System dynamics—a personal view of the first fifty years†

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Jay W. Forrester is Professor of Management, emeritus, at the Sloan School, Massachusetts Institute of Technology. After growing up on a Nebraska cattle ranch and studying electrical engineering at the University of Nebraska, he came to MIT in 1939 and participated in the early development of hydraulic and electrical feedback control systems for military applications. Starting in 1946 he pioneered in the early days of digital computers and their applications as combat information control centers. Transferring to the MIT School of Industrial Management in 1956, he started the development of system dynamics. He is now engaged in system dynamics as a foundation for a new kind of kindergarten through 12th grade education and research on dynamics of economic systems. He has received nine honorary doctorates and awards from several professional societies.

Abstract

I present a personal recollection of the history of system dynamics and observations about its present state. The article treats the history in two parts: first, my personal background and how all the threads came together to initiate the field of system dynamics; and second, the historical development of the cornerstone projects that shaped the field. These early works include industrial dynamics, urban dynamics, world dynamics, and the national economic model. The paper continues with an assessment of the present condition of the field. A companion paper (System Dynamics—The Next Fifty Years, also in this issue of *System Dynamics Review*), highlights challenges for the future. Copyright © 2007 Jay W. Forrester.

Syst. Dyn. Rev. **23**, 345–358, (2007)

Origins

I grew up on a cattle ranch in Nebraska in the middle of the United States. A ranch is a crossroads of economic forces. Supply and demand, changing prices and costs, and economic pressures of agriculture become a very personal, powerful, and dominating part of life. Furthermore, in an agricultural setting, life must be very practical. It is not theoretical; nor is it conceptual without purpose. It is full-time immersion in the real world. In high school, I built a wind-driven electric plant that provided our first electricity. That was a very practical activity. When I finished high school, I had received a scholarship to go to the Agricultural College when one of those important turning points intervened. Three weeks before enrolling at the Agricultural College, I decided it was not for me. Herding cattle in Nebraska winter blizzards never had appealed to me. So instead, I enrolled in the Engineering College at the University of Nebraska. Electrical engineering, as it turns out, was about the only academic field with a solid, central core of theoretical dynamics. And so, the road to the present began.

After the University, my first year as a research assistant at the Massachusetts Institute of Technology brought another turning point. I was commandeered by Gordon S. Brown, who was the pioneer in "feedback control systems" at MIT. During World War II my work with Gordon Brown developed servomechanisms for the control of military radar antennas and gun mounts.

† Parts originally published in various articles and speeches by Jay W. Forrester, in particular Forrester (2002).

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Received April 2007; Accepted June 2007

System Dynamics Review Vol. 23, No. 2/3, (Summer/Fall 2007): 345–358
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/sdr.382

Again, it was research toward an extremely practical end that ran from mathematical theory to the military operating field, and I do mean the operating field. At one stage, we had built an experimental control for a radar to go on an aircraft carrier to direct fighter planes against enemy torpedo bombers. The captain of the carrier *Lexington* came to MIT and saw this experimental unit, which was planned for redesign to go into production a year or so later. He said, "I want that, I mean that very one, we can't wait for the production ones." He got it. And about 9 months later we heard that the experimental control units had stopped working. I volunteered to go to Pearl Harbor to see why the controls were not functioning. Having discovered the problem, but not having time to fix it, the executive officer of the ship came to me and said they were about to leave port and asked if I would like to come with them to finish my job. I said, "Yes," having no idea what that meant. We were offshore during the invasion of Tarawa and then took a turn through the middle of the Sunrise and Sunset chains of the Marshall Islands. The islands were occupied on both sides by Japanese fighter-plane bases and they didn't like having a U.S. Navy Task Force wrecking their airports. So they kept trying to sink our ships. After dark they dropped flares along one side of the task force and came in with torpedo planes from the other side. Finally at 11 p.m. they succeeded in hitting the *Lexington*, cutting off one of the four propellers and setting the rudder in a hard turn. Again, it gave a very practical view of how research and theory are related to field applications.

