; it is not evident that we have caused our own crises, so, there is a strong tendency to blame others. However, the practice of blaming others diverts attention from the real cause of trouble, which is usually our own actions. By looking to others as the culprits, we take attention off the more embarrassing, but more productive, need to change our own actions. A management will blame the competition, or bankers, or its employees for low profits or falling market share, even though other companies in the same business, that deal with the same customers and bankers, are successful. The difference must lie in the policies of the failing company. The United States has a problem of illegal drugs, so drug supplying countries are blamed, rather than asking why our country is the largest market for drugs. There would be no suppliers if there were no users. In simple systems, the source of a problem is evident and lies in our own actions. In complex systems, causes are hidden and blame can be attributed to scapegoats through which correction is not possible.

### *6.6 Collapse of Goals*

In simple systems, goals are reinforced and maintained. The goal of staying in the proper highway lane is sustained by the threat of an accident. In less obvious systems, goals can gradually erode. One's goal of maintaining a sound financial condition can yield to pressure to borrow for a vacation or to purchase a fancier automobile. The goal can gradually decline from a safe financial condition, to wanting to fall no farther into debt, to striving to meet debt payments, to hoping to avoid foreclosure on one's house. In some countries there was a time when unemployment rates of 4% were considered high, gradually the goal eroded until 8% or more became the norm.

Unless a public emerges from our schools with an understanding of the ways in which real-life systems in families, schools, business, and politics must be handled in ways very different from the lessons learned from simple systems, we will continue to have stress-creating failures.

## 7. 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.

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 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.

## 8. MODELS OF PLOTS IN LITERATURE

Almost every activity in K-12 education can be enhanced by system dynamics modeling. Some applications have surprised even those of us who already had high optimism.

