From the Ranch to System Dynamics: An Autobiography

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A chapter for

Management Laureates:
A Collection of Autobiographical Essays, Vol. 1
edited by Arthur G. Bedeian
Published by JAI Press, 1992

Edited, January 27, 2000

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Since 1956 I have had the exciting and challenging opportunity to found and develop the new field of system dynamics. System dynamics deals with how the structure of a system and its information flows determine behavior—the control of growth, stability, decay, success, and failure. The field focuses on the way internal feedback-loop relationships cause a system to change through time. Understanding why a system behaves as it does permits redesign of structure and policies to improve behavior. The ideas and methods of system dynamics are applicable to natural, human, and technical systems. The field combines theory and computer simulation with a very practical application to real-world problems.

As I look back, I see that my career evolved through several critical changes in direction. When opportunities knocked, I was willing to give up the past and turn in new directions. Each change led to pioneering in new and more challenging arenas. With the succession of experiences came the growing realization that new ideas will naturally be met with skepticism. One must have the courage and persistence to sustain a long-term vision against oppositions that arise along the way. Everything that I have done converged to make the development of system dynamics possible.

THE BEGINNING

My childhood experiences came from a cattle ranch in the Nebraska Sandhills located in the middle of the United States. My father and mother were the original homesteaders in about 1910 on that late-developing part of the American frontier.[1]

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[1] M. M. Forrester (Marmaduke Montrose), known as "Duke," born January 3, 1883 in Emerson, Iowa, died April 19, 1975 in Portland, Oregon; and Ethel Pearl Wright Forrester, born March 16, 1886 in Hastings, Nebraska, died December 27, 1958 in Portland, Oregon. Children: Jay Wright Forrester, born July 14, 1918 at Climax, Nebraska (no longer in existence, half way between Dunning and Arnold), and Barbara Frances Forrester Sliger, born April 21, 1921, at Climax. See Susan S. Forrester, 1989, *Descendants of Oliver C. Forrester*, Concord, MA: 29 King Lane 01742.

Shopping was 18 miles away by horse and wagon. Although we lived in a concrete block house with running water, most of our first neighbors built sod houses from the top layer of the grass land. It was a community of pioneers settling under the Kincaid Homestead Act, which allowed a square mile of land per family. When early attempts to farm the thin top soil failed, and most settlers left, those who stayed turned to cattle ranching.

My parents were the only people in the community with a college education. Dad had graduated from Hastings College in Nebraska and had been a football player, and on the track team, glee club, and debating society, while also working as a newspaper reporter. Mother attended Hastings College three years and then worked in libraries in Springfield, Massachusetts and Jacksonville, Florida. In later years, the superintendent of the Anselmo, Nebraska, high school, which I attended, described his first visit to our home as the discovery of a cultural oasis in the intellectual wilderness.

When they first settled on the ranch, both my parents taught in one-room country schools. After she gave up her position as public school teacher, my mother taught me at home during my first two years of school. Later, I rode a horse a mile and a half to third and fourth grades at a one-room school taught by my father. Women who had been my father's students taught me in grades five through eight at the same school. It was there that my interest in electricity started with experiments on batteries, doorbells, and telegraphs. Inspiration came from the Nebraska "traveling library" that sent a box of books on loan to the school each year.

A ranch is a cross-roads 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, activities must be very practical. One works to get results. It is full-time immersion in the real world. Children have their regular chores as part of the family business. In such closely knit activities, my parents guided learning and character development. Although ranch obligations were demanding, I was fortunate in being allowed time to develop interests that were not immediately related to the daily needs.

While a senior in the Anselmo, Nebraska, high school, I built a 12-volt wind-driven electric plant that provided the first electricity on our ranch. It powered the radio, lights in the house, and motors for shop work. Building an electrical system from discarded automobile parts was a very practical undertaking and another step in learning how to succeed in uncharted territory.

On finishing 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 in agriculture, I decided it wasn't for me. Caring for sick cattle and herding them in Nebraska winter blizzards never had captured my enthusiasm. I had preferred the tractors, machinery, and shop work. My parents had never tried to limit my interests or direct my future vocation. So, I enrolled in the Engineering College at the University of Nebraska. Electrical engineering, as it turns out, was the only academic field with a solid, central core of theoretical dynamics. The road began toward my work in the behavior of systems.

Finishing at the University brought another turning point. I came to the Massachusetts Institute of Technology for two reasons. First, they offered me a $100 per month research assistantship, which was more money than any other university had offered. Second, my mother, from her library experience in Springfield, Massachusetts, knew about MIT. In the high plains of the United States at that time, “M.I.T.” more often implied salesmen for a financial institution, the Massachusetts Investors Trust, than an engineering school.

MY INTRODUCTION TO FEEDBACK SYSTEMS

In my first year at MIT came another of the decisive branches in my career. I was employed in 1940 as a research assistant by Gordon S. Brown when he founded the Servomechanisms Laboratory and began to pioneer "feedback control systems" at MIT for military equipment. During World War II with Brown, I developed servomechanisms for the control of radar antennas and gun mounts. Departing from my training in electrical engineering, the work focused on designing mechanical hydraulic variable-speed pumps, motors, and high-gain hydraulic amplifiers because at that time the military mistrusted vacuum tubes in anything except radios.[2]

Again, it was research toward an extremely practical goal that ran from mathematical theory of control and stability to the military operating field, and I do mean the operating field. At one stage, we built experimental hydraulic controls for a radar designed at the MIT Radiation Laboratory. After redesign, the radar was intended for aircraft carriers to direct fighter planes against enemy targets. The captain of the carrier U.S.S. Lexington visited MIT and saw this experimental unit, which was planned for production a year or so later. He said, "I want that; I mean that very one; we can't wait for the production equipment." He got it.

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[2] Brown and Forrester patent (1946).

In the following nine months the experimental laboratory radar had directed fighters in shooting down some 20 enemy planes before they came close enough to see the Lexington. But then, the experimental control units stopped working. In November 1943, I volunteered to go to Pearl Harbor to find the reason and repair the hydraulic controls.

Having discovered the problem, but not having time to fix it, I was approached by the executive officer of the Lexington who said they were about to leave Pearl Harbor. He asked me to come with them to finish my job. I agreed, having no idea where that might lead.

