Profiles in Operations Research:

Jay Wright Forrester

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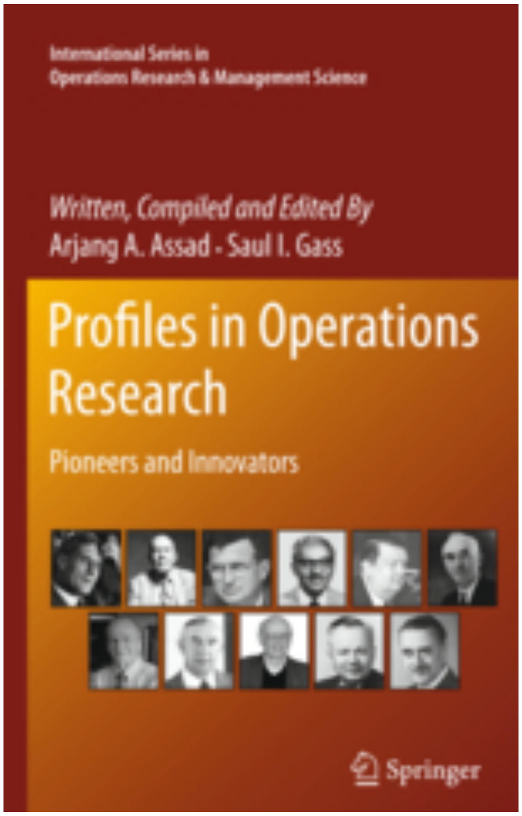

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Jay Wright Forrester

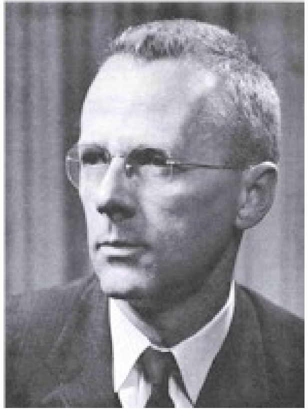
Jay Wright Forrester's distinguished career at the Massachusetts Institute of Technology (MIT) began with pioneering work in servomechanisms and digital computation. Drawing on that work, he then developed and founded the field of system dynamics. By integrating concepts of feedback control theory and digital computation, he created a new approach to simulating the behavior of social systems, explaining that behavior and designing effective policies to improve system performance. He established system dynamics as an academic discipline at MIT's Sloan School of Management. He led path-breaking research applying system dynamics to critical business and public policy problems, from high-tech start-ups to urban policy and global development. System dynamics is now one of the most widely used systems approaches in the world, with academics and practitioners on every continent pursuing work in diverse fields. His writings continue to inspire the field and he remains actively involved in its development.

He is a Member of National Academy of Engineering and a Fellow of the Institute of Electrical and Electronic Engineers (IEEE). His honors include: U.S. National Medal of Technology; Medal of Honor, (IEEE); Pioneer Award, IEEE Aerospace and Electronic Systems Society. He was inducted into the International Federation of Operational Research Societies (IFORS) Operational Research Hall of Fame, and has honorary degrees from nine universities.

Frontier Years and Beyond

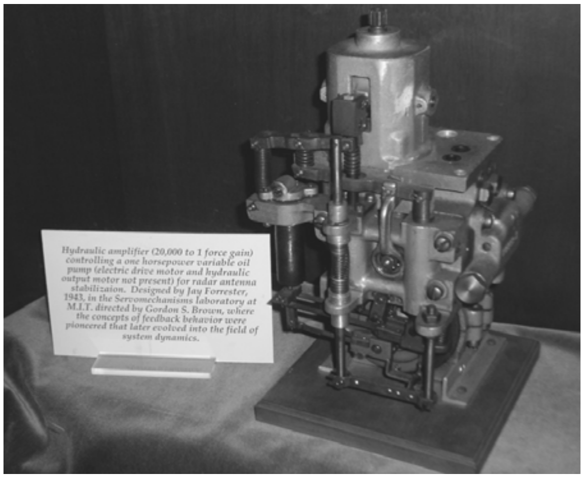
Jay Wright Forrester was born on July 14, 1918 on a cattle ranch near Climax, Nebraska, to Ethel Pearl Wright Forrester (1886-1958) and Marmaduke (Duke) Montrose Forrester (1883-1975). Their daughter, Barbara Francis, was born in 1921. Both parents attended Hastings College, Nebraska. They were the original homesteaders of this land close to the American frontier. When they arrived in Nebraska around 1910, both worked as country schoolteachers. Jay was taught at home by his mother for his first two years of schooling. After that, he rode his horse one and a half miles to a one-room school house. There, for the first two years, he was taught by his father.

Jay developed an early interest in electricity, tinkering with doorbells, batteries and telegraphs. He recalls that being raised on a Nebraska cattle ranch offered plenty of opportunities to get his hands dirty finding practical solutions to real problems such as building a wind-powered generator to provide the first electricity to the ranch (Forrester 1992). He was offered a scholarship to an agricultural college, but decided that the life bucolic was not for him and, instead, enrolled in the University of Nebraska to study electrical engineering.



