Chapter 10
Jay Forrester

Jay Wright Forrester was an American engineer and management thinker. He founded System Dynamics, an approach based on computer modelling which arguably has done more than any other method to provide a practical and realistic analysis of change processes in systems. System Dynamics (SD) has been taken up across the world, initially by Forrester's students and colleagues, but increasingly by a much wider community. It has had profound and influential applications in a range of fields, most prominently organisational management, urban planning and environmental policy. Forrester summed up his concerns and his understanding of SD in an 'elevator pitch' (a statement short enough to be spoken in an elevator ride) on an email list:

> System dynamics deals with how things change through time, which includes most of what most people find important. It uses computer simulation to take the knowledge we already have about details in the world around us and to show why our social and physical systems behave the way they do. System dynamics demonstrates how most of our own decision-making policies are the cause of the problems that we usually blame on others, and how to identify policies we can follow to improve our situation. (Forrester 1997)

Jay Forrester was born in 1918 in rural Nebraska, in the midwestern United States, and died in 2016 near Boston. He grew up on a cattle ranch where he had the experience that "in an agricultural setting, life must be very practical. It is not theoretical; nor is it conceptual without purpose. It is full-time immersion in the real world" (Forrester 2007a, p. 345). Although he considered continuing in agriculture, he took his undergraduate degree in electrical engineering at the University of Nebraska, graduating in 1939. This study gave him a further important lesson – in his view electrical engineering was "about the only academic field with a solid, central core of theoretical dynamics" (Forrester 2007a, p. 345).

These two aspects of his character – a focus on results and on being practical combined with a theoretical interest in dynamics – shaped his work throughout his life. Two colleagues described him after his death as "faultlessly courteous. He was direct and unambiguous with criticism and praise. He was also hospitable and

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convivial, enjoying a good joke and quick to share humorous stories himself" (Lane and Sterman 2018, p. 96).

In 1939, Forrester moved to the Massachusetts Institute of Technology, where he spent his entire career, formally retiring in 1989. His initial work was in the Servomechanisms Laboratory, founded by Gordon Brown who was to become his mentor over 50 years, "substantially responsible for helping me develop my career" (Forrester 1996, p. 350). Brown was Forrester's employer as a research assistant during the years of the Second World War; he supervised Forrester's Masters thesis (passed in 1945); and it was even through Brown that Forrester met his wife, Susan. Moreover, the "feedback system theory that I learned in his Servomechanisms Laboratory became the foundation for the field of system dynamics" (Forrester 1996, p. 350).

Servomechanisms are mechanical devices which control the behaviour of a larger system through feedback. A classic example is the thermostat controlling the boiler of a heating system. During the war, Brown and Forrester worked on servomechanisms to control the behaviour of radar antennae and gun mounts. Following the war, Forrester began work on the design of an early aircraft flight simulator. The simulator was intended to be based on an analogue computer, but ended up as one of the very first digital computers, Whirlwind, which in due course evolved into SAGE (Semi-Autonomous Ground Environment), an air defence system.

Whirlwind, for which Forrester was project leader (it began operation in 1951), was ground-breaking: it was the first digital computer to operate in real time and to use video displays for output. A further important innovation in the Whirlwind project was Forrester's invention of magnetic core memory, for many years the dominant form of computer memory and for which he held the patent along with MIT, making him quite wealthy (Buck and Dey 2018). A key employee on this work was Ken Olsen, the founder of Digital Equipment Corporation, on whose board Forrester served for many years.

By 1956, Forrester felt that "the pioneering days in digital computers were over" (Forrester 1989, p. 4). He remained at MIT but moved to its School of Management. This was less of a large shift than it might seem – as head of the Whirlwind project, he had already experienced several years as a manager of a very large scale project, involving negotiation and contracting with several partner organisations. His initial goal in moving to the School of Management was to apply the lessons he had learned about technology to issues of management. In doing so he created the field of system dynamics.