We were off shore during the invasion of Tarawa and then took a turn down between the Ratak and Ralik chains of the Marshall Islands. The islands on both sides held enemy air bases, and the Japanese didn't like having a U.S. Navy Task Force wrecking their airports. They kept trying to sink our ships. Finally, twelve hours later and after dark they dropped flares along one side of the task force and come in with torpedo planes from the other side. About ll:00 PM, they succeeded in hitting the Lexington, cutting through one of the four propeller shafts and setting the rudder in a hard turn. Again, the experience gave a very concentrated immersion in how research and theory are related to practical end uses.

PIONEERING IN DIGITAL COMPUTERS

At the end of World War II came yet another turning point for which I am indebted to Gordon Brown. I had about decided either to get a job or start a company in feedback control systems when Brown, who was my mentor for many years at MIT, again intervened. He offered a list of projects that he thought might be of interest. I picked the building of an aircraft flight simulator. It was to be rather like an elaborate aircraft pilot trainer. However, it was to be precise enough to take wind tunnel data from a model of a proposed plane and predict the behavior of the full-scale airplane before construction.

The aircraft analyzer project was promoted by Admiral Louis deFlorez of the U.S. Navy. deFlorez was a flamboyant individual with a pointed waxed mustache. He was apparently the only person who had somehow acquired standing permission to land a sea-plane on the sailing basin in front of MIT. He came to MIT on Alumni Day and the Metropolitan District Police cleared the basin of sail-boats so he could land his sea-plane. He attended part of the program and, when the speeches became boring, would rev up the seaplane engines and take-off with the noise drowning out the program he was leaving behind.

The Admiral taught me a number of helpful insights about dealing with government bureaucracies. Later, when we were building a digital computer, we needed another hundred thousand dollars to continue. The response from deFlorez was “Impossible! That is above my approval authority and too little to justify going to the Secretary of the Navy. You must ask for either fifty thousand or two hundred thousand.” We chose the latter figure.

At this time, Gordon Brown added a new dimension to my life by introducing me to Susan Swett. We were married July 27, 1946.[3] My parents, Gordon Brown, and Susan are the ones to whom I owe the most for whatever I may have accomplished over an interval of seventy plus years. Susan has given steadfast encouragement and sympathy, compensation for my frequent insensitivity to others, tolerance for my often putting work at the top of the priority list, and an uninterrupted supportive home environment.

The aircraft simulator started as an analog computer. It took a year to decide that an analog machine of that complexity would do no more than respond to its own internal idiosyncrasies. An analog computer could not deal with the problem at hand.

Still another critical break in my career came when Perry Crawford, an MIT graduate and then in the Special Devices Center of the Navy headed by Admiral deFlorez, suggested that we shift our attention to the digital computer field in which work was just beginning. Design of the aircraft analyzer was recast around the untested concept of a digital computer. But times were changing, the need for the aircraft analyzer became less pressing, and military tactics were outgrowing the capability of information handling by a human network operating through telephones.

Beginning in 1947, the MIT Digital Computer Laboratory, under my direction, designed the Whirlwind I digital computer.[4] Whirlwind was the first general-purpose digital computer at MIT. It filled two roles, as a scientific

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[3] Our children: Judith, 1948, graduated from Goucher College, has been a teacher, world traveller, and most recently is living on and managing our family ranch in Nebraska; Nathan Blair, 1950, received a bachelor’s degree from Oberlin and a Ph.D. in system dynamics from MIT and is a consultant in the field; Ned Cromwell, 1953, has a B.Sc. and M.Sc. from MIT in electrical engineering, was an engineer for several years at the Digital Equipment Corporation, and more recently an engineer on the Alvin deep-sea research submarine at the Woods Hole Oceanographic Institute.

[4] For the story of this pioneering program, see Kent C. Redmond and Thomas M. Smith (1980), *Project Whirlwind*, 280 pages, Digital Press, Educational Services Division, Digital Equipment Corporation, Bedford MA 01730.

computer and as an experimental laboratory for testing the use of digital computers in military combat information systems.

The reader today with a desktop computer can hardly appreciate the skepticism in the late 1940s to a suggestion that computers could ever be made to work reliably, or that they would be needed even if they worked. One computer pioneer of that time was quoted as saying that, if all the five digital computers then under experimental development should by any chance work, they would more than saturate any conceivable need for such machines. Only the experience of having succeeded in past pioneering programs and the belief that history would repeat sustained us against the opposition of the doubters.

Robert R. Everett worked with me from 1946 to 1956 as associate director of the Digital Computer Laboratory and as associate division head in the Lincoln Laboratory. I am greatly indebted to him for his technical skill and his gift for leadership of an engineering organization. We had started together in the early 1940s in the Servomechanism Laboratory and shared the same background. After I left the computer field in 1956, Everett continued to lead the organization we had established together. That activity separated from MIT to become the MITRE Corporation, from which Everett has recently retired as president.

When development of Whirlwind began, no satisfactory devices existed for high-speed internal information storage. A few early computer projects chose one-dimensional storage, consisting of a tube of mercury, in which shock waves, transmitted and received by crystals at the two ends, represented binary digits in transit. Other computer projects based design on two-dimensional storage in the form of cathode-ray tubes in which digits were stored as positive and negative charges on the inside faces of the tubes. But all these were slow or unreliable or both.

My invention of the coincident-current random-access magnetic computer memory in 1949 was a classic case of necessity being the mother of invention.[5] I was responsible for a computer development project and a mission in combat information systems that could not succeed with the existing technology for computer memory. The newly conceived and developed magnetic memory was fast, completely reliable, and became the standard computer memory for about 20 years until replaced by solid-state micro circuits.

Again, the slow pace of acceptance of new ideas was evident. It took us about seven years to convince industry that magnetic-core memory was the

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[5] See Forrester (1951), Digital Information Storage in Three Dimensions Using Magnetic Cores, *Journal of Applied Physics*; and Forrester (1956), Patent No. 2,736,880.

solution to a missing link in computer technology. Then we spent the following seven years in the patent courts convincing them that they had not all thought of it first.

From the Whirlwind computer program came technology for the first practical digital control of machine tools. For many years, numerical control in manufacturing operated under the patent emerging from that early work.[6]

In its final redefinition of mission, the Whirlwind computer became a laboratory for exploring how digital computers could serve as military combat information centers. At a time when no high-speed digital computer had yet operated reliably, such a proposal to use them to analyze and control military operations was met with disbelief and hostility by military officers who felt that only their training and field experience could serve as a basis for handling military situations. Such confidence in the earlier human-network handling of tactics persisted in the face of clear evidence that speed and complexity of military technology had far outstripped unaided human command and control.

