# THE FEEDBACK CONCEPT IN AMERICAN SOCIAL SCIENCE, WITH IMPLICATIONS FOR SYSTEM DYNAMICS

George P. Richardson

System Dynamics Group
Sloan School of Management
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

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ABSTRACT

The feedback concept is perhaps the single most essential characteristic of the system dynamics approach. However, the application of the feedback concept to social systems is neither original nor unique to the field. Loops of mutual causality appeared explicitly in classical social science literature as early as the mid-1800s, and there were implicit indications of the loop concept as an adjustment mechanism as early as the 1700s. A major thread in the use of the feedback concept in the social sciences developed out of the cybernetics movement that emerged in the 1940s.

System dynamics arises in a line of feedback thinking separate and distinct from cybernetics, which is termed in this paper the servomechanisms thread. Through the 1960s the cybernetics and servomechanisms threads differ in their approaches to problems, most fundamentally in their purposes, their assumptions about the source of system dynamics of interest, and their beliefs about what can be achieved with the feedback perspective.

This paper places the feedback perspective of system dynamics in historical context. It identifies the system dynamicist's "endogenous point of view" as a significant development in the use of the feedback concept in the social sciences, and draws some implications for practice in the field.

## Introduction

The feedback concept is perhaps the single most essential characteristic of the system dynamics approach. From the earliest beginnings of the field the feedback loop has been identified as the fundamental building block of system dynamics models [1,2,3]. Rapidly it emerged as the basic unit of analysis of system behavior [5]. At the heart of the field is the tenet--a grand conjecture, an article of faith, or a proposition repeatedly verified in practice--that "dynamic behavior is a consequence of structure," and there is no doubt that in the concept called "structure" the system dynamicist assumes loops of information feedback. One can easily imagine system dynamics studies without DYNAMO or DYSMAP (even BASIC will suffice),[1] or even without computer simulation (if the system is simple enough or linear enough), or perhaps even without mathematics of any sort (if diagrams and verbal analyses seem adequate to the task [9]). But an analysis without feedback loops unquestionably belongs to some other approach.

In view of the central place of the feedback concept in the system dynamics approach, it is important to know how others have used the concept in the social sciences. How did people come to apply to human systems a concept first perceived in engineering? What contributions can be traced to the use of the feedback loop to address human problems? What difficulties do people perceive in the use of the

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1 For introductions to the use of DYNAMO in system dynamics modeling, see [6] or [7]. For DYSMAP, see [8]. For system dynamics models in BASIC see the Teachers' Manual accompanying [7].





concept? What is the perceived potential of its application in the social sciences? Finally, where differences exist in the use or perceived potential of the feedback concept in human affairs, what might account for the differences and what are their implications for the field of system dynamics?

Answers to such questions would serve two purposes. They would help us better understand our own methodology--how we fit into the broader flow of ideas in the social sciences, how we are like others, how we differ, what our distinctive contributions can be. And they would help others understand us, as we communicate our work enlightened by having seen it in its historical context.

## Ideas Behind the Feedback Concept in the Social Sciences

The mature concept of the feedback loop in twentieth-century social science is a blend of intuitions and ideas from no less than four sources: engineering, of course, biology, mathematical models of biological and social systems, and, perhaps surprisingly, classical social science literature itself. As a result, when the engineering concept and the word "feedback" became widely known in the 1940s, they fell on fertile ground in the social sciences that had been well-prepared by prior, closely related ideas. But people differed in their exposure to these prior ideas, and they made different associations. The story proves again that context informs content: what people have done with the feedback concept and what they perceive its power and limitations to be depend on the sources of their understandings of it.

Engineering

The engineers' contribution to our understanding of feedback is often thought to begin with the dramatic proliferation of feedback devices in the late eighteenth century, the classic example being James Watt's governor for the steam engine (1788). But Watt came rather late into the feedback business. Mayr [10] traces the history of feedback all the way to the golden age of Greece. He credits Ktesibios (250 B.C.) with the first known feedback device--a float valve used to create a steady drip of water into a cylindrical vessel, enabling the construction of an accurate water clock. From our current point of view it is interesting to note that Ktesibios used the valve to compensate for changes in a quantity in the system--the height of the water (and resulting water pressure) in the storage tank from which water dripped into the clock. Ktesibios would have been quite comfortable with the observation that feedback can reduce the sensitivity of a system to parameter variations.[2]

Although feedback devices were used with increasing frequency from the time of Ktesibios on, and although formal analysis of their structure and behavior began as early as 1868 with Maxwell's paper "On Governors," the loop concept underlying them remained completely unrecognized until the twentieth century. Before Maxwell, regulators were constructed with little theorizing and a lot of experimenting. The famous analyses of Maxwell, Routh (1876), Lyapunov (1892), and Hurwitz (1895)[3] were phrased in terms of differential equations. The

2 See [11]. For the same idea in system dynamics literature, see [12], p. 172, and [6], pp. 281-286.

3 For complete citations see [10], p. 131.





loop notion remained hidden until the development of Laplace-transform methods and block diagrams [10, p. 129].

Mathematical Models

Though it remainded hidden until the 1930s, the loop idea was present in differential and difference equations used to model biological and societal phenomena. Embedded in the famous predator/prey equations of Volterra[4] for example, is a closed-loop view of an ecosystem:

$$\frac{dx}{dt} = ax - bxy, \quad x(t) = \text{prey at time } t;$$

$$\frac{dy}{dt} = -cy + dxy, \quad y(t) = \text{predator at time } t.$$

The loop structure of this nonlinear system is shown in figure 1. The loop structure in such systems is easy to miss if one concentrates, as Volterra did, on finding a closed-form solution.

