to attribute spurious causal significance to events that merely correlate with observed peaks and valleys.

Culbertson's use of the feedback concept serves to alert us to the potentially great significance of the form of representation of system structure. The choice of representation sets up a number of implicit, usually unexamined *a priori* presumptions.[8] Further comments on the significance of the choice of the representation of feedback structure are contained in Chapter 6.

5.4 System Dynamics

In the thirty years since the publication of Forrester's *Industrial Dynamics* (section 3.3), the approach he outlined has been applied far beyond its original corporate context. A field of study has grown up, and the name has evolved to "system dynamics" to indicate its perceived generality. The field has academic and applied practitioners worldwide, degree-granting programs at a few major universities, newsletters and journals, an international society, and a large and growing body of literature.[9] Its book-length applications include studies of the dynamics of regional planning, research and development, urban stagnation and decay, commodity cycles, problems of growth in a finite world, economic development, economic fluctuations, community drug policy, human services delivery, energy lifecycles and transitions, dynamics and management of ecosystems, and various corporate policy studies.[10] There are at least ten texts in the field, not counting nonEnglish works or translations.[11] One of its publications, *The Limits to Growth* (Meadows et al. 1972), the controversial popular report of a global study sponsored by the Club of Rome, has been translated into 22 languages.

To do justice to the extent of the field of system dynamics is not possible here. Instead, I shall select particular aspects of published work in the field that contribute in significant ways to the evolution of the feedback concept in the social sciences. I will deal with these aspects under the headings of Principles of System Structure, Insights About Behavior of Complex Systems, Compensating Feedback, and Nonlinear Dynamics, each of which will be discussed in terms of system dynamics publications of the last twenty years.

Principles of System Structure

Over time Forrester honed his particular vision of the structure of a dynamic social system. By 1968 he had distilled it to the point that he could describe it in three pages (Forrester 1968a, 1969) and could

summarize it in a list of "principles of systems" (Forrester 1968b). Naturally in these publications, dynamic system structure involves feedback, but that is only one of its characteristics. The theory came to be described and exemplified in a four-tiered hierarchy (Forrester 1969, p. 12; see also 1968a, p. 83 and 1968b, p. 4-17):

Closed boundary around the system
    Feedback loops as the basic structural elements within the boundary
        Level (state) variables representing accumulations within the feedback loops
        Rate (flow) variables representing activity within the feedback loops
            Goal |
            Observed condition | as components
            Detection of discrepancy | of a rate variable
            Action based on discrepancy |

It is interesting to note the place of these ideas in the evolution we have been tracing. The concept of the closed boundary signals the system dynamicist's endogenous point of view, which we saw frequently emphasized in the servomechanisms thread. It also serves indirectly to show Forrester's independence of von Bertalanffy and the general system theorists, whose work contributes to the cybernetics thread. A "closed system" in general systems theory is a system that experiences no interchange of material, energy, or information with its environment—a corked bottle at constant external conditions, for example. In contrast, Forrester's concept represents a system that is not "materially closed," but rather "causally closed"—the closed boundary separates the dynamically significant inner workings of the system from the dynamically insignificant external environment:

> Formulating a model of a system should start from the question "Where is the boundary, that encompasses the smallest number of components, within which the dynamic behavior under study is generated?" . . . Thinking in terms of an isolated system forces one to construct, within the boundary of his model, the relationships which *create* the kinds of behavior that are of interest (1968b, p. 4-2, emphasis in original).

Thus Forrester thinks of a "closed system" in *causal* terms, as a set of interacting components that in and of themselves cause, or generate, the dynamic behavior they exhibit. He summarized this point of view as his first principle of system structure, the principle of the closed boundary:

> In concept a feedback system is a closed system. Its dynamic behavior arises within its internal structure. Any interaction which is essential to the behavior

mode being investigated must be included inside the system boundary (pp. 4-1,2).

But it is a misleading summary, which has caused confusion (see, e.g., Eden and Harris 1975, pp. 130–131). The two views of closed systems—materially closed and causally closed—are related but are significantly different. No serious system dynamics model is closed in the general system theory sense. Every one exchanges material with its environment—the little clouds representing sources and sinks in Forrester-like flow diagrams represent stocks of material outside the system boundary. Because of such exchanges, Forrester's "closed boundary" systems are, in von Bertalanffy's terms, "open systems." This terminological confusion is one more bit of evidence that these two authors and their ideas of system closure are not in the same feedback thread.[12]

Even more significant, however, is the *importance* Forrester places on the concept of the closed causal boundary. It appears at the top of his hierarchy of system structure. The endogenous point of view has top billing. There is a good reason: although he does not say so, it is possible to argue for a feedback perspective solely on the basis of the assumption of a closed causal boundary. Without causal loops, all variables must trace the source of their variation ultimately outside the system. We would be forced into an exogenous view of the causes of system behavior. Assuming instead that the causes of all significant behavior in the system are contained within some closed boundary forces causal influences to feed back upon themselves, forming causal loops. In Forrester's extreme endogenous point of view, all significant dynamic variation comes from the interactions of variables internal to the system. Exogenous explanations of system behavior are simply not of interest. Feedback loops enable the endogenous point of view and give it structure.