By gaining the support of a few daring individuals in the military, it was possible to carry on development until the merits of these seemingly radical new proposals became evident. Professor George E. Valley of the MIT physics department, who was chairman of the Air Defense System Engineering Committee, played a key role in converging our proposals for digital computers in command and control with financial support from the U.S. Air Force, which was then seeking an improved air defense system.

Largely on the basis of this early work, the MIT Lincoln Laboratory for air defense research was formed. I headed Division 6 of Lincoln, which designed computers for the SAGE (Semi-Automatic Ground Environment) air defense system for North America. Valley headed the division handling the radar side of the system. Whirlwind grew to become the nucleus of the Experimental Cape Cod Air Defense System for demonstrating how a digital computer could analyze and coordinate radar information and issue directions to defensive weapons.

The SAGE air defense system was another of those practical undertakings 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 upward of 60,000 vacuum tubes. Many people had criticized the concept on the basis that such a large electronic assembly would fail too often to be

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[6] See Forrester, et al (1962), Patent No. 3,069,608, *Numerical Control Servo-System*. For a history, see J. Francis Reintjes (1991), *Numerical Control: Making a New Technology*, New York: Oxford University Press.

useful. Such a prediction was reasonable based on prior engineering experience. Vacuum tubes had a life of about 500 hours. Agreeing that such performance would make our proposals inoperative, we undertook to discover the reason that tubes had been failing, redesigned them to remove the cause, and increased the average life by a thousand fold in one design step. Even that was not enough. In addition, a "marginal checking" system was incorporated that could find any deteriorating electronic component before it reached the point of causing an error.

The SAGE computer centers were installed in the late 1950s; the last was decommissioned in 1983. They were in service about 25 years. Historical statistics show that individual centers were operational 99.8% of the time. That would be less than 20 hours a year that a center was out of operation. Even today, such reliability is a challenging record to match in military systems.

MOVING TO MANAGEMENT EDUCATION

Completion of the SAGE system design coincided with another crucial incident and the opening of another door of opportunity. James R. Killian, Jr., who was then president of MIT, brought a group of visiting dignitaries to the Lincoln Laboratory. While we were walking down the hall, Killian told me of the new management school that MIT was starting, and suggested that I consider joining. Discussions over the next several months with Associate Dean Eli Shapiro and Professor Edward L. Bowles led to my becoming a full professor in management. It was my first academic appointment; earlier work had all been on the MIT research staff.

People often ask why I made such an abrupt change as going from engineering to the Management School. There were several reasons. By 1956, I felt the pioneering days in digital computers were over. That might surprise readers looking back on the major advances during the last 35 years. But the multiple by which computers improved in speed, reliability, and storage capacity in the decade from 1946 to 1956 had been greater than the multiple in any decade since. Furthermore, moving to a management school was not a break from a purely technical background. I was already in management.

We had been running a vast operation in which we had control from basic research to military operational planning. We wrote the contracts between the participating corporations and the Air Force. We designed the computers with full control over what went into production. We defended the Air Force's budget before the Bureau of the Budget because the technology was so new that it was outside the experience of the military commands. We had been managing an enterprise that involved the Air Defense Command, the Air Material Command, the Air Research and Development Command, Western Electric, A.T.&T., and I.B.M. The move from Lincoln Laboratory was not so much a radical change as a shift to a different perspective from which to view management.

The MIT School of Management, later to be renamed the Sloan School, had been founded in 1952 with a grant of ten million dollars from Alfred P. Sloan, Jr., the man who built the modern General Motors Corporation. The money was given with the expectation that a management school in a technical environment such as MIT would develop differently from one in a liberal arts environment like Harvard, or Columbia, or Chicago. Such a school might be better, but in any case different, and Sloan believed it worth ten million dollars to run the experiment.

In the four years before I joined the School in 1956, standard management courses existed, but nothing had been done about the concept of a management school within an engineering environment. By that time, I had 15 years of participation in the science and engineering side of MIT and bringing that background to bear on management offered an interesting challenge.

Others, and probably I also, 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. My first year was free of other duties except to decide why I was at the Management School. On computers for management information, activity was growing rapidly among manufacturers of computers, and banks and insurance companies were actively using computers. It did not seem that a few of us in a management school would have major impact on the already existing momentum. Regarding operations research, it seemed interesting; it no doubt was useful; but it was not working with issues that made the difference between corporate successes and failures. Operations research did not have that compelling practical importance that had always characterized my work.

LAUNCHING SYSTEM DYNAMICS

Again chance intervened when I found myself in discussions with several people from General Electric. They were puzzled by why their household appliance plants in Kentucky sometimes worked at full capacity with overtime and then two or three 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 entirely convincing.

After talking with the manufacturing people about how they made hiring and inventory decisions, I started to do some simulation. The analysis based on the feedback viewpoint from my earlier experience used very simple simulations with pencil and paper on a notebook page. The computation started at the top with columns for inventory, employees, production rate, backlog, and orders. Given these initial conditions and the policies being followed in manufacturing, one could enter how many people would be hired in the following week. Because of time delays and trend projections, production did not adjust smoothly to demand.

A fluctuating (oscillatory) response would follow a small change in demand. The internal structure and policies defined a manufacturing system that tended toward unstable behavior. Even with constant incoming orders, employment instability could result from commonly used decision-making policies. That first inventory control system with pencil and paper simulation was the beginning of system dynamics.[7]

Viewed in the context of management research, the social sciences, and economics, system dynamics differs in having been developed through intimate contact with the real worlds of practicing management and politics. System dynamics shows how structures and policies, which are well known in the operating arenas, can produce the successes and difficulties that are being experienced.

My *Industrial Dynamics* book in 1961 first presented the philosophy and methodology of system dynamics. The book grew partly out of teaching Sloan Fellows who are managers age 30 to 40 with substantial corporate and managerial experience. Their master's theses explored many dynamic business issues, including commodity markets, evolution of nuclear energy, military research and development management, corporate growth, and design lead time and market penetration in the automobile industry. The book also benefited from our teaching two-week intensive summer session programs for managers. At the same time, we developed the systems concepts while applying them in sponsored corporate research projects that formed a meeting ground for theory and practice.

An example of the close linkage of practice and analysis arose in my early excursions into the dynamics of corporate growth.[8] At the time system dynamics was starting, I joined the board of the Digital Equipment Corporation. The founders of the company offered the invitation because they had worked with me in the Whirlwind computer days.

