Author's Notes:

The Power of the Bond Between Cause and Effect (Full version):

Jay Wright Forrester and the Field of System Dynamics

Full version of the article published in *System Dynamics Review* **23**(2-3)

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Content

This is a longer version of an article published in the *System Dynamics Review* in 2007, see Lane (2007). Although there are numerous places where the text expands on the published version, there are four main points of additional information:-

1. The drawing of the parallel between the defence systems work by Forrester, Blackett and Archimedes.
2. A 'perspectives' section; which treats the links between system dynamics and the fields of system science, the links between group modelling in system dynamics and 'problem structuring methods', and the institutional relationships between system dynamics and operational research.
3. An appendix; which provides a one page biography of the key biographical facts of Forrester's life so far and also aspires to be a comprehensive record of the various form of recognition (including his awards and honours) afforded him. The short format is intended to make this an easily accessible resource for the field.
4. The illustrations; the original photographs have been enlarged and additional ones have been included. Some of the photograph captions are quotations from emails which Forrester sent to the author when providing the photographs.

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David C. Lane
London, February 2008

The Power of the Bond Between Cause and Effect (Full version): Jay Wright Forrester and the Field of System Dynamics[1]

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Abstract
This article presents a treatment of Jay Wright Forrester's life and achievements. The concentration is on the intellectual provenance of system dynamics, its emergence and growth, and its links with the other disciplines such as systems science and operational research, as well as the nature of the man whose accomplishments these are.

Introduction

The name Jay Wright Forrester needs no introduction for most people consulting the website of the System Dynamics Society. However, whilst Society members celebrate the fiftieth anniversary of the field that he founded, it is worth remarking that we system dynamicists are not alone in noting his achievements. Over the span of his long career Forrester has been the recipient of many prizes, awards and honours (see Appendix 1). The list of institutions and associated disciplines offering these acknowledgements is impressive – and the list still grows. For example, Forrester's work is now seen as part of the history of OR (Gass & Assad 2006) and he was inducted into the International Federation of OR Societies' Operational Research Hall of Fame in 2006.[2]

As part of the celebration of our field's foundation, this article offers an account of the life and work of Forrester. The trail that leads to the creation of system dynamics may seem winding. In 1956 he patented coincident-current magnetic core memory – what is the

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2. The IFORS OR Hall of Fame "celebrate[s] the significant contributions made by the OR pioneers" and it has 23 members. The induction was announced in July 2006 at the international conference of the System Dynamics Society in Nijmegen, The Netherlands. Induction is accompanied by the publication of a biography of the honoured individual (Lane 2006). For further information on the scheme go to http://www.ifors.org/hall/

relevance to policy modelling? His creation and development of system dynamics occurred after this date, so can the previous activities be ignored? No. The stark intellectual division which mere chronology might indicate is a mirage. In fact, the achievements across his entire career can be seen to possess a unity. System dynamics is very much a path-dependent creation and that whole path merits understanding and celebration.

Two caveats are necessary. First, an apology in advance for the exclusions; for the missing anecdotes (I am aware that there are many) but more seriously for any aspect of the field or any of its personalities that some might consider under-represented. Pages are finite and choices must be made. In such situations one can only struggle to fulfil Goethe's maxim: "In der Beschränkung zeigt sich erst der Meister". Second, this account is that of a system dynamicist. The range of Forrester's research contributions is great and one can quite imagine different accounts of his achievements which concentrate on, say, Forrester the servo-mechanism engineer, Forrester the computing pioneer, Forrester the defence systems innovator etc. His contributions to those other areas are certainly included here but this commentary focuses on his creation of the field of system dynamics – as is right and proper for this celebratory edition of the *Review*.

Figure 1
Forrester's father, photographed around 1940.
"This is a picture of my father, Marmaduke (Duke) Montrose Forrester in his favorite setting with horse and cattle. This was his life. He taught school in his early days just to make some money. He was a homesteader, the first private owner of the land where I grew up. We are that close to the American frontier."
© JWF.

Figure 2
Forrester's mother, photographed around 1940.
"This is a picture of my mother, Ethel Wright Forrester, probably around 1940."
© JWF.

The Trail to System Dynamics

A Nebraska Ranch, a Massachusetts Laboratory

Jay Wright Forrester was born on 14th July 1918 on a cattle ranch near Climax, Nebraska, USA[3] to Ethel Pearl Wright Forrester (1886-1958) and Marmaduke ("Duke") Montrose Forrester (1883-1975). His father was a graduate of Hastings College, Nebraska, which his mother also attended. Arriving around 1910, they became the first private owners of the ranch-land. They built a concrete-block ranch house. Forrester has said, "Almost all other homesteader houses in the community … when this house was built were made of native sod. Ours was very much the exception with indoor plumbing and running water. As I understand it, my mother would not agree to be married unless she had a house with plumbing. The concrete blocks were made on site with the native sand and imported cement that was brought 18 miles by team and wagon from a town on the railroad." (*pers. comm.*, 2007)

Although Forrester has described his father's favorite setting as being among horses and cattle, both parents worked initially as country school teachers to make money (*ibid.*).

3. The town of Climax no longer exists; "Climax is now only a water well for cattle and has long since disappeared from the maps" (Forrester, *pers. comm.*, 2007). The original site is between Arnold and Dunning.

Young Forrester was taught at home by his mother for his first two years' schooling. Subsequent education was obtained by his riding his horse Roany one and a half miles to a one-room school. For his first two years there he was taught by his father.

Figure 3
JWF's horse, Roany, and in the background the ranch house where he grew up. Taken around 1939.
"This is the ranch house with its 40-acre front yard where I grew up. It was taken about 1939. My horse, Roany, in the foreground is the one that I rode to the one-room country school house. The final printed version may not support seeing the three wind towers on the skyline. The right-hand one is the 12-volt generator … [t]he left tower is the water windmill, and the tall center one is the commercial 120-volt wind-electric generator that replaced the one I had built" (see also Figure 4).
© JWF.

Forrester recounts how his tinkering with doorbells, batteries and telegraphs gave expression to his emerging interest in electricity. Moreover, he argues that being raised on a Nebraskan cattle ranch gave him plenty of opportunities to get his hands dirty finding practical solutions to real problems - his building a wind-powered generator to bring electricity to the ranch being but one example. A scholarship to agricultural college notwithstanding, he decided that the life bucolic was not for him and went instead to the University of Nebraska to study electrical engineering. There, a solid core of theoretical dynamics was central to his undergraduate education – along with the idea of circuits having charge both flowing as current and also accumulating and discharging. The combination of practical viewpoint and theoretical grounding seen in system dynamics has its roots in Nebraska, in the personal outlook and academic training of Forrester.

Figure 4 (above)
The 12 volt wind generator (RHS) built by JWF whilst he was a senior in high school. It provided the first electricity to the ranch. On the LHS is a water windmill.
© JWF.

Figure 5 (caption on next page)

Figure 5 (previous page)
The Forrester family eating chocolate: JWF's mother, JWF, his sister, Barbara, and his father. Taken in 1938, his last year in college.
"… We are enjoying one of the boxes of candy that my father repeatedly bought."
© JWF.

Obtaining his undergraduate degree in 1939, Forrester alleges that he then moved to the East Coast only because the Research Assistantship offered by MIT came with a higher salary then obtainable elsewhere, and because his mother knew what 'MIT' meant, having worked in a library in Massachusetts. Such a capricious basis notwithstanding, Forrester took the post and began working on high voltage electrostatic generators.

His post also allowed him to work with Gordon Brown, the pioneer in servomechanism theory and feedback control systems (Brown & Campbell 1948). In 1940 he co-founded and became Associate Director with Brown of MIT's Servomechanism Laboratory. An offshoot of the Department of Electrical Engineering, staff at the laboratory went on to do research on various aspects of feedback control systems, including control for rods in nuclear reactors and numerically controlled milling machines. However, during World War II much work was done for the U.S. government and associated contractors on fire control systems and servo-control systems involving radar.

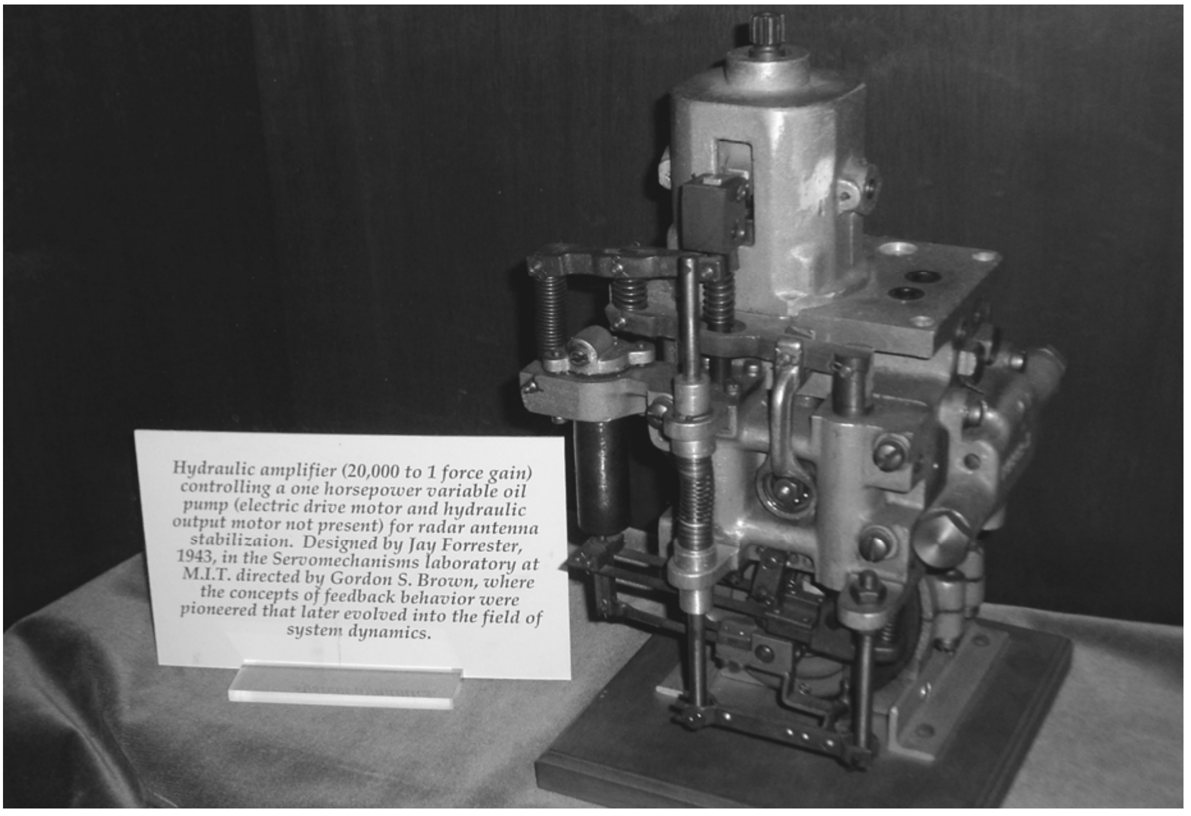

Figure 6
Servo-mechanisms: The hydraulic servo-mechanism built by Forrester and Brown and installed on the *Lexington*, on display in the Forrester Conference Room (E52-598) in the MIT Sloan School of Management. Photographed by John Sterman.