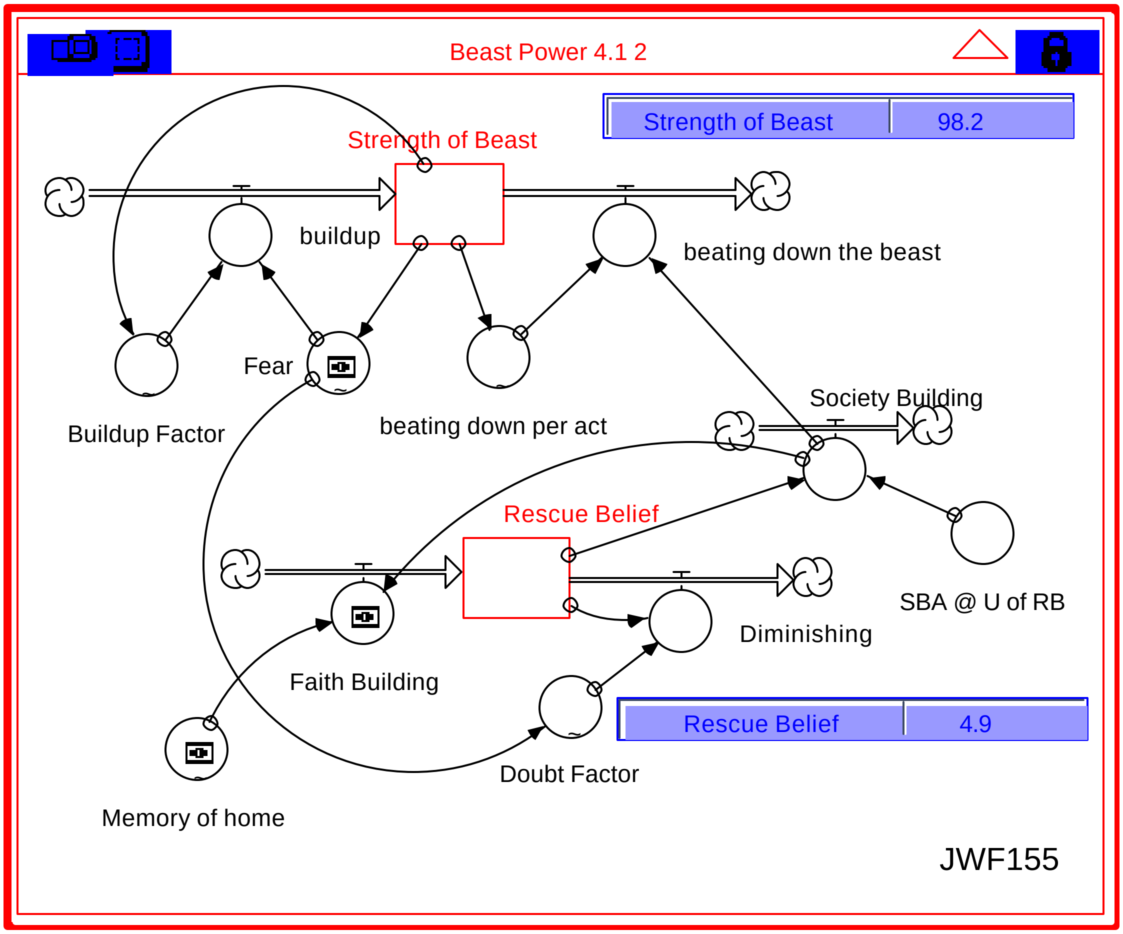


Figure 6.

To illustrate going from a written description to a system dynamics model, English teachers have created models to show social and psychological pressures that cause plots in literature to unfold. Thus far, most such models may be overly simple, maybe even naive, nevertheless, they point a direction and provide a vehicle for intensified discussion of a book.

One such model by Timothy Joy, a Catholic high school English teacher in Milwaukie, Oregon, arose from Golding's *Lord of the Flies*. Figure 6 shows the model structure and Figure 7 a simulation output.

Image unavailable.

Figure 7.

About this model, Tim Joy writes:

> “I honed two models for Golding’s novel; one based on the boys’ declining civility, another describing how the boys’ loss of hope drives the increasing power of the beast.
>
> “I was left with how to introduce system dynamics and the STELLA software to 135 sophomores within the guise of an English class.
>
> “Graphs in hand, the students were arguing positions before I could take attendance, peering over books and tables, pointing out misjudgments and omissions.
>
> “This simple model was readily understood by most students. An amount of civility is transformed, through isolation and turmoil,

into savagery. It was not until after running the model that some sophomores saw the model's weakness.

"Students were not ready to accept their first attempt. Indeed, quite a few wanted to redo it. Some asked for more time to run another graph on a different boy. Others were just plain dissatisfied and came after school, on Friday no less, or the following Monday to finish the work. This was a new experience for me."

Timothy Joy on his experiences in teaching:

"I taught writing and literature for 13 years and always suspected I was party to some intellectual crime. Why is it that so many students thought the world of language began and ended at the door of the classroom? Then I discovered system dynamics.

"System dynamics has a logic-based grammar, a universal language that students can readily learn and manipulate to create meanings. What have I found? Creating "meaning" results in bolder QUESTIONS, whole new views which do not house traditional understandings.

"In some ways, it's been terrifying. I have to give over some portion of the direction and instruction of the material to their own instincts and inquiry. It's slower at the start, but the curve steepens as we discuss and build models. For instance, I have changed the phrasing of questions in literature--we speak of influences (change of rate) to character motivations (levels or stocks), we focus on whether one defining moment is greater than another (in essence, it's a mathematical discussion on a literary event). Let's face it, reading a Charles Dickens' novel is to plunge headlong into a very complex system; STELLA provides a means through it.

"I'll never be the same teacher, never go back to teaching only one thing. When I think of living, I just can't recall a time when ONLY ONE THING happened; lots of things happen, all the time, each in differing degrees. What happens in a classroom ought to prepare people for those realities.

Referring to his church-sponsored high school Tim Joy continues:

> "I still teach writing and literature but it's changing radically. We use STELLA (software) at all levels and in many disciplines: Physics, English, Government, Economics. This year we'll add models in Health and Biology. We're still hoping to convert the Religious Studies Department."

## 9. COMPUTER MODELS AND MENTAL MODELS

**Models**

All actions based on models

Mental models
- Basis of human activity.
- Major strength:
  - Tremendous store of information
- Major weakness:
  - Unreliable in handling complexity and dynamic change.

JWF12

Figure 8.

System dynamics builds two-way communication between mental models and simulation models. Mental models are the basis for every-day 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.