After earning a bachelor's degree in electrical engineering in 1939, Jay moved to MIT. He worked as a research assistant with Gordon Brown, a pioneer in servomechanism theory and applications (Brown and Campbell 1948). During World War II, Jay worked on feedback control systems and servo-control systems for radar. For his master's thesis, he designed and built a servo to stabilize radar antennae on naval ships. In 1943, the prototype was installed on the aircraft carrier Lexington and Jay subsequently traveled to Pearl Harbor to ensure its continued functioning. Though a civilian, he volunteered to stay on board when the fleet was ordered to sea to make sure the servo (and thus the ship's radar) worked. During the mission, the Lexington participated in the retaking of the Marshall Islands and survived a torpedo strike. He received an S.M. degree in Electrical Engineering from MIT in 1945; his thesis was titled "Hydraulic Servomechanisms Developments."

On the Lexington



The hydraulic servo-mechanism to stabilize radar antennae built by Forrester and Brown. The prototype was installed on the Lexington. This one is on display in the Forrester Conference Room at the MIT Sloan School of Management. Photo: John Sterman.

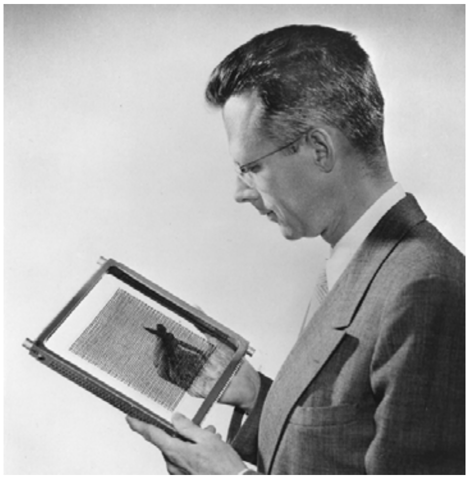
From 1940-1951, Jay was Associate Director of MIT's Servomechanism Laboratory and then Head of the Digital Computer Division in MIT's Lincoln Laboratory (1951-1956). He directed the ASCA project (Airplane Stability and Control Analyzer), aimed at developing flight simulators to test new aircraft designs. Originally envisioned as an analog computer, Jay realized that the real-time requirements of the planned simulator could not be met with analog components. Jay learned of digital computation through MIT alumnus Perry Crawford. He then visited the computing centers at Harvard and the University of Pennsylvania's Moore School of Electrical Engineering where the ENIAC was being built. There he met the Princeton mathematician John von Neumann, who was helping to design the Moore School's next generation computer, the EDVAC, and J. Presper Eckert, one of the developers of the ENIAC. These visits convinced Jay that the ASCA project would be based on digital computation, a bold decision given that all existing digital computers were far too slow and limited to meet the requirements of ASCA. As director (from 1951) of the MIT digital computer laboratory, Jay led the development of the Whirlwind computer, which was, for years, the only machine fast enough for real-time simulation of complex dynamical systems such as an aircraft.

Whirlwind became the central element of the SAGE (Semi-Automatic Ground Environment) system and became the first computer produced in volume. SAGE was built to defend North America from Soviet bomber attack and consisted of a network of digital computers and long-distance communication systems that sent target tracking information from radar stations to computers. The Whirlwind-based computers in each center processed the data and computed flight plans for interceptor aircraft and missiles, a demanding real-time application requiring high reliability (Jacobs 1986). With roughly 80,000 vacuum tubes in each of the approximately three dozen SAGE centers, reliability was an immense technical challenge. Jay's legendary drive for quality and reliability led to design improvements and manufacturing standards yielding unprecedented results - when the last of the SAGE centers was decommissioned in 1983, the system-wide uptime over their roughly 25 years of service was 99.8%, making it probably the most reliable military command and control system ever implemented. Jay's colleagues and students during this period went on to major accomplishments. Robert Everett, Jay's second in command in the Whirlwind project, went on to lead the MITRE Corporation (originally, MIT Research and Engineering), created by the spinoff of the digital computer division of MIT's Lincoln Laboratory. Kenneth Olson, one of Jay's students, went on to found and lead the Digital Equipment Corporation.

Computer memory became a major bottleneck early in the development of Whirlwind. Memory cost $1 per digital bit per month. Electrostatic tubes provided some storage, but were expensive and unreliable. Mercury delay lines were tried, with the bits stored as sound waves traveling down a tube of mercury (Slater 1987). Jay even considered leasing a microwave relay line between Boston and Buffalo, New York, to store bits in a pulse train of electromagnetic radiation. The need for fast, high-capacity data storage spurred Jay to create coincident-current magnetic core memory in 1949 (Forrester 1951, 1953; US Patent Office 1956). Core memory was cheap, stable, and reliable. It was the industry standard for decades (Evans 1983) and was the memory device that flew to the moon on the Apollo missions. For its invention, the IEEE awarded Jay its Medal of Honor in 1972. In 1979, he was made a member of the US National Inventors' Hall of Fame, and, in 1989, along with Robert Everett, was awarded the Presidential Medal of Technology.

Whirlwind

Whirlwind: Jay (centre, standing) and on his left Robert Everett at Whirlwind I test control in 1950. Used with the permission of The MITRE Corporation. Copyright © The MITRE Corporation. All Rights Reserved.

National Medal of Technology	**Core Memory**
 In 1989, along with Robert Everett, Forrester received the National Medal of Technology, the nation's highest award for technical achievement. Photo: George Bush Presidential Library and Museum.	 Coincident Coil Magnetic Core Memory: Jay holding a 64x64 core memory plane, 1954. Picture used with the permission of The MITRE Corporation. Copyright © The MITRE Corporation. All Rights Reserved.