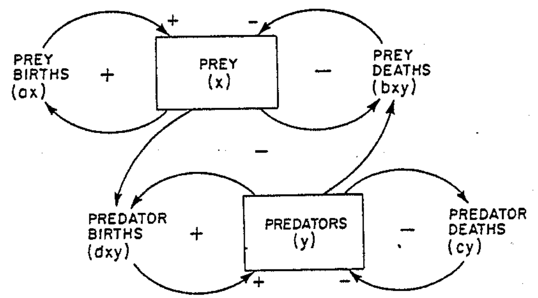


Figure 1: Loop structure of the Volterra predator/prey equations.

4 Contained in [13]. For an excellent treatment and the story behind the model, see [14].

Human systems were also represented in such terms. The population equation of Verhulst [15] provides an instructive example:

$$\frac{dP}{dt} = aP - bP^2, \qquad P(t) = \text{population at time } t.$$

The term involving the square of population was intended by Verhulst to represent conflict and stress arising from contacts between people (proportional to P x P). The result is the familiar nonlinear logistic equation, which exhibits sigmoid growth. Feedback cognoscenti can see in this equation a pair of loops, one positive and one negative. The nonlinearity produces a gradual change in dominance from the positive to the negative loop, shifting the behavior from exponential growth to exponential adjustment to a maximum population.[5] (See figure 2.) To solve the equation, however, it is not necessary to see the loops and the shift in loop dominance; there is no evidence that Verhulst made any use of the loop concept in formulating or analyzing his model.

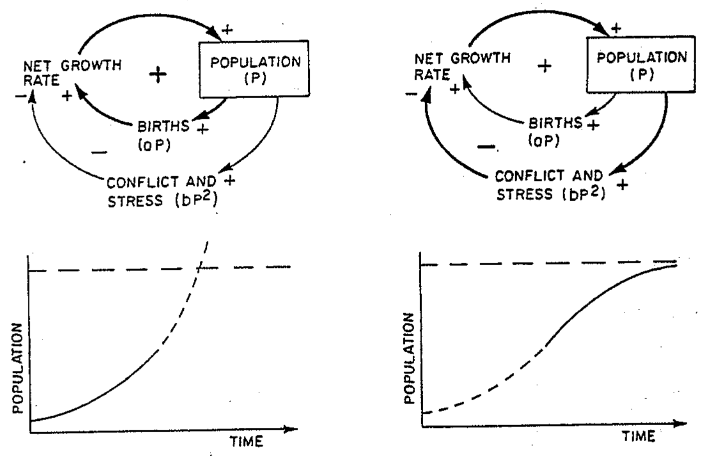


Figure 2: Shift in loop dominance in the nonlinear Verhulst population equation.





Biology and Homeostasis

In addition to the loop idea implicit in mathematical models of ecosystems, biology contributed the concept of homeostasis. The idea has been traced back to Claude Bernard (1878), Leon Fredericq (1885), Charles Richet (1900),[6] and L. J. Henderson [17,18]. However, it was Walter Cannon (1928) who coined the term "homeostasis" and, in The Wisdom of the Body [16], provided its most complete development. What intrigued these authors was the apparent stability of some organisms in the face of dramatically changing external and internal conditions. Variations in temperature, atmospheric pressure, humidity, heat and lactic acid generated by muscular activity, and so on, are not nearly as profoundly disturbing to highly developed creatures as one would expect. Cannon concluded that the word "equilibria" did not do justice to the phenomenon:

> The coordinated physiological processes which maintain most of the steady states in the organism are so complex and so peculiar to living beings - involving, as they may, the brain and nerves, the heart, lungs, kidneys, and spleen, all working cooperatively - that I have suggested as special designation for these states, homeostasis. The word does not imply something set and immobile, a stagnation. It means a condition - a condition, which may vary, but which is relatively constant [16, p. 24].

Cannon went so far as to speculate that the means used by highly evolved animals for maintaining homeostasis might suggest principles by

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5 The dominant polarity can be defined rigorously as the sign of

$$\frac{dP'}{dP}, \qquad \text{where } P' = \frac{dP}{dt}.$$

Here $P' = aP - bP^2$, so $dP'/dP = a - 2bP$, which is positive for $P < a/(2b)$ and negative for $P > a/(2b)$. Thus the dominance in this system shifts from the positive loop to the negative loop when P reaches half its maximum (a/b).

6 See [16], pp. 26 and 40, for complete citations.

which social and industrial systems establish and regulate steady states.[7]

With the emergence of the engineer's concept of negative feedback in the 1940s, the concept of homeostasis was linked to a loop mechanism that promised to explain all the varied homeostatic phenomena. The symbiosis between the two concepts was so enticing that it led some social scientists attracted to the feedback notion to ignore almost totally the concept of positive feedback.[8]

Social Science Literature Before 1945

The social sciences contribute two lines of thinking to the modern conception of the feedback loop. In one line, containing relatives of biological homeostasis and ancestors of goal-seeking negative feedback, the loop idea is only implicit. Nonetheless, it is hard to resist drawing parallels between the self-equilibrating economy of Adam Smith's Wealth of Nations, for example, and the burgeoning diversity of feedback devices of the late 1700s. Mayr concludes:

> Smith's theory that deviations from an optimal state of the economy would automatically be corrected by the system of free enterprise and the law of supply and demand implies a conception of the closed causal loop that is in principle the same as the feedback loop [10, p. 129].