Forrester's hallmark combination of pragmatism and rigorous thinking is illustrated by the story of a servomechanism that controlled a radar antenna in order to guide intercepting aircraft. The hydraulic apparatus continuously adjusted the tilt of the radar to correct for the rolling and pitching of the ship on which it was mounted, the aim being to keep the radar beam pointed at the horizon in all directions.[4] Challenged by a US Navy Captain immediately to deliver his experimental version of the apparatus, this first device was installed on the aircraft carrier *Lexington* (see Fig. 6). Its effectiveness was clear; "The system made it possible to direct fighter planes that over several months intercepted some two dozen Japanese bombers when they were still out near the horizon." (*pers. comm.*, 2006). In part this may well explain why, nine months later when the electrical coils in the hydraulic controls failed, Forrester volunteered to fly to Pearl Harbour in order to fix the problem. This Forrester vignette climaxes with his completing his work only after the *Lexington* had sailed to participate in the retaking of the Marshall Islands in late 1943 and getting torpedo bombed. Of the ship's inability to manoeuvre properly because of damage to its rudder, Forrester describes archly how this experience gave him "a very practical view of how research and theory are related to the field application" (1990a, p. 3).

ASCA, Whirlwind and SAGE

Other radar-associated projects followed.[5] Certainly, as Associate Director of MIT's Servomechanism Laboratory and then Head of the Digital Computer Division in MIT's Lincoln Laboratory (1951-1956), Forrester's experiences from 1940-1951 were immensely significant for his subsequent work on system dynamics.

In 1944 Forrester became the director of the ASCA project (Aircraft Stability and Control Analyzer). Initially, the aim of this U.S. Navy project was to develop an aircraft flight simulator capable of testing designs that had yet to be built by using wind tunnel data to predict behaviour (see Fig. 7). This activity combined servomechanism theory with the discipline of practical modelling – a simulator can look absurdly unlike an aircraft and yet still simulate enough of its operation to provide important lessons on which instruments to look at and which control levers to pull, and when.[6] The initial intent had been to use analogue technology in the simulator but Forrester came to believe that only digital technology would be adequate to the task. As a result, in 1946 this research was redirected towards the development of a high-speed digital computer able to generate real time simulations.

4. Forrester describes how this device involved "mechanical hydraulic variable-speed pumps, motors, and high-gain hydraulic amplifiers because at the time the military mistrusted vacuum tubes in anything except radios" (Forrester 1992, p.339). The device employed positive as well as negative feedback effects and was patented by Brown and Forrester in 1946.
5. The servomechanism work extended beyond the device used to stabilise a radar dish. The projects at the MIT Servomechanisms Laboratory also involved stabilising gun platforms and, ultimately, the use of radar data to automatically control anti-aircraft guns. In this latter case the input signal needed help before it could move something as heavy as a weapon but a solution was found: "The torque from the driven synchro was very slight and I invented and designed a feedback hydraulic amplifier with a force gain in a single stage of amplification of perhaps 10,000 to 1 to couple the synchro to control the hydraulic pump. This was used in Army 40 mm guns" (Forrester, *pers. comm.*, 2006).
6. Note the parallel with Forrester's subsequent advocacy of system dynamics simulation models as means of test-piloting a new structural form for an organisation (Forrester, 1961).

Figure 7
Aircraft Simulation: Assistant director of MIT's Digital Computing Laboratory Robert Everett trying out the Control Force Demonstrator developed by the ASCA project (1947). Picture used with the permission of The MITRE Corporation. Copyright
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Christened 'Project Whirlwind', in 1951 and still under Forrester's direction, this activity moved from the Servomechanisms Laboratory into the new Digital Computer Laboratory. This led to the design and building of *Whirlwind*, then the world's only real-time digital computer (Redmond & Smith 1980).

Under the aegis of the US Department of Defense, in 1951 MIT's Lincoln Laboratory was created. The *Whirlwind* researchers subsequently formed the Laboratory's Division 6. Developing proposals by George Valley and Perry Crawford that computers could be used to manage naval and air forces, the computer was used to experiment with designs for military information systems. Early demonstrations showed that *Whirlwind* could analyse radar data supplied by telephone line, track an approaching bomber and direct an interceptor aircraft. Furthermore, this was done only with, "1024 bytes of memory. Not megabytes. Not kilobytes. Just bytes." (Forrester 2001, p. 3). This led to the development of SAGE (Semi-Automatic Ground Environment). SAGE was built to defend the airspace over Canada and the USA from attack and consisted of a network of digital computers and long-distance communication systems which sent target tracking information from radar stations to computers. This then allowed operators to deploy fighter aircraft and surface-to-air missiles in response to perceived threats (Jacobs 1986). This vast system, developed under Forrester's responsibility, involved 24 hardened 'direction centres' and the largest computer program written up to that time. Data was presented to operators not as printed output but as real-time displays on cathode ray tubes, with some input coming from 'light pen' pointing devices (see Fig. 11). These were key innovations in interactive computing (Palfreyman & Swade 1991). The core of this system was the 275-ton IBM FSQ-7, essentially the next generation *Whirlwind* and the first computer produced in volume. Despite being the size of a house and having tens of thousands of vacuum tubes, painstaking diagnosis and component re-design resulted in computers which are widely acknowledged to have been very reliable (see e.g. Evans 1983; Jenkins & Landis 2004), a source of evident pride to Forrester (1990a).

Figures 8
Electrostatic storage tube: Forrester examining one of the memory components used in Whirlwind. Colleagues Pat Youtz, Stephen Dodd are also shown. (Photograph taken in 1950).
© The MITRE Corporation.

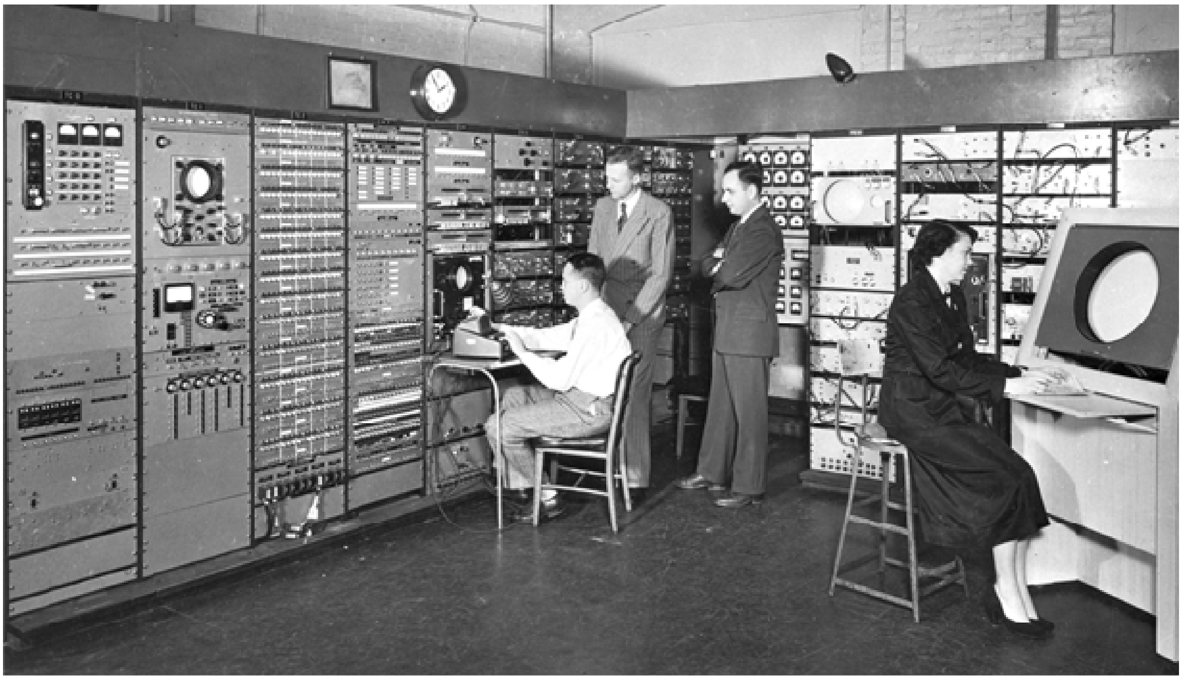


Figure 9
Whirlwind: Stephen Dodd, Jay Forrester, Robert Everett, and Ramona Ferenz at the Whirlwind I test control in 1950.
© The MITRE Corporation.

Figure 10
Whirlwind: Forrester (far left, standing) inspecting completed circuitry in 1952.
© The MITRE Corporation.