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[7] See Forrester (1957), Systems Technology and Industrial Dynamics; and (1958), Industrial Dynamics--A Major Breakthrough for Decision Makers.

[8] See Forrester (1964), Common Foundations Underlying Engineering and Management; (1966), Modeling the Dynamic Processes of Corporate Growth; and (1968), Market Growth as Influenced by Capital Investment.

I did not understand the nature of high technology growth companies as well as I felt I should as a board member. Also, if the emerging field of system dynamics was as powerful as we believed, it should shed light on why new companies exhibit such widely varying degrees of success. I undertook to model the general nature of high-technology growth companies 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% of the variables in that corporate growth model lay beyond the usual tangible variables. They included 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 decision making. The model also dealt with the interactions between capacity, price, quality, and delivery delay.

In our corporate work on how structure and policies determine behavior, we found we could go into a troubled company and uncover the reasons for its problems. The difficulty might be falling market share, or fluctuations in production with employment varying from working overtime one year to having half the work force laid off two years later, or a lower profitability than other companies in the industry. Such difficulties are widely known to employees, the community, and the business press.

Our background about how feedback loops relate to behavior guides examination of a company. Information comes from interviewing people about how they make decisions at their individual operating points. These statements describing the basis for decisions are the rules or policies governing action. As I use the term "policy," it represents all the reasons for action, not just formal written policy.

These interviews are extensive and penetrating. There may be several sessions with each of many individuals. The discussions range widely from normal operations, to what is done in various kinds of crises, what is in the self interest of the individual, where are the influential power centers in the organization, what would be done in hypothetical situations that may have never been experienced, and what actions are being taken to help in solving the serious problem facing the company.

We find that talking to a manager can reveal a clear and comprehensive picture of the rules and conditions driving decisions at that position in the corporation. Then, when one talks to another manager about the first manager, the same picture usually emerges. In other words, people see themselves very much as others see them. There is substantial consistency throughout the organization as to the actual operational policies that are guiding decisions. Furthermore, the policies are usually justified in terms of how those policies are expected to help overcome the great difficulty that the company is experiencing.

During this interview stage, the examination of such a company follows the case-study approach used in management education. That is, a comprehensive examination of all related parts of the company is made in the context of the problem that is to be solved. The pieces of the picture are described in words. But, if left at this point, the weakness of the case-study method would intrude and dominate the outcome. A descriptive model of the company would have been assembled, but the human mind is not able to deal with the inherent dynamic complexity of such a situation.

For readers who have studied mathematics through differential equations, such a descriptive case-study type of model is equivalent to a high-order nonlinear differential equation. No scientist or mathematician can solve such a system mentally. Just as with the operation of a chemical plant, only computer simulation methods are capable of revealing the behavior implicit in the structure built from knowledge about the many local decision-making individuals and their linkages.

After obtaining a description of the important policies, information flows, and interconnections in a company, the next step translates that description into a computer simulation model. Such a model allows the computer to act out the roles of each decision point in the corporate system and feed the results to other connected decision points to become the basis for the next round of decisions. In other words, a laboratory replica of the company then exists in the computer where one can observe the behavioral consequences of the policies that were described in the interviews—policies that were intended to solve the company's problem.

To the surprise of those unfamiliar with the devious nature of such dynamic systems, a computer model, based on policies known to people in the company, will generate the very difficulties that the company has been experiencing. In short, the policies that are expected to solve the problem are, instead, the cause of the problem. Such a situation creates a serious trap and often a downward spiral. If the policies being followed are believed to alleviate the problem, but, in hidden ways, are causing the problem, then, as the problem gets worse, pressures increase to apply still more strongly the very policies that are causing the problem.

EXTENDING SYSTEM DYNAMICS TO SOCIAL AND ECONOMIC BEHAVIOR

A series of incidents in 1968 moved my work from corporate modeling to broader social systems. John F. Collins, who had been mayor of Boston for eight years, decided not to run for reelection. MIT gave him a temporary appointment as Visiting Professor of Urban Affairs to bring him into the academic orbit as a way to meet students, interact with faculty, and advise the administration on political issues.

Collins had been a victim of polio in the Massachusetts epidemic of the mid 1950s and walks with two arm canes. He needed an office in a building with automobile access to the elevator level. The building with my office was one of the few that qualified. The professor next door to me was away for a sabbatical year, so John Collins was assigned the adjacent office.

In discussions with Collins about his many years of coping with Boston urban problems I developed the same feeling that I had come to recognize in talking to corporate executives. The story sounded plausible but it left an uneasy sense that something was wrong or incomplete or being misinterpreted. So, I suggested to Collins that we might combine our efforts, taking his extensive practical experience in cities and my background in modeling, and look for interesting new behavioral insights about cities. He immediately asked how to go about it.

I told Collins that we would need advisers who knew a great deal about cities from personal experience, not those whose knowledge came only from academic study and reading. We needed people who had struggled with cities, worked in them, and knew what really happens. And furthermore, we would not know what would come of the effort, or how long it might take. The process would be to gather a group that would meet half a day a week, probably for months, to seek insights into those urban processes that could explain stagnation and unemployment.

Collins listened and said, “They'll be here on Wednesday afternoon.” Collins' position in Boston then was such that he could phone almost anyone in politics or business, and get a commitment of time for a half day per week. He delivered the people. It was out of the following discussions over an interval of six months that the *Urban Dynamics* book evolved.

Urban Dynamics was the first of my modeling work that produced strong, emotional reactions. The model simulations suggested that the major United States policies all lay somewhere between neutral and highly detrimental, either from the viewpoint of the city as an institution, or from the viewpoint of the low-income, unemployed residents.

Our examination of urban behavior showed that the most damaging policy was to build low-cost housing. At that time, building low-cost housing was believed essential to reviving the inner cities. But the construction of low-cost housing occupies land that could have been used for job-creating structures, while at the same time the added housing draws in people who need jobs. It creates a social trap that increases unemployment, and reduces the economic vitality of both the city and the individual residents.

Although I believe the *Urban Dynamics* book has survived the test of time, the conclusions offended many people around 1970. When the book first appeared, one faculty colleague came to me and said, “I don't care whether you are right or wrong, the results are unacceptable.” So much for academic objectivity! Others, probably believing the same thing, put it more acceptably as, “It doesn't make any difference whether you're right or wrong, urban officials and the residents of the inner city will never accept such 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 understand what the urban dynamics model was revealing. Urban officials and members of the black community in the inner city became increasingly negative and emotional during those introductory hours. If they had not been in a captive audience, they would have walked out before they understood and accepted the way in which low-cost housing is a double-edged sword for making urban conditions worse. Constructing low-cost housing drives a powerful process for creating poverty, not alleviating it.