At the end of World War II came another turning point. I had about decided either to get a job or start a company in feedback control systems. Gordon Brown again intervened; he was my mentor for many years at MIT. He had a list of projects that he thought might interest me. I picked from the list the building of an aircraft flight simulator. It was to be rather like an aircraft pilot trainer, except that it was to be so precise that instead of acting like a known airplane, it could take wind tunnel data of a model of a proposed plane and predict the behavior of the airplane before it was built. This project was promoted by Admiral Louis deFlorez of the U.S. Navy. The aircraft simulator was planned as an analog computer. It took us only about a year to decide that an analog machine of that complexity would do no more than solve its own internal idiosyncrasies. An analog computer could not deal with the problem at hand. Through a long sequence of changes we came to design the Whirlwind digital computer for experimental development of military combat information systems. The Whirlwind computer eventually evolved into computers for the SAGE (Semi-Automatic Ground Environment) air defense system that was installed across North America.

The SAGE air defense system was another one of those practical jobs where theory and new ideas were only as good as the working results. The SAGE system had about 35 control centers, each 160 feet square, four stories high, and containing about 80,000 vacuum tubes. These computer centers were installed in the late 1950s, and the last was decommissioned in 1983. They

Published online in Wiley InterScience
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were in service about 25 years. The statistics show they were operational 99.8 percent of the time. That would be less than 20 hours a year that a center was out of operation. Such reliability was a remarkable result, considering that these centers contained so many vacuum tubes. Even today, such reliability is a hard record to match.

It was time for yet another turning point. In 1955, James Killian, who was then president of MIT, brought a group of visiting dignitaries to see us at the Lincoln Laboratory. While walking down the hall with Killian, he told me of the new management school that MIT was starting, and suggested that I might be interested. The Sloan School of Management had been founded in 1952 with a grant of 10 million dollars from Alfred Sloan, the man who built the General Motors Corporation. The money was given on the expectation that a management school in a technical environment like MIT would probably develop differently from one in a liberal arts environment like Harvard, Columbia, or Chicago. Maybe better, but in any case different, and it was worth 10 million dollars to run the experiment.

In the 4 years before I joined the School in 1956, standard management courses had been started, but nothing had been done about what a management school within an engineering environment might mean. By that time, I had 17 years in the science and engineering side of MIT and it seemed like an interesting challenge to look at what an engineering background could mean to management. Many assumed that an application of technology to management meant either to push forward the field of operations research, or to explore the use of computers for the handling of management information systems. I had a year free of other duties except to decide why I was at the Sloan School.

Chance intervened when I found myself at times in conversation with people from General Electric. They were puzzled by why their household appliance plants in Kentucky were sometimes working three and four shifts and then, a few years later, half the people would be laid off. It was easy enough to say that business cycles caused fluctuating demand, but that explanation was not convincing as the entire reason. After talking with them about how they made hiring and inventory decisions, I started to do some simulation. This was simulation using pencil and paper on one notebook page. It started at the top with columns for inventories, backlogs, employees, orders, and production rate. Given these initial conditions and the policies they were following, one could decide how many people would be hired in the following week. This gave a new condition of employment, inventories, and production. Each line could be computed from the preceding line. It became evident that there was potential for an oscillatory or unstable system whose behavior was entirely internally determined. Even with constant incoming orders, one would get employment instability as a consequence of commonly used decision-making policies within the supply chain. That first inventory-control system with pencil and paper simulation was the beginning of the system dynamics field. The early supply-line simulation is perpetuated today as the "beer game",

Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/sdr

which is available from the System Dynamics Society (www.systemdynamics.org/Beer.htm; also see Sterman, 1989, 2006).