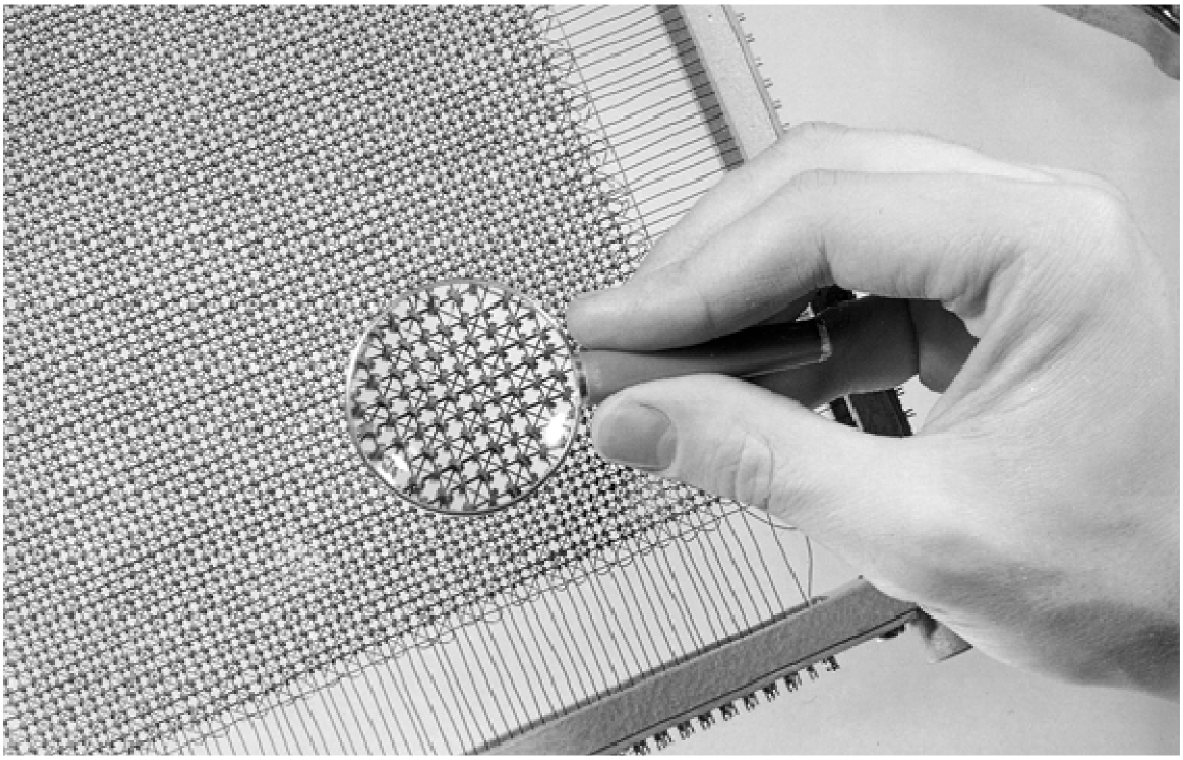
Figure 11
SAGE in service (c. 1958): operators of Tracker Initiator Consoles using light guns. When a return signal appeared on the screen, the light beam instructed the computer to allocate a track number and to relay the speed, direction, and altitude of the target to various other consoles in the network. All of the information being used here is handled by IBM FSQ-7 computers, developed from the Whirlwind.
© The MITRE Corporation.

The work during WWII and on SAGE have interesting parallels with the work on the air defence of the UK done in the late 1930s and early 1940s - plausible candidates for the world's earliest OR projects. At that time OR pioneers A.P.Rowe, B.G. Dickens and P.M.S. Blackett were involved in a number of projects which used ideas and methods from the natural sciences to devise defences against air attack. Research was done on the best way of using the newly developed technology of radar and on the actual operations of anti-aircraft gunners. These projects resulted in the creation of a highly effective early warning and fire control system which allowed the collection and triangulation of visual, aural and radar detection information to track attacking bombers. The information on the range and course of such targets was carefully co-ordinated, allowing fighter aircraft to be directed to make controlled interception of the attackers and, at shorter ranges, to direct anti-aircraft gun fire accurately (Kirby & Capey 1997; Price 2004).

Forrester's work has a further parallel with the deepest roots of OR: the work of Archimedes. An exemplar of, "political and military leaders [consulting] scientists for solutions to the problems of war, he was perhaps the first precursor of operational research" (Trefethen 1995, p. 48). Using ideas from his research in mechanics, geometry and the stability of floating bodies, Archimedes devised the defences for his home city of Syracuse;

in effect an ancient fire control system. During the Roman general Marcellus' assault of the city in 213-212 BCE, the series of machines that Archimedes designed - and whose operations he is supposed to have directed - were able to repel the attackers by propelling rocks and arrows of various sizes to long, medium and short ranges, whilst very short range defence was provided by a claw device which physically grabbed ships, lifting and then dropping them so that they capsized.[7]

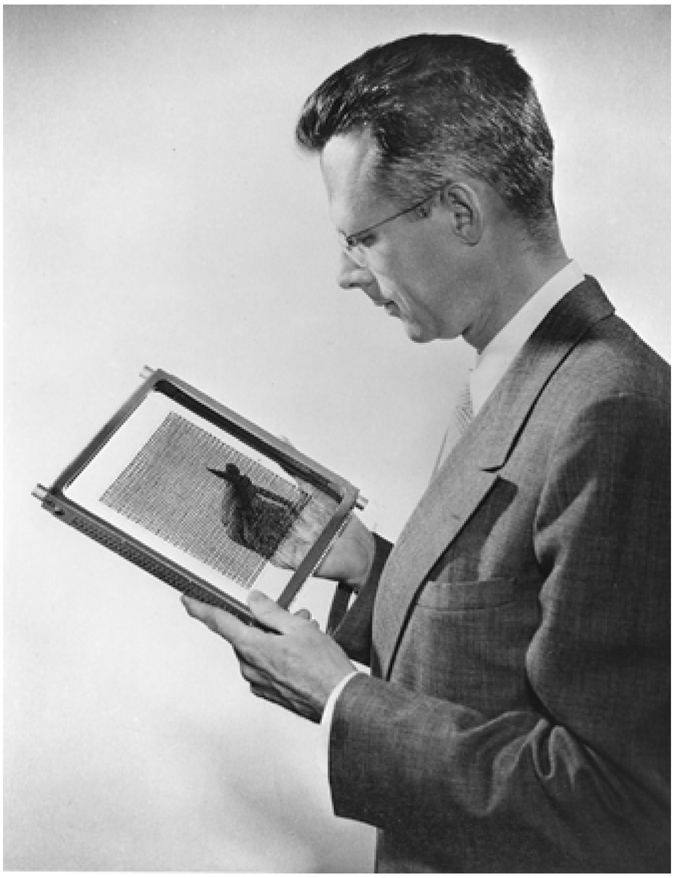
These defensive systems make a remarkable troika. Because of the work of Forrester and others on the SAGE project, North America had the best air defences in the world at that time. Because of the work of Blackett and other pioneers, Britain had the best air defences in the world at that time. Because of the work of Archimedes, Syracuse had the best defences in the world at that time. However, the most interesting link is the way that these systems were developed: these men had made distinguished theoretical contributions but then applied those ideas to improve real world operations.



Figures 12 (This and following page)
Magnetic Core Memory: structure in detail and, next page, Forrester holding a 64x64 core memory plane. (Photographs taken in 1954). In much larger arrays, this form of storage was used in SAGE.
© The MITRE Corporation.

7. With a military engagement fought more than two millennia ago triangulation across various sources and disciplines is needed to produce a plausible account. The closest contemporary source is the *History* of Polybius (c. 200 – after 118 BCE). The situation is complicated by the fact that Polybius' specific book covering the Syracuse siege has been lost to the modern era, though, it is believed, not before Plutarch (c. 46 – c. 120 CE) was able to draw on it when writing his life of Marcellus in *Parallel Lives*, texts of which are extant. However, to this material must be added the work of scholars on the emergence of Greek science (Gregory 2001), the general strategies, operations and equipment of Greek and Roman armed forces (Bagnall 2002; Connolly 1998) and the specific machinery and tactics of siege warfare (Campbell 2006; Kern 1999).

Figures 12 (This and previous page)



The need for fast and reliable data storage within *Whirlwind* , combined with the extra reliability needed for a military system like SAGE, precluded the use of the electrostatic storage tubes that *Whirlwind* at first utilised (see Fig. 8). It was this which spurred Forrester to create coincident-current magnetic core memory in 1949 (Forrester 1951; 1953; US Patent Office 1956). This key innovation in computer technology was for 20 years the industry standard for memory (Evans 1983). For its invention, in 1972 the (US) IEEE awarded Forrester its Medal of Honor, "For exceptional advances in the digital computer through his invention and application of the magnetic-core random-access memory, employing coincident current addressing" and in 1979 he was made a member of the (US) National Inventors' Hall of Fame.

During this time Forrester's achievements were extraordinary. They are dealt with only briefly here simply to allow concentration on his subsequent work concerning system dynamics. These projects gave Forrester experience in the management of complex, high technology projects. Naturally, his life also had personal dimensions of no less significance. It was early in this period that Brown introduced Forrester to Susan Swett. They married on 27th July 1946 and went on to have three children. Only in 2007 did the two move from the brown-shingled house in Concord, Massachusetts that they bought in 1952.

Creating System Dynamics

Serendipitous emergence

In 1956 Forrester decided to leave the development of computers to others, subsequently observing that this was partly because he felt that “the pioneering days in digital computers were over” (1990a, p.2). Believing also that he had already been practicing management via the large projects that he had run, he took up a chair at MIT’s Sloan School, General Motors executive Alfred Sloan’s then four-year-old experiment in founding a management school in a technical institution. Forrester was given a year to contemplate what contribution he might make to the School.

Surveying the world of MS/OR as it then was, he concluded that it had limited relevance. He acknowledged that it, “did pay its way”, but saw it as not dealing with, “major [problems] that made the difference between the companies that succeed and those that stagnate or fail" (Forrester 1968b, p. 399). What, then, might an engineer contribute?

Serendipitously, Forrester then became involved in a project with the General Electric Corporation. Managers at their Kentucky appliance plant were puzzled by oscillations with a three-year period in their component inventories and in their workforce numbers. The working hypothesis was that the oscillations were caused by exogenous effects; there were business cycles and these and general ‘noise’ was continuously imported from the market. Yet this was not a sufficient explanation and these oscillations endured despite managers’ best efforts to remove them. They looked at current inventory and staffing levels and took action to try to reduce the unwelcome effect - but to no avail. The policies did not produce the intended effect; the managers’ intuition had failed them. By talking to the managers Forrester elicited an account of how the system was put together, how it behaved over time and how they took actions intended to correct the oscillations.