In his use of the concept of a self-equilibrating system, Adam Smith was preceded by other exponents of laissez-faire, including particularly David Hume, writing On the Balance of Trade (1752). There

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7 [16], pp. 25-26 and the Epilogue: Relations of Biological and Social Homeostasis, pp. 287-306.

8 For an indication of this tendency, note the rediscovery of positive feedback loops in [19].





were similar lines of thinking about government: Platt [20] argues persuasively that the "checks and balances" assiduously built into the U.S. Constitution were a conscious effort to design a system of "stabilization feedbacks." In The Federalist papers, a series of 85 newspaper articles written by Hamilton, Jay, and Madison to persuade the public to favor the new Constitution, there are clear indications of designing for stability, for speed of response without instability, for different time constants of response for different purposes, and for achieving a desirably self-regulating structure out of the natural self-interests of the participants [20]. Finally, some see in the writings of Thomas Malthus [21] on the preventitive and positive checks on population growth an implicit understanding of both self-reinforcing and self-controlling loop processes.

Thus the loop concept underlying information-feedback and mutual causality permeates implicitly the thoughts and devices of the late eighteenth century. However, there is no evidence that the economists, politicians, philosophers, and engineers of the time pictured loops of any sort in their thinking [22].

In contrast, the other line of thinking in the social sciences that contributes to the modern concept of a feedback system makes explicit reference to "circular processes" and loops of "mutual causality." As early as the 1840s there were explicit descriptions of loop-like processes, as exemplified by the following vivid description of speculation by John Stuart Mill:

> When there is a general impression that the price of some commodity is likely to rise, from an extra demand, a short crop, obstructions to importation, or any other cause, there is a disposition among dealers to increase their stocks, in

> order to profit by the expected rise. This disposition tends in itself to produce the effect which it looks forward to, a rise of price: and if the rise is considerable and progressive, other speculators are attracted, who, so long as the price has not begun to fall, are willing to believe that it will continue rising. These, by further purchases, produce a further advance: and thus a rise of price for which there were originally some rational grounds, is often heightened by merely speculative purchases, until it greatly exceeds what the original grounds will justify. After a time this begins to be perceived; the price ceases to rise, and the holders, thinking it time to realize their gains, are anxious to sell. Then the price begins to decline: the holders rush into market to avoid a still greater loss, and, few being willing to buy in a falling market, the price falls much more suddenly than it rose [23].

Mill's description of this self-reinforcing speculation process is particularly impressive because it traces the dynamic implications of what amounts to a positive feedback loop, in both the rise and the fall. It even contains a hint of the feedback structure that could act to halt the rise of speculative behavior and start its collapse, as sketched in figure 3.

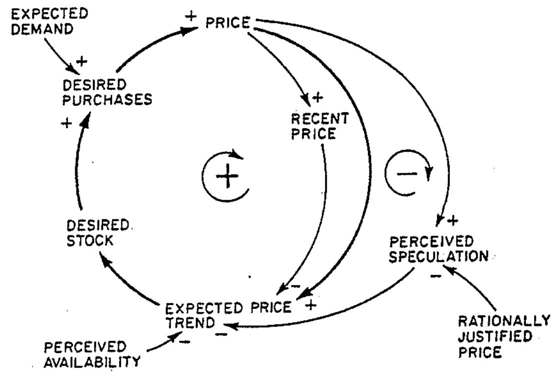


Figure 3: Mutual causal loops in John Stuart Mill's description of speculation.





By the mid-1900s, observations of circular processes exhibiting loops of mutual causality had become commonplace in the social sciences. There are the vicious circle, in which bad leads to worse; the bandwagon effect, in which a movement gains supporters in part because it has been perceived to be gaining in popularity; the less well-known concept of "schismogenesis" (the generation of a schism) developed by the anthropologist Gregory Bateson [24] to analyze the dynamics of culture contact; Robert King Merton's "self-fulfilling prophecy" [26,27], exemplified by a run on a bank that starts from fears of the bank's collapse and ends by producing that very result; Paul Samuelson's multiplier-accelerator model of economic cycles [28]; and Gunnar Myrdal's "principle of circular and cumulative causation," used in his monumental study of American race relations [29].

It is interesting to observe that virtually every instance in which circular processes were recognized in the social sciences before the 1940s involved self-reinforcing, positive loops. Apparently, the loop notion was easier to see when positive feedback was involved, but more difficult to perceive in cases involving negative feedback. Presumably the availability of other metaphors, such as the balancing metaphor, obviated the need for negative loops.[9]

From the perspective of a modern-day system dynamicist, the work of Gunnar Myrdal is particularly significant. In An American Dilemma [29] and later in Rich Lands and Poor [31], Myrdal delves deeply into loop structures in socioeconomic systems:

9 The use of the balancing metaphor to describe what is clearly a negative feedback process appears even after the emergence of the feedback idea; see [30].

> A deeper reason for the unity of the Negro problem will be apparent when we now try to formulate our hypothesis concerning its dynamic causation. The mechanism that operates here is the 'principle of cumulation,' also commonly called the 'vicious circle.' <u>This principle has a much wider application in social relations. It is, or should be developed into, a main theoretical tool in studying social change</u> [29, p. 75, emphasis added].