In his teaching text (1968b), Forrester also elevated his notions of levels and rates in feedback loops to principles of system structure:

> (1) A feedback loop consists of two distinctly different types of variables—the levels (states) and the rates (actions). Except for constants, these two are sufficient to represent a feedback loop. Both are necessary.
> (2) Levels integrate (or accumulate) the results of action in a system. . . .
> (3) Levels are changed only by the rates. . . .
> (4) Levels and rates are not distinguished by units of measure. . . . The identification must recognize the difference between a variable created by integration and one that is a policy statement in the system.
> (5) Rates [are] not instantaneously measurable. . . . No rate can, in principle, control another rate without an intervening level variable.
> (6) Rates depend only on levels and constants. . . .
> (7) Level variables and rate variables [in a feedback loop] must alternate. . . .
> (8) Levels completely describe the system condition (Forrester 1968b, pp. 4-6–4-12).

The source of these principles about levels and rates is clear: Forrester is describing in nonmathematical terms the engineer's and the mathematician's notion of a state-determined system. Integrations and rates of change are presented as necessary components of feedback loops. They appear not as mathematical entities, however, but as formalizations of processes of accumulation and change in real systems. These principles of system structure appear in a teaching text, not a philosophical work, so we should not expect alternative structural views, but nonetheless it is significant that they are presented as the way feedback-loop structure must be captured. Difference equations that fail to distinguish accumulations and rates of change are not, according to these principles, an appropriate representation of a feedback system. Neither, presumably, would be diagrams or verbal descriptions of feedback loops that ignore their rate/level substructure.

It is noteworthy here that a form of representation of a feedback loop has been raised to the level of a principle of feedback structure. To be sure, we have noted before that Forrester by choice adopted a continuous point of view (see section 3.3). The choice of representation appears to be a consequence of that point of view. Nonetheless, as we have seen, these are choices that are not shared by all social scientists making use of the feedback concept. We shall return to the question of the significance of system representation in Chapter 6.

Insights About Behavior of Complex Systems

The expressed goal of the system dynamics approach is understanding how a system's feedback structure gives rise to its dynamic behavior. Increasingly, Forrester came to emphasize what he perceived to be generic insights, derived from specific modeling studies but, because of their general structure and behavior, apparently applicable to a wide range of settings.

The first published statement of such generic insights appeared in *Urban Dynamics* (1969) in a chapter on "Notes on Complex Systems." The urban dynamics modeling study grew out of an extended series of discussions at MIT between Forrester, former mayor of Boston John Collins, and a number of others with practical experience in urban affairs. Forrester contributed the approach, while the others supplied the knowledge of "the pressures, motivations, relationships, reactions, and historical incidents needed to shape the theory and structure of the specific social system" (1969, p. ix). The result of the collaboration was a system dynamics model that reproduced the pattern of growth, stagnation, and decline characteristic of many large urban centers.

Experiments with the model suggested that some favorite policies for reviving the cities are either neutral or actually detrimental. Increased low-cost housing, for example, was found to exacerbate the decline of the central city. A government-sponsored job program for the underemployed turned out in the long run to be, at best, ineffective. A job-training program providing marketable skills for 19,000 underemployed people each year resulted in a net increase in upward mobility of only 11,000 per year. External financial aid to the city, which initially generated increased tax revenue per capita with no increase in city tax rates, showed modest improvements, but surprisingly eventually forced up the taxes needed from internal sources within the city (pp. 51–70).

Policies found to help the city return to economic health include the reasonable notions of incentives for new business construction and more rapid removal of declining business structures, as well as the surprising and controversial ideas of the discouragement of worker-housing construction and more rapid demolition of slum housing (pp. 71–106). One might expect that these combined policies work because they banish the poor from the city. In fact, however, the opposite is true: in the long run the revival policy increases the net migration of underemployed into the city (p. 103). The policy works because it restores the city's ability to be a "socio-economic converter." It results in greater upward mobility of the underemployed into skilled workers and skilled workers into managerial and professional roles.

Forrester concluded that such counterintuitive results are to be expected from complex systems. Since he defined a "complex system" to be "a high-order, multiple-loop, nonlinear feedback structure," it is evident that feedback loops are perceived to be a major source of puzzling behavior and policy difficulties.

> Intuition and judgment, generated by a lifetime of experience with the simple systems that surround one's every action, create a network of expectations and perceptions that could hardly be better designed to mislead the unwary when he moves into the realm of complex systems. One's life and mental processes have been conditioned almost exclusively by experience with first-order, negative feedback loops (1969, p. 109).

But complex, multi-loop systems capable of shifting loop dominance behave differently. Cause and effect in such systems, Forrester asserts, are not closely related in time and space (p. 110). Worse, there are

many "coincident symptoms" that look like causes but are merely correlational.

> In a situation where coincident symptoms appear to be causes, a person acts to dispel the symptoms. But the underlying causes remain. The treatment is either ineffective or detrimental. With a high degree of confidence we can say that the intuitive solutions to the problems of complex social systems will be wrong most of the time. Here lies much of the explanation for the problems of faltering companies, disappointments in developing nations, foreign-exchange crises, and troubles of urban areas (p. 110).