Forrester's first study involved fluctuations in levels of sales, inventory and employees in household appliances at General Electric (GE). The company was going through inexplicable cycles, apparently unrelated to normal business demand, where sometimes their workers would be terribly over-stretched and at other times the company would have to sack people. Forrester was able to model the cycles and observe that they created positive feedback loops arising from delays in interactions between different departments of the company. Initially he modelled these using paper and pencil, but he was convinced of the importance of computers for enhancing management decision-making, and as part of the project a colleague built a compiler that allowed the direct entry of the feedback equations into a computer. This compiler later developed into DYNAMO, which was used for many years as the basis of simulation models within system dynamics. The model of GE's inventory control, and especially the delay between different departments, was later re-expressed in terms of beer production by Forrester's graduate students and became the basis of a classic simulation game used in many introductory courses, the MIT Beer Game.

Forrester published his first results as an article in the *Harvard Business Review* (Forrester 1958), later expanded to a book (Forrester 1961) – both with the title of 'Industrial Dynamics' which served as the name of the field for its first decade. As he presented it, the work rests on four foundations: feedback control theory, an understanding of decision-making processes, simulation, and the use of digital computers to enable mathematical modelling. Of these, he believed the first to be the most important, directly arising from work on servomechanisms. He wrote that from this theory we learnt about "the effect of time delays, amplification, and structure on the dynamic behaviour of a system … [and] that the interaction between system components can be more important the components themselves" (Forrester 1961, p. 14).

The first 10 years of work on system dynamics resulted in a solid theoretical core which continues to be the basis of the field to this day. In 1968, Forrester published a textbook which outlined the main concepts and methods of system dynamics (Forrester 1968a). He was very clear that SD was driven by the *structure* of systems and that the structure was described by a set of interlocking feedback loops. Importantly, "a model of a system is formulated by starting with the loop structure, not by starting with components of loops" (Forrester 1968b, p. 407). The interaction between these loops produces the behaviour of the system.

SD's strong emphasis on feedback and control suggests close parallels with cybernetics, and indeed the early development of both approaches was largely done at MIT. However, it is clear from Forrester's account that he took his understanding of feedback from quite different sources, largely that of servomechanisms, and had no connection with cybernetics. Richardson (1991) identifies two parallel threads of the use of feedback ideas in social sciences (the servomechanisms thread and the cybernetics thread) with important distinctions, placing Forrester along with a number of economists who applied feedback in their work, most notably Herbert Simon who later won the Nobel prize for his work on management decision-making. In particular, Richardson argues that those in the cybernetics thread treat feedback as a "tool for controlling systems in the face of [external] disturbances" while those in the servomechanisms thread see feedback loops "as an internal aspect of the structure of social systems" (Richardson 1991, p. 164).

In the late 1960s, Forrester and his colleagues (by then a well-established group at MIT) began to branch out to other fields beyond management. This was especially inspired by the outgoing mayor of Boston becoming a 1 year visiting professor at MIT, with an office next to Forrester's. Through this contact, Forrester became interested in the modelling of urban issues, and was able to assemble a group of those who understood the nature and problems of cities. The result was a detailed

SD model of a city, published in the book *Urban Dynamics* (Forrester 1969). The book's conclusion was controversial: "that all of the major urban policies that the United States was following lay somewhere between neutral and highly detrimental, from the viewpoint either of the city as an institution, or from the viewpoint of the low-income, unemployed residents" (Forrester 1989, p. 8). Its methodology was no less controversial – instead of drawing upon existing literature on urban planning, it worked entirely from a computer model. The book tended to polarise opinions, some very positive and others very negative. The ideas in Forrester's book were later taken up (in the late 1980s) as the basis for a highly successful computer game, SimCity, which simulated the behaviour of a number of cities and allowed players to control aspects of their design and management.