Out of that first dynamic analysis came the early beginning of what is now the DYNAMO compiler for system dynamics modeling. An expert computer programmer, Richard Bennett, worked for me when I was writing the 1958 article, "Industrial dynamics—a major breakthrough for decision makers", for the *Harvard Business Review*. That article is Chapter 2 of *Industrial Dynamics* (Forrester, 1961). For that article I needed computer simulations and asked Bennett just to code up the equations so we could run them on our computer. However, Richard Bennett was a very independent type. He said he would not code the program for that set of equations but would make a compiler that would automatically create the computer code. He called the compiler "SIMPLE", meaning "Simulation of Industrial Management Problems with Lots of Equations". Bennett's insistence on creating a compiler is another of the important turning points; it accelerated later modeling that rapidly expanded system dynamics. Jack Pugh later extended the early system dynamics compilers into the very influential DYNAMO series. Others who joined the early efforts leading to system dynamics included J. L. Enos, Willard Fey, and Edward Roberts.

Historical development of the early cornerstone projects

At about the time system dynamics was starting, I was asked to be on the board of a high-tech computer company. I did not understand the nature of high-technology growth companies as well as I would like and created a system dynamics model to guide my own position on the board. From the modeling came a number of insights about why high-technology companies often grow to a certain level and then stagnate or fail. This modeling of corporate growth moved system dynamics out of physical variables like inventory into much more subtle considerations. Over 90 percent of the variables in that model lay in the top-management influence structure, leadership qualities, character of the founders, how goals of the organization are created, and how the past traditions of an organization determine its decision making and its future. The model also dealt with the interactions between capacity, price, quality, and delivery delay. This corporate growth model was one of the very early system dynamics modeling projects (Packer, 1962; Forrester, 1962; see also Forrester, 1975).

Another turning point in my career and in the development of system dynamics came in 1968, which moved system dynamics from corporate modeling to broader social systems. John F. Collins, who had been mayor of Boston for 8 years, decided not to run for re-election. MIT gave him a 1-year appointment as a Visiting Professor of Urban Affairs, bringing him into the academic orbit to meet students, interact with faculty, and advise the

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administration on political issues. In discussions with Collins about his 8 years coping with Boston urban problems I developed the same feeling that I had come to recognize in talking to corporate executives. His story sounded persuasive, but it left an uneasy sense that something was wrong or incomplete. So, I suggested to Collins that we might combine our efforts, taking his experience in cities and my background in modeling, and look for interesting insights about cities. I told him we would need advisers who knew a great deal about cities from personal experience, not just from study and reading. The process would be to gather a group that would meet half a day a week, probably for months, to seek insights into the structure and processes of cities that could explain stagnation and unemployment. Collins' position in Boston at that time was such that he could call up almost anybody in politics or business, ask for their Wednesday afternoons for a year, and get them. He delivered the people and it was out of those discussions that the urban dynamics model and book developed.

Urban Dynamics (Forrester, 1969) was the first of my modeling work that produced strong, emotional opposition. The book suggested that all of the major urban policies that the United States was following lay somewhere between neutral and highly detrimental, from the viewpoint either of the city as an institution, or from the viewpoint of the low-income, unemployed residents. And it showed that building low-cost housing was a most damaging policy. Such housing used up space where jobs could be created, while drawing in people who needed jobs. Constructing low-cost housing was a powerful process for creating poverty, not alleviating it. At that time, building low-cost housing was believed to be essential to reviving the inner cities. The conclusions of our work were not easily accepted. I recall one full professor of social science in our fine institution at MIT coming to me and saying, "I don't care whether you're right or wrong, the results are unacceptable." So much for academic objectivity! Others, probably believing the same thing, put it more cautiously saying, "It doesn't make any difference whether you're right or wrong, urban officials and the residents of inner cities will never accept those ideas." It turned out that those were the two groups we could count on for support if they became sufficiently involved to understand. That is a very big "if"—if they came close enough to understand. Three to five hours were required to come to an understanding of what urban dynamics was about. Urban officials and members of the black community in inner cities would become more and more negative and more and more emotional during those three to five hours. If they were not a captive audience, they would walk out before they understood the way in which low-cost housing was a double-edged sword for making urban conditions worse.