From the report on a teachers' conference at the System Dynamics Group, Trinity College, Vermont:

> "Models provide a common language with which to engage learners with diverse learning styles and interests. Simulations are especially engaging, and draw out many who might not otherwise participate in more traditional discussions and activities.
>
> "Models are extraordinarily powerful for helping to convert abstractions into concrete realities. A learner's ability to 'see' a system—what goes into a stock, where feedbacks exist—and then to run a model and ascertain how the system operates under varied conditions, renders abstractions into real meaningful, concrete terms. This discovery is true for students at all levels.

> "Models provide a vehicle through which students see issues as involving trade-offs rather than having one or two sides (as in the debate format). Positions move from being simplistically labeled 'good' and 'bad' to being seen as much more multi-faceted.
>
> "Models which deal with real issues in student's lives—such as financial and interpersonal—render learning especially meaningful.
>
> "Participants agreed that many of the greatest benefits of a systems approach are in disciplines like literature, the arts, and history. A great work like 'Animal Farm' expands from a piece of writing into a powerful vehicle for learning more about general human behavior.
>
> "Kids' enthusiasm for learning carries over into other classes and leads other teachers to express interest in learning about systems."

The above report mentions discovery being true "for students at all levels." And one can add for students of all academic rankings. Evidence is accumulating that there is no correlation between how students have previously been ranked as fast or slow learners and how they do in the system dynamics setting. Some top students remain at the top. But some top students have ranked high only because they learn and repeat facts but without deep understanding of the meaning of the facts; such students may do poorly in the systems framework. On the other hand, some students who have been graded at the bottom of their classes may be there not for stupidity but because they see the academic work as irrelevant and not engaging; they often blossom when given the chance to bring their real world into a focused systems context.

## 10. 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 bath tub, 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 category and put them 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 who had been working with me. They looked at the rising unemployment 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 remain 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." By this process a new medical syndrome had been identified.

## 11. SOURCES OF INFORMATION

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

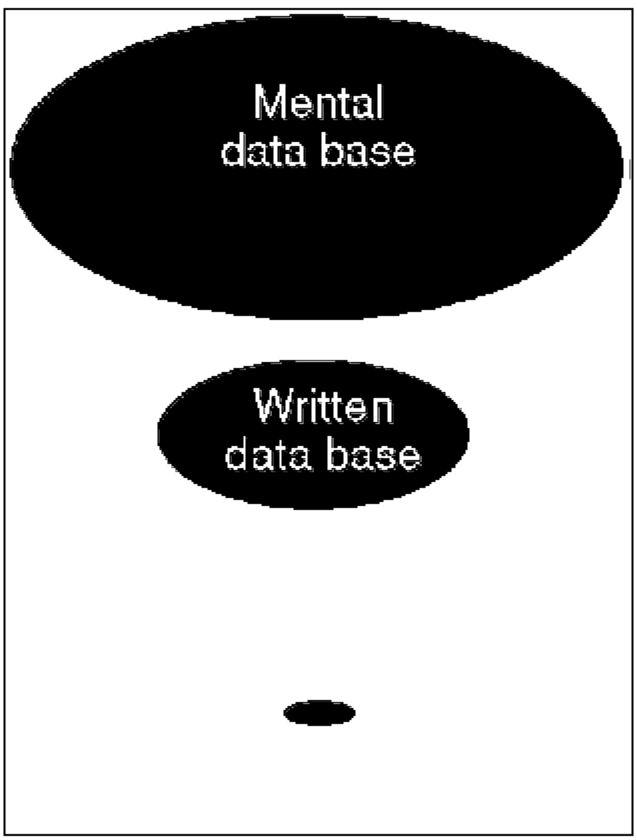


Figure 9.

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 school system. Imagine that at 10 o'clock some morning every teacher and administrator suddenly leaves and is replaced by a person who can read but has no experience with a school 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 that 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.

Pamela Hopkins, 11th grade English literature teacher, in the Desert View High School, Tucson, AZ:[6]

> "The *Hamlet* model was used with my students… Teaching Shakespearean drama has traditionally been difficult… a high crime area… drug-related activities are ever-present… many of our students are members of dysfunctional families… The lower socioeconomic level of the students further complicates the issue… students are distracted by financial difficulties… tired from working part time… Shakespeare fails to draw their attention.
>
> "When we used a STELLA model which analyzed the motivation of Shakespeare's Hamlet to avenge the death of his father in HAMLET… The students were engrossed throughout the process… The amazing thing was that the discussion was completely student dominated. They were talking directly to each other about the plot events and about the human responses being stimulated. They talked to each other about how they would have reacted and how the normal person would react. … My function became that of listening to their viewpoints and entering their decisions into the computer. It was wonderful! It was as though the use of precise numbers to talk about psychological motives and human responses had given them power, had given them a system to communicate with. It had given them something they could handle, something that turned thin air into solid ground. They were directed and in control of learning, instead of my having to force them to keep their attention on the task."