He makes use of his 'principle of cumulation' in no fewer than twenty distinct places in <u>An American Dilemma</u>, and he devotes an entire section of one chapter and an appendix to discussions of the workings of the 'principle.' While his examples of circular processes are insightful, even more interesting are his related methodological comments:

> It was during this study [<u>An American Dilemma</u>] that I first came to realise the inadequacy of the equilibrium approach, and to understand that the essence of a social problem is that it concerns a complex of interlocking, circular and cumulative changes.
>
> ...The main scientific task is, however, to analyse the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes... The scientific ideal is not only to split the factors into their elements and to arrange them in this way, but to give for each of the elements quantitative measures of its ability to influence each of the others, and to be influenced itself by changes in other elements within the system or by changes in exogenous forces.
>
> ...Ideally the scientific solution of a problem like the Negro problem should thus be postulated in the form of an interconnected set of quantitative equations, describing the movement--and the internal changes--of the system studied under the various influences which are at work.
>
> ...it is useless to look for one predominant factor, a 'basic factor' such as the 'economic factor'...as everything is cause to everything else in an interlocking circular manner.
>
> ...if the hypothesis of cumulative causation is justified, an upward movement of the entire system can be effected by measures applied to one or the other of several points in the system; but this certainly does not imply that from a





> practical and political point of view it is a matter of indifference where and how a development problem is tackled. The more we know about the way in which the different factors are inter-related...the better we shall be able to establish how to maximise the effects of a given policy effort designed to move and change the social system.
>
> Nevertheless, it is unlikely that a rational policy will work by changing only one factor [31, pp. 26-32].

In these statements Myrdal sounds astonishingly like a modern system dynamicist. He foresaw the need for formal models embodying the causal-loop point of view in policy analysis. Furthermore, he advocated a dynamic view, not only of the movement of the system but also its "internal changes," foreshadowing the system dynamicist's use of nonlinearities.

## <u>Emergence of the Feedback Concept in the Social Sciences</u>

The first unequivocal recognition, that I know of, of a connection between self-regulation in living systems and automatic control in engineering devices is contained in a famous essay sent to Darwin by Alfred Russel Wallace, the "other man" most responsible for the theory of evolution. In it, Wallace writes:

> The action of this principle [the struggle for existence] is exactly like that of the steam engine, which checks and corrects any irregularities almost before they become evident; and in like manner no unbalanced deficiency in the animal kingdom can ever reach any conspicuous magnitude, because it would make itself felt at the very first step, by rendering existence difficult and extinction almost sure to follow [25, p. 428].

Gregory Bateson called this the first cybernetic model. Yet it remained an isolated observation until the explosion of interest in the 1940s and 1950s in the application of engineering feedback to human systems.

Credit for the first published article linking people and feedback must go to Rosenblueth, Wiener, and Bigelow [32]. They instigated a debate in the pages of Philosophy of Science over whether machines could be termed "purposeful." Contributing a modern slant to the age-old argument about the place of teleological explanations in science, they argued that any machine or organism that was controlled by information feedback deserved to be called purposeful. In the process they linked the feedback concept of control engineering to a cat pursuing a mouse, a bloodhound following a trail, and a person drinking a glass of water or throwing a stone at a moving object.[10]

For our purposes the significance of the Rosenblueth, Wiener, and Bigelow paper lies in its contribution to the start of an intellectual movement centered on the concept of feedback: cybernetics. The paper was read at a conference in 1942 sponsored by the Josiah Macy, Jr. Foundation, devoted to "problems of central inhibition of the nervous system." It led to the organization of the first Macy Foundation Conference on "Feedback Mechanisms and Circular Causal Systems in Biological and Social Systems," held in 1946. The Macy Foundation went on to sponsor a total of ten such conferences, the last being held in 1953. Over the years the participants included some very respected social scientists, perhaps the most famous of whom were Gregory Bateson, Karl Deutsch, Kurt Lewin, and Margaret Mead.

10 It is interesting to note, however, that the authors ruled a snake striking at a frog to be non-feedback behavior because "there are no signals from the goal which modify the activity of the [snake] in the course of the behavior." Their use of the feedback concept was apparently limited to "error-controlled" processes. For them the "course of the behavior" did not include the snake's preparation for the strike, in which loops of information-feedback are obviously essential for success.





The Cybernetics Thread

Within a few short years of the first Macy conference, many more social science articles using the concept of feedback began appearing. Early among them were Kurt Lewin [34], Karl Deutsch [35], Gregory Bateson [36,37], O. H. Mowrer [38], Charles Slack [39], James G. Miller [40], and, of course, Norbert Wiener [41,42]. With the possible exception of Wiener, none of these would have called himself a "cybernetícist" or claimed to be "doing" cybernetics. They were social scientists who learned of the engineers' concept of feedback from the cybernetics movement. What emerges is a "cybernetics thread" in the use of the feedback concept in the social sciences--a network of social scientists who acquire a particular set of understandings and points of view about feedback because they connect, through books or personal contact, to the field of cybernetics.

Feedback thinking moved at such a pace that by 1948 Wiener could say,

> It is certainly true that the social system is an organization like the individual, that it is bound together by a system of communication, and that it has a dynamics in which circular processes of a feedback nature play an important part [41, p. 24, emphasis added].

Just five years after the publication of Cybernetics an article in The Scientific Monthly can boldly state: "Just as the nineteenth century was the Age of Power, the twentieth century is the Age of Communication and Control." [43]

It is fair to say that what most social scientists know of the feedback concept comes from the cybernetics movement that Wiener initiated. Yet careful scrutiny of the use of the feedback concept in the cybernetics thread shows some significant differences from its use in system dynamics.

Wiener, for example, doubted that cybernetics could be applied fruitfully to societal problems because, he said,

> ...the main quantities affecting society are not only statistical, but the runs of statistics on which they are based are excessively short...The human sciences are very poor testing grounds for a new mathematical technique [41, pp. 24-25].