As described in Slater (1987), Jay's achievements during the period of 1940-1955 were extraordinary (for Jay's perspective, see Forrester 2007a). Jay's experiences proved of great value in the next chapter of his scientific life—the development of his major work, the field of system dynamics and its application to critical problems in business and public policy. Naturally, his life also had personal dimensions of no less significance. It was early in this period that Gordon Brown introduced Jay to Susan Swett. They married on July 27, 1946 and went on to have three children. In 1952, they moved into a brown-shingled house in Concord, Massachusetts, their home until 2007.

The Emergence of System Dynamics

By the mid-1950s, Jay felt that "the pioneering days in computers were over" and, ever seeking new frontiers, was looking for new challenges (Forrester 1992, 343). His work with servomechanisms, digital computation, and SAGE had provided extensive experience in the management of complex organizations and large-scale high technology projects. He relates a conversation with the then-president of MIT James Killian, who

> … 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 [MIT alumnus] 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 (Forrester 2007a, 347).

Jay joined the Sloan faculty in 1956. He spent the first year considering what contribution digital computation and control theory might make to management. A 1956 memo to the faculty research seminar titled “Dynamic models of economic systems and industrial organizations” laid out his initial thinking, and became the first in a series of D-Memos (dynamic modeling memos). Jay organized an industrial dynamics group and he and its members began to log their models, reports, class assignments, papers, and musings in the D-memo series, which continued through the 1990s, when computers and the internet made it unnecessary to keep such paper files. The D-Memos, now in the MIT archives, are a remarkable record of the evolution of a new field (most are available on a DVD distributed by the System Dynamics Society).

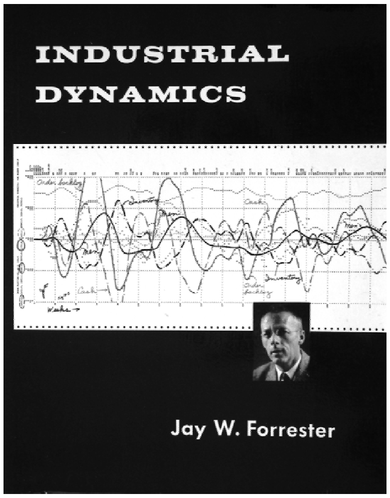
Jay’s first dynamic model arose through chance conversations with executives at the General Electric Corporation (GE) (Forrester 1992, 2007a). GE managers were puzzled by large fluctuations in production, inventories, employment, and profit. These oscillations endured despite the managers’ best efforts, and were attributed to outside forces, specifically business cycle fluctuations in incoming orders. By talking to the managers and observing how the different departments were run, Jay elicited an account of how individual managers, from the retail level, through distribution channels, to the factories, responded to the information locally available to them as they tried to control their piece of the organization. Rather than attribute the fluctuations to exogenous events, he saw the production and distribution of appliances as a system of interacting units. The managers in each link in what today is called a supply chain were responding in a locally rational fashion to the incentives and information they faced; for example, the need to provide good customer service while avoiding excessive inventories. The resulting changes in orders, production, hiring, and other decisions then fed back to alter inventories, backlogs, prices, and advertising, creating a system consisting of multiple feedback loops, just as a servomechanism consisted of a closed-loop control system. Managers at each link of the supply chain altered the orders they placed with suppliers to compensate for variations in orders and inventories, just as his antenna stabilization servo adjusted the position of the antenna to compensate for the pitch, roll, and yaw of the Lexington. Where, however, the servo damped out the variations in the environment, the feedback structure of the supply chain amplified them into persistent cyclical swings.

In building this first model, Jay retained several vital features of the situation, including an explicit stock and flow network for resources such as inventories and labor, the long time delays between actions and outcomes such as shipping and production delays, and nonlinearities such as the impact of inventory on shipments and nonnegativity constraints on production. Retaining these features meant that the system was not analytically tractable. Simulation was required. Jay carried out the first simulation of this system by hand, calculating production, shipments, hiring, and other flows from inventory, work in progress, workforce, and other system states, then updating these stocks, week by simulated week. The results, recorded in a lab notebook, showed how the management policies of the firm generated robust oscillations even when demand was constant. Although inventories and backlogs are intended to absorb temporary fluctuations in orders so that costly production changes can be minimized, Jay found that the firm's own policies, sensible and rational from the perspective of the managers at each decision point, led to substantial amplification of perturbations in orders, and instability for the system as a whole, a phenomenon now known as the bullwhip effect.

Jay soon moved to computer simulations of this problem. Further work showed how feedback control theory could be adapted to understand puzzling, counterintuitive behavior in a range of management and human systems (Forrester 1956). He called the approach industrial dynamics (Forrester 1958).

Industrial Dynamics

Jay recruited talented MIT undergraduates as research assistants—Willard Fey, Jack Pugh, Edward Roberts and others—and spent the next years developing applications and laying out a vision of the contribution that they could make to management (Forrester 1959, 1960). These ideas led to his classic book, *Industrial Dynamics* (Forrester 1961).



As described in Richardson (1991), systems concepts including feedback control, mutual causality, deviation-correcting and deviation-amplifying processes were in the air during the middle of the last century. Jay's unique contribution, detailed in *Industrial Dynamics*, was to develop ideas about systems, feedback, control, and dynamics that were previously restricted to engineering and physical contexts into a rigorous yet practical method for enterprise design, a method designed to "find management policies and organizational structures that lead to greater success" (Forrester 1961, 449). Richardson (1991) documents the connections and parallels between Jay and other pioneers of cybernetics, systems theory, and operations research (OR). Many of the principles Jay articulated to guide effective modeling and policy design for complex systems had no precedent in the work of others in systems theory and OR, and were revolutionary in their implications—on principles for modeling (Forrester 1960, 1968b, 1968c, 1987), on the design of corporations (Forrester 1965), and on the counterintuitive behavior of social systems (Forrester 1971b).