My first experience with reactions to *Urban Dynamics* came soon after the book was published. The Sloan School had been running 4-week urban executive's programs twice a year for department-head level people from larger cities to teach various aspects of management. A group was convening shortly

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(www.interscience.wiley.com) DOI: 10.1002/sdr

after *Urban Dynamics* came out. I was asked to take a Monday afternoon and a Wednesday morning to present the *Urban Dynamics* story. I have never had a lecture on any subject, any place, any time go as badly as that Monday afternoon. In the group was a man from the black community in New York who was a member of the city government. He was from Harlem, intelligent, articulate, not buying a thing I was saying, and carrying the entire group with him. At one point he said, "This is just another way to trample on the rights of the poor people and it's immoral." At another point he said, "You're not dealing with the black versus white problem, and if you're not dealing with the black versus white problem, you're not dealing with the urban problem." And when I said decay and poverty in Harlem in New York or Roxbury in Boston was made worse by too much low-cost housing, not too little, he looked at me and said, "I come from Harlem and there's certainly not too much housing in Harlem." That is a sample of the afternoon. With that antagonistic prelude, I started the Wednesday morning session.

An hour into Wednesday morning, the New Yorker's comments began to change character. He was no longer tearing down what was being said. His questions began to elicit information. Two hours into the morning, he said, "We can't leave the subject here at the end of this morning. We must have another session." He went to the administration and scheduled another session. Later he made an appointment to come to my office to ask that I talk to a group he would organize in New York—his colleagues on his home turf. He sat in my office as relaxed as could be and said, "You know, it's not a race problem in New York at all, it's an economic problem." He gave me a report out of his briefcase documenting the amount of empty housing in every borough of New York, including Harlem, and the rate at which it was being abandoned. My point had been that too much housing meant that there was too much for the economy of the area to support. He had all the proof right in his briefcase. He simply had not realized what his knowledge meant until it was all put together in a new way.

Urban Dynamics was the key that led to both the System Dynamics National Model, and the *World Dynamics* and *Limits to Growth* projects. The urban work established my contact with the Club of Rome through a meeting on urban difficulties in Italy at Lake Como. There I first met Aurelio Peccei, founder of the Club of Rome. Later I was invited to a meeting of the Club in June, 1970, in Bern, Switzerland. Working with the Club of Rome became another turning point in my career with system dynamics. The world problems discussed at the Bern meeting became the basis for the model in *World Dynamics*, which was used in a 2-week meeting with the executive committee of the Club of Rome at MIT in July 1970. What followed is more fully described in the introduction to *World Dynamics*.

The public responses to system dynamics have always surprised me. Usually I have been wrong in anticipating the effect that system dynamics books will have. In 1971 *World Dynamics* seemed to have everything necessary to

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guarantee no public notice. First, it had 40 pages of equations in the middle of the book, which should be sufficient to squelch public interest. Second, the interesting messages were in the form of computer output graphs that most people do not easily understand. Third, the book was only the second one from that publisher and I doubted that it would have the commercial status even to get reviewed. Fourth, the interesting behavior in the computer simulations lay 50 years in the future and presumably beyond the time horizon of interest to most people. I thought I was writing for maybe 200 people who would like to try an interesting model on their computers. But, as you know, I was wrong.

World Dynamics came out the first week of June, 1971. The last week of June it was reviewed on the front page of the *London Observer.* In August the book had the full front page of the second section of the *Christian Science Monitor*, in September a page and a half in *Fortune*, and in October a column in the *Wall Street Journal*. It was running through editorial columns of mid-America newspapers, it was the subject of prime-time documentary television in Europe, it was debated in the environmental press, the zero population growth press, and the anti-establishment underground student press. And, if you don't like your literature on either the establishment right or the establishment left, then right in the middle of the political spectrum, it had a full-length article in *Playboy*.

Nine months after *World Dynamics*, the successor, *Limits to Growth*, was published (Meadows *et al.*, 1972). The message was essentially the same, although much more work on assumptions had been done and the book was more popularly written. Public attention seemed to go up another factor of ten after the appearance of *Limits to Growth* (for a recent update see Meadows *et al.*, 2004; Dana Meadows, in this issue, provides her perspective on the origins and controversy around the *Limits* study).