Forrester saw the situation as having many feedback loops, each made up from an inventory level, a manager’s collecting information on that level, the decision he then took and the subsequent effects on the level. Forrester’s servomechanism-based insight was that the combination of these numerous loops could result in the managers’ actions producing the surprising, intuition-defeating effects. Then, by representing the levels, actions and hence loops in a very broad brush way, and doing calculations of their values in a paper notebook, he was able to confirm that the company’s policies which tried to maintain inventories at set amounts actually had the opposite effect: they amplified any oscillations that might arise. Indeed, when subject to a single small change the system was perfectly capable of generating internally – endogenously - large, sustained oscillations. No complex external explanation was needed. Using the precision and formality of his model Forrester was then able to design policies which the managers could use successfully to calm the oscillations.[8]

In early 1958 colleague Richard Bennett wrote SIMPLE (Simulation of Industrial Management Problems with Lots of Equations), the first system dynamics modelling

8. This founding application of system dynamics appears in Jarmain’s book (1963) and led to the creation of the ‘beer distribution game’. This demonstration of some of the fundamental concepts of the field shows how a simple board game representing the inventories of an integrated beer manufacturing, distributing, wholesaling and retailing company can amplify and sustain inventory oscillations when a one-time step change in orders to the retailers is applied. (In fact, not even this simple exogenous stimulation is required. At the 2007 international conference of the System Dynamics Society John Sterman – and a large number of conference attendees – showed that oscillations were generated even when orders remained constant.)

language (Bennett 1958a, b). Forrester was then able to develop computer simulations of this specific problem; these confirmed and extended his insights.[9]

More significant were his general conclusions, as these were critical to the development of system dynamics. They concerned both the limitations of existing modelling approaches and advanced the idea that servomechanism theory could be adapted to understand surprising, puzzling, counter-intuitive behaviour in human systems (Forrester 1956). Broad brush, quite aggregated models could, he argued, give an explanation of the source of the behaviour. Moreover, such models could then provide a rigorous basis for simulating the effects of different policies, building improved intuition about the consequences of those policies and helping managers choose policies which resulted in the long-term behaviour that they actually wanted. Forrester called the approach 'Industrial Dynamics' and the characteristically bold title of the resulting paper (1958) indicated that he had found what an engineer might contribute to the field of management studies.

Foundations of a new management science discipline

Forrester developed these ideas. In 1959 a new piece of software called DYNAMO (DYNAmic MOdels) was written by Phyllis Fox and Alexander "Jack" Pugh. Evolving versions of this code were the standard tool of system dynamics simulation for three decades.[10] There were further applications (e.g. 1959) and a significant account of the basis of system dynamics and the contribution that it could make to management is found in Forrester (1960).

This latter, seminal paper presented what are now known as the '14 obvious truths' which Forrester set out to disprove. Indeed, their rejection constitutes an intellectual agenda. Forrester rejected the use of linear equilibrium analyses with the aim of optimisation or prediction. He believed that both physical and less tangible concepts could be formalised, descriptive data on them collected and ideas about their structural inter-relationships unambiguously represented using information-feedback thinking. The same applied to human decision-making. Such models would embody an approach not of the physical sciences but more like those of engineering; allowing controlled experiments and leading users not to a specific decision but to the crafting of workable policies which indicate how decisions are made in a wide range of circumstances.

These ideas, combined with further applications by Forrester and his co-researchers, and supported by computer simulations using the tailor-made DYNAMO compiler came together in the *magnum opus* of system dynamics: Forrester's 1961 book *Industrial Dynamics*.

'Industrial Dynamics'

Forrester opens the book with a survey of the state of management studies. He saw merely a "very skilled art" generated by a *mêlée* of empirical observations. He therefore proposed that system dynamics could transform this state of affairs, creating a revolution in management science. His view was that feedback ideas were a solid theoretical analytical approach which would act as an integrating framework for diverse descriptions and explanations of the behaviour of social systems. Companies, economies, all social systems, should be modelled as accumulations and rates of flow threaded together by information feedback loops involving delays and non-linear relationships. Computer simulation was

9. For more information on this first application of system dynamics, see also MIT D-memos 1, 2, 3 and 6.
10. For contemporary notes on the development of the software, see the two 1959 MIT D-memos by Fox et al.

then the means of deducing the time evolutionary dynamics endogenously created by such system structures. The purpose was first to learn about their modes of behaviour and understand the underlying causal mechanisms. Beyond such explanation then came the true goal of system dynamics: organisational re-design. Using a computer simulation model it was possible to identify useful performance measures and key leverage points, promote individual and organisational learning, improve performance, and impart "a better intuitive feel [which] improves ... judgement about the factors influencing company success" (p.45).

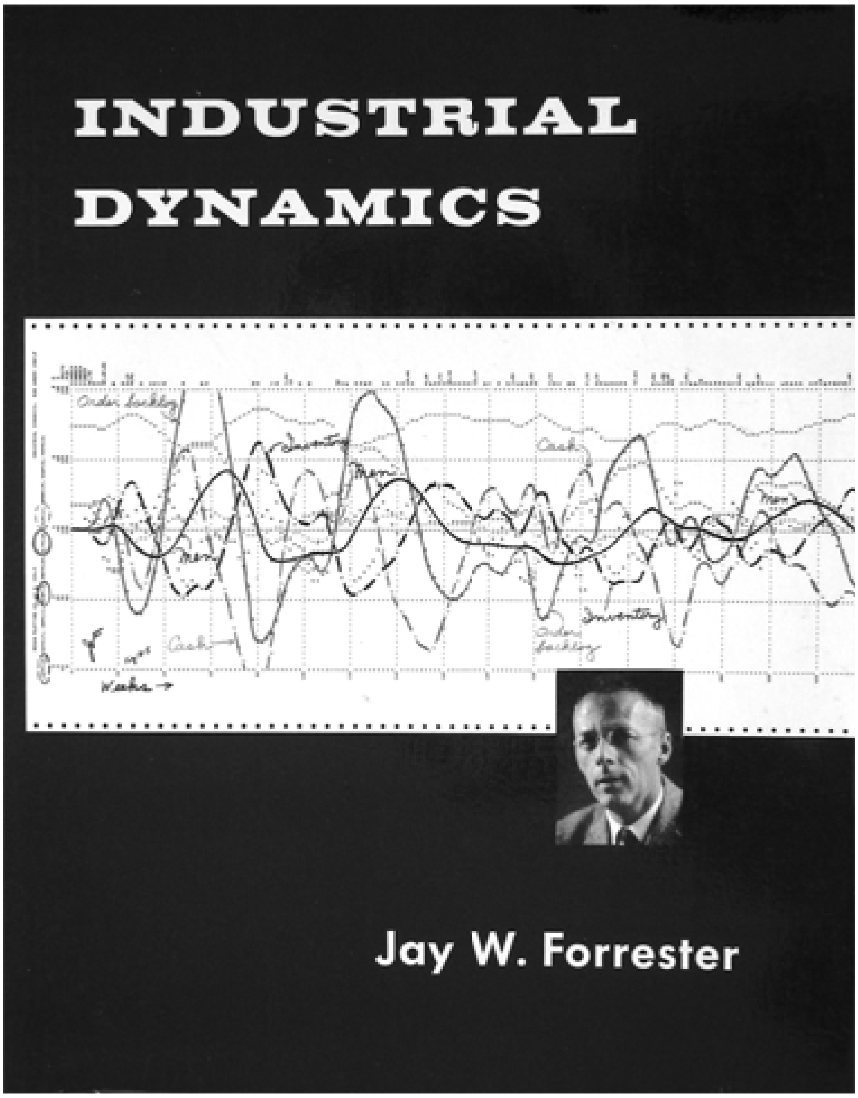


Figure 13
Creating a new field: the cover of Forrester’s 1961 book.

Industrial Dynamics makes this argument using a range of examples - including the GE case, output from which appears on the cover (see Fig. 13) - as well as describing the approach to be used when building system dynamics models.

In the chapter 'Future of Industrial Dynamics' Forrester then underscores the breadth of system dynamics by outlining further applications and, in a reprise of his scene-setting introduction on the state of management studies, argues that organisational case studies can be brought to life using system dynamics models, these models acting as experimental laboratories both for research and in support of management education.

The year after publication *Industrial Dynamics* won the Academy of Management Award. The contemporary reaction to this book merits more detailed comment (Lane 1997a); two brief examples from book reviews must suffice here. The review in *JORS* included; "… this is an important book, possibly even an indispensable one . . . There is a strong artery of common sense running through it, a heart of enthusiasm driving it and a backbone of achievement supporting it" (Battersby 1963, p. 101). The *Management Science* reviewer said; "At the press of a computer button, Forrester listens to the heart beat, checks the respiration rate, and measures the reflexes of a firm" (Wagner 1963, p. 184). The use of biological – rather than mechanical – analogies is noteworthy.

One can usefully identify the three defining elements of system dynamics. The role of the first - 'feedback loops' - has been described above. The second element is the use of computer simulation. System dynamics is based on the idea that although humans may be able to conceptualise complex causal relationships they lack the cognitive capacity to infer their consequences over time; contrastingly, simulation rigorously deduces dynamic behaviour. The interaction of state variables and non-linear relationships within loops causes different parts of a model to be important – dominant – at different times. With simulation the surprising, counter-intuitive behaviour can be studied in a rigorous yet flexible and compelling way.

The third element I think of as 'engagement with mental models'. Managers have mental models, their assumptions about cause and effect, which are the source of their intuition and hence the basis for policy making. Yet with social systems it is information that is not written down but which exists only in these mental models which is perhaps most important. The only way to address a managerial problem is therefore to engage with the mental models of the appropriate managers. Modelling must stay close to managers, working to elicit their current mental models and express them in a computer model. Similarly, experimentation with such a model should yield learning, and help managers to improve their intuition and create a new, shared mental model which is the basis for improved future policy making.

Perspectives on 'Industrial Dynamics'

The three defining elements of system dynamics given above – feedback, simulation, engagement with mental models - allow Forrester's ideas to be put in context.