Forrester thus concludes that our difficulties with understanding and managing complex systems stem fundamentally from their multi-loop nature. The reader may recall that Merton made a very similar suggestion many years before in his paper on "The Unanticipated Consequences of Purposive Social Action" (Merton 1936; see section 2.5). Forrester (1971a) repeats and extends this line of thinking on the "counterintuitive behavior" of social systems.

In addition to their counterintuitive tendencies, Forrester identified six other properties of complex systems that had emerged from his simulation studies up to and including particularly the urban work.

- Complex systems are remarkably insensitive to changes in many system parameters (1969, p. 110).

The claim is an observation about the nonlinear, high-order, multi-loop simulation models he and his colleagues and students at MIT had investigated over the previous ten years. It appeared to be a property of such systems that changes of as much as 50 percent or more in most parameters often had little effect on the patterns of behavior exhibited by the model. Forrester interpreted the result in real terms, noting that the behaviors of diverse firms, different economies, and distinct cities had fundamental similarities in spite of their obvious "parameter" differences.

- Complex systems counteract and compensate for externally applied corrective efforts. (pp. 109, 111).

The problem, Forrester asserted, is that corrective programs "shift the system balance so that the corresponding natural processes encounter more resistance and reduce the load they were carrying." His example was the job-training program mentioned above, which was only 60 percent effective because of a decline in naturally occurring upward mobility. He concluded that "Probably no active, externally imposed program is superior to a system modification that changes internal incentives and leaves the burden of system improvement to internal processes" (p. 111). A nice conclusion for an endogenous point of view.

- Complex systems resist most policy changes (p. 110).

The reason is a combination of parameter insensitivity and systemic compensation. Simulating policy changes involves either changing parameters or altering model structure. Interpreted in real terms, the two previous characteristics of complex systems imply that most policy changes will not produce the results expected.

- Complex systems contain influential pressure points, often in unexpected places, from which forces will radiate to alter system balance (p. 109).

Occasionally, complex systems are sensitive to certain parameter changes, and sometimes compensating feedback does not foil a policy intervention and may even aid it. But in Forrester's modeling experience, such successful policies are often hard to find and "must be discovered through a careful examination of system dynamics."

- Complex systems often react to a policy change in the long run in a way opposite to how they react in the short run (pp. 109, 112).

Forrester noted that in the urban model the short-run effects of the underemployed training program, the low-cost housing program, and the slum-housing demolition program were all directly opposite to their long-term effects. "Worse-before-better" makes beneficial policies hard to implement and maintain to the point where they bear fruit. "Better-before-worse" makes policies that are detrimental in the long run hard to abandon.

- Complex social systems tend toward a condition of poor performance (p. 112).

A consequence of all of the preceding properties, the drift to low performance results primarily from misunderstanding what will improve things, doing things that are beneficial in the short run, and redoubling our efforts when results begin to worsen. Forrester concluded, "Again the complex system is cunning in its ability to mislead."

These principles of complex systems are now part of the lore of system dynamics. They appear again in Meadows (1982), where they are accompanied by causal-loop diagrams exposing the generic feedback structure underlying each one. To Forrester's list, Meadows adds addiction, official addiction (shifting the burden to the intervener), and high-leverage policies pushed in the wrong direction.

To system dynamicists, such generic insights relating feedback structure, dynamic behavior, and policy analysis are ample reason to press the feedback point of view that spawned them. The insights acquire part of their force from the fact that they are indeed empirical observations about the behavior of complex systems—although we must remember that the complex systems for which they are unquestionable empirical results are nonlinear, multi-loop, simulation models structured around levels and rates. The fit between the models and the structure and behavior of real systems may be perceived to be very close, but transferring insights from models to reality still requires leaps of logic and faith. Skeptics may wish to argue that these insights may pertain only to the simulation models.

An example of the derivation of an insight relating feedback structure and dynamic behavior may help to show how much logic and how much faith are really involved. Shortly before embarking on his urban work, Forrester published a brief article on corporate growth that has become something of a system dynamics classic. "Market Growth as Influenced by Capital Investment" (Forrester 1968a) presented the elements of the systems dynamics approach in the context of a modeling study of a firm experiencing erratic and stagnant growth in an essentially unlimited market. The assumption of an unlimited market is of course not realistic, but it makes one of Forrester's propositions abundantly clear: the firm's own internal policies are responsible for its erratic and stagnant behavior. Although a real firm might tend to blame such troubles on market weaknesses, there are none in the model. Thus to the extent that the model can be viewed as a reasonable abstraction of some aspects of the structure and behavior of real firms, it gives substance to Forrester's endogenous point of view.

One insight attributed to analysis of the structure and behavior of the market growth model concerns potentially pernicious effects of adaptable or "sliding" goals. Figure 5.7 shows two simulations of the model. In Figure 5.7a, growth in salesmen, orders booked, and production capacity, although erratic, is eventually evident. The results in figure 5.7b, however, are much less promising. The firm is losing production capacity, the sales force peaks and declines toward the end of the run, and orders booked are on a distinct downward trend.

The only difference between these two runs is a slight change in the firm's policy for ordering production equipment. This firm is assumed to base its capacity acquisition plans on its recent average delivery delay, the time it takes to process and ship an order. In both simulations, orders for production capacity are progressively increased whenever the observed delivery delay increases beyond a target delay set by management. In (a) the target or acceptable delivery delay is held fixed; in (b) the assumption is made that the target delivery delay is a long-term average of past performance. In (b) the goal slips, and with it goes the firm's potential for growth.