Industrial Dynamics contributed a set of four principles for effective modeling of complex systems: counter-intuitive system behavior is driven by system structure, structure involves non-linear relationships, computer simulation is necessary to explore behavior, and that applying the previous three ideas provides a rigorous yet pragmatic way for managers to improve the design of organizations.

Jay's first principle was that the puzzling (counter-intuitive) behavior of companies, economies, indeed, all systems, whether physical, physiological, economic, or social, emerged endogenously from their structure. That structure includes physical elements such as stocks of inventory, labor, capital, order backlogs; information systems that determined what information was available to each decision maker and the extent to which that information is delayed, smoothed, aggregated, biased, or otherwise corrupted by processes of measurement, reporting, and subjective adjustment; and, most importantly, by the policies and decision processes of the actors at each decision point in the system. He stressed the importance of discovering and representing the mental model of the decision maker. Similar to, but largely independent of, the view of Herbert Simon and his colleagues (Simon 1957, Cyert and March 1963), Jay emphasized that effective models of human systems must capture the bounded rationality of the agents' decision processes. Decision making should be represented in models as it is, warts and all, and not presumed to be the fully rational optimizing behavior of the mythical homo economicus.

Policies and Decisions

"… understanding of decision making has been greatly handicapped by the presumption that it is a more subtle and more sophisticated process than it actually is…. It is my feeling that in a dynamic information-feedback system the human decision maker is usually using a great deal less than the total amount of information available to him. Furthermore, the information available to him is a great deal less than that commonly presumed. In general, his actions with respect to any given decision stream will be almost entirely conditioned by less than ten information inputs."

(Forrester 1961, 100)

The interaction of the physical structure, information flows, and decision processes creates a network of feedback loops that generates the dynamics of the system. People use information about system states such as inventory, labor, order backlogs, and the company's reputation for service quality to make decisions; those decisions then condition production, shipments, hiring, orders, and other rates of flow that alter the system states. These processes form closed loops, some of which constitute control processes (negative feedbacks) such as the loop whereby excessive inventories led firms to cut production below shipments, thus lowering inventory levels. Some form self-reinforcing processes (positive feedbacks), such as the loop whereby customers react to an increase in supplier lead times by increasing their safety stock targets and ordering farther ahead, actions that further deplete supplier inventories and swell order backlogs, causing still longer delivery delays, a process known today as phantom ordering and one that played a major role in the tech bubble of the late 1990s (Sterman 2000).

The second principle is that nonlinearity plays a central role in the dynamics of complex systems. Jay knew from his experience with electromechanical systems that nonlinearities decisively conditioned their structure and behavior. Jay saw that economic and social systems were also intrinsically nonlinear and could not be adequately approximated with linear methods. Structurally, nonlinearities abound in the real world.

Product shipments are generally determined by orders, until inventory is depleted, at which point shipments necessarily fall to zero. Production increases with work hours up to a point, then peaks and falls as fatigue cuts productivity, boosts errors, and triggers accidents. Behaviorally, linear systems cannot exhibit locally unstable behavior and global stability, cannot exhibit bifurcations, endogenous shifts in their modes of behavior, and cannot evolve. Yet, with few exceptions, such as the Lotka-Volterra predator-prey model (Murray 1989), OR, economics, and dynamical theory were dominated at that time by linear models. Linear theory dominated because it was analytically tractable. Even after the computer became widely available, nonlinearity was slow to penetrate these disciplines. Jay designed his modeling method from the start to incorporate nonlinearities easily and intuitively. Subsequent developments have shown the prescience of Jay's focus on nonlinearity (Strogatz 1994, Mosekilde 1996). Physical and social scientists now recognize the intrinsically nonlinear character of physical, biological, and socio-economic systems. Though the terms chaos and self-organization were unknown at the time, Jay's early models are among the first models of human behavior ever developed to exhibit phenomena such as deterministic chaos, self-organization, and increasing returns.

Jay's third principle, that simulation was needed to explore system behavior, led to the development of a practical computer simulation methodology for business, economic and social systems. He and his first students created tools for simulating complex human systems that included diagramming conventions and general purpose computer simulation languages. The first compiler for such simulations, developed by Richard Bennett, was dubbed SIMPLE (Simulation of Industrial Management Problems with Lots of Equations). SIMPLE was followed by DYNAMO (DYNAMic MOdeling), which remained the standard for system dynamics modeling for several decades. Subsequently, the personal computers and graphical user interfaces triggered rapid growth in the number of software packages for dynamic modeling, including iThink, Powersim, Vensim, and many others.