'Industrial Dynamics' and Systems Science

Concentrating on those first two elements it is clear that Forrester's view was fundamentally a systems one. He saw managers in different parts of an enterprise making decisions which had repercussions elsewhere in the organisation. He saw those repercussions flowing round a feedback loop to return to the originator. At the broadest level one might argue that Forrester was not the first to take this stance. Yet even – perhaps especially – the most technical disciplines in management studies had failed to bring this systemic insight to life in a practical way. Although Forrester's ideas have various connections and antecedents - Wiener's (1948) control theories and Tustin's (1953) feedback study of economic systems – it is computer simulation which provides the vivifying power. Richardson acknowledges that similar thinking existed prior to Forrester but suggests that system dynamics generated an evolutionary leap in the 'servomechanistic thread' of 'Feedback Thought'. The 'cybernetic thread' - exemplified by Beer's work - aimed to understand events and decisions by focussing on the role of feedback in processes of communication and control. In contrast, the servo mechanistic thread placed prime importance on patterns of behaviour of feedback systems and the policies which produced these (Richardson 1991). It was the electrical engineer who had developed flight simulators and digital computers and innovative ways of interacting with them who was just the man to create this leap, to bring this feedback insight to vibrant life.

It is from this systems perspective that Forrester's dismissive remarks about MS/OR should be seen. Indeed, though independent, his remarks are strikingly in tune with Russell Ackoff's concerns, including Ackoff's comment that MS/OR was applied to "problems of limited scope" (Kirby & Rosenhead 2005, p. 130). Ackoff, speaking from the founding core of MS/OR, was writing in exactly the same year as Forrester.

'Industrial Dynamics' and The Problem Structuring Methods of OR

Let us turn now to the third element of system dynamics, the importance attached to engagement with mental models. This is the idea – elaborated in later publications (e.g. Forrester 1971a) but clearly present in *Industrial Dynamics* - that managers 'playing' with a model can learn, can improve their intuition and can create a new mental model which becomes the shared basis for policy making.

In broad management studies terms the idea of shared mental models anticipates Mintzberg's work on 'organizational memory' and the 'organisational learning' work of the 1990s. The notion of creative play with computers echoes Papert's work on developing geometry skills in children using a programmable robot (Papert 1980). However, the connection between Forrester's ideas and those of the PSMs that began to appear in the 1970s (see Rosenhead 1989) is of particular interest. In both system dynamics and PSMs practice models are seen as contingent entities, whilst both fields also emphasise group participation and the modelling process as learning experience and the value of the model being judged by a specific group dealing with a specific issue at a specific time (see Eden & Sims 1981; Phillips 1984).

Forrester's championing of these ideas significantly pre-dates its detailed handling within the OR community. This is often overlooked and system dynamics is criticised as being merely an application of 'hard' systems thinking (c.f. Checkland 1979), a 'unitary' approach dealing with 'simple' systems (Flood & Jackson 1991), "an attempt to apply the ideas of control engineering to socio-economic problems" (Keys 1988, p.218).

Although one would hardly expect these ideas in *Industrial Dynamics* to be identical to today's PSMs thinking, the roots of modern system dynamics practice were clearly present in 1961. The form of group working practiced then was considerably limited by participants' ability to engage easily with computer models. However, considering the software available until the late 1980s (Richmond 1985) it is a testament to the power of the system dynamics approach that any of Forrester's consulting assignments done directly with managers took place at all. That they did, and that he identified this as an important aspiration for system dynamics, speaks highly of his personality and imaginative intellectual vision. Subsequent research has linked system dynamics with more general work involving OR modelling in groups and with the literature on group decision support (Lane 1992; Richmond 1997; Vennix 1996).

That system dynamics is concerned with the process of model building in groups and with the associated importance of experiential learning has not always been understood. When it has been noticed it has been labelled as a new development, an almost revolutionary change in the field's ideas. This is false, as a careful reading of *Industrial Dynamics* makes clear. Modern forms of 'group model building' in the system dynamics field are a natural evolutionary development of the field's earliest assumptions (Lane 1999); a testament to the imagination and richness of Forrester's ideas.

'Industrial Dynamics' and the Institutions of MS/OR

The above comparisons revisit an old question: why was system dynamics for so long an activity mostly separate from the institutions of MS/OR? (Note that this question does not concern the underlying intellectual connections; these are strong, as described above.)

A detailed study of the two fields suggests the following explanation for the institutional separation. In the late 1950s Forrester's ideas were so far outside what passed then as OR that he was probably correct in judging that for them to flourish a clear separation from OR would be beneficial. This was a new discipline which challenged current thinking in various ways and which needed its own space to root itself and to blossom. For instance, it is notable that Forrester observed that those with an OR training had much less success than others when trying to pick up the ideas of the new field (1960). This detached approach has allowed the subject of System Dynamics to grow - but has clearly separated it from the world of MS/OR. However, today we see that those who practice the ideas in Forrester's book are increasingly connected to the field of MS/OR, and operational researchers are reaching conclusions which sit well with, indeed, which develop, Forrester's earlier ideas. The detailed argument for this may be found elsewhere (Lane 1994; 1999; 2001) but is summarised by Forrester himself. Commenting on a description of 'hard' and then 'soft' OR, he observes that; "System dynamics fits the latter part of this description much better than the first part" (1994, p.251).

Developing a Discipline

Forrester's diagnosis of managerial problems was bold and clear. People employ simple models in which cause and effect are close in space and time. In complex systems, when cause and effects are related in a very different way, intuition based on experience with those simple systems can lead to policies which are ineffective and even damaging. Sometimes a policy seems to work for a while but is actually generating slower responses which in times have detrimental consequences; 'better before worse'. Sometimes a policy many simply be ineffective as an organisation displays 'policy resistance'. The appropriate response in such cases is to stop implementing the policy or, as Forrester likes to put it, "don't do something, just stand there". However, analysis of the complexity of the system can uncover effective policies. Even then a 'worse before better' response may result, implying that stakeholders need to understand such surprising dynamics if a truly effective policy is to be implemented – and seen through.

Forrester consistently argued that senior managers should build models to understand their organisations. Furthermore, he believed that a manager's role was not merely as 'captain of the ship' but as 'designer of the ship'. This 'corporate designer role' was an innovative approach to both modelling and management and he went on to promote it throughout his career (e.g. Keough & Doman 1992). Throughout the 1960s Forrester and his collaborators applied the system dynamics approach to a wide range of problems using research projects, courses and improved software, at the same time developing the field further.

From 'Principles of Systems' to 'Urban Dynamics'

Forrester drew on the experiences acquired by himself and his co-workers to publish *Principles of Systems* (1968d). This book introduces the basic ideas of system dynamics using a wide range of exercises and applications. His membership of the board of the Digital Equipment Corporation (DEC) also allowed him very clearly to deliver on the promise implicit in his rejection of OR. His 'market growth model' provides powerful insights on why, "… companies often grow to a certain level and then stagnate or fail"

(1968c; Forrester 1990a, p. 6). He summarised the achievements of his field after a decade of work whilst re-stating and extending 'the task ahead' (Forrester 1968b). He also responded to an intelligent critique of system dynamics from within the MS/OR community (Ansoff & Slevin 1968). His reply is both one of the best short treatments of the field and a reminder of how its features continued to be quite distinct from much of MS/OR thinking at that time – and easy to misunderstand in consequence (Forrester 1968a).

The more general name 'system dynamics' was adopted for the field towards the end of the decade and has remained since then. A further significant shift from corporate/industrial modelling came with an extension into public policy as a result of Forrester's work with ex-mayor of Boston John Collins. *Urban Dynamics* (1969) was a study of the mechanisms underlying the development, stagnation, decline and recovery of a city. The date of the work is significant; as Forrester observes, "The plight of our older cities is today the social problem of greatest domestic visibility and public concern" (*ibid.*, p. ix). The book's audacity and courage are characteristically Forrestian - a contemporary reviewer referred to Forrester's "unflinching confidence" (Ingram 1970).

Forrester was able to use Collins' extensive contacts and so elicit knowledge from field experts on urban affairs. His book presents a generic model of a city and studies the types of behaviour that can result and the policies which might reverse decline. Forrester concluded that the construction of low cost housing created poverty traps, thereby exacerbated poverty rather than reducing it. He proposed instead that the zoning and tax laws should be reversed, so encouraging the demolition of low income housing to allow the creation of jobs and a general increase in the standard of living for those in the city.

This analysis generated great controversy and Forrester has described elsewhere the strongly hostile reactions to this work. However, he is also able to cite examples in which surprising 'converts' were made. 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 Forrester's testimony to a US House of Representatives sub-committee on urban growth gives an idea of how he went about explaining his ideas (Forrester, 1970a).

More generally, Forrester's book contains 'Notes on complex systems'. With these he offers a set of general, qualitative insights about the surprising, counter-intuitive way that social systems can behave. What is remarkable is the claim that these insights have the potential to be applicable across many domains. This chapter therefore contains one of the most importance assertions of the ability of system dynamics to understand surprising behaviour in terms of a formal, analytical framework which allows insights learned in one domain to be transferred to another.

World Dynamics

In 1970 Forrester was invited to travel to Bern to attend a meeting of the Club of Rome on 29th-30th June. Asked at the meeting whether system dynamics could be used to increase understanding of 'the predicament of mankind' - the Club's defining concern – he answered in the affirmative and invited the Executive Committee to visit MIT in late July. On 1st July, during the Paris/Boston leg of his return air journey, Forrester spent about an hour sketching the stock/flow diagram of what became one of the most significant and widely debated models in the history of system dynamics (see Fig. 14). Next able to spend more time on the topic on Saturday 4th July, he completed the diagram, formulated the equations and generated two key runs. The WORLD1 Model had been born. This model was refined through variants World1A and World1B.[11] A matter of days later, for the visit to MIT by Club of Rome members on 20th–31st July, WORLD2 was available for discussion, its structural assumptions made available for all participants to see via a drawing made on a bed sheet (Seeger 2000).

The aim was to understand the dynamics of aggregate global development. Forrester used his system dynamics model to represent the links between population, natural resources, pollution, agricultural and industrial production, capital investment and quality of life. The final WORLD2 model was used for the resulting book, *World Dynamics* (1971b); its structure was remarkably similar to Forrester's first sketch (see Fig. 15) . The object of worldwide discussion in popular and scholarly fora, the book asked sharp questions about the relationship between growth and quality of life.