My first experience with reactions to *Urban Dynamics* came soon after the book was published. The Sloan School had been running a four-week program for urban executives twice a year for department-head level people from larger cities to teach various aspects of management. A group was convening shortly after *Urban Dynamics* came out and organizers of the program asked me 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, at 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 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 explained how decay and poverty in Harlem in New York or Roxbury in Boston had been worsened by too much low-cost housing, he said, “I come from Harlem and there's certainly not too much housing in Harlem.” Those are samples of the afternoon.

On Tuesday evening, the group met for dinner. Neither Collins nor I could go; but several of our students attended. One student called me at home after dinner to report what was rather obvious anyway—that the group was very hostile. On that bit of encouragement, I started Wednesday morning.

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.” I ignored the request to see what would happen next. In about twenty minutes, he repeated it. I agreed to meet them again if he could find a time and place in the crowded program. I was not trying to put him off, but that usually ends such an exchange. However, he persisted and went to the administration and arranged another session.

Later the New Yorker made an appointment to come to my office to ask that I talk to a group he would invite in New York—his colleagues on his home turf. He sat in my office completely relaxed and said, “You know, it's not a race problem in New York at all, it's an economic problem.” Four days earlier he had asserted that I was not even addressing the urban problem if not dealing with the black versus white issue. He gave me a report out of his brief case documenting the amount of empty housing in every borough of New York, including Harlem, and the rate of abandonment. My point in saying there was 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 brief case. He simply had not realized what his knowledge meant until it was all put together in a new way.

Two years later a journalist asked me what people thought in the aftermath of *Urban Dynamics*. I suggested that he talk to others, and especially with the man in New York whom I had not contacted in the intervening two years. After the interview, the journalist phoned to say he had been told “they don't just have a solution to the urban problem up there at MIT, they have the only solution.” The lesson about urban behavior had stayed clear and alive for two years even back home in his political environment. The five hours of exposure to *Urban Dynamics* had made a lasting impression. But we have not solved the challenge of how to bring enough people across the barrier separating their usual, simple, static viewpoint from a more comprehensive understanding of dynamic complexity.

Urban Dynamics led to both the *World Dynamics* and *Limits to Growth* projects and to the System Dynamics National Model program.

WORLD DYNAMICS AND THE CLUB OF ROME

The urban work initiated my contact with the Club of Rome. I met Aurelio Peccei, the founder, at a meeting on urban difficulties held in Italy at Lake Como in 1968. Later, after being asked to join, at a meeting of the Club in June 1970 in Bern, Switzerland, came another turning point in my career with system dynamics. What followed is more fully described in the introduction to *World Dynamics*.

The "world problematique" discussed at the Bern meeting became the basis for the model in *World Dynamics*. In the three weeks after the Bern meeting, I created the model for *World Dynamics* and 80 pages of text. This material became the centerpiece for a two-week meeting with the executive committee of the Club of Rome at MIT in July 1970. Included in the group was Eduard Pestel, president of the Technical University of Hannover. Pestel was a very forceful person and quickly saw the power of system dynamics. The executive committee decided to finance research at MIT to go beyond the material that had been presented at the meeting. Pestel arranged for the Volkswagen Foundation to support work that resulted in the *Limits to Growth* book.[9]

The public responses to system dynamics have always surprised me. People ask what I think the reaction will be when the National Model books are released. I don't know. Usually I have been wrong in anticipating the effect that system dynamics books will have.

In 1971 when *World Dynamics* first appeared, the book seemed to have everything necessary to guarantee no public notice. First, it had forty pages of equations in the middle, that should be sufficient to squelch public interest. Second, the main messages were presented as computer output graphs, and most of the public does not understand such presentations. Third, the publisher of the book had published only one previous book and I doubted that *World Dynamics* had the commercial status even to be reviewed. I intended the book for maybe 200 people in the world who would like to study an interesting model on their computers.

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[9] Donella H. Meadows, et al (1972), *The Limits to Growth*, New York: Universe Books.

The book showed the long-term interplay of population, industrialization, resource depletion, agriculture, and pollution. But, I was wrong about the audience.

World Dynamics came out the first week of June 1971. The last week of June, it was reviewed in the *London Observer*, which then circulated around the world. A letter from a professor in New York asked for more information because he had been reading about the book in the *Singapore Times!* 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, and 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, for those not liking their literature on either the establishment right or the establishment left, then in the middle of the political spectrum, the *World Dynamics* book was the subject of a full-length article in *Playboy*. But as a communications medium for conveying system dynamics, that magazine was a disappointment. Out of eight million copies printed, the only response I received was a request to conduct a two-day meeting for the Board of Overseas Missions after the article was read by a man at the National Council of Churches.

Nine months after *World Dynamics* appeared, *Limits to Growth* was published. The message was essentially the same, although much more research and verification had been done. The book was more popularly written, but even so, after the earlier attention from the media, it seemed that the second book could only be an anti-climax. The results showed that one can be wrong twice in succession in exactly the same way. Public attention jumped another factor of ten after appearance of *Limits to Growth*.

The two books gained wide visibility and created great controversy. *Limits to Growth* has sold several million copies and been translated into about thirty languages. Due to the system dynamics approach, the books were able to clarify issues that troubled the public and that people wanted to understand better.

As with earlier modeling, reactions surprised us. Who would react to rising environmental pressures that will progressively restrain growth of population and industrialization over the next fifty years? We assumed the subject would be anathema to chief executives of corporations. On the other hand, we expected little interest in the social sciences. Wrong on both. On the whole, the books received favorable responses from chief executives of corporations, members of Congress, and by young people. Disparagement often came from middle-level managers, the Executive Department of the U.S. Government, and economists.

Particularly surprising were the bitter and emotional attacks on the two books by many economists. We would have thought the books lay outside their area of interest until we realized that the books threatened the underlying theology supporting the belief that growth can continue forever. Even though largely unjustified, such published criticisms have left their impact, especially on people who have not read the books.

One now occasionally sees newspaper comments referring to the "discredited *Limits to Growth,*" while in that paper are articles about acid rain, water shortage in California, forests dying of pollution, threatened species, and the debate about global warming; all illustrating the central message of the books about the dynamics that result from growth in population and industrialization overrunning the world's environmental capacity.