The fourth and perhaps most radical of Jay's innovations was his focus on system dynamics as both a rigorous tool to develop scientific knowledge and a practical tool to improve the performance of organizations. He consistently argued that senior managers should build models to understand and improve their organizations. He believes that a manager's role is not merely captain of the ship but designer of the ship (Keough and Doman 1992). This corporate designer role was an innovative approach to both modeling and management, one he has advocated throughout his career. To carry out rigorous scientific modeling and develop models that made a difference required engagement with the mental models of managers and other stakeholders; while understanding might develop without the active participation of key decision-makers, implementation of new policies could not. There are practical and theoretical links here with recent developments in OR (Lane 1994, 1999). Jay' focus on implementation and the need to engage the decision makers in the modeling process underlies subsequent work on organizational learning (Forrester 1971c, Senge 1990) and the development of protocols for group model building (Lane 1992, Richmond 1997, Vennix 1996, Vennix, Richardson and Andersen 1997).

Management laboratories for enterprise design	**The model versus a modeling process**
“Industrial dynamics is the investigation of the information-feedback character of industrial systems and the use of models for the design of improved organizational form and guiding policy. “It is only through costly experience and errors that managers have been able to develop effective intuitive judgment. We need to expedite this learning process. Other professions in similar circumstances have turned to laboratory experiments .... Controlled laboratory experiments on industrial and economic situations are now possible with computers to do the work .... The manager, like the engineer, can now have a laboratory in which he can learn quickly and at low cost the answers that would seldom be obtainable from trials in real organizations. “Industrial dynamics is an approach that should help in important top-management problems ... The attitude must be one of enterprise design ... . The goal should be to find management policies and organizational structures that lead to greater success.” (Forrester 1961; 13, 43, 449)	“In any real-life applications of modeling to the generation of policy ... the models are always in a continuous state of evolution. Each question, each reaction, each new input of information, and each difficulty in explaining the model leads to modification, clarification, and extension. “I believe we are proposing the 'Process' of modeling rather than particular frozen and final models. The difference in viewpoint becomes especially important as we move into the implementation phase. It seems to me that the average person will be greatly concerned if he feels that the future and alternatives are being frozen once and for all into a particular model. Instead, we are suggesting that models will help to clarify our processes of thought: they will help to make explicit the assumptions we are already making and they will show the consequences of the assumptions. But as our understanding, our assumptions, and our goals change, so can the models. “Rather than stressing the single-model concept, it appears that we should stress the process of modeling as a continuing companion to, and tool, for, the improvement of judgment and human decision making.” (Forrester 1971c)

Developing a Discipline

Throughout the 1960s, Jay and his students applied system dynamics to a growing range of problems through teaching, research, consulting, and practical management applications (Roberts 1978a, Richardson 1996, Sterman 2007). Jay, as a member of the original DEC board of directors, built a series of models examining the growth of high technology start-ups and used them to inform his position on key issues facing the company (Forrester 1964, 1968a, 1975). DEC became the second largest computer firm in the world; much of its early success can be attributed to the policies that Jay—informed by his models—advocated as a member of the board. The corporate growth model included production capacity, inventory, and shipments, financial management, product development and the other key tangible assets and processes. A key aspect of the model, however, was its portrayal of intangible elements such as the knowledge, skills and attitudes of managers, engineers, and salespeople; standards for product quality and the pressures altering them; organizational routines for pricing and resource allocation; and the ability of top management to project its goals throughout the organization (Forrester 2007a). Such intangibles are now known as dynamic capabilities and constitute an active focus of research in strategy (Teece, Pisano, and Shuen 1997). The story of DEC's later demise (long after Jay left the board) is a fascinating tale consistent with many of the dynamics Jay described his early corporate growth models (Schein 2003).

Jay's co-workers went on to contribute to the spread of these ideas. Will Fey taught industrial dynamics as a professor at Georgia Institute of Technology. Ed Roberts became the David Sarnoff Professor at the MIT Sloan School of Management, where he contributed important work applying system dynamics to the management of technology, health care, and public policy (Roberts 1978a, 1978b). He and Jack Pugh founded Pugh-Roberts Associates, the first of many consulting firms to apply industrial dynamics.

Urban Dynamics

Towards the end of the 1960s, Jay and his students began to address public policy issues and the more general term system dynamics replaced industrial dynamics. *Urban Dynamics* (Forrester 1969) was a study of the processes underlying the development, stagnation, decline, and recovery of cities. The project began when the mayor of Boston, John F. Collins, chose not to run for a third term and became a visiting professor at MIT with an office next to Jay's. In the former mayor's struggles with urban problems, Jay recognized the same policy resistance and unintended consequences he had so often observed in corporate contexts. He suggested to Collins that they develop a systems dynamics model of the problem situation. Characteristically, the model was developed not merely by reference to theory, but in conjunction with Collins and others with first-hand experience managing large cities. The model endogenously generated the dynamics of urban growth and stagnation over several hundred years. As the simulated city evolved, population growth, crowding and aging of the housing stock and industrial base gradually shifted the city from an engine of upward mobility to a poverty trap. The model explained why so many policies implemented during the 1960s and 1970s to alleviate urban poverty failed, and in some cases made the problems of the cities and their citizens, particularly the poor, worse. Subsequent events have shown this analysis to be largely correct, but it was enormously controversial at the time. The hostile reactions to the work, as well as examples in which support arose from unexpected quarters, are discussed in Forrester (1992). The key seemed to be spending sufficient time with the model to understand its assumptions and the source of its dynamics and policy insights. The account of Jay's testimony to a U.S. House of Representatives sub-committee on urban growth gives an idea of how he went about explaining his ideas; an edited version was published as "Counterintuitive behavior of social systems" (Forrester 1971b).