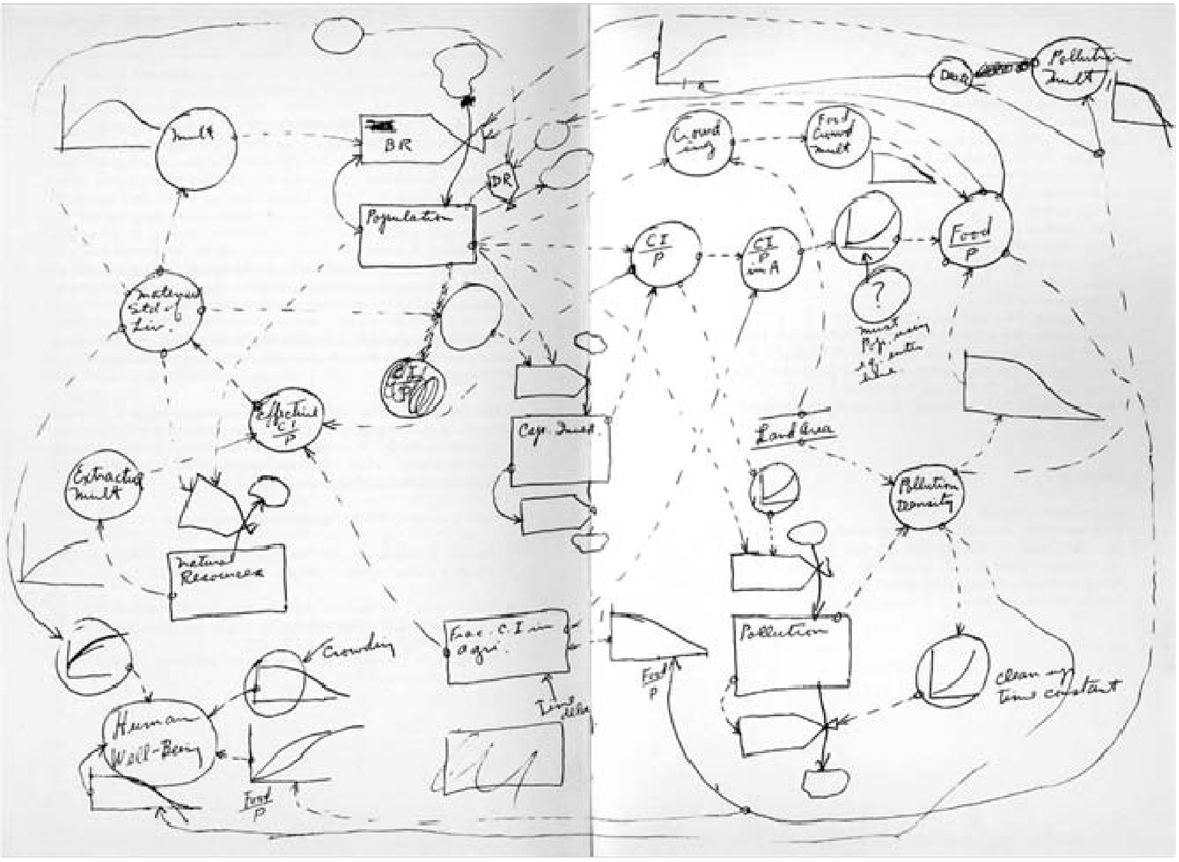


Figure 14
World Dynamics takes flight: The first draft rate-level diagram of the WORLD1 model, as sketched by Forrester on his journey home from the 1970 Club of Rome meeting which initiated this work. A surprisingly well sedimented myth has it that this sketch was done on a napkin. In a conversation that I had with JWF on 31st July 2007 at the System Dynamics Conference in Boston he confirmed that this was not the case. Figure reproduced from Forrester (1970b).

11. A fascinating and detailed account of the development of this work can be found in a document preserved as a number of MIT D-memos (Forrester 1970).

The Club of Rome supported a longer research project with funding from the *Volkswagen Stiftung*. Still deeply involved in his *Urban Dynamics* work, Forrester recommended one of his former PhD students, Dennis Meadows to be the project's Director. Meadows and his colleagues created WORLD3 and published *The Limits to Growth* (Meadows*, et al.* 1972), a further dispatch from this research frontier. This achieved en outsold *World Dynamics* and created even more debate (McCutcheon 1979; Meadows*, et al.* 1973). More on the progress of this strain of work, including public reaction to it and a characteristically elegant treatment of its underlying ideas may be found in Meadows (2007).

A subsequent long-term research program deepened and extended this analysis, producing a series of publications (Meadows 1985; Meadows*, et al.* 1982; Meadows*, et al.* 1974; Meadows & Meadows 1973), including more work by Forrester to engender public discussion of the consequences of the work (Forrester 1975b).

With this stream of work system dynamics was applied to arguably the most important area of social policy and this work has been instrumental in shaping public thinking on environmentalism, development, pollution and resource restrictions. Forrester's insights on the aim of caring for the environment and the need to make trade-offs between long-term versus short-term effects have an important place in environmentalist thinking today and his original model is the founding work of global modelling (de Steiguer 1997). Commenting on the contribution of the Club of Rome work, economist Paul Ormerod 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, p.36)

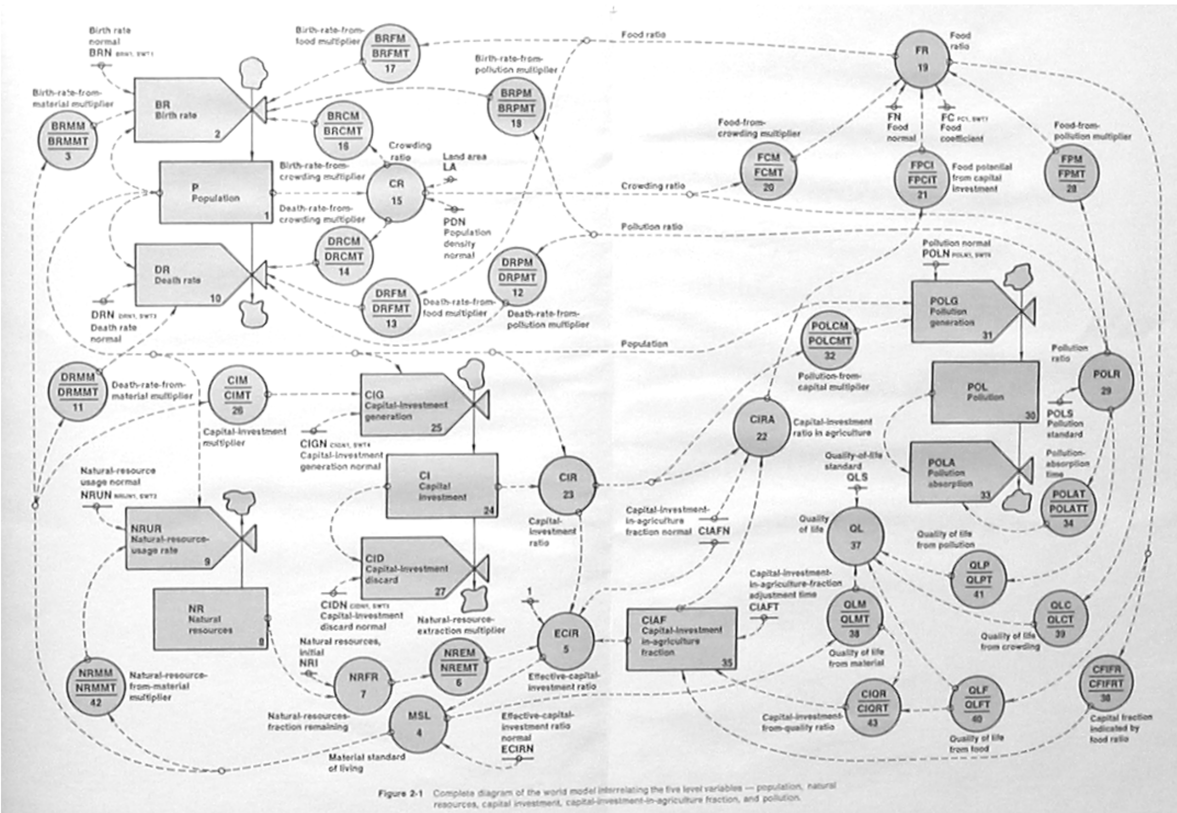


Figure 15
The model behind *World Dynamics*: The rate-level diagram of the WORLD2 model supplied with the book. Compare with Fig. 14.

For a certain generation the *World Dynamics* work seems to be the most well known system dynamics activity. I have myself observed that the result of such knowledge has not always been respect. Indeed, for quite unjust reasons harm has been done to the reputation of the field by those who reject system dynamics on the basis of a quite incorrect grasp of these studies. In this inaccurate view the global modelling work is almost portrayed as Chicken Little, warning that the sky is falling. Worse yet, it is occasionally described as if it proposed something of a reverse Bishop Ussher analysis, offering a date when the Earth will end.

Actually reading the original texts – always to be recommended – rapidly dispatches these portrayals to the dustbin of uninformed commentaries. The actual finding of this work might be restated as follows: although most people act as if growth can continue without end – and some people advance this as an explicit policy aim – we can find no plausible explanation for why this might be possible. On the contrary, analysis indicates that this aim could have all manner of damaging consequences for mankind as growth in human activity overwhelms the planet's carrying capacity. However, the analysis also suggests alternative policies which could make the future much better for many people and in a sustainable way. As Forrester frequently expressed it, "We don't have the option to grow forever. Our only option is to choose our own limits, or let nature choose them for us."

These are not Cassandra-like ravings, or absurd point predictions. Certainly some of the detail was out; as Randers observed, in the early years great importance was attached to consumption restrictions resulting from shortages of natural resources, whereas today more emphasis would be given to the effect of pollution caused by over-consumption (Randers 2000). However, this is secondary to the general dynamic insight offered by Forrester (WORLD1, WORLD2 and WORLD3 are as one in this regard): unlimited growth is implausible, there are various limits to that growth and just bumping up against them will be bad news. This insight is still utterly relevant. Its implementation in policy terms may be mankind's most important challenge in this new century. That this insight was obtained using system dynamics is a towering achievement by Forrester.