SYSTEM DYNAMICS NATIONAL MODEL

As this is written in February 1991, I am completing a long program of applying system dynamics to understanding the behavior of national economies. Two books are under way to set forth what we have learned.

The *Urban Dynamics* book led to our work on the System Dynamics National Model. After a talk at a joint NATO/US conference on cities in Indianapolis, Indiana in 1971, William Dietel, now recently retired as 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. Since then, the work continued with private-sector support from individuals and corporations.

The approach is very different from the conventional econometric models, which are structured on the basis of macroeconomic theory with parameters drawn from statistical analysis of historical data and with a heavy dependence on exogenous time-series to drive the dynamics of the model. From the system dynamics view point, econometric models are essentially curve-fitting exercises. They do not contain the essential feedback structures that create the kinds of dynamic changes that are seen in real economies.

As with all my earlier work, the emphasis has been on connecting research to actual practices in the operating world. In that tradition the National Model contains policies that can be observed in managerial practice in corporations, banking, households, and government.

The results are far exceeding our original expectations. The model generates endogenously the major kinds of behavior that have been observed in actual systems—business cycles, inflation, stagflation, growth, and the economic long wave or Kondratieff cycle. Business cycles have peaks of activity three to 10 years apart. The longer Kondratieff cycle has much larger economic deviations with peaks spaced 45 to 60 years.

The National Model supplies for the first time a theory for the economic long wave, which we believe accounts for the great depressions that occurred around 1830, 1890, and in the 1930s. The long wave arises from major interactions among capital investment, saving, monetary policy, real interest rate, and speculation. It generates severe economic downturns at five-to-seven-decade intervals.

As with prior work, we can anticipate that publication on the dynamics of economic systems will generate controversy because the results differ with previous understandings about how economic behavior arises. Also the approach suggests a very different way of looking at the study of economic systems. Instead of thinking of economics as a social science, we believe that the study of economics should be seen as a systems profession comparable to engineering, management, and medicine. Like the analysis and design of a chemical plant, understanding an economy should be based on identifying the internal structure of the system. The parts can then be interrelated in a simulation model to demonstrate how they interact to generate observed, economic behavior.

GROWTH OF THE SYSTEM DYNAMICS FIELD

It is gratifying to see how the work that started in 1956 has grown into an active profession. The System Dynamics Society has a worldwide membership and publishes the *System Dynamics Review*.[10] Educational programs in the field exist in a number of countries. Annual international conferences move from country to country.

A NEW KIND OF MANAGEMENT EDUCATION

Throughout its development, system dynamics has offered a basis for a much improved kind of management education. The suggestion has been resisted for a number of reasons. It would break down the boundaries between academic disciplines. It would undermine the assumption that doing the "best" as viewed from within each separate functional area is best for the organization as a whole. It

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[10] Available from John Wiley & Sons, England.

would tend to force faculty members to understand other disciplines and how those other disciplines relate dynamically to their own. Also, the approach depends heavily on knowledge about structure and policies obtained directly from participants in actual corporate practice, but in academia, such sources are often distrusted and seen as being nonscientific.

However, if the goal is worthwhile, patience and persistence prevail in time. There is clearly a movement toward seeing management success as depending on the interaction of many policies. There is a widening understanding that analysis of individual policies will not reveal the behavior of the whole.

An improved understanding of corporate systems points the way to a future advancement in management education. Beyond that, it suggests a new kind of manager for the future. One can now see clearly a kind of management education that we might call "enterprise design." And in the future there is a role for the output of such an education, the "enterprise designer."[11]

A fundamental difference exists between an enterprise operator and an enterprise designer. To illustrate, consider the two most important people in the successful operation of an airplane. One is the airplane designer and the other is the airplane pilot. The designer creates an airplane that the ordinary pilot can fly successfully. Is not the usual manager more a pilot than a designer? A manager runs an organization. Often there is no one who consciously and intentionally fills the role of organizational designer.

Organizations built by committee, by intuition, and by historical happenstance often work no better than would an airplane built by the same methods. Time after time one sees venture capital groups backing new enterprises in which the combinations of corporate policies, characteristics of products, and nature of the markets are mismatched in a way that predetermines failure. Like a bad airplane design that no pilot can fly successfully, such badly designed corporations lie beyond the ability of real-life managers.

Management education, in all management schools, has tended to train operators of corporations. But there has been rather little academic attention to the design of corporations. The determination of corporate success and failure seldom arises from functional specialties alone, but grows out of the interactions of functions with one another and with markets and competitors. Management education underemphasizes policies governing such interactions.

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[11] See Forrester (1988) *Designing Social and Managerial Systems*, and (1985) *System Dynamics in Management Education.*

We need to deal with the way policies determine corporate stability and growth in an intellectual, challenging, quantitative, and effective way. Such management education leads to what I refer to as enterprise design. Such an education would combine two innovations that have developed separately in this century.

The first innovation came from the Harvard Business School, which pioneered the case-study method of management education around 1910. The case method has achieved a wide following because it addresses the problems of general management and the interactions among parts of the corporate-market-competitor system. The case method also draws great strength from being based on the full range of descriptive information and the mental data base of practicing managers. But the case method, has a major weakness. The description of a case captures policies and relationships that describe a system so complex that it can not be reliably analyzed by discussion and intuition. Such attempts often draw the wrong dynamic conclusions and fail to reveal why corporations in apparently similar situations can behave so differently.

The second innovation, the understanding of the dynamics of feedback systems, emerged from engineering to become an organizing concept for human systems as well. Feedback processes govern all growth, fluctuation, and decay. They are the fundamental generators of all change. They allow new insights into the nature of managerial and economic systems that have escaped past descriptive and statistical analysis. System dynamics modeling can organize the descriptive information, retain the richness of the real processes, and build on the experiential knowledge of managers. A simulation model reveals the variety of dynamic behaviors that follow from different choices of policies. I anticipate this will become the frontier of new developments in management education during the next twenty years.

Bringing these two innovations together offers the potential for a major breakthrough in management education. The combination will permit going far beyond the case-study method of management education by adding a rigorous dynamic dimension to the rich policy and structural knowledge possessed by managers. The difference between present and future management schools will be as great as the difference between a trade school that trains airplane pilots and a university engineering department that trains aircraft designers.

Pilots continue to be needed, and so will operating managers. But just as successful aircraft come from skilled airplane designers, so in the future will successful corporations rely on enterprise designers. Competition will force reduction in the number of design mistakes in the structure and policies of our social institutions.