Forrester's urban modelling also led directly to the most famous application of SD, the modelling of the world economy and ecosystem. This work was carried out through the Club of Rome, an informal and small group of influential people in business, academia and politics, founded by Aurelio Peccei, an Italian business executive. Learning of Forrester's urban work, Peccei invited him to join the Club and to attend a meeting in Switzerland in 1970. The Club had been offered a grant from the Volkswagen Foundation if they could propose a clear research project to tackle what they called the '*problématique humaine*': the interlocking issues of global population, crime, pollution, resource depletion, terrorism etc. (Kleiner 1996). Forrester proposed the development of an SD model of these interlocking global issues, and invited the Club to visit MIT to explore the approach and its potential. The bulk of the modelling work was carried out within the MIT SD group by a team led by one of Forrester's former students, Dennis Meadows. Forrester wrote a further book based on this work, *World Dynamics* (Forrester 1971) which was a surprise bestseller and highly controversial, even being reviewed on the front pages of some newspapers; the more popular book which followed, *Limits to Growth* (Meadows et al. 1972) sold still better and was still more controversial. This work is discussed in greater depth in the chapter on Donella Meadows. It was during the Club of Rome project that Forrester's group started to use the term 'system dynamics' rather than 'industrial dynamics', given that the focus of the work was much broader than industrial applications (Meadows 2002).

The modelling work on the Club of Rome project was often criticised for the poor-quality data used to shape its conclusions. This was partly due, as Edwards (2010) argues, to a lack of availability of good-quality long-term data sources on issues such as pollution, industrial output and non-renewable resource use. However, more widely it relates to Forrester's preference, as discussed earlier, for taking a structural rather than a statistical approach to modelling. In later work on a 'National Model' of the US economy, Forrester argued strongly that "inadequacies of economic analysis can be substantially attributed to inappropriate and biased use of available information [such as] overemphasis on finding statistical relationships between economic variables and underemphasis on the internal causal mechanisms that produce economic behavior" (Forrester 1980, p. 555). This work on the National Model was the subject of a number of years of work and publications, but did not have the same influence as Forrester's earlier work.

System dynamics has had considerable impact on practical issues in the areas of management, urban planning and environmental change. The approach often uses a deeply rigorous approach, but its practical impact has been less than might be expected, particularly in addressing social concerns. Forrester (2007b, p. 361) himself asked, 50 years after the start of his work, "Why is there so little impact of system dynamics in the most important social questions? It is because we have not yet taken the steps that would earn us a role in the great issues." In a similar vein 10 years later, Forrester's successor as head of the SD group at MIT, John Sterman, argued that "impact that leads to sustained improvement requires both effective implementation methods and models that yield reliable, rigorous, evidence-based recommendations" (Sterman 2019, p. 40).

Towards the end of his working life and throughout his retirement, Forrester actively pursued the use of SD in education at all levels, with a particular interest in teaching it to school-children. He held the view that "if begun early enough, everyone can gain an appreciation for the complex dynamics of natural and human systems, and then use those insights to create a better world" (Lane and Sterman 2018, p. 96), and this approach led to the successful teaching of system dynamic modelling in a number of school settings (Fisher 2018).

Two other aspects of Forrester's further development of SD are especially interesting. First, he actively led a large research group at MIT for almost 50 years, during which time the group produced almost 5000 working papers. However, Forrester made no attempt to create an 'official' version of system dynamics to the exclusion of others' ideas. In fact, the ownership of SD as a field is now held by the System Dynamics Society, founded as an international society in 1983 and now with more than 1100 members in 75 different countries (at time of writing). This society holds an annual conference and publishes a successful journal. Forrester was its founding president, and is recognised and honoured as the founder of the field, but his voice became only one of many.

The second striking aspect of Forrester's later work was his treatment of models. Computer-based modelling is central to system dynamics, and the chief criticisms of the field often arise from this, assuming that the models are used in a simplistic way. Forrester took a realist position on model-building, explicitly positioning himself against Peter Checkland's interpretivist view and arguing that "in system dynamics, we have a set of principles, incomplete as they may be, that I believe do represent the actual nature of physical and social reality" (Forrester 1994, p. 250). There are subtler issues involved, however. As SD has developed, it has become clear that the modelling *process* is as important as the resulting model. As Sterman (2002, p. 521) has written, citing a much earlier paper of Forrester's, "because all models are wrong, we reject the notion that models can be validated in the dictionary definition sense of 'establishing truthfulness', instead focusing on creating models that are useful … we argue that focusing on the process of modelling rather than on the results of any particular model speeds learning and leads to better models, better policies, and a greater chance of implementation and system improvement". Given this attitude to modelling, Lane has argued that it is meaningless to situate SD as a 'hard systems thinking' approach; rather it has a "much more participative and contingent relationship between a model and those working with it" (Lane 2000, p. 18).