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6 Hopkins, Pamela Lee. (1992). Simulating *Hamlet* in the Classroom. *System Dynamics Review*, Vol. 8 (1, Winter), pp. 91-98.

Hopkins also said the students would tell her in quantitative terms how to change the personality of a character to alter the plot and to see who got killed instead. Students found that fascinating.

## 12. MODELS DETERMINE ALL HUMAN ACTIVITIES

Models are central to all human activities.

Mental models and computerized models should not be considered polar extremes, but rather as overlapping and mutually reinforcing ways to understand reality.

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Figure 10.

Again from Tim Lucas, in Ridgewood, NJ

> "teachers, especially at the elementary level, have found it very easy to integrate systems thinking across their curricula. It is not another subject to be added, but instead it integrates and supports our work with… composition… use of technology… science and mathematics… and … interdisciplinary projects in all areas.
>
> "At this point we have students, teachers, parents, and the larger community working toward a better understanding of the use of systems thinking in school programs, parenting issues, and as a tool for understanding the changes we are facing.… This has been a grass-roots effort with support that continues to grow as we learn more."

One can include in a formal model anything that can be described explicitly in words. To say, "We want life to be better," is not explicit, it has no operational content. However, to say, " We want more income," or, "We need more free time," is coming closer to a concrete statement. Modeling forces a person to go from empty statements to ones with operational content.

From Jan Mons, who is the systems mentor to assist other teachers in incorporating systems concepts into their classrooms in Glynn County, Georgia:

> "My most fruitful experiences occur when I discuss classroom discipline systems. We have both students and teachers build a discipline system together so that all parties will know what the system is capable of producing. When we do this many students have an

"Aha!" experience and state that they now understand how a teacher's frustration can accumulate over time. Teachers have their own insights as well--they begin to understand how they have often built discipline systems that were "preprogrammed" to result in unpleasant situations."

Albert Powers, science high-school teacher, Concord, MA:

Computer Simulation

Make mental models explicit

Discover inconsistencies

Determine future implications

Improve mental models

JWF15

Figure 11.

"My favorite vignette is one that occurred while three girls were working in a chemistry lab predicting shifts in reaction rates, concentration, and mass action values as a chemical system is repeatedly stressed. I overheard one student ask her partner what would happen if they plotted all of these variables together on a single graph. Her partner said, 'Let's do it!'.... and they did. Upon observing the graphs evolving together, one said, 'What a mess!' Her partner then exclaimed, 'But look! Everything's happening at once!' This last remark piqued my curiosity. I asked her what she meant by it. Her reply: 'First we studied rate changes. Then we looked at concentration changes. Then we did the mass action behavior. I thought that first one thing happened… then the next: and then the next. But it all happens at once! Everything depends on everything else!'

"Here we had a linear thinker who made a quantum leap towards more systemic thinking. It's interesting to note that her overall class performance also took a quantum leap from that moment forward (C all the way to an A).

Those comments from teachers remind me of a TV producer who was filming opinions, insights, and discussions among parents, teachers, and students who were involved is a school using system dynamics. The TV producer turned to one eighth-grade boy and asked, "What has all this meant to you." The immediate answer, "I am much better able to deal with my mother."

## 13. Generic or Transferable Structures

Many structures of levels and rates are found repeatedly. They are "generic structures" 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 the student with power to move between subjects with the learning on one subject being applied to other subjects.

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.

**Generic Structures**

**Transferable between:**
**Past and present**
**From one setting to another**

**A small number cover a wide range of situations**

**When understood in one setting, they are understood in all settings**

**Basis for effective education**

JWF7

Figure 12.