Counterintuitive testimony to Congress

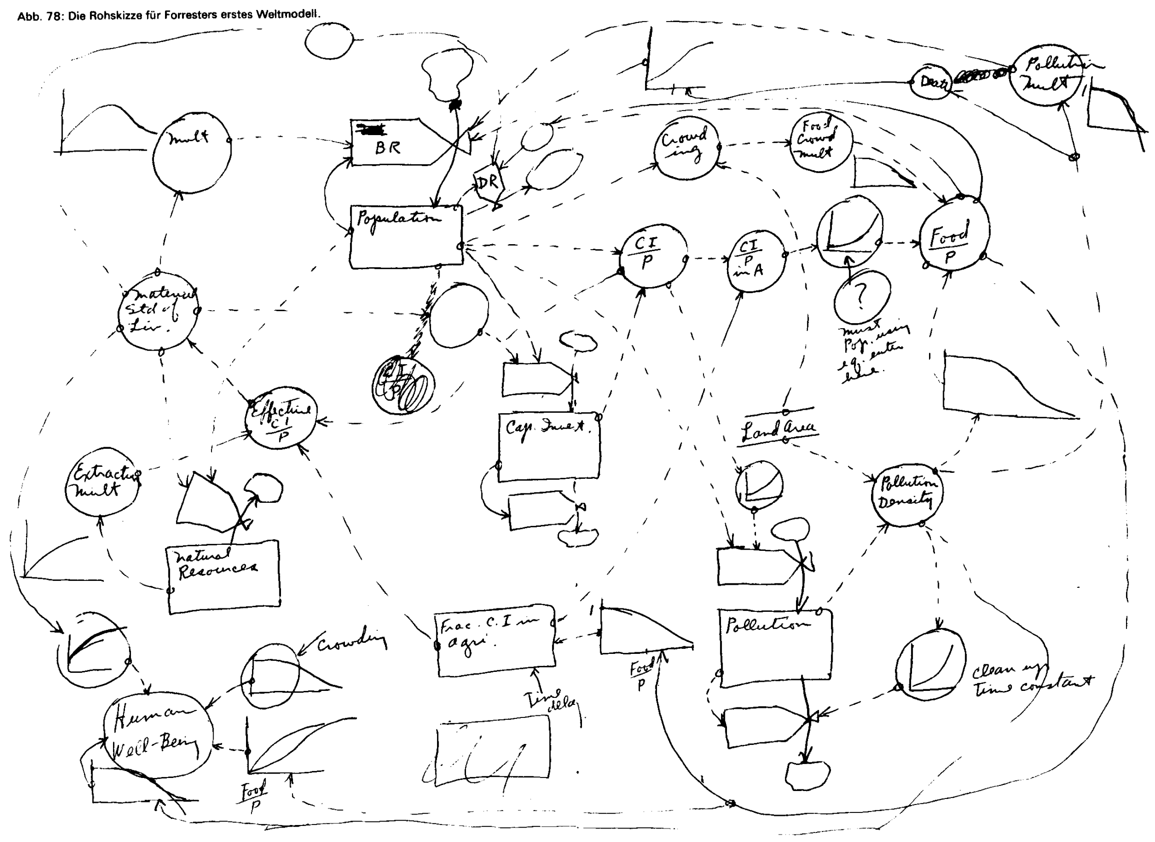
"The nation exhibits a growing sense of futility as it repeatedly attacks deficiencies in our social system while the symptoms continue to worsen. Legislation is debated and passed with great promise and hope. But many programs prove to be ineffective. Results often seem unrelated to those expected when the programs were planned. At times programs cause exactly the reverse of desired results.

> “It is now possible to explain how such contrary results can happen. There are fundamental reasons why people misjudge the behavior of social systems. There are orderly processes at work in the creation of human judgment and intuition that frequently lead people to wrong decisions when faced with complex and highly interacting systems.
>
> “People would never attempt to send a space ship to the moon without first testing the equipment by constructing prototype models and by computer simulation of the anticipated space trajectories. No company would put a new kind of household appliance or electronic computer into production without first making laboratory tests. Such models and laboratory tests do not guarantee against failure, but they do identify many weaknesses which can then be corrected before they cause full-scale disasters.
>
> “Our social systems are far more complex and harder to understand than our technological systems. Why, then, do we not use the same approach of making models of social systems and conducting laboratory experiments on those models before we try new laws and government programs in real life? The answer is often stated that our knowledge of social systems is insufficient for constructing useful models. But what justification can there be for the apparent assumption that we do not know enough to construct models but believe we do know enough to directly design new social systems by passing laws and starting new social programs?”
>
> (Forrester 1971b, 52-53).

World Dynamics

In 1970, Jay began work with the Club of Rome to apply system dynamics to perhaps the most important issues of social policy: the dynamics of global development. (“The Club of Rome is independent of any political, ideological and religious interests. Its essential mission is ‘to act as a global catalyst for change through the identification and analysis of the crucial problems facing humanity and the communication of such problems to the most important public and private decision makers as well as to the general public’ ” (Club of Rome 2009). Jay developed a model capturing feedbacks among population, natural resources, pollution, agricultural and industrial production, capital investment, and quality of life.

The resulting book, *World Dynamics* (Forrester 1971a), posed sharp questions about the relationship between growth and quality of life, generating heated discussion in popular and scholarly forums worldwide. *World Dynamics* led to a more detailed modeling study directed by Dennis Meadows, who had just received his Ph.D. under Jay and had joined the MIT faculty. Described in *The Limits to Growth* (Meadows et al. 1972), that study triggered worldwide controversy and debate (Forrester, Low, and Mass 1974). More important, because the world models were fully documented and easily replicated, they led to a wide range of critiques and extensions (Meadows, Meadows, and Randers 1992, 2004; Meadows, Richardson, and Bruckman 1982).