The feedback structure responsible for this disappointing behavior from sliding goals has been abstracted by Meadows (1982) (see Figure 5.8). The significant "state of the system" in the market growth situation is the perceived delivery delay. The negative loop in the figure is a

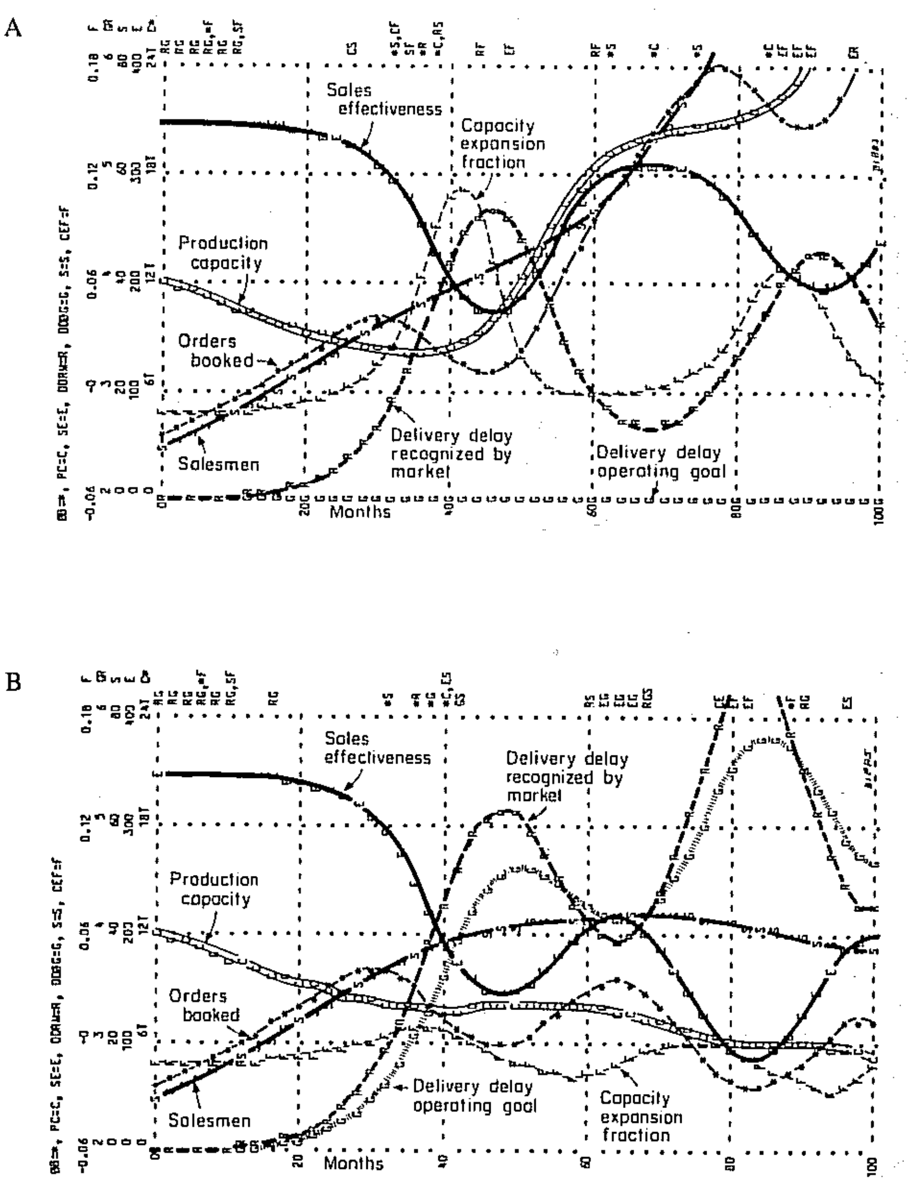

FIGURE 5.7: Behavior of the market growth model under two different capacity expansion policies: (a) fixed goal for delivery delay; (b) delivery delay target based on past performance. Source: Forrester (1968a, pp. 99, 100).

goal-seeking process which increases orders for production capacity to try to hold the perceived delivery delay at or near the desired target value. But if the desired target value is itself dependent upon the past performance of the system, a positive loop is created around the negative loop, which weakens the system's control capabilities. In Forrester's original analysis:

> The goal structure of the organization is now floating. It simply strives to achieve its historical accomplishments. For the more subtle goals in an organization, this striving to equal the past, and conversely being satisfied if one equals the past, is a strong influence.
>
> The result of changing the goal structure from a fixed goal to a goal set by tradition is shown here in [Figure 5.7b] . . . After delivery delay rises, the operating goals rises after a time delay. . . . This means that delivery delay does not produce the degree of concern that it did when the goal was fixed and low. As a consequence, expansion does not seem so justified or so important. In [Figure 5.7b] the goal structure continues to collapse. Delivery delay continues to rise, the traditional goal rises after it, the discrepancy is never great enough to produce active expansion of capacity, and there is a constant erosion of capacity (Forrester 1968a, p. 223).

The derivation of the structure/behavior insight is thus a combination of simulation experiments, model analysis, and thought about the real system.