Correct design can make the difference between a corporation that is vulnerable to changes in the outside business environment and one that exhibits a high degree of independence from outside forces. Correct design can improve the stability of employment and production. Correct design in the balance of policies for pricing, capital plant acquisition, and sales force, can often make the difference between growth burdened by debt and growth out of earnings. Correct design can help avoid the adoption of policies offering short-term advantage at the expense of long-term degradation. Correct design can help prevent expenditure of managerial time in debating policies that are inherently of low leverage and therefore unimportant. Correct design can help identify the very small number of high-leverage policies capable of yielding desirable change.

Future training in enterprise design will include study of a library of generic management situations combining descriptive case studies with dynamic computer models, each of which has wide applicability in business. I estimate that about 20 such general, transferable, computerized cases would cover perhaps 90 percent of the situations that managers ordinarily encounter. Several powerful examples already exist. They include a model of stability and fluctuation in a distribution system,[12] a model of capital investment as it often restricts growth,[13] a model of promotion chains and the evolution into a top-heavy distribution of management personnel when growth slows, and a model dealing with imbalances between design, production, marketing, and service as these influence market growth. Each such model manifests many modes of behavior ranging from troublesome to successful depending on the policies employed within it.

STARTING AT THE BEGINNING—PRE-COLLEGE EDUCATION

Slowly over the years, we have come to realize the difficulty people face in making the transition to a dynamic and systems view of the world around them. After writing *Industrial Dynamics*, I thought the task of showing how policies and structure could be analyzed to understand corporate change was finished. It seemed that managers and educators would quickly pick up and begin to apply the concepts of feedback behavior, simulation of policy interactions, and corporate design. For several years I even turned my attention to quite different activities, feeling that nothing more would be needed. Not only was that optimism unjustified, but later efforts in system dynamics have repeatedly shown the high hurdle to cross in drawing people to the dynamic viewpoint when they were

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[12] See chapters 2, 15, and 16 in Forrester (1961), *Industrial Dynamics.*

[13] See Forrester (1968), Market Growth as Influenced by Capital Investment.

already mature in established statistical, or open-ended, or static views of their surrounding environments.

Understanding dynamic behavior comes slowly. No single learning process suffices. One can encounter feedback dynamics in the form of mathematical differential equations, in computer simulations, in physical laboratory experiments, and in informed observation of surrounding natural and social processes. But no one of these suffices, and even a combination does not immediately produce insights.

In corporate consulting, it can take several years for a management to understand and accept the way in which their own policies are creating the problems that they are experiencing. By that time, the individuals have often retired or died, and one faces a new oncoming generation of managers and must start over.

It now seems clear that we are asking for a paradigm transition of the kind discussed by Kuhn.[14] Such a transition tends to be strongly resisted both because it contradicts past assumptions and because it is difficult to understand from within the prior perspective. A pessimistic, but not entirely unrealistic, picture of paradigm revision suggests that adherents to an older paradigm are seldom converted; instead, they are in time replaced.

If then we hope for a time when managers and political leaders possess a more effective grasp of how their actions affect the future, what are we to do? The educational system compartmentalizes knowledge, hides the unity of systemic interactions, and teaches facts at the expense of synthesis. By so doing, it creates a paradigm that becomes progressively harder to alter as the individual develops.

Without the cause having been clearly identified, I believe much of the current dissatisfaction with pre-college education arises from past inability to show things whole, to convey how people and nature interact, and to reveal causes for what students see happening. Education is becoming less relevant as society becomes more complex, crowded, and tightly interconnected.

Education is fragmented. Social studies, physical science, biology, and other subjects are taught as if they were inherently different from one another even though dynamic behavior in each rests on the same underlying concepts. For example, the dynamic structure that causes a pendulum to swing is identically the same as the core structure that causes employment and inventories to fluctuate in a

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[14] Thomas S. Kuhn (1962, second edition 1970), *The Structure of Scientific Revolutions*, Chicago: University of Chicago Press.

production-distribution system or in economic business cycles. Humanities fail to relate the dynamic sweep of history to similar behaviors on a shorter time scale that a student can experience in a week or a year.

High schools teach a curriculum from which a student is expected to synthesize a perspective and framework for understanding the social and physical environment. But that framework is never explicitly taught. A student is expected to create a unity from the fragments of the educational experience. But the teachers themselves have seldom achieved that unity.

Missing from most education is a direct treatment of the time dimension. What causes change from the past to the present and the present to the future? How do present decision-making policies determine the future toward which we are moving? How are the lessons of history to be interpreted to the present? Why are so many corporate, national and personal decisions ineffective in achieving the intended objectives? Conventional educational programs seldom offer such understanding. Answers to questions about how things change through time lie in the dynamic behavior of social, personal, and physical systems. Dynamic behavior, common to all systems, can be taught as such. It can be understood.

The educational system has been teaching static snapshots of the real world. But the world's problems are dynamic. The human mind grasps pictures, maps, and static relationships in a wonderfully effective way. But in systems of interacting components that change through time, the human mind is a poor simulator of behavior. Yet, even a junior high school student with a personal computer and coaching in dynamic behavior can advance remarkably far in understanding such complex systems.

In system dynamics, understanding how things change through time is facilitated by using the process of integration (or accumulation) rather than differentiation as the foundation for dynamic behavior. Those in science and technology formulate most dynamic behavior in terms of differential equations. But a derivative is a difficult concept to understand. Differentiation is obscure because it is no more than a figment of the mathematician’s imagination. Nowhere does nature take a derivative. Nature only integrates. Any child who can fill a water glass or take toys from a playmate knows what accumulation (or integration) means. By going directly in computer simulation to the real-life structures involving integration, the procedure seems entirely natural and common place.

Education faces the challenge of undoing and reversing much that a person has learned by observation of simple dynamic situations. Simple experiences in everyday life deeply ingrain lessons that are deceptively misleading in dealing with more complex social systems. For example, from burning a hand on a hot stove, one learns the lesson that cause and effect are closely related in both time and space—the hand is burned here and now. Almost all understandable experiences reinforce the belief that causes are closely related to results in time and location. But in more complex systems, the cause of a difficulty is usually far distant in both time and space—the cause lies back in time and in a different part of the system from the point where the symptoms appear.

To make matters even more misleading, a complex feedback system presents what we have come to expect, an apparent cause that lies close in time and space to the symptom. However, that apparent cause is usually only a coincident symptom through which there is little leverage for producing improvement. Education does little to prepare students for living successfully when simple, understandable lessons so often point in exactly the wrong direction in the complex real world.