*13.1 Generic Structure of a Clock and Economic Business Cycles*

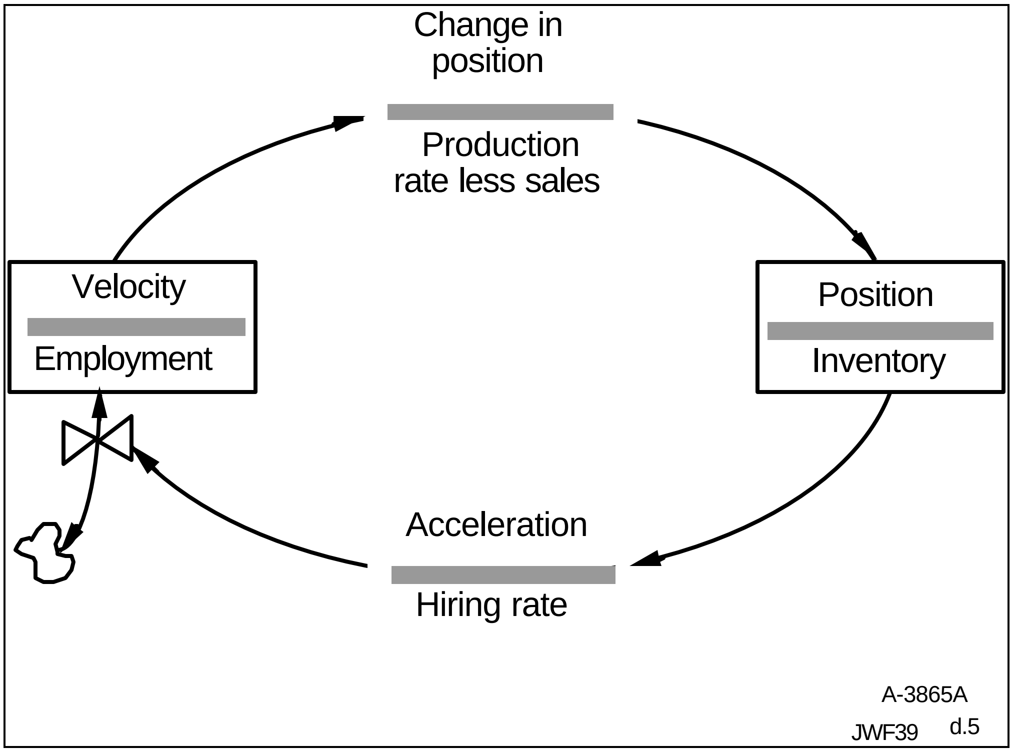


Figure 13.

Figure 13 shows two sets of nomenclature. The upper definitions relate to the swinging pendulum of a clock. The lower definitions 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 13 results in only a sustained oscillation. Additional structure in 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 are made by the rates (policy statements) 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 70 years apart, and still others show how companies can grow so rapidly that they cause their own failure.

## 14. OTHER COUNTRIES

System dynamics is entering K-12 education in other countries. We are now translating a book from German that uses system dynamics for teaching high school physics.

Pal Davidsen, professor at the University of Bergen in Norway, has led of a Scandinavian consortium for introducing system dynamics into high schools:

> "In Norwegian and Nordic schools, we have chosen to utilize the conceptual framework offered by system dynamics for our educational purposes… Academic boundaries no longer constitute the boundaries of our imagination or our investigation. Historic and economic considerations are merged with physics and chemistry in our study of ecological issues."

Michael Radzicki, professor at Worcester Polytechnic Institute, in Massachusetts writes of a trip to Japan:

> "My most recent experience with K-12 education and system dynamics was this summer in Japan. We did a two-day seminar for Japanese high school students (15 year olds), their teachers, and observers from Japanese industry. We were asked to focus on teaching physics and biology using system dynamics. Students worked in groups of three. In two days we were able to cover the following:

velocity, acceleration, and position
the basics of stocks and flows
growth of yeast cells, adding feedback and exponential growth
radioactive decay
mass on a spring with damping

"Students were VERY engaged in the activities. They refused to take breaks; they preferred to keep working on the problems or to try building their own models."

## 15. 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. No where in nature does nature take a derivative. Nature only integrates, that is, accumulates. 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 levels (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.

Helen Zhu, 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 schoolers can understand the same things by using system dynamics modeling. It's really amazing."

## 16. REPORTS FROM CLASSROOMS

157

CHANGE IN NATURE OF CLASSROOMS

LEARNER-CENTERED LEARNING

PROBLEMS COME BEFORE SOLUTIONS

RELEASING STUDENT INITIATIVE

TEACHER BECOMES COACH AND ADVISOR

INTERDISCIPLINARY

STUDENT ENTHUSIASM AND CAPACITY

JWF157

Figure 14.