W. Ross Ashby, commenting upon variations in the definition of feedback, concluded that an exact definition is nowhere important:

> The fact is that the concept of 'feedback,' so simple and natural in certain elementary cases, becomes artificial and of little use when the interconnexions between the parts become more complex [44, p. 54].

Compare this with Forrester's numerous statements on the importance of feedback in system dynamics:[11]

> The first and most important foundation [for progress in management science] is the concept of servo-mechanisms (or information-feedback mechanisms)....the concepts of information-feedback systems will become a principle basis for an underlying structure to integrate the separate facets of the management process [2, pp. 53-54].

> The first year of exploration [in industrial dynamics] pointed toward the concepts of feedback systems as being much more general, more significant, and more applicable to social systems than had been commonly realized...Feedback processes emerged as universal in social systems and seemed to hold the key to structuring and clarifying relationships that had remained baffling and contradictory [45, p. 134].

Stafford Beer's Cybernetics and Management [46] parallels Forrester's Industrial Dynamics in time of publication and apparent

11 See especially the section entitled "Status of Feedback Theory" in [45], reprinted in [4], pp. 137-141.





purposes. Yet in contrast to Forrester, Beer advocates modeling "exceedingly complex" systems, such as corporations or economies, as "black boxes," information processors of unknowable structure that convert inputs (somehow) into outputs. Following Ashby, Beer assumes that it is not possible to understand the feedback structure of a complex system or to link that structure to the system's behavior. In Beer's scheme feedback is to be used to control such an exceedingly complex system by linking "outputs" back to "inputs" through an external add-on feedback control mechanism.

How to design such a controller is hard to discern from these sources. The process, touched on in Ashby [44] and Beer [46] and elaborated in Klir [47], appears to involve a discrete point of view and binary/logical models that trace back to the neural nets of McCulloch and Pitts [48]. A system "state" to these authors, for example, is not an integration but rather a set of particular values of all the variables of interest. In this view a system of $n$ variables, each of which can take on the values 0 or 1, has $2^n$ possible "states." It is this view of the state of a system that leads to Ashby's "Law of Requisite Variety" [44,46] that describes the conditions necessary for maintaining the system in some desired state in spite of variation in the system inputs. A discrete view is essential here: the "variety" of any continuous variable is infinite. In this approach to complex systems, dynamic patterns are not of interest. A system is either controlled or it is not controlled. The effort is to provide a controller that can counter disturbing inputs.

A discrete view appears again in the influential work of Miller, Galanter, and Pribram, Plans and the Structure of Behavior [49]. Though in no sense would these psychologists be called "cyberneticists," they are in what I am calling the cybernetics thread, the network of feedback thinkers that traces back to cybernetics writers. Their book was nothing short of an attempt to place the feedback loop at the foundation of psychology. Their version of the feedback loop was called the TOTE unit, in which one Tests to see if a goal is met, Operates to approach the goal, Tests again, and Exits from the loop when the goal is reached. Their classic example was hammering a nail: Test = Is the nail in? If not, Operate = Hammer. Then Test again. Whenever the test shows the nail is in, Exit from this loop. A TOTE unit thus appears to have two ancesters, the negative, goal-seeking feedback loop and the repetitive DO-loop from computer programming.

TOTEs can be arranged in complex hierarchies: any operation in a TOTE can be broken down into a TOTE unit all its own. "Hammer" could become $T_1$: Is hammer up? $O_1$: Lift hammer. $E_1$: Exit to $O_o$. $O_o$: Hammer! Embedded in the original $T_oO_oT_oE_o$ unit, we would have $T_o(T_1O_1T_1E_1)O_oT_oE_o$. Presumably, whether to enter into the "Hammer" TOTE or the "Take a nap" TOTE would also be a TOTE. To those who like this point of view, all intentional human behavior (plans) are TOTEs made up of TOTEs made up of TOTES... Some see that this version of the feedback concept, as it links with tranformational grammars and artificial intelligence, may eventually be able to account for all manner of human behavior [50,51].





Looking back over these examples we see that a set of messages about the potential of the feedback concept in the social sciences was built up in the cybernetics thread. Many of these messages connected with traditional lines of thinking in the social sciences, the most obvious being checks and balances, control, stability, and homeostasis. But also resonating here are an emphasis on discrete events, the difficulty of understanding complexity, the tendency to couch analyses in words rather than mathematics, the significance of randomness in complex systems, the need to make random variation an object of study in itself, an input/output point of view, and a resulting tendency to look outside a system for problematic inputs and external control. We would expect social scientists in the cybernetics thread to continue to reflect some of these tendencies as the thread weaves through time.

The Servomechanisms Thread

There is, however, a separate and distinct thread of feedback thinking in the social sciences that does not trace back to cybernetics origins. Its forebears are more appropriately seen to be engineering servomechanisms and mathematical biology. It is in this other thread that system dynamics emerges.

The early authors in this other thread are A. W. Phillips [52,53], W. W. Cooper [54], Richard M. Goodwin [55,56], Herbert Simon [57,58], and Arnold Tustin [59]. Each of these draws directly on the concepts and mathematics of engineering servomechanisms to discuss the dynamics of economic systems. Phillips, an economist with undergraduate training in engineering, starts by discussing mechanical models designed to mimic economic cycles [52]. In 1954 he published a paper using the mathematics of servomechanisms to analyze policies for stabilizing the business cycle [53]. Along with Tustin, Phillips is seen as the originator of a control systems approach to macroeconomics that failed (so far!) to penetrate the mainstream of economic thought [60].