In creating system dynamics, Jay Forrester built more than a method or theory – he created a whole new form of thinking. While focused on computer-based modelling and thus expert-driven, it is highly practical and oriented towards real change in real situations. As Morecroft and Homer (2007, p. 20) have written, Forrester has "established for [system dynamics] an analytic paradigm that combines boldness and broad vision with rigor and depth". In doing so he has made a great and long-lasting contribution.

Reading from Forrester's work

Forrester, Jay Wright 1975 from "Counterintuitive Behaviour of Social Systems", in Chapter 14 of *Collected Papers of Jay W. Forrester*. Waltham, MA: Pegasus Communications.

Computer Models of Social Systems

People would never send a space ship to the moon without first testing prototype models and making computer simulations of anticipated trajectories. No company would put a new household appliance or airplane 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 be corrected before they cause full-scale disasters.

Social systems are far more complex and harder to understand than technological systems. Why then do we not use the same approach of making models of social systems and conducting laboratory experiments before adopting new laws and government programs? The customary answer assumes that our knowledge of social systems is not sufficient for constructing useful models.

But what justification can there be for assuming that we do not know enough to construct models of social systems but believe we do know enough to directly redesign social systems by passing laws and starting new programs? I suggest that we now do know enough to make useful models of social systems. Conversely, we do not know enough to design the most effective social policies directly without first going through a model-building experimental phase. Substantial supporting evidence is accumulating that proper use of models of social systems can lead to far better systems, laws, and programs.

Realistic laboratory models of social systems can now be constructed. Such models are simplifications of actual systems, but computer models can be far more comprehensive than the mental models that would otherwise be used.

Before going further, please realize that there is nothing new in the use of models to represent social systems. Each of us uses models constantly. Every person in private life and in business instinctively uses models for decision making. The mental images in one's head about one's surroundings are models. One's head does not contain real families, businesses, cities, governments, or countries. One uses selected concepts and relationships to represent real systems. A mental image is a model. All decisions are taken on the basis of models. All laws are passed on the basis of models. All executive actions are taken on the basis of models. The question is not to use or ignore models. The question is only a choice among alternative models.

Mental models are fuzzy, incomplete, and imprecisely stated. Furthermore, within a single individual, mental models change with time, even during the flow of a single conversation. The human mind assembles a few relationships to fit the context of a discussion. As debate shifts, so do the mental models. Even when only a single topic is being discussed, each participant in a conversation employs a different mental model to interpret the subject. Fundamental assumptions differ but are never brought into the open. Goals are different but left unstated.

It is little wonder that compromise takes so long. And even when consensus is reached, the underlying assumptions may be fallacies that lead to laws and programs that fail. The human mind is not adapted to understanding correctly the consequences implied by a mental model. A mental model may be correct in structure and assumptions but, even so, the human mind – either individually or as a group consensus – is apt to draw the wrong implications for the future.

Inability of the human mind to use its own mental models becomes clear when a computer model is constructed to reproduce the assumptions contained in a person's mental model. The computer model is refined until it fully agrees with the perceptions of a particular person or group. Then, usually, the system that has been described does not act the way the people anticipated. There are internal contradictions in mental models between assumed structure and assumed future consequences. Ordinarily assumptions about structure and internal governing policies are more nearly correct than are the assumptions about implied behavior.

By contrast to mental models, system dynamics simulation models are explicit about assumptions and how they interrelate. Any concept that can be clearly described in words can be incorporated in a computer model. Constructing a computer model forces clarification of ideas. Unclear and hidden assumptions are exposed so they may be examined and debated.