The project-oriented research organization of the learner-centered-learning classroom shares with students the role of teaching. One of the best ways to learn is to explain a subject to another person. Al Powers reports student reactions in his chemistry classes:

> "Working in groups was incredibly effective. Often it is easier to understand concepts when they are explained by a peer."
>
> "I feel that everyone is heard and, therefore, the people are more willing to contribute to the discussions and admit to being uncertain about a concept."
>
> "The graphs and simulations brought the concepts to life."
>
> "I found myself explaining concepts to people in other classes. This has never happened to me before. I think they would have benefited just as much as I did if they had had the opportunity."
>
> "Being a visual learner, it really helped to see the reactions in easy schematics. The graphs produced were even more helpful. My father and I spent long hours discussing the graphs and talking about what was the initial change and what was the reaction to that change."
>
> " This was a great lab! Using the computer made it easier for me to understand what was going on in the reaction."

From Robert Gotwals, education specialist, North Carolina Supercomputing Center:

“Last year I was asked to help with a large 6th-grade class project on Africa. The class had discovered that diseases play a major role in the culture and customs of the peoples. I was asked to build epidemiological template models of several diseases for the students to use. The students wanted no part of that, so they, with help of myself and a graduate student, researched the literature and built models from scratch. One student even located one of the authors on the Internet and corresponded with him through email. The project was so successful that the 6th grade kids presented an ‘epidemiology conference’ to a group of epidemiologists from Duke University. Without a doubt, the kids clearly understood the mechanisms involved in the various diseases, and used the models to make some interesting observations about Africa’s future.”

Frank Draper, 8th grade biology teacher, Tucson, AZ

“Our classrooms have undergone an amazing transformation. Not only are we covering more material than just the required curriculum, but we are covering it faster (we will be through with the year’s curriculum this week and will have to add more material to our curriculum for the remaining 5 weeks) and the students are learning more useful material than ever before. Facts are now anchored to meaning through the dynamic relationships they have with each other. In our classroom students shift from being passive receptacles to being active learners. Our jobs have shifted from dispensers of information to producers of environments that allow students to learn as much as possible.

“We now see students come early to class (even early to school), stay after the bell rings, work through lunch and work at home voluntarily (with no assignment given). There are essentially no motivation or discipline problems in our classrooms.”

From Ellen Mandinach, Educational Testing Service, Princeton, NJ and Director of the Systems Thinking and Curriculum Innovation Project involving some eight schools in different parts of the country:

“The teachers in the STACI Project perceive the systems thinking approach to be both an effective instructional strategy and a professional development opportunity. Many of the project teachers have altered completely the way they structure their classroom activities. Both students and teachers benefit from the systems approach. For teachers, it is the stimulus for changing the fundamental role of the teacher to facilitator, coach, and mentor rather than the purveyor of information and facts."

Jeff Potash, history teacher, Trinity College, Vermont, after a summer training workshop for teachers:

> "Last summer we assembled middle and high school teachers who use system dynamics and STELLA in their classrooms. Again, we learned a phenomenal amount from them. Perhaps the most important message relates to the degree that middle school and high school teachers are at fundamental odds with one another. Innovative middle school people, like those in Glynn County Georgia, seek to expose their students to 'real world' models which demand involvement and choice, with the conscious desire to 'empower' kids to view themselves as active players in decision-making. High school teachers, sadly, seek to inculcate discipline-based knowledge. We need to rethink this system.
>
> "When we engage in modeling, we move beyond the traditional boundaries of disciplinary 'turf' and seek to develop common ground upon which to better communicate the workings of the real world, a world that too often refuses to respect the simple disciplinary borders of the academic specialist."

I attended one conference of some 200 K-12 teachers involved in system dynamics. Widely divergent views were evident. Some teachers felt they would need to devote a full introductory term to teaching system dynamics and modeling before the ideas could be introduced into normal subjects. Others had already demonstrated that students could pick up what they needed on their own in a few days. Several teachers commented to me, "I never realized that the students could do so much."