Tustin [59] brings his engineering background to a reconsideration of then existing macroeconomic models. In Keynes' General Theory, the multiplier-accelerator model of Hicks and Samuelson, and other economic theories, he finds "closed sequences of dependence," which he explicitly identifies as feedback loops. It is clear from Tustin's work that no list of "pre-feedback thinkers" in the social sciences is complete without the name of Keynes. Tustin is interested in the causal connection between loop structure and dynamic behavior:

> The problem to be investigated is whether the closed sequences of dependence are such as account for business cycles. The general notion that 'interdependence' is a key to the understanding of the behaviour of economic systems is of course a very old one. It was, for example, precisely what Engels was attempting to express by his 'dialectic relationship,' but the consequences of interaction in a complex system escape purely verbal analysis [59, pp. 5-6].

So he gave to his economics audience the mathematics of feedback control engineering for the analysis of economic dynamics.

Cooper [54] proposes to extend the classical theory of the firm beyond rational models of planning to include the operational behavior within the firm. He notes the analogy between an accounting system to control costs and "a servomechanism in which the accountant serves as a filter (with certain criteria built into it) in the feedback."





Moreover, he represents the behavior of agents in the firm in simple mathematical models that he recognizes as negative feedback control systems and notes the possibility of exponential adjustment or oscillatory behavior.

It is in Cooper's work that Herbert Simon finds the beginnings of his notion of "bounded rationality."[12] At the heart of that concept and the picture of adaptive behavior that it implies, Simon places the concept of feedback. To sketch the idea of adaptive human behavior, he describes a simple, hypothetical setting in which a manufacturer uses a single raw material from which to fabricate a single product [58]. From $x$ units of the raw material, he can make $y$ units of the product [$y = y(x)$]. His costs depend on how much he buys [cost = $C(x)$], and the price he charges depends on how much he makes [price = $P(y)$]. How much raw material does he buy? The classical profit maximization criterion gives a unique optimal answer, the value of $x$ that makes the derivative of profit equal to zero:

$$\frac{d}{dx}\,[y\,P(y) - x\,C(x)] = 0$$

A more realistic picture of the situation, Simon says, would capture the dynamics of the manufacturer's adjustments in $x$ to reduce the discrepancy between the actual condition of his profits and this optimal condition. He proposes the following model of adaptive behavior:

$$\frac{dx}{dt} = b\,\{\frac{d}{dx}\,[y\,P(y) - x\,C(x)]\}, \qquad b > 0.$$

12 See [61]. For connections to system dynamics, see [62].

He then observes that this is a negative, goal-seeking feedback process familiar to servomechanisms engineers:

$$\frac{dx}{dt} = b\ (\theta_s - \theta_o)$$

where $\theta_s = 0$ [the desired condition],

$\theta_o = -\frac{d}{dx}\ [y\ P(y) - x\ C(x)]$ [the actual condition],

and $(\theta_s - \theta_o)$ = the "error" between desired and actual.

In the remainder of the article, Simon expands on the notion of feedback models of adaptive behavior, giving examples involving motivation, learning, and group processes. The significance for us of this early work is in its explicit use of feedback in quantitative models to capture realistic, adaptive human behavior. As Simon states:

> It might be pointed out that the notion of a servomechanism incorporating human links is by no means novel...The idea of social, as distinguished from purely physiological, links is relatively new [57].

## The Emergence of System Dynamics

The most obvious contribution of Jay W. Forrester to this line of feedback thinking is the use of computer simulation. Like his predecessors in this servomechanisms thread, Forrester turns to mathematics to make the link between assumptions about feedback structure and conclusions about dynamic behavior. But requiring closed-form solutions restricts realism and significance. Simulation dramatically extends the range of models that can be formulated and analyzed. Systems of many equations can be easily handled[13] and nonlinearities pose no special problems.

13 The forerunner of DYNAMO was called SIMPLE--Simulating Industrial Management Problems with Lots of Equations.





Yet, more important than simulation, Forrester contributed a point of view and a set of biases about how models should be constructed to aid policy analysis. The shortest statement of the approach Forrester envisioned is contained implicitly in a set of fourteen "obvious truths" he found prevalent in management science in 1960 and with which he disagreed. In each of the following categories, the system dynamicist would be presumed to take an opposite point of view:

1. Linear analysis. That a linear analysis is an adequate representation of industrial and economic systems.

2. Stable systems. That our social systems are inherently stable and can be attacked with methods that are valid only for stable systems that tend toward equilibrium.

3. Prediction function. That the obvious purpose and test of a model of an industrial system is its ability to [point] predict specific future action.

4. Data. That the construction of a model must be limited to those variables for which numerical times-series data exists.

5. Accepted definitions. That a model must be limited to considering those variables which have generally-accepted definitions.

6. Descriptive knowledge. That our vast body of descriptive knowledge is unsuitable for use in model formulations.

7. Exact vs. social. That there is a sharp distinction between the 'exact' and the social sciences.

8. Source of analogy. That the physical and genetic sciences provide the proper analogy for model building in the social sciences. The 'laws' of physics usually relate to open[-loop] systems rather than information-feedback systems. Furthermore, they relate to fragments of systems rather than to entire systems.

9. Accuracy of structure. That accuracy of parameters is more important than system structure.

10. Accuracy vs. precision. That accuracy must be achieved before precision is useful.
11. Optimum solutions. That it is necessary to find optimum solutions to managerial questions.
12. Controlled experiments. That the social sciences differ fundamentally from the physical sciences by inability to conduct 'controlled experiments.'.
13. Human decisions. That human decision making is obscurely subtle and impenetrable.
14. Decision vs. policy. That emphasis in models should be on decision making [2, pp. 49-51].