The *Urban Dynamics* book also led to our work on the System Dynamics National Model. After I gave a talk at a joint NATO/U.S. conference on cities in Indianapolis, Indiana, William Dietel, past president of the Rockefeller Brothers Fund, came up from the audience to discuss their future programs. From that meeting came initial funding for our work in applying system dynamics to behavior of economic systems, which would be later known as the "National Model". The purpose of the research on the National Model was to understand better the behavior of national economies and seek alternative policies for improving behavior.

In academic economic teaching, there are two fields: microeconomics and macroeconomics. Microeconomics deals with firms and households. Macroeconomics deals with the overall behavior of an economy. There are few linkages between the two. Microeconomics does not explain the behavior studied in macroeconomics, even though one must believe that the behavior of the whole system is a consequence of the interactions of its many parts. The System Dynamics National Model represented the microstructure of an economy

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with corporations, an aggregate household, price setting, money flows, debt, government, and monetary controls. When the microstructure interacts, we find that macro-behavior is generated (Forrester, 1977, 1979, 1980, 2003).

The National Model exhibited the several different dynamic modes observed in an industrial economy—growth, ordinary short-term business cycles, stagflation, and the economic long wave. Business cycles are the familiar variations of economic activity with peaks 3–10 years apart. The economic long wave, also called the Kondratieff cycle, is much larger in amplitude, with peaks 45–70 years apart (Kondratieff, 1984; Sterman, 1985). These two economic disturbances arise from quite different processes in an economy. Business cycles are driven primarily from over production of consumer products followed by cutbacks and labor layoffs while inventories are brought back into balance. Rise and fall of inventories and production of goods occur over a short span of a few years. Business cycles are small economic variations compared to rise and fall of the economic long wave.

The economic long wave is caused by over-building of capital plant during several decades of economic expansion, followed by a depression lasting 10 or 15 years while capital-producing sectors collapse and the excess of factories, hotels, and office buildings are worn out and depreciated on the account books. The economic long wave creates, and is accentuated by, large changes in prices, debts, money supply, and real interest rates.

Although, from our system dynamics perspective, the Great Depression of the 1930s was a characteristic long-wave depression, most American economists have tried to explain it as nothing more than an unfortunately severe business-cycle recession. The idea of an economic long wave has been dismissed because there was no theory to explain such behavior. But, the National Model generates such long-wave fluctuation, and a system dynamics model is a theory of the behavior that the model generates. Therefore, we feel that a theory for long-wave behavior now exists.

When we started this work we had not heard of the long wave but first encountered it in behavior of the System Dynamics National Model. A huge oscillation with about 50 years between peaks resulted from interactions among ordinary, everyday, policies existing mostly in the private sector. However, governments do participate in making the long wave more severe; for example, easy credit for several decades encourages over-building, leading to collapse of real estate values. I am now writing a book, perhaps to be entitled "A General Theory of Economic Behavior", that will summarize the insights from several years of economic modeling.

This section has given a brief historical summary of the early cornerstone projects in the field, covering roughly two decades between 1960 and 1980. In 1983, the International System Dynamics Society was formed (see Andersen *et al.* in this issue). Since the early 1980s, applications have expanded to a very wide spectrum, including supply chains, project management, educational problems, energy systems, sustainable development, politics, psychology,

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internal medicine, health care and many other areas. Significant methodological advances have also been made in the last two decades. Perhaps the most significant one in the 1980s was the emergence of user-friendly simulation software with advanced graphical user interfaces (such as STELLA, Powersim, and Vensim). Interactive simulation games have been effectively used by John Sterman and others to test various decision rules by direct experimentation. Such "management flight simulators" have also been a door opener to introduce system dynamics to business managers. Some of the generic simulation models/games have been developed into "simulation-based case studies", an enhanced version of the traditional case studies often used in management education (see, for example, Graham *et al.*, 1994, and Sterman 2000, Ch. 1). System Dynamics Society membership in 2006 exceeded 1100, a ninefold increase from its 1983 level of about 120, and is growing with a current doubling time of about 9 years. The number of practitioners is much higher than the Society membership.