In fact, the students, if given a chance, may be the leaders in an educational revolution. Lola Piper, computer science teacher, Blair Magnet Program Silver Spring, MD, describes their experience:

> "We have a group of experienced student modelers and a collection of student-developed models. Our next step is to get these models actually integrated into the curriculum of other courses.
>
> "Our biggest problem to date is getting our staff to integrate system dynamics into their curriculum.… Our biggest success to date is having our students reach out to the teachers by asking the teachers to be their mentors in the development of models that could then be used within the teachers' classes. Given the personal touch of a student-teacher mentorship we hope to generate the teachers' interest and through one-on-one meeting we hope to demystify modeling for the teachers."

At the Silver Springs school, students and teachers have modeled:

Ecological Succession from Sand Dune to Maritime Forest
A Comet's Flight Through the Earth's Atmosphere
Oxygen Levels in a River Resulting from various Dumped Wastes
Squirrel Population Dynamics

## 17. FUNDING FOR EDUCATIONAL INNOVATION

Some people have expressed concern for how the transition to education based on system dynamics can be funded. Teachers must have released time to learn. Teachers should attend the conferences that allow them to hear what is being done in other schools. Some schools will need to add computers and software. A school system will make the most rapid progress if a more experienced system dynamics modeler can be hired as a mentor to assist teachers. Schools have solved these funding demands in various ways.

Government can sometimes be a source of funds, but that is often blocked by unresponsive bureaucracies. However, the National Science Foundation provided more than a half million dollars for teacher training in system dynamics in Oregon. In Massachusetts, one of 25 charter schools was approved to be based on system dynamics.

Many schools are overlooking the strong appeal that a persuasive new approach to education can have with private individuals. Several million dollars have been given by individuals to foster system dynamics in a number of schools.

Private funding is often easier to arrange, and is more flexible than money from government or large foundations.

A great national concern drives the search for better K-12 education. But many of the interventions have been futile, or even have contributed to making matters worse. Very often, the misplaced efforts for improvement have put additional stress on doing more of what is already causing the decline in education--more authoritarian control, more accountability, more testing, more pressure. Such misplaced emphasis removes the fun and challenge from learning.

One New York business man who thought he might devote personal time and money to system dynamics in education became involved after visiting a junior high classroom on a Friday afternoon. He was convinced when the final bell of the day and final bell of the week rang and not a single student got up to leave.

## 18. MORE ON SYSTEM DYNAMICS

Study materials are available from the Creative Learning Exchange and the web site at MIT. The Internet discussion group has several hundred participants. The web site at MIT receives one or two thousand accesses per week for downloading material. About two-thirds of those accesses 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.

**System Dynamics books:**

Pegasus Communications, Inc.
One Moody Street
Waltham, MA 02453-5339

tel: 781-398-9700
fax: 781-894-7026

Alfeld, Louis Edward, and Alan K. Graham. 1976. *Introduction to Urban Dynamics*. Waltham, MA. Pegasus Communications. 333 pp.

Forrester, Jay W. 1961. *Industrial Dynamics*. Waltham, MA. Pegasus Communications. 464 pp.

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Forrester, Jay W. 1969. *Urban Dynamics*. Waltham, MA: Pegasus Communications. 285 pp.

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Forrester, Nathan B. 1973. *The Life Cycle of Economic Development*. Waltham, MA: Pegasus Communications. 194 pp.

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Lyneis, James M. 1980. *Corporate Planning and Policy Design: A System Dynamics Approach*. Waltham, MA: Pegasus Communications. 520 pp.

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Meadows, Dennis L. 1970. *Dynamics of Commodity Production Cycles*. Waltham, MA: Pegasus Communications. 104 pp.

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Roberts, Nancy, David Andersen, Ralph Deal, Michael Garet, William Shaffer. 1983. *Introduction to Computer Simulation: A System Dynamics Modeling Approach.* Waltham, MA: Pegasus Communications, 562 pages.

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isee systems encourages the incorporation of Systems Thinking in schools to promote better understanding of the world and how it works. From simple Causal Loop Diagrams to complex System Dynamics models, we want the Stella software to be a tool that schools can afford to use. We offer licensing options with educational discounts for qualified teachers and students. These discounted licenses are available for Stella Architect, Stella Professional, and Stella Designer. Note that each product has a different price that will become visible once you are qualified.Â  K-12 Schools, K-12 Teachers and students. The following are isee systems license options for K-12. K12 License Options. License options for Stella Architect, Stella Professional, and Stella Designer. Faculty License. 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 studentsâ€™ 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.