Meadows (1982, pp. 104–105) applied this generic insight to inflation, air quality standards, and trash on city streets. She argued that in each case there are natural human tendencies to set standards based upon past performance, with the result that "performance is very likely

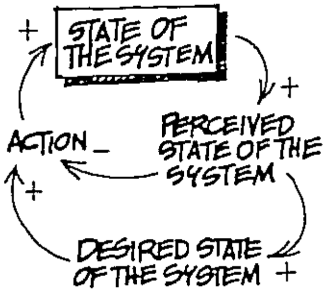

FIGURE 5.8: Generic feedback structure underlying a drift to low performance caused by sliding goals. Source: Meadows (1982, p. 105).

to drift downhill." Personally, I find the insight persuasive and have applied it with students to the interesting question of the source and dynamics of a student's goals in a course—and of the teacher's goals for the student. Presumably these applications, and the original insight relating feedback structure and dynamic behavior in the formal market growth model, would have to be judged like all insights, on the extent to which they open lines of thinking for people. Insights do require leaps. Formal validation of a quantitative model would probably not add much to a skeptic's belief in the "sliding goals" principle.

Compensating Feedback

Perhaps the most significant feedback theme repeatedly encountered in the system dynamics literature is the notion of compensating feedback. The phrase refers to a tendency observed in system dynamics models for a parameter or structural change to call forth natural adjustments of other factors within the model that counteract the direction of the imposed change. A feedback system has the capacity to compensate for imposed changes, pushing itself back toward its original condition. Ashby referred to the phenomenon indirectly in his notion of "ultrastability." In the system dynamics literature, however, compensating feedback is seen in less theoretical terms as a natural characteristic of complex systems, with dramatic policy implications.

A simple but graphic example of compensating feedback appeared in Forrester's study of the "global problématique"—rising population, industrialization, and pollution in the face of declining natural resources and the ability of areas of the globe to feed themselves (Forrester 1971b). A policy of ZPG (zero population growth) achieved by reductions in global birth rates was simulated as if it were instituted world-wide in 1970. It halted population growth only for a decade or so. Growth resumed. One reason for the return to growth is a compensating negative feedback loop in the model that links population, per capita standard of living, and birth and death rates. A stable population, combined with rising global industrialization, creates a rising per capita standard of living that feeds back to reduce infant mortality and increase average life spans. Family sizes that stabilize population in 1970 would result in a growing population in a later, more affluent globe. The step down in the crude birth rate in 1970 is thus compensated for by a feedback loop that acts to raise the net birth rate and restore population growth. Forrester observed that the phenomenon raises serious questions about the effectiveness of birth control alone as a means of controlling population. The feedback loop that compensates here is not a mysterious mechanism, but it is frequently overlooked by those of us who advocate ZPG as a prime cure for global difficulties. We learn from the simulation that what we really intend is a global tendency to maintain very low or zero net growth in spite of natural feedback tendencies in the system to defeat that aim. We also should learn the importance of including a population endogenously in any analysis of policies intended to improve its lot.

In a system dynamics study of heroin use in a community (Levin, Hirsch, and Roberts 1975), a large number of potentially compensating feedback effects for heroin- and crime-control policies were noted. Several of them work through the price system. Stepped-up police activity that succeeds in reducing the supply of heroin to the community ought to reduce heroin-related crime, but instead, the authors suggested, it increases it, in the short to medium term at least. The reason is obvious: the price of heroin rises, and addicts who support their habits with criminal activity have to resort to a higher frequency of revenue-raising crimes. More subtly, if it becomes too difficult to import heroin into the community, suppliers may switch to substitutes such as methadone which can be produced within the community and which are even more difficult to control. Both of these are potentially compensating effects for policies aimed at controlling crime by reducing the heroin supply.

Analyzing the opposite policy produced more evidence for the importance of the notion of compensating feedback. Suppose the community tries to reduce heroin-related crime by providing addicts with

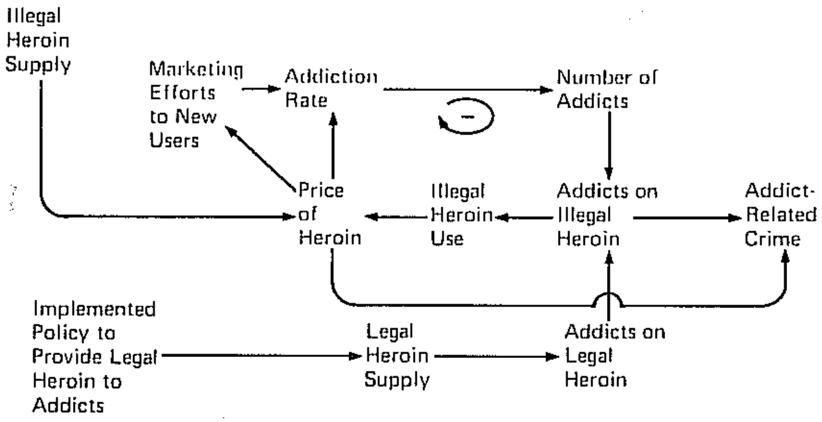

FIGURE 5.9: Compensating feedback loop active in a policy to provide legal heroin to addicts. Source: Levin, Hirsch, and Roberts (1975, p. 11).