The present

Today, interest in system dynamics is growing faster than the supply of skilled professionals in the field. At present, the bottleneck is in education for system dynamics expertise. New fields, like system dynamics, that cut across boundaries of existing fields, but do not lie within any one of those fields, lack a home and a supporting constituency in universities. It is like the early days of physical science and engineering, which for a long time were excluded from the old, established, liberal arts universities.

At the beginning of this paper I mentioned having been introduced to feedback systems by Gordon Brown in the MIT Servomechanisms Laboratory in the early 1940s. He eventually became Dean of Engineering before retiring in 1974. In the meantime, I went on to develop the field of system dynamics based on that early background in feedback systems. Later Gordon completed the circle by picking up system dynamics and introducing it into a junior high school in Tucson, Arizona, where he spent the winters. He started by loaning STELLA software for a weekend to Frank Draper who, at that time, taught 8th grade biology. Draper first expected to use computer simulation in one or two classes during a term. Then he found that system dynamics and simulation were becoming a part of every class. That led to concern that he would not have time to cover all of the required biology subject material if so much time was being spent on the system dynamics component. However, two-thirds of the way through the term, he had completed all of the usual biology content. The more rapid pace resulted from integration of the subject matter and the greater student involvement made possible by the systems viewpoint and the "learner-directed learning" process. As Draper wrote, "There is a free lunch" (Draper, 1983; Draper and Swanson, 1990).

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The greatest successes in the experimental and pioneering use of system dynamics in K-12 education are coming from a combination of system dynamics and learner-directed learning. Learner-directed learning defines a classroom environment in which students, even as early as age 10 years, work in teams of two or three on significant projects. The teacher is no longer a lecturer, or the source of all wisdom, or an authoritarian figure. Instead the teacher becomes a coach and advisor. The atmosphere is more like that of a university research laboratory. Problems are encountered before necessary information for a solution has been acquired. The project focus creates motivation to find the background information that is required. Some dramatic experimental successes have already been achieved in using system dynamics as a foundation that gives underlying unity to the teaching of mathematics, physics, social studies, biology, economics, environmental change, and even literature (Forrester, 1993). System dynamics should not be taught as a separate subject but as a common thread running through all subjects. In the United States there are dozens of K-12 schools making significant progress with system dynamics and probably several hundred doing something. At biannual conferences on system dynamics in pre-college education, as many as 200 people attend. A book of exercises developed in Germany uses system dynamics and the STELLA software for teaching physics in high schools. Pre-college schools from kindergarten through age 17 are now pioneering the use of system dynamics as a foundation under most subjects. Teachers and students are building simulation models of environmental, family, city, and political systems. English teachers are experimenting with simulation of plots in literature. Students are fascinated with the insights gained by modeling psychological dynamics as in Shakespeare's *Hamlet* (Hopkins, 1992).

Early system dynamics analyses were in the "consultant" mode, in which a system dynamicist would study a corporation, go away and build a model, and come back with recommendations. Usually these suggestions would be accepted as a logical argument, but would not alter behavior. Under pressure of daily operations, decisions would revert to prior practice. Recent trends in system dynamics aim at changing those mental models that people use to represent the real world. To this end, there have been significant developments in the areas of "group model building" and "modeling for learning" (Vennix, 1996; Morecroft and Sterman, 1994). To achieve this, a person must become sufficiently involved in the modeling process to internalize lessons about dynamic feedback behavior. For this type of learning, exposure to dynamic thinking should start at an early age before contrary patterns of thought have become inflexibly established. Apparently exposure to cause-and-effect feedback thinking and computer modeling can successfully begin in schools for students as young as 6 years old.