Jay’s first sketch of the world model (German edition of *World Dynamics*).

With this stream of work, Jay launched the field of global modeling (de Steiguer 1997), an activity that also provoked storms of criticism. His willingness to endure it seems to stem from a refusal born of intellectual courage to deny the consequences of one’s analysis. Whether, for example, asking hard questions about the role of churches in influencing population growth (Forrester 1973), or questioning the assumption that unending economic growth is both desirable and necessary (Forrester 1971a, 1971b). Consequently, Jay drew the wrath of left and right, conservatives and progressives, often at the same time. His work has been instrumental in shaping public thinking on the interactions among the environment, development, pollution, and natural resources. The economist, Paul Ormerod, commenting on the contribution of *World Dynamics* and *Limits to Growth*, observed that its “true and lasting significance ... was the development of a fundamentally different approach to understanding the workings of the economy to that of orthodox economics” (Ormerod 1994, 36).

Developments in the more than 35 years since the publication of *World Dynamics* have only underscored the importance of Jay’s insights. Perpetual growth of population and material production on a finite planet is impossible. Long time delays in the response of the economy and technology to resource scarcity and environmental degradation cause human activity to overshoot the carrying capacity of the planet. Research, unavailable when Jay formulated his world model, now shows clearly that humanity has already overshot the global carrying capacity and is rapidly consuming and degrading the natural capital stocks upon which our civilization depends, from groundwater to soils to fish stocks to the climate (Wackernagel et al. 2002; Meadows, Meadows, and Randers 2004). An article (*Wall Street Journal* 2008), headlined, "New limits to growth revive Malthusian fears," observed that, "the resource constraints foreseen by the Club of Rome are more evident today than at any time since the 1972 publication of the think tank's famous book, *The Limits of* [sic] *Growth*." Yet Jay's most important insight in *World Dynamics* is not about how much oil remains in the ground, how much CO_2 we can dump into the atmosphere, or the potential for technology to find alternative energy sources or reduce pollution. It is that there is no purely technical solution to the challenge of creating a sustainable society. Technological innovation, market forces, and government policies are all aimed at ameliorating the symptoms of stress—pushing back the limits to growth by finding more energy, reducing greenhouse gas emissions, irrigating marginal lands and designing new cultivars to boost food production, thus allowing growth to continue until another limit is reached. In a series of email posts to the system dynamics community discussion list (Forrester 2008), Jay stated "obvious and self-evident courses of attacking symptoms rather than underlying causes will be futile….[T]reating one symptom can unleash a different overwhelming reaction." "[G]rowing population and industrialization will overwhelm the short-term efforts if we do not restrain these forces that are exceeding the carrying capacity of the earth."

To The Present

System dynamics began to coalesce into an academic field in the 1970s. Programs were started at universities in the U.S. and around the world. Conferences were organized and textbooks written. The System Dynamics Society was created in 1983, with Jay its first president. A dedicated journal was created, the modern form of which, *The System Dynamics Review*, appeared in 1985. In the following year, IBM's Thomas Watson, Jr. endowed the Jay W. Forrester Chair in Management at MIT. In his book, *The Fifth Discipline,* Peter Senge (1990) explored the relationship between system dynamics and organizational learning, attracting a new generation of managerial interest. The MIT System Dynamics Group continues research into a wide range of complex systems issues, from organizational change to climate change. System dynamics is one of the most popular electives at the MIT Sloan School of Management, attracting over 400 students per year (compared to an MBA program of about 375 per year). Jay's students and those he inspired, including the authors of this profile, went on to found or lead academic programs in system dynamics around the world (Sterman 2007).

Over the years, Jay remained active and began a large modeling study of economic dynamics, which integrated endogenous accounts of business cycles, inflation and stagflation, the growth of government, and the great waves of economic expansion and depression (Forrester 1977, 1979, 1980; Forrester, Mass, and Ryan 1976; Sterman 1985).

Jay formally retired from the MIT Sloan School in 1989, an event which he said "has had no effect whatsoever on my work" (Forrester, 1997). Ever focused on the high leverage points to foster enduring change, he has for some years devoted most of his time to catalyzing the education of young people in the principles of systems (Forrester 1990, 1993). Interest in the education of young people and how they could learn systems thinking is a long-established area of application for system dynamics (Roberts 1978b). A new wave of experiments to develop the systems thinking and modeling capabilities of young people began in the late 1980s when a then-retired Gordon Brown introduced Tuscon, Arizona middle school teacher Frank Draper to system dynamics. The enthusiastic response of Draper and his students was the creation of the K-12 project and the introduction of dynamic modeling in schools throughout the United States (Creative Learning Exchange 2009).

Consistent with his early focus on engaging managers in the modeling process, Jay not only believes young people should and can learn system dynamics and modeling, but calls for a revolution in pedagogy as well. He believes that effective education requires learner-directed learning in which teachers are not the source of answers but guides and coaches who help learners develop the inquiry skills they will need to become systems citizens (Creative Learning Exchange 2009). The theory of political and social change these beliefs represent is fundamentally optimistic, hopeful and empowering. It is a view that, if begun early enough, everyone can gain an appreciation for the complex dynamics of natural and human systems, and then use that insight to design policies to create a better world.