legal heroin. The authors of the study sketched the feedback structure shown in Figure 5.9 and argued that the increased supply would cause prices to fall. The rate of addiction would go up, they argued, for two compounding reasons. Each long-term addict who had built up a considerable tolerance and need for the drug and who converts to the legal supply would free up enough heroin to support the habits of four or five new users. Furthermore, price declines would mean that pushers would more aggressively recruit new buyers. The authors concluded:

> Thus, while legal heroin might reduce addict-related crime, it would probably significantly increase the total number of addicts. Note that [Figure 5.9] indicates the presence of another negative feedback loop, one that leads to the undesired policy consequence. The increase of addicts on legal heroin quickly reduces the number of addicts on illegal supply; this diminishes illegal heroin use, decreases heroin price, and induces an increased rate of new addictions. The increased flow of new addicts adds to the total addict pool, increasing those on illegal heroin. The loop is initiated by a force aimed at decreasing illegal heroin addiction, but ends on an up-beat of increased illegal addiction (Levin, Hirsch, and Roberts 1975, pp. 11–12).

The mechanism of these compensating effects for the policy intervention is thus seen to be a negative feedback loop. Within the field of system dynamics, the search for compensating feedback loops, and the interpretation of policy interventions in terms of them, is now a fixture of the methodology.

Nonlinear Dynamics

The notion of nonlinearity and the importance of representing nonlinearities accurately has been fundamental to the perspective of the thinkers in the servomechanisms thread. As seen in section 2.2, the mathematical concept has an intuitive and useful interpretation in feedback loop terms. It is nonlinearity that shifts the dominance among feedback loops in a system. More precisely, nonlinearities in mathematical models can endogenously change over time the causal significance of variables in a dynamic system. Nonlinearities can change the structures that are active or influential. Thus nonlinearities are viewed by system dynamics practitioners as vital determinants of the interesting or problematic behavior of a dynamic social system.

Nonlinearity is a critically important idea, emphasized repeatedly by feedback authors we have investigated, but the situation is now known to be much more dramatic than early writers could have imagined. Discovered by a diverse group of mathematicians and physicists in the 1960s and 1970s, and only now becoming widely known, is the potential of nonlinear mathematical models to exhibit apparently *random* behavior. Even some very simple nonlinear systems have the potential to show dynamic patterns that are extraordinarily complex. The phenomenon is known as deterministic chaos, and it is the focus of a great deal of excitement and research today. (For a nontechnical overview see Gleick 1987.)

Two developments in this burgeoning field are significant for the evolution of the feedback concept in the social sciences and the two conceptual threads we have been following.

First, as a consequence of our earlier discussions (e.g., sections 2.2 and 3.3) we have the inescapable conclusion that the nonlinear models that exhibit deterministic randomness and chaotic behavior are feedback systems. Figure 5.10, for example, shows a representation of the loop structure of the famous Lorenz model:

$$\frac{dx}{dt} = \sigma y - \sigma x,$$
$$\frac{dy}{dt} = x(r - z) - y,$$
$$\frac{dz}{dt} = xy - bz.$$

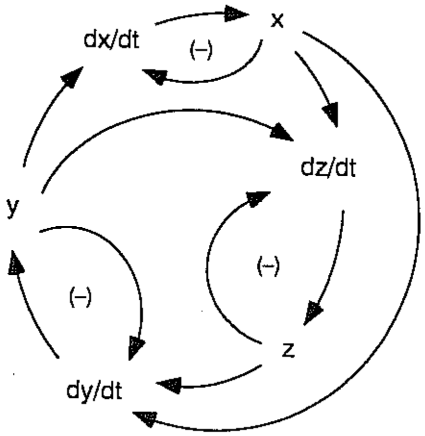

FIGURE 5.10: Feedback loop structure of the Lorenz model.

The model was originally designed to be a highly simplified picture of certain weather-related variables in an atmosphere heated from below: x is related to convection, while y and z represent horizontal and vertical temperature variations (Lorenz 1963). As shown in Figure 5.10, the Lorenz model contains six loops: three little loops involving x, y, and z individually, and three major loops involving x and y, y and z, and x, y, and z. Because x and y can take on both positive and negative values, the polarities of the major loops can shift back and forth. For particular values of the parameters, this stock-and-flow feedback structure exhibits deterministic chaos and extreme sensitivity to initial conditions ($\sigma = 10$, $r = 28$, $b = 8/3$ is one such parameter set.)

The closed-loop feedback character of such chaotic systems has been noted by some (see, e.g., *System Dynamics Review,* Special Issue on Chaos 4(1–2) 1988). But just as it was in Maxwell's time, the loop structure of chaotic models is not central to the mathematical analysis of such systems. Yet since nonlinear models can show chaos, and nonlinear models can endogenously change dominant structure, it is tantalizing to consider whether the complex behavior patterns arise as consequences of shifting loop dominance. It has been shown, for example, that a classic kind of bifurcation in a simple continuous nonlinear system occurs because of a shift in dominance between positive and negative loops at an equilibrium point (Richardson 1984). The evolution of chaos in a model of migrating populations (Mosekilde et al. 1985; Mosekilde, Aracil, and Allen 1988; Reiner, Munz, and Weidlich 1988) has been intuitively analyzed in terms of the feedback loop structure of the system (Richardson and Sterman 1988). There exists the possibility that the feedback concept and loop dominance may provide intuitive insight into the causes of complex nonlinear dynamics.