In management education, we expect a major breakthrough in scope and effectiveness when system dynamics is fully adopted to move beyond the case study method of teaching managers. Case studies were pioneered by the Harvard

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(www.interscience.wiley.com) DOI: 10.1002/sdr

Business School beginning around 1910. A case study starts in the same way as a system dynamics analysis, by gathering and organizing information from the actual managerial setting. But the case study leaves that information in a descriptive form that cannot reliably be used for inferences about policy because of the dynamic complexity that is involved. System dynamics modeling can organize the descriptive information, retain the richness of the real processes, build on the experiential knowledge of managers, and reveal the variety of dynamic behaviors that follow from different choices of policies (Forrester, 1991). System dynamics model-based case studies point to the frontier of new developments in management education.

Whether we think of pre-college or management education, the recent emphasis in system dynamics is on "generic structures". A rather small number of relatively simple and compact structures are found repeatedly in different businesses, professions, institutions, and problems. One of Draper's junior high school students, working with bacteria in a culture and in computer simulation, looked up and observed, "This is the world population problem, isn't it?" Such transfer of insights from one setting to another will help to break down the barriers between disciplines. It means that learning in one field becomes applicable to other fields. There is now a promise of reversing the trend of the last century that has been moving away from the "Renaissance man" toward fragmented specialization.

"Systems thinking" has become a very popular term (Senge, 1990). The term is coming to mean thinking about systems, observing that systems are important, and talking about systems. But, in general, it is not the kind of quantitative and dynamic simulation analysis that leads to understanding behavior. In systems thinking, I would include management simulation games. Management games demonstrate the existence of complexity. Games show people that they can not get the best results from using merely experience and rules of thumb. But management games are usually not presented in a way that carries the participant into the inner working of the game and to an understanding of why the dynamic behavior occurs. Management games focus on decision-making, whereas system dynamics should emphasize the design of policies for guiding decisions.

Systems thinking can be a door opener to system dynamics. The danger comes from encouraging people to believe that systems thinking is the whole story. Systems thinking is a sensitizer; it calls attention to the existence of systems. Some people feel they have learned a lot from the systems thinking phase. But they have gone perhaps only 5 percent of the way into understanding systems. The other 95 percent lies in the system dynamics structuring of models and simulations based on those models. It is only from the actual simulations that inconsistencies within our mental models are revealed. Systems thinking can be a first step toward a dynamic understanding of complex problems, but it is far from sufficient.

System dynamics deals with concepts that have been almost entirely absent in education. We have found that identically the same system dynamics teaching

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materials and methods can be used anywhere from elementary school to chief executive officers. The insights are new and relevant at all levels. But the systems viewpoint is a paradigm, a frame of reference, a way of looking at one's surroundings, that takes a long time to internalize, probably several years. Developing such a systems perspective takes less time with a young, inquisitive, and open mind than with a mind that has already been conditioned to see the world in terms of unidirectional cause to effect. I think we will have only limited success in achieving widespread understanding of business and social systems until the ideas take root very early in a person's education and are nourished and reinforced continuously thereafter.

The future

As we make our way in the 21st century, the greatest challenges facing system dynamics are related to education. The first challenge involves education of system dynamics experts. The second challenge is to use system dynamics as an organizing philosophy for a new kind of management education in the 21st century. The third challenge is to make system dynamics a common foundation under most of what is taught in pre-college education, from kindergarten through high school.

It is time to start working toward an integrated educational process based on an understanding of systems that is more effective, more appropriate to a world of increasing complexity, and more compatible with unity in life. During the past century, the frontier of human advancement has been the exploration of science and technology. Science and technology are no longer frontiers; they have receded into the fabric of everyday activity. I believe that we are now embarking on the next great frontier, which will be to explore a much deeper understanding of social and economic behavior. I elaborate on these themes and the challenges facing the field of system dynamics in the companion to this paper, "System dynamics—the next fifty years".

Acknowledgements

I am indebted to Yaman Barlas for his substantial effort in selecting and organizing material for this article from several of my papers.

References

Andersen D, Morecroft JDW, Spencer R. 2007. How the System Dynamics Society came to be: a collective memoir. *System Dynamics Review* **23**(2–3): 219–227.