In his penetrating discussion of the learning process, Bruner states, "The most basic thing that can be said about human memory… is that unless detail is placed into a structured pattern, it is rapidly forgotten."[15] For most purposes, such a structure is inadequate if it is only a static framework. The structure should show the dynamic significance of the detail—how the details are connected, how they influence one another, and how past behavior and future outcomes result from decision-making policies and their interconnections.

System dynamics can provide that dynamic framework to give meaning to detailed facts, sources of information, and human responses. Such a dynamic framework provides a common foundation beneath mathematics, physical science, social studies, biology, history, and even literature.[16]

Several high schools, curriculum-development projects, and colleges are beginning to build study units in mathematics, science, social studies, and history around a system dynamics core. These have not yet reached the point of becoming a fully comprehensive educational structure. Some other countries (Norway, Germany, Japan, and China) appear to be moving ahead in using system dynamics as a foundation for designing a more powerful educational system below the college level.

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[15] Jerome S. Bruner (1963), *The Process of Education*, p. 24, New York: Vintage Books.

[16] I have recently been moved to add literature to this list after reading about the powerful impact on students from a computer simulation of the psychological dynamics in Shakespeare's *Hamlet* done by Pamela Hopkins, an eleventh-grade English teacher at the Desert View High School in Tucson, Arizona.

Such 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 around ten years old.[17]

Through the efforts of Barry Richmond[18] and others, system dynamics is now being established in some twenty junior and senior high schools. Macintosh computers and the STELLA software are particularly user friendly and suitable for pre-college education.

I have described my introduction to feedback systems by Gordon S. Brown in the MIT Servomechanisms Laboratory in the early 1940s. Brown later became head of the Electrical Engineering Department and then Dean of Engineering before retiring in 1973. In the late 1980s, Brown has completed the circle by picking up system dynamics and introducing it into the Orange Grove Junior High School in Tucson, Arizona, where he spends the winters. He started by loaning a Macintosh computer and STELLA software for a weekend to Frank Draper, who teaches 8th grade biology. Draper came back on Monday to say, “This is what I have always been looking for, I just did not know what it could be.”

At first Draper expected to use computer simulation in one or two classes during a term. Then he found that systems thinking and simulation were becoming a part of every class. That led to concern that he would not have time to cover all the biology subject if so much time was being devoted to the system dynamics component. But two thirds of the way through the term, Draper found he had completed all the usual biology content. The more rapid pace had resulted from the way biology had become more integrated and from the greater student involvement resulting from the systems viewpoint. Also, much credit goes to the “learner-directed learning” organization of student cooperative study teams within the classroom that was introduced at the same time.[19] To quote Draper, “There is a free lunch.”

Whether we think of pre-college or management education, the emphasis will focus on “generic structures.” A rather small number of relatively simple structures appear repeatedly in different businesses, professions, and real-life

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[17] The earliest exploration of system dynamics at the fifth and sixth grade levels was started by Nancy Roberts (1978), Teaching Dynamic Feedback Thinking: An Elementary View, *Management Science*, Vol.24, No. 8, April.

[18] Barry Richmond, Ph.D. in system dynamics from MIT, president, High Performance Systems, supplier of the STELLA software, 45 Lyme Road, Hanover, NH 03755.

[19] See Forrester (1990) “System Dynamics as a Foundation for Pre-College Education” for a more complete description of the combination of systems thinking and learner-directed learning.

settings. One of Draper's junior high school students grew bacteria in a culture dish, then looked at the same pattern of environmentally limited growth through computer simulation. From the computer, the student 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 promise of reversing the trend of the last century that has been moving away from the "Renaissance man" idea toward fragmented specialization. We can now move back toward an integrated, systemic, educational process that is more efficient, more appropriate to a world of increasing complexity, and more supportive of unity in life.

ACADEMIC DEGREES

1939	B. Sc. University of Nebraska, Electrical Engineering
1945	M. Sc. Massachusetts Institute of Technology, Electrical Engineering

HONORARY DOCTORATES

1954	University of Nebraska, Engineering
1969	Boston University, Science
1971	Newark College of Engineering, Engineering
1973	Union College, Science
1974	University of Notre Dame, Engineering
1979	University of Mannheim, Germany, Political Science
1988	State University of New York, Humane Letters
1990	University of Bergen, Norway, Philosophy
1998	University of Seville, Spain

HONORS AND AWARDS

1962	Academy of Management Award for *Industrial Dynamics* book
1967	National Academy of Engineering
1968	Inventor of the Year, George Washington University
1968	Fellow, American Academy of Arts and Sciences
1969	Valdemar Poulsen Gold Medal, Danish Academy of Technical Sciences
1969	Fellow, Academy of Management
1970	Member, Club of Rome
1970	Publications Award, for *Urban Dynamics*, Organization Development Council

1972 Medal of Honor, Institute of Electrical and Electronics Engineers
1972 System, Man, and Cybernetics Award for Outstanding Accomplishment, Institute of Electrical and Electronics Engineers
1972 New England Award, The Engineering Societies of New England
1972 Benjamin Franklin Fellow, The Royal Society of Arts, London
1972 Appointed to the Germeshausen Professorship Chair, Massachusetts Institute of Technology
1974 Howard N. Potts Medal, The Franklin Institute
1976 Honorary Member, Society of Manufacturing Engineers, in recognition of the work of several at MIT in digital control of machine tools
1977 Harry Goode Memorial Award, American Federation of Information Processing Societies
1979 Inventors Hall of Fame
1979 The Common Wealth Award of Distinguished Service
1980 Fellow, American Association for the Advancement of Science
1982 Computer Pioneer Award, IEEE Computer Society
1986 Jay W. Forrester Chair in Computer Studies at MIT, endowed by Thomas J. Watson, Jr.
1987 James R. Killian, Jr. Faculty Achievement Award, Massachusetts Institute of Technology
1987 Honorary Professor, Shanghai Institute of Technology, China
1987 Forrester-Yang Reading Room for System Dynamics, Fudan University, Shanghai, China
1987 Agricoltura 2000 Award, Rome, Italy
1988 Information Storage Award, IEEE Magnetics Society
1988 Lord Foundation Award
1989 U.S. National Medal of Technology (with Robert R. Everett)
1990 Pioneer Award, IEEE Aerospace and Electronic Systems Society (with Robert R. Everett)
1998 Price Waterhouse Information Technology Leadership Award for Lifetime Achievement

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Revised, March 13, 2000