Naturally, responses came from the academy (e.g. Barnett 1972). However, it is perhaps the extent to which this work excited public comment that should be emphasised. *World Dynamics* has been described as the *A Brief History of Time* of its era (Lane 1997b). Measured by public interest this is true but it diminishes the extent of the achievement. The book presents a simulation model - equation by equation - and contains numerous plots of runs with various assumptions and policies. In contrast, Hawking reports that he was advised to minimise the number of equations in his book in order not to diminish sales.

However, in terms of practical implications to public thinking perhaps a better comparison is Keynes' *The General Theory of Employment, Interest and Money*. Forrester sets great store by the ability of system dynamics work to inform discussion amongst a wide range of people, not just 'policy makers'. His view is that policy makers are most strongly influenced when they are answerable to those who have a good grasp of the dynamic consequences of policy options. He applies this idea to corporations (Forrester 1965) but also to matters of public policy. He recently observed; "*World Dynamics* and *Urban Dynamics* … became subjects for discussion in such forums as the League of Women Voters and parent-teacher groups. A member of the House of Representatives from Iowa told me he decided to run for Congress because of *World Dynamics*. He established in each precinct of his district a man and wife team to convene discussion groups about the future" (Forrester 2007c). These comments are of more than historical interest - they indicate the boldness of the aspirations that Forrester still has for his field.

To The Present

One can see a weaving together of effects resulting in the institutionalisation of Forrester's ideas through the 1970s and into the 1980s. A selection of his papers appeared (1975a). From the late 1970s onwards annual conferences were organised, with the publication of proceedings following soon after. Textbooks by other practitioners began to appear – a natural feature of the field which continues today. The System Dynamics Society was created in 1983, with Forrester its first President. More academics were attracted to the subject. System dynamics was taught in more and more universities in more and more countries. A dedicated journal was created, the modern form of which, *The System Dynamics Review,* appeared in 1985. In the following year Thomas Watson Jr. endowed the Jay W. Forrester Chair in Management at MIT. It is currently held by John Sterman. *The Fifth Discipline* (Senge 1990) explored the relationship between system dynamics and ideas of organisational learning; the field had produced an 'airport best-seller', attracting a new generation of managerial interest. Around this time there was an explosion of growth in membership of the society – though Forrester, naturally, likes to see this simply as the operation of a continual reinforcing process yielding exponential growth. The year 2007 saw the celebration of the field's 50th anniversary.

Figures 16
The logos of the System Dynamics Society and of the various activities associated with the 2007 celebrations of the field's creation.
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And Forrester himself remained active. Emerging from the *Urban Dynamics* study was a broader research project concerned with the problems in the US economy. The 'National Model' took much time and effort to assemble. Various bulletins reporting both progress and significant structural insights into the causes of such phenomena as business cycles and 'stagflation' emerged from Forrester himself (1977a; 1977b; 1978; 1979a; 1979b; 1980a; 1981; 1983; 1985; 1987; 1989; 1997) and his co-researchers (e.g. Forrester, *et al.* 1976; Graham & Senge 1980; Mass 1975; Senge & Mass 1983; Sterman 1985, 1987, 1988). The culmination of this project is another book by Forrester. Long in the planning (e.g. Forrester 1995), tantalising chapters have now been seen within the system dynamics community and in early 2007 Forrester was considering the title "A General Theory of Economic Behavior," (Forrester 2007b). The publication of the finalised version is greatly anticipated.

In 1989 Forrester formally retired from Sloan, an event which, as he once described to me in an email, "has had no effect whatsoever on my work" (Forrester, *pers. comm.*, 1997). Ever someone to recommend the high leverage point in a system, he has taken his ideas on management education and argued that they should be applied to the education of young people (1990b; 1993). This has long been an interest of the field (e.g. Roberts 1978b) but gained particular impetus in the late 1980s when a now-retired Gordon Brown introduced Tuscon, Arizona teacher Frank Draper to system dynamics. The enthusiastic response of his students and of Draper himself led in the 1990s to the creation of the 'K-12' project.

The project's purpose is to bring to children 'learner-directed learning' using system dynamics so that, "the ideas take root very early in a person's education and are nourished and reinforced continuously thereafter" (Keough & Doman 1992, p. 26). Moreover, this work also relates strongly to Forrester's wish to create a broad base of citizenry with a deeper awareness of the counter-intuitive effects of policies. He has spent considerable time talking with school teachers in the USA and working to create materials to help them to engage with students from kindergarten age upwards to using the 'learner-directed learning' approach applied to as wide a range of subjects and disciplines as possible. An excellent set of such materials was recently published (Fisher 2005); this draws on, and acknowledges the contribution of, the ideas and experiences of staff at MIT and the many teachers across the country involved in this initiative. Forrester's courageous and bold long-term aspiration for this work is nicely caught in a wry question which he likes to use at academic conferences; "When all of our schoolchildren have been exposed to system dynamics via these materials what are all of you university professors going to teach?"

It is easy to view Forrester solely as a researcher, yet he is also a fine teacher. That he was so significantly shaped by his schooling, and that both of his parents were themselves teachers, together add an element of harmonious completion to his involvement in the K-12 project. He continues vigorously to champion this initiative today.[12]

Personal Reflections

The account so far gives an indication of the personality of the man. In person he is quiet, imposingly tall and faultlessly courteous. He speaks slowly and in an assured way, producing analyses of a complexity seldom found in conversation. An indication of this style is recorded in his testimony to congress (Forrester, 1970a). He is direct and unambiguous in what he wishes to convey; firmly and consistently supportive of people and ideas he approves of. Of those he does not support he can be trenchant and devastating, or nuanced and delicate, seemingly depending on the approach that he judges will be most effective in delivering his message. At times he can be assured and lofty almost to the point of being Olympian. At others Forrester is hospitable and convivial, happy to enjoy a joke and quick to share humorous stories himself – sometimes against himself.

All of his work shows the operation of an incisive mind. I remember the first time that his inquiries were turned on me. The early 1990s brought another discussion about whether qualitative mapping was sufficient or whether simulation was a prerequisite to understanding dynamic behaviour. At that time I was arguing that system dynamics had much in common with PSMs in terms of their interests in strategic issues in organisations and the importance both attached to working with groups and changing mental models. I was invited to a 'brown bag lunch' at MIT to discuss my ideas with Forrester and various PhD students and other guests. All had been sent a working paper of mine on my research. Things went well, staying on topic. Then Forrester turned to asking me about my views on the role of simulation. He

12. In 2003, when Forrester returned to his *alma mater* as "one of the most notable graduates (EE '39) of the UNL College of Engineering & Technology", he chose to lecture on 'Designing the Future: Research Takes Alum Back to Kindergarten'.

drew my attention to a clause in my working paper – not a section, a paragraph, or even a sentence but just a clause – from which he had inferred that I thought simulation to be essential. Somewhat flustered by the closeness of his attention and so caught considerably off balance I attempted an affirmative response. Comforted on this point and generally satisfied that I had committed to simulation the Forrester searchlight was switched off.

Forrester is quite aware of how very differently many human activities would be conducted if they were based on system dynamics analysis, be it the operation of a company (Forrester 1965), a city, a country or even the planet. Emphasising this point sometimes provides enjoyment to him. Attending the 1990 system dynamics conference in Boston I was chatting in a small group of which Forrester was a member and reflecting on the curious process of entering the country. I commented that when I was asked at Customs whether I was 'carrying any material likely to bring down the government of the United States' I had replied 'No' but did not feel very good about it. Forrester's immediate response was, "You should have said 'I certainly hope so' ".

Forrester is no stranger to controversy. This seems to stem from an unwillingness to avoid hard questions and a refusal born of intellectual courage to deny the consequence of one's analysis. Whether, for example, asking hard questions about the role of churches in influencing population growth, or questioning the moral basis of the 'duty' of countries which have carefully husbanded their natural resources to assist those that have short-sightedly squandered theirs, Forrester is not one to duck the real world consequences of his research (1973). Self-evidently there is no national or cultural bias in such statements. Indeed, whatever the prevailing wisdom on a subject he seems to see little point pretending that something will work if he believes otherwise. There is something almost Solzhenitsyn-like in his determination, 'not to take part in the lie, not to support deceit': Forrester is compelled to speak out about policies which he identifies as being incapable of producing their declared aims. However unpopular and controversial his findings on a given issue, if he believes that a policy is doomed to failure and that an alternative policy promises success then he speaks out.

However, on every occasion he has shown himself willing to defend his views in depth. Forrester does not make controversial statements and then vanish. Indeed, in my opinion, it is exactly when challenged that Forrester seems at his best. His defence of system dynamics itself (1968a), his patient unpicking of the modelling errors he is accused of having made in the *World Dynamics* work (Forrester, *et al.* 1974) and his response to criticisms of the approach in his National Model study (1980b) all reveal a mind quite willing to be challenged on expressed opinions because of the solid foundations on which those opinions were based.

Though concentrating here on system dynamics, one must not forget the range of achievements of this man. Back in 2002 I showed him my first memory stick, all 128 MB and 11 grams. of it. As he examined this tiny artefact with characteristic curiosity I remember briefly looking up at the early circuits framed on his office wall at MIT and then back to him whilst reflecting, "This is the man who built a computer big enough to walk through and who invented magnetic core memory - though he still managed to get an experimental air defence system to operate with only 1024 bytes!"

Not surprising then that his remarkable mind is also open to approaches other than system dynamics. Having sometimes experienced the promotion of system dynamics as virtually a panacea when first joining that field, I remember asking him at the end of a lecture whether there were any situations in which he would recommend not using the approach. He immediately acknowledged that system dynamics was not a universal tool and listed a number of situations where it would be useless if applied. For good measure he recommended alternative approaches – MS/OR approaches - for dealing with such situations. I also recall a car journey with him during which – rather perilously I now reflect – I attempted to persuade him of the importance of exploring system dynamics using sociological theory, and illustrated this by explaining Husserlian phenomenology and its relationship to his ideas on mental models. He listened with what may very well have been a large helping of simple courtesy but, judging from his questions, also contained genuine intellectual curiosity. In the broader project of demonstrating the commonality of ideas and interests between system dynamics and OR in the UK I also found him quite open to PSMs, again obviously intrigued by the ideas (Forrester 1994).

For those who have not had the pleasure of meeting Forrester, the clarity of his mind, the quality of his ideas and the boldness of his aspirations is well conveyed in Appendix O of *Industrial Dynamics*, ‘Beginners’ Difficulties’. Reading these eight pages would doubtless interest and probably benefit all model builders. As something to rouse one’s spirit I would particularly recommend the opening section on ‘Courage’. When reading this encouragement to boldness in modelling one might recall the intellectual - and physical - courage displayed by its author during his long career.

Forrester’s Legacy

Forrester 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. The institutionalisation of his ideas goes from strength to strength. The System Dynamics Society at the end of 2006 had members in 58 countries. *The System Dynamics Review* was taken by 1290 libraries. The subject had a recorded presence in 89 universities across the world. Each annual conference attracts more attendees than the previous, a series of European workshops has been initiated, and 15 national chapters are operating.

Consequently, system dynamics continues to be applied to a vast array of phenomena. Further urban dynamics-style research projects have been undertaken since Forrester’s founding work as the model and its insights were adapted to others situations. This application domain continues to be a lively and productive one for system dynamics (Alfeld 1995; Alfeld & Graham 1976; Mass 1974; Schroeder, *et al.* 1975). Global modelling has continued and been extended (Meadows, *et al.* 1992; Meadows, *et al.* 2004; Randers 2000; von Weizsaecker, *et al.* 1995). The original corporate roots of system dynamics remain perhaps the field’s most active area - with a volume of publications far too great to do justice to here so some key books only are cited (Lyneis 1980; Roberts 1978a; Warren 2002).

In fact, the range of system dynamics applications is extraordinary, from environmental dynamics (Ford 1999) to psychological effects (Levine & Fitzgerald 1992a, b). Following the model of *Principles of Systems*, treatments of the field evidence this breadth of application (e.g. Goodman 1974; Richardson & Pugh 1981; Roberts, *et al.* 1983) and Sterman (2000) provides a superb *tour d’horizon*. Taking their cue from Forrester, system dynamicists continue to ask hard questions about surprising, puzzling phenomena. Why do large projects, be it ship building or writing software code, so frequently over-run (Abdel-Hamid & Madnick 1990)? Why do attempts to generate and manage development growth so frequently fail (Saeed, 1991)? When renewable resources such as fish stocks are eradicated, to the detriment of all participants, is the standard ‘tragedy of the commons’ explanation enough or do non-linear dynamics also play a key role (Moxnes 1998)? Can bounded rationality ideas help explain complex behaviour (Morecroft, 1985)? Why do individuals misestimate the effort needed to deal with global warming (Sterman & Booth-Sweeney 2002)? How can global warming itself be tackled (Fiddaman 2002)? What rules and heuristics might people be using to manage complex systems and might these explain undesirable behaviour (Sterman 1989)? How can one make sense of the various, seemingly contradictory data sources on cocaine usage (Homer 1993)? How can the sequential adoption and diffusion of innovations in technology be explained (Milling 1996)? How can the many insights about the surprising, counter-intuitive behaviour of complex systems be acquired using non-technical software

(Richmond 1985; Richmond, *et al.* 1987) or be explained in simple but compelling language (Meadows 1989; 1991)?

It is, perhaps, the continuing ability of system dynamics to offer plausible explanations for seemingly puzzling phenomena across such a wide range of disciplines that is a key measure of Forrester's contribution and that explains the attraction of system dynamics to academic researchers, school teachers, consultants, managers and policy-makers. Forrester's publications continue to illuminate the field of system dynamics. His books richly reward reading today and we are still teasing out their subtlety and insight. He continues to present the field with challenges for its future (Forrester 2007a).

Figure 17
Jay Wright Forrester, 1940. Photograph by his father.
"This horse liked to jump ditches and small haystacks."
© JWF

Reflecting on his childhood in Nebraska, Forrester wrote; "life must be very practical. It is not theoretical, it is not conceptual without purpose. One works to get results" (1990a, p.2). His work in many fields has produced immensely impressive results. Considering the range of practical results emerging from the use of system dynamics modelling - his creation and masterwork – Jay Wright Forrester might surely be allowed to claim:

" I know the power of the bond
Between cause and effect." Aeschylus - *Agamemnon*. 458 BCE[13]

13. The translation - somewhat free but nevertheless exquisite - is by British poet Ted Hughes (Aeschylus 1999).

Acknowledgements

I am very grateful to John Sterman for taking the photograph in Fig. 6. I am also very grateful to Jay Forrester, for the detailed support and encouragement that he gave to this project, for sharing with me his memories of his early years, and for allowing me to use various photographs from his private collection. Any shortcomings are my own responsibility.

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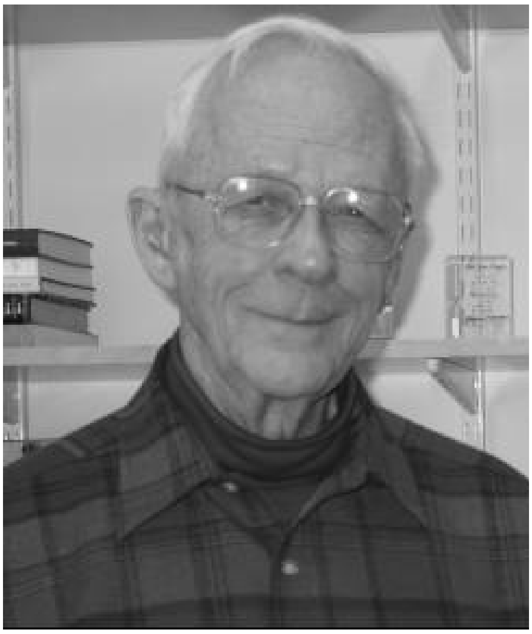
David Lane is Reader in Management Science at LSE. His research, teaching and consultancy focus on strategic modelling and systems thinking. He has worked with many companies, consulting firms and government organisations.

He has mathematics degrees from Bristol and Oxford Universities and a Doctorate in mathematics also from Oxford and was a consultant in Shell International and a marketing manager in Shell UK.

Dr. Lane is on the editorial boards of *Systems Research and Behavioral Science* and *International Journal of Operational Research*. He is co-editor of the *SR&BS* collections emerging from the series of European System Dynamics Workshops, a member of both the Council and the Accreditation Panel of the OR Society and a Fellow of the OR Society. In 2005 he received an LSE award for outstanding performance and innovation in teaching. In 2007 he received the International System Dynamics Society's Jay Wright Forrester Award for outstanding contribution to the field of system dynamics.

Appendix: Jay Wright Forrester

Academic and consultant; innovator in servomechanism and digital computer technology; creator of the system dynamics modelling technique and a life-long practitioner and advocate of its use to promote long-term policy analysis, learning about complex organisations and the redesign of such organisations.



Forrester in his study at MIT, late 2002. © DCL

Born: 14th July 1918 in Climax, near Arnold, Nebraska, USA.

Education: B.S. Electrical Engineering, University of Nebraska (1939)
S.M. Electrical Engineering, Massachusetts Institute of Technology (1945)

Currently: Germeshausen Professor Emeritus and Senior Lecturer, Massachusetts Institute of Technology, USA

Key Positions: Research Assistant, MIT Department of Electrical Engineering (1939-1944); Associate Director, MIT Servomechanism Laboratory (1940-1951); Director, ASCA project (1944-1946); Director, Whirlwind project (1946-1951); Head of Digital Computer Division, MIT Lincoln Laboratory (1951–56); Professor of Management, MIT (1956-1972); Germeshausen Professor, MIT (1972-1989); Professor Emeritus and Senior Lecturer (1989 to present)

Key Publications:
Industrial Dynamics (1961) MIT Press.
Principles of Systems (1968) MIT Press.
Urban Dynamics (1969) MIT Press.
World Dynamics (1971) Wright-Allen Press.
Collected Papers of Jay W. Forrester (1975) Wright-Allen Press.

Honorary Degrees: D.Eng. University of Nebraska, USA (1954); D.Sci. Boston University, USA (1969); D.Eng. Newark College of Engineering, USA (1971); D.Sci. Union College, USA (1973); D.Eng. University of Notre Dame, USA (1974); D.Pol.Sci. University of Mannheim, Germany (1979); D.Humane Letters, State University of New York, USA (1988); D. Philosophy, University of Bergen, Norway (1990); D. Honoris Causa, Universidad de Sevilla, Spain (1998).

Awards and Honours: Fellow, Institute of Electrical and Electronic Engineers (1955); Academy of Management Award for *Industrial Dynamics* (1962); Member, National Academy of Engineering (1967); Inventor of the Year, George Washington University (1968); Fellow, American Academy of Arts and Sciences (1968); Fellow, Academy of Management (1969); Valdemar Poulsen Gold Medal, Danish Academy of Technical Sciences (1969); Organizational Development Council Publications Award for *Urban Dynamics* (1970); Member, Club of Rome (1970); Medal of Honour, Institute of Electrical and Electronics Engineers (1972); Benjamin Franklin Fellow of the Royal Society of Arts (London) (1972); Systems, Man, and Cybernetics Award for Outstanding Accomplishment, Institute of Electrical and Electronic Engineers (1972); New England Award, The Engineering Societies of New England (1972); Howard N. Potts Medal, The Franklin Institute (1974); Honoury Member, Society of Manufacturing Engineers (1976); Harry Goode Memorial Award, American Federation of Information Processing Societies (1977); inducted into the National Inventors Hall of Fame (1979); The Common Wealth Award of Distinguished Service (1979); Fellow, American Association for the Advancement of Science (1980); Computer Pioneer Award, IEEE Computer Society (1982); James R. Killian Faculty Achievement Award, Massachusetts Institute of Technology (1987); Honorary Professor, Shanghai Institute of Technology (1987); Agricoltura 2000 Award, Italy (1987); Information Storage Award, IEEE Magnetics Society (1988); Lord Foundation Award (1988); U.S. National Medal of Technology (1989); Pioneer Award, IEEE Aerospace and Electronic Systems Society (1990); Price Waterhouse Information Technology Leaders Award for Lifetime Achievement (1998); inducted into the International Federation of OR Societies' Operational Research Hall of Fame (2006).