Draper F. 1993. A proposed sequence for developing systems thinking in grades 4–12 curriculum. *System Dynamics Review* **9**(2): 207–214.

Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/sdr

Draper F, Swanson M. 1990. Leaner-directed systems education: a successful example. *System Dynamics Review* **6**(2): 209–213.

Forrester JW. 1961. *Industrial Dynamics*. Pegasus Communications: Waltham, MA.

——. 1962. A model for the study of corporate growth. System Dynamics Group Memo D-434. Available from the System Dynamics Society: http://systemdynamics.org/MITCollectionDVDinfo.htm [10 September 2007].

——. 1969. *Urban Dynamics*. Pegasus Communications: Waltham, MA.

——. 1971. *World Dynamics*. (2nd edn 1973). Pegasus Communications: Waltham, MA.

——. 1975. *Collected Papers of Jay W. Forrester*. Pegasus Communications: Waltham, MA.

——. 1977. Growth cycles. *De Economist* **125**(4): 525–543.

——. 1979. An alternative approach to economic policy: macrobehavior from microstructure. In *Economic Issues of the Eighties*, Kamrany NM, Day RH (eds). Johns Hopkins University Press: Baltimore, MD.

——. 1980. Information sources for modeling the national economy. *Journal of the American Statistical Association* **75**(371): 555–574.

——. 1991. Beyond case studies: computer models in management education. In *Systemmanagement und Managementsysteme*, Milling P (ed.). Duncker & Humblot: Berlin; 33–42.

——. 1993. System dynamics as an organizing framework for pre-college education. *System Dynamics Review* **9**(2): 183–194.

——. 2002. On the history, the present and the future of system dynamics. In *EOLSS: The Encyclopedia of Life Support Systems—System Dynamics Volume*, Barlas Y (ed.). UNESCO-Eolss: Paris.

——. 2003. Economic theory for the new millennium. In *Proceedings of the 21st International Conference of the System Dynamics Society*, New York.

Graham AK, Morecroft JDW, Senge PM, Sterman JD. 1994. Model-supported case studies for management education. In *Modeling for Learning Organizations*, Morecroft JDW, Sterman JD (eds). Productivity Press: Portland, OR; 219–241.

Hopkins PL. 1992. Simulating Hamlet in the classroom. *System Dynamics Review* **8**(1): 91–100.

Kondratieff N. 1984. *The Long Wave Cycle*. Richardson & Snyder: New York.

Meadows DH. 2007. The history and conclusions of *The Limits to Growth*. *System Dynamics Review* **23**(2–3): 191–197.

Meadows DH, Meadows DL, Randers J, Behrens III WW. 1972. *The Limits to Growth*. Universe Books: New York.

Meadows DH, Meadows DL, Randers J. 2004. *Limits to Growth: The 30-Year Update*. Chelsea Green: White River Junction, VT.

Morecroft JDW, Sterman JD (eds). 1994. *Modeling for Learning Organizations*. Productivity Press: Portland, OR.

Packer DW. 1962. Introduction to the industrial dynamics study of corporate growth. System Dynamics Group Memo D-433. Available from the System Dynamics Society: http://systemdynamics.org/MITCollectionDVDinfo.htm [10 September 2007].

Senge P. 1990. *The Fifth Discipline: The Art and Science of the Learning Organization*. Doubleday: New York.

Sterman JD. 1985. A behavioral model of the economic long wave. *Journal of Economic Behavior and Organization* **6**(2): 17–53.

——. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill: New York.

Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/sdr

——. 2006. Operational and behavioral causes of supply chain instability. In *The Bullwhip Effect in Supply Chains*, Carranza O, Villegas F (eds). Palgrave Macmillan: New York; 17–56.

Sterman J. 1989. Modeling managerial behavior: misperceptions of feedback in a dynamic decision making experiment. *Management Science* **35**(3): 321–339.

Vennix J. 1996. *Group Model Building: Facilitating Team Learning Using System Dynamics*. Wiley: Chichester, U.K.

Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/sdr