Furthermore, we now face the likelihood that the enormous range of feedback systems social scientists have observed includes structures that can endogenously generate unpredictable behavior. Recent work by John Sterman, for example, has found that the decision rules people actually use in simple dynamic games involving nonlinearities and circular causality can generate deterministic chaos (Sterman 1987, 1988, 1989). We have a new *source* of randomness. Tustin's seminal question (section 3.3), whether the "closed sequences of dependence" in an economy account for business cycles, is now being extended: Can nonlinear feedback structures in economic interactions be responsible for any of the *unpredictability* we observe in economic cycles, without invoking exogenous random disturbances? Given the ubiquity of feedback thinking, and all sorts of puzzling social system behavior, similar

questions will be raised in many corners of the social sciences. Answering them will require the creation of increasingly sophisticated nonlinear models of puzzling social and policy systems.

A second development emerging from the literature on complex nonlinear dynamics adds further support to the separation of feedback threads we have been tracing. Ilya Prigogine and his colleagues in the so-called "Brussels school," with others, have cast a new light on the phenomenon of *self-organization* in complex systems (Prigogine and Stengers 1984; Yates 1987).

The ideas began in thermodynamics and physical systems. A mixture of two different gases in a container with a hot side and a cold side is seen to separate, with one of the gases concentrating on the hot wall and the other on the cold wall (Nicolis and Prigogine 1977, p. 3). A liquid contained between two cylinders is observed to form and reform layers of various sorts as one of the cylinders spins faster and faster (Abraham 1987). As a parameter smoothly changes in a simple nonlinear model, the behavior of its variables moves in sudden shifts to oscillations of increasingly long period, eventually leading to an infinitely long period of random, chaotic behavior (Feigenbaum 1980/1983). Or if the parameter moves in the other direction, the model's behavior is seen to move from patternless, unpredictable ups and downs to stable oscillations of definite period and amplitude. Patterned behavior appears to self-organize out of chaos.

The reader will recall that there was considerable interest in the cybernetics thread in the phenomena of self-reference and self-organization (see sections 3.2 and 4.3; also Yovitz and Cameron 1960, von Foerster and Zopf 1962, and Varela 1975, 1979). Now we have renewed interest in the notion of self-organization, but among the literature and practitioners in the servomechanisms thread. The two feedback threads in the social sciences would appear to converge on the issue of self-organization.

Yet there are dramatic differences, recognized somewhat by the authors themselves. Yates, for example, in his preface to a volume of papers on *Self-Organizing Systems: The Emergence of Order* that grew out of an invited conference held in Yugoslavia in 1979, writes:

> Many natural systems become structured by their own internal processes; these are the self-organizing systems, and the emergence or order within them is a complex phenomenon that intrigues scientists from all disciplines. Unfortunately, complexity is ill-defined. Global explanatory constructs, such as cybernetics or general systems theory, which were intended to cope with complexity, produced instead a grandiosity that has now, mercifully, run its course and died (Yates 1987, p. xi).

In deep contrast to the earlier work in the cybernetics thread, the writers in this volume looked at self-organization dynamically and employed formal mathematical models to represent and explain complex self-organizing behavior.

Put most succinctly, of those who focused on self-organization, writers in the cybernetics thread focused on self-organization of *structure*, while writers in the servomechanisms thread focused on self-organization of *behavior*. In the cybernetics thread, self-organization was discussed verbally. The metaphor for change was the *rewriting* of system structure—exogenous or endogenous changes in the *rules* governing the behavior of a social system. In the writings of people in the Brussels school and the authors in the Yates volume, self-organization emerges out of nonlinear mathematical models of complex systems. The model itself is not rewritten and does not change over time, but endogenously shifts its dominant or active structure because of nonlinearities it encounters when operating far from equilibrium. The behavior-over-time generated by the model changes character, moving among regions of stability and instability, organized patterns and disorganized chaos.

Just as the word *feedback* takes on different meanings in the two threads of feedback thinking in the social sciences, so does the phrase *self-organization*. And the differences again center on the verbal versus mathematical models and a focus on discrete events versus dynamic patterns over time.

Summary

The system dynamicist sees four overriding benefits from looking at societal problems from a feedback perspective. First, feedback loops—circular causal loops of positive and negative polarity composed of accumulations and their rates of change—are seen as the structure underlying dynamic behavior. Second, feedback loops are seen to be responsible for the counterintuitive behavior and policy resistance observed in real social systems. Consequently, the system dynamicist hopes that by understanding their roles in creating such behavior, people can improve over time their ability to create workable and desirable social policy. Third, feedback loops and the notion of loop dominance provide an intuitive and accessible description of mathematical models created to study the behavior of complex social systems, even those capable of extremely complex nonlinear dynamics and deterministic chaos. Fourth, and perhaps most important, feedback loops enable the creation of self-contained theory. In the system dynamicist's endogenous point of view, patterns of dynamic behavior are understood as consequences of the internal (feedback) structure of causally closed systems. Such feedback-based endogenous theory is seen to be much stronger, much more worthy of analysis, than theory that relies on external influences to explain behavior.