Legacy and the Next Frontier

In person, Jay is quiet, imposingly tall and faultlessly courteous. He speaks slowly and confidently, producing analyses of a complexity seldom found in conversation. He is direct and unambiguous with both praise and criticism. He is also often hospitable and convivial, happy to enjoy a joke and quick to share humorous stories himself.

He speaks of his parents, Gordon Brown, and his wife Susan as those to whom he feels most indebted. His discharging of this debt has produced work the legacy of which is immense.

Along with other pioneers of computer science, Jay’s innovations in hardware, software, and computer simulation ushered in the digital age. Simulation is now used routinely throughout the natural and social sciences, hailed as a third branch of science, standing alongside theory and experiment as a unique and vital method to advance human knowledge (Pool 1992).

The field of system dynamics is healthy and growing. System dynamics is increasingly used in corporations, government and other organizations. It is taught in a growing number of universities and schools. It is applied to issues from organizational change to climate change, from physiology to fiscal policy. On a lighter note, *Urban Dynamics* inspired video game designer Will Wright to create SimCity (Seabrook 2006). Only a few years ago, simulation was difficult, expensive, and scarce. Today children in elementary school routinely create and manage simulated worlds of stunning complexity through interactive computer games. Of course system dynamics is much more than a method for computer simulation, more than mathematical models grounded in control theory and nonlinear dynamics. It is also a practical tool policy makers use to help solve important problems. It is qualitative and quantitative, hard and soft, a theoretical discipline and a pragmatic approach for group modeling and policy design. Key concepts of system dynamics, including feedback, counterintuitive behavior, limits to growth, nonlinearity, tipping points, and many others are now integrated into the discourse of management, social theory and everyday life. Discussions of critical public policy issues routinely refer to unintended consequences and policy resistance. Scientists, policymakers and the media discuss the many positive feedbacks that can cause runaway climate change and debate whether we have passed the tipping point leading to irreversible melting of polar ice sheets.

Yet Jay, ever questing, ever focused on the important problems, is not satisfied. Speaking at the 2007 International System Dynamics Conference celebrating the 50th anniversary of the founding of the field, Jay, rather than reviewing the achievements of a half-century, challenged the field to move boldly into the next frontier, to tackle the most important problems no matter their difficulty:

> The first 50 years of system dynamics have established an introduction to the field. We have shown the importance of achieving a better understanding of complex systems in nature and human affairs. Now, the field is on a plateau ready to launch the next great thrust forward. … We are now at about the same state of advancement that engineering was when MIT first opened its doors in 1865. … System dynamics started 50 years ago with academic programs that focused on the outside world with emphasis on major issues outside of academia. However, the pressures inherent in academic institutions are driving our field back into academic journals and away from the public that we should be serving. … System dynamicists must go behind the symptoms of trouble and identify the basic causes. At first, such arguments will be met with disbelief, scorn, and ridicule. To prevail, the battle must be sustained until public understanding begins to change" (Forrester 2007b, 359-360, 370).

No one should be surprised. From the Sand Hills of Nebraska to the MIT servo-mechanism laboratory, from the Marshall Islands to the dawn of the computer age, from *Industrial Dynamics* to *World Dynamics*, from corporate boardrooms to elementary school classrooms, Jay Wright Forrester has lived his entire life on the frontier.

On the Frontier	On His Way
 Jay Wright Forrester, 1940 © JWF	 Jay at a celebration of the 100th anniversary of the MIT Electrical Engineering Department in 2003. He stands on a Segway, a nonlinear dynamic system of sensors, servos, and real-time digital feedback controls, directly descended from innovations Jay helped pioneer. Photo: Dan Bricklin. All rights reserved.

Honors and Awards

Jay is a Member of National Academy of Engineering, a Fellow of the IEEE, the American Academy of Arts and Sciences, Academy of Management, and the Royal Society of Arts (London). His honors include: Medal of Honor, IEEE; Systems, Man, and Cybernetics Award for Outstanding Accomplishment, IEEE; Howard N. Potts Medal, The Franklin Institute; Inventor of the Year, George Washington University; U.S. National Medal of Technology; Pioneer Award, IEEE Aerospace and Electronic Systems Society; Valdemar Poulsen Gold Medal, Danish Academy of Technical Sciences. He was inducted into the IFORS' Operational Research Hall of Fame (Lane 2006). Jay has received honorary Doctorate of Engineering degrees from the University of Nebraska, Newark College of Engineering, and the University of Notre Dame; and honorary Doctorate of Science degrees from Boston University and Union College. He also received honorary doctorate degrees from the University of Mannheim (Political Science), State University of New York (Humane Letters), University of Bergen (Dr. Philosophy), and the Universidad de Sevilla (Honoris Causa).

David C. Lane

John D. Sterman

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Acronyms

ASCA	Airplane Stability and Control Analyzer
EDVAC	Electronic Discrete Variable Computer
ENIAC	Electronic Numerical Integrator and Computer
D-Memos	Dynamic Modeling Memos
DEC	Digital Equipment Corporation
DYNAMO	DYNAMic MOdeling
IEEE	Institute of Electrical and Electronics Engineers
GE	General Electric Corporation
MIT	Massachusetts Institute of Technology
OR	Operations Research/Operational Research
SAGE	Semi-Automatic Ground Environment
SIMPLE	Simulation of Industrial Management Problems with Lots of Equations