As modeling assumptions to avoid, these fourteen points constitute a negative characterization of the field of system dynamics as Forrester envisioned it. Feedback is present in number 8 and underlies part of 9; number 1 gives feedback structure the adaptability necessary to model societal systems; computer simulation is in 1 and 12; something of the proper relationship between mental and formal models is hinted at in 5, 6, and 10; a bias toward continuous models can be glimpsed in 14; and a bit of "bounded rationality" shows in 6 and 11. As an implicit definition of the field, however, the list is no doubt incomplete. Notably missing, for example, are the significant distinction between conserved flows and information, the central role of information in determining behavior, the emphasis on patterns of behavior (defining problems dynamically), and tools for reliable model building (such as testing extreme conditions). But our concern here is with feedback, and for that focus an even more notable omission from this list is the system dynamicist's "endogenous point of view."





The Endogenous Point of View

Forrester's most significant contribution to the evolution of the feedback concept in the social sciences is his concept and use of the <u>closed boundary</u>:

> The boundary encloses the system of interest. It states that the modes of behavior under study are created by the interaction of the system components within the boundary. The boundary implies that no influences from outside of the boundary are necessary for generating the particular behavior being investigated [5, p. 112].
>
> If a particular difficulty in a system is being investigated, the system described within the boundary should be capable of generating that difficulty. The closed-boundary concept implies that the system behavior of interest is not imposed from the outside but created within the boundary [63].

The closed boundary is the feedback notion pressed to its greatest extreme. The notion is that all dynamically varying quantities are contained within the closed boundary, and all derive their dynamic patterns from interactions with other variables inside the boundary. The concept of the closed boundary is an expression of <u>an endogenous point of view</u>, a focus inward on the inner workings of a system rather than outward on the environment of a system.

> The closed boundary does not mean that the system is unaffected by outside occurrences. But it does say that those outside occurrences can be viewed as random happenings that impinge on the system and do not themselves give the system its intrinsic growth and stability characteristics [63].

In the Macy cybernetics meetings, feedback came to be defined as "alteration of input by output" [64]. Forrester's view gives a markedly different feeling in which system "inputs" and "outputs" have much less importance. In the endogenous point of view, it is the interactions of variables in closed loops that produce a system's dynamic behavior. Randomness may stimulate behavior modes latent in a system's structure, but no quantity is seen as varying merely as a function of time. The opposite extreme from this endogenous point of view is a completely "open-loop" perspective, in which no feedback loops are pictured. In this extreme exogenous point of view, all dynamic variation is caused by variables outside the system boundary. In the absence of loops, all dynamic variation in a model would have to be captured in functions of time.

Thus feedback views of social systems can be placed on a continuum ranging from the extreme open-loop perspective (no feedback or mutual causal properties) to the extreme closed-boundary perspective (all quantities that vary embedded in feedback loops). Any view of social system dynamics can be placed somewhere on this continuum. A single regression equation in the form $Y = b_o + b_1X_1 + b_2X_2 + \ldots + b_pX_p + e$ is an example of a model at the extreme open-loop end of this continuum. Most macroeconometric models are somewhere near the middle of this continuum, deriving some of their dynamics from exogenous variables modeled as functions of time and some from resulting interactions of variables in feedback loops [65]. One legacy of the cybernetics thread is that most social scientists who make use of the feedback concept are also somewhere in the middle of this continuum. Any of Forrester's published models is an example of the extreme endogenous point of view.

Set against the history of the feedback concept in the social sciences, Forrester's conception of the closed model boundary amounts to two rather startling claims: (1) that it is desirable to derive the observed dynamics of a social system from nothing more than its





information-feedback/mutual causal-loop structure;[14] and (2) that it is possible to do so! Feedback thinkers and devotees of mutual causality would probably agree on the desirability; others, we must remember, may not see what's to be gained and that a lot might be lost (such as easy, regression-automated model building). And almost everyone is likely to doubt the possibility.

Why? First, there is the likely assumption that "more is going on" than can be captured in a finite set of mutually causal loops. There are downturns in the economy, decisive moves by charismatic leaders, unpredictable randomness, and so on that suggest exogenous variables are necessary to mimic reality. Second, the knowledge that social systems learn, adapt, and change over time seems to imply that a formal model with fixed structure can never be an adequate representation. No doubt some are biased toward mental models because they can be changed so much more quickly than a formal model. Third, there is real interest in being able to predict events, not just patterns of behavior. Accurately anticipating events that have a random component has value. The endogenous point of view, trying to derive all of a system's patterned behavior from internal feedback structure, seems to fail in each of these considerations.

Some of the apparent failure here is real, and some stems from differences in point of view. The issue of fixed model structure is something of both. Nonlinearities act to change loop dominance in a system dynamics model and thus act to change "active structure" over

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14 Levels and rates are assumed to be part of feedback structure.

time. A nonlinear model can indeed adapt and change over time, and its ability to do so deserves to be better understood. But such adaptations are built into nonlinear models from the start; a system dynamics model invents no new structure as it runs. Seeing that society "invents" new structure as it evolves, some people hope formal models can be built with the same inventiveness. Those who take this point of view have moved beyond the goal of using a formal model to gain understanding; they hope that the formal model will solve societal problems and point the way toward desirable societal evolutions. A system dynamics model will not do this. By endogenously changing its active structure over time, however, a nonlinear system dynamics model can expose the implications of any structural change envisioned by the modeler. Such advances in understanding are the goal of the system dynamicist's endogenous point of view.