The primary advantage of a computer simulation model over a mental model lies in the way a computer model can reliably determine the future dynamic consequences of how the assumptions within the model interact with one another. There need be no doubt about a digital computer accurately simulating the actions that result from statements about the structure and policies in a model.

In some ways, computer models are strikingly similar to mental models. Computer models are derived from the same sources; they may be discussed in the same terms. But computer models differ from mental models in important ways.

Computer models are stated explicitly. The ‘mathematical’ notation used for describing the computer models is unambiguous. Computer simulation language is clearer, simpler, and more precise than spoken languages. Computer instructions have clarity of meaning and simplicity of language syntax. Language of a computer model can be understood by almost anyone, regardless of educational background. Furthermore, any concept that can be clearly stated in ordinary language can be translated into computer-model language.

There are many approaches to computer models. Some are naive. Some are conceptually inconsistent with the nature of actual systems. Some are based on methodologies for obtaining input data that commit the models to omitting major relationships in the psychological and human areas that we all know to be crucial. With so much activity in computer models and with the same terminology having different meanings in the different approaches, the situation is confusing to a casual observer. The key to success is not in having a computer; the important thing is how the computer is used. With respect to models, the key is not to computerize a model, but, instead, to have a model structure and decision-making policies that properly represent the system under consideration.

I am speaking here of system dynamics models – the kind of computer models that are only now becoming widely used in the social sciences. System dynamics models are not derived statistically from time-series data. Instead, they are statements about system structure and the policies that guide decisions. Models contain the assumptions being made about a system. A model is only as good as the expertise which lies behind its formulation. A good computer model is distinguished from a poor one by the degree to which it captures the essence of a system that it represents. Many other kinds of mathematical models are limited because they will not accept the multiple-feedback-loop and nonlinear nature of real systems.

On the other hand, system dynamics computer models can reflect the behavior of actual systems. System dynamics models show how difficulties with actual social systems arise, and demonstrate why so many efforts to improve social systems have failed. Models can be constructed that are far superior to the intuitive models in people’s heads on which national social programs are now based.

System dynamics differs in two important ways from common practice in the social sciences and government. Other approaches assume that the major difficulty in understanding systems lies in shortage of information and data. Once data is collected, people have felt confident in interpreting the implications. I differ on both of these attitudes. The problem is not shortage of data but rather inability to perceive the consequences of information we already possess. The system dynamics approach starts with concepts and information on which people are already acting. Generally, available information about system structure and decision-making policies is sufficient. Available information is assembled into a computer model that can show behavioral consequences of well-known parts of a system. Generally, behavior is different from what people have assumed.

Counterintuitive Nature of Social Systems

Our first insights into complex social systems came from corporate work. Time after time we went into corporations that were having severe and well-known difficulties. The difficulties would be obvious, such as falling market share, low profitability, or instability of employment. Such difficulties were known throughout the company and were discussed in the business press.

One can enter a troubled company and discuss what people see as the causes and solutions to their problems. One finds that people perceive reasonably correctly their immediate environments. They know what they are trying to accomplish. They know the crises which will force certain actions. They are sensitive to the power structure of the organization, to traditions, and to their own personal goals and welfare. When interviewing circumstances are conducive to frank disclosure, people state what they are doing and can give rational reasons for their actions. In a troubled company, people are usually trying in good conscience and to the best of their abilities to help solve the major difficulties. Policies are being followed that they believe will alleviate the difficulties. One can combine the stated policies into a computer model to show the consequences of how the policies interact with one another. In many instances it emerges that the known policies describe a system which actually causes the observed troubles. In other words, the known and intended practices of the organization are sufficient to create the difficulties being experienced. Usually, problems are blamed on outside forces, but a dynamic analysis often shows how internal policies are causing the troubles. In fact, a downward spiral can develop in which the presumed solutions make the difficulties worse and thereby cause greater incentives to redouble the very actions that are the causes of trouble.

The same downward spiral frequently develops in government. Judgment and debate lead to a program that appears to be sound. Commitment increases to the apparent solution. If the presumed solution actually makes matters worse, the process by which degradation happens is not evident. So, when the troubles increase, the efforts are intensified that are actually worsening the situation.

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