5.5 Summary and Directions

In section 3.3 we characterized the beginnings of the servomechanisms thread in the social sciences as follows:

- The patterns of behavior of a dynamic system were traced to its feedback structure.
- Formal dynamic models were employed.
- The dynamic behavior of a feedback system was considered to be difficult to discern without the aid of formal mathematical models.
- Feedback loops were seen as an intrinsic part of the real system, not merely as possible mechanisms of external system control.
- Positive loops were present in the analyses, along with negative loops.
- Well-intentioned policies were seen to have the potential to create or exacerbate the problem behavior they were intended to cure.
- Nonlinearities were perceived to be a persistent characteristic of real socioeconomic feedback systems. Consequently, they were considered to be a necessary characteristic of reliable formal models of such systems.
- The work tended to be directed toward policy analysis.

In addition there were two characteristics that both feedback threads in the social sciences shared:

- Feedback was seen as the mechanism of systems that adapt over time.
- The concept of feedback was employed to conceptualize system structure.

All of these characteristics have continued in the servomechanisms thread. However, with the exception of the spread of the field of system dynamics itself, the influence of this thread on feedback thinking in the social sciences appears to be slight compared to the influence of the cybernetics thread.

Econometrics and the Servomechanisms Thread

In the 1940s and 1950s Gunnar Myrdal outlined a program for the social sciences involving the quantitative modeling of "interlocking, circular and cumulative changes" and "the causal inter-relations within the system as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes" (Myrdal 1944, p. 1068; 1957, pp. 27, 30; see section 2.5). Essentially, there are only two expressions of that approach to the analysis of dynamic phenomena in social systems today: system dynamics and econometrics. One traces its origins to statistical traditions in the social sciences, while the other traces to engineering servomechanisms. The two approaches share a loop view of circular causal interactions and interdependence in social systems. Both approaches can be said to be feedback perspectives on social system dynamics. Both have by now come to be seen as somewhat related quantitative, computer-oriented approaches to socioeconomic behavior. But there are elements of the two approaches that reflect their different origins.

One important distinction between the two approaches stems from a technical difference in basic model structure. Econometric models are formulated almost entirely of linear difference equations, while system dynamics simulation models are composed of nonlinear differential (or integral) equations. An econometric model thus expresses a discrete, period-to-period or quarter-to-quarter view of economic or social change, while a system dynamics model tries to capture a continuous perception of accumulations and change. In addition, the linear nature of econometric models means that they cannot exhibit changes in loop dominance such as we observed, for example, in the logistics equation structure or the Lotka-Volterra predator-prey system. Both of these characteristics of econometric models are consequences, essentially, of the form of equations required to fit whole models to data using formal statistical procedures.

A repeated theme, however, in both of the feedback threads that we have been tracing is that social systems exhibit changes in feedback structure over time—cause maps are redrawn, new information changes the state of things, or nonlinearities shift loop dominance, altering active system feedback structure. In this sense, the econometric tradition is somewhat outside both of the feedback threads that we have been tracing. Econometric models cannot alter structure endogenously, either by nonlinearities or by self-referential rewrites of equations, so they must rely on exogenous influences to capture structural change. I personally prefer a more endogenous view, but my purpose here is not to criticize but to observe there is a difference. A characteristic of the servomechanisms thread from its earliest beginnings in the work of Goodwin and Tustin is an endogenous point of view. The focus is inward, and the attempt is to derive system dynamics and even structural change from internal circular causal processes. The econometric tradition is a mixed endogenous-and-exogenous view.

Directions

In spite of these differences with the servomechanisms thread, some aspects of econometrics are seen to be part of the legacy of Tustin and Phillips, particularly the use of optimal and adaptive control techniques with econometric models. Furthermore, Simon's conceptualization of feedback structure in organizations (section 5.2) links his feedback view to econometrics. Given these perceived connections, but acknowledging that little of econometrics actually traces to engineering servomechanisms, there appear to be four main directions that the servomechanisms thread now points:

- system dynamics—computer simulation of continuous, nonlinear feedback systems, emphasizing an endogenous point of view
- econometrics—statistical modeling and estimation of socioeconomic systems for prediction and policy analysis
- control theory in economics—application of optimal and adaptive control techniques from engineering to econometric models
- causal-loop diagramming—striving to derive behavioral implications intuitively from causal-loop diagrams of circular causal feedback systems.

The last entry in this list, causal-loop diagramming, matches a similar tendency growing out of the cybernetics thread. Many such efforts exist. It would be hard to determine direct connections to, or separations from, either feedback thread, unless there is telltale evidence in the form of references to "stability and instability" or "patterns of behavior."[13]

Notes

1. Aoki (1976), Aoki and Marzollo (1979), Baum and Howrey (1981), Chow (1970), Fair (1974, 1978), Kendrick (1976), Pitchford and Turnovsky (1977). See also bibliographies in Cochrane and Graham (1976) and Athans and Kendrick (1974), and also publications of the Society for Economic Dynamics and Control.

2. In a much later independent development, Forrester and the MIT System Dynamics Group have come to very similar conclusions about mechanisms underlying economic long waves (Forrester 1976