The role of randomness in the pattern of events is also a mixture of viewpoint and purpose. To many, a random influence (noise of some distribution) is used to replace influences omitted from a model, influences either overlooked or purposely not represented.[15] Some see the randomness as the dominant influence on system behavior. Those who try to predict specific events or decisions, for example, are forced to give randomness and probabilistic considerations a major role. System dynamicists, who focus on the pattern of events and decisions, can afford to relegate randomness to the minor role of stimulating patterns

15 Forrester points out that there are two types of omitted influences--omitted feedback links between model variables, and exogenous variables unaffected by variables in the system--and randomness is an adequate substitute only for the latter [12], pp. 107-108.





determined by system structure. They view exogenous influences as potential "triggers" of behavior but see feedback structure as the "cause." It becomes a question of what is deemed most important or how one prefers to see the world. Those who stress the pattern of events and decisions downplay their acknowledged inability to predict specific events or decisions. Others, who want to focus on the events and decisions themselves, downplay the significance of a focus on mere patterns. The endogenous point of view cannot go beyond patterns.[16]

To the system dynamicist, there are four benefits from the extreme endogenous point of view. First, a focus inward on a system is, rather obviously, the only way to expose internal sources of problems. If the dynamics of urban stagnation are assumed to be caused by external influences, then internal tendencies that cause or exacerbate the stagnation will be missed. Second, it is an empowering point of view which tries to identify internal policy changes that can minimize problems. Make the city as strong as it can be whether or not the federal government provides aid. Third, and probably most important, the endogenous point of view leads to self-contained, consistent theories of the behavior of social systems. A model that looks like and can endogenously behave like the real system is seen to be a stronger theory than one that owes aspects of its behavior to exogenous variables.

16 In light of Appendix K in [12], it is questionable whether any point of view--stochastic, event-oriented, or whatever--will ever go beyond patterns.

A fourth value of the endogenous point of view is simply an extension of the benefit of seeing and representing any feedback loops at all. Consider compensating feedback, for example. A policy of economic aid to a region, which appears beneficial in a model that assumes population is an exogenous variable, may very well be compensated for in reality by less constrained population growth. Only the endogenous view, placing population within the boundary, has the potential to uncover the compensating feedback. The perception of any single loop can expose a self-regulating, compensating, or self-reinforcing tendency in a system. The perception of many loops can expose many such tendencies. Only an extreme endogenous point of view can expose the full range of compensating and reinforcing feedback tendencies in a system.

Thus, although there are many feedback thinkers, and several feedback threads in the social sciences, system dynamicists occupy a unique position among them. The presumption of the field is that one stands to learn the most from models of social systems if one takes an extreme feedback perspective, the endogenous point of view.

Implications of These Observations for System Dynamics Practice

This story of the evolution of the feedback concept in the social sciences helps to place system dynamics in context. It suggests how system dynamics resembles other approaches, how it differs, and, most important, how it may be misperceived when surface similarities obscure deep, philosophical divisions. Not all computer modelers are feedback thinkers; not all feedback thinkers connect the notion to "the entire range of dynamic phenomena that occur within closed (self-contained)





systems" [3]; and certainly not all feedback thinkers share the endogenous point of view.

How can the field of system dynamics make its strongest contribution? The story suggests the following:

(1) System dynamics is a part of a long tradition in the social sciences concerned with loops of information and mutual causality. At every chance acknowledge, indeed, celebrate our connection to that tradition. It can only enhance everyone's understanding of what we are about.

(2) The central concept in system dynamics is the loop notion underlying information-feedback and mutual causality. Emphasize feedback explanations of behavior patterns. Avoid explanations that fail to expose the connection between the loop structure of a system and its behavior. Without an emphasis on feedback explanations, insights about endogenously generated behavior will be remain buried in equations.

(3) Some social scientists try to use the concept of feedback to control a complex system without understanding; the system dynamicist tries to use the concept of feedback to understand complexity. The goal of both groups may be improved system management, but one group choses to get there by improving understandings of the causes of behavior. Repeatedly emphasize the role of a model in improving understanding. Do not be content with a model that merely assembles complexity into a black box that people are not intended to understand.

(4) The system dynamics emphasis on the continuous substructure of a social system differs from the more prevalent focus in the social sciences on discrete events and decisions. Take pains to motivate the continuous point of view and to identify its links to discrete events and decisions.

(5) Among feedback thinkers in the social sciences, only system dynamicists approach the extreme endogenous point of view. Expose inadequacies in understanding or policy analysis that would result from deviating from the endogenous point of view. Always make the model boundary explicit; illuminate the consequences of taking a wider or narrower boundary.

(6) There is widespread concern about the ability of a formal model to represent a system that endogenously changes its own structure. Nonlinearities can change the feedback structures that are active or dominant in a system. Emphasize the role of nonlinearities in changing active system structure. Identify dominant loops in modes of behavior, and expose the consequences of shifts in loop dominance.

(7) Feedback knowledge in the social sciences is fragmented, localized in pockets, separated among and even within disciplines. Take steps to accumulate feedback knowledge. Strive for linkages, assimilation of prior ideas, and generalization into insightful feedback principles.[17] One goal of the system dynamics approach should be the general improvement of nonquantitative intuitions about the dynamics of feedback systems.

17 See, for examples, [63, chapter 6], [66], and [67]. The fact that I can point to only these three references proves we need to take more steps to accumulate and promulgate feedback knowledge.





(8) The feedback view of social systems has not yet spread far enough or gone deep enough to have exhausted its potential. Continue to press the endogenous point of view until it begins to fail to solve problems or generate insights. A paradigm, if this is what the closed-loop, closed-boundary view is, can only reach and teach its maximum if its pratitioners are doggedly persistent [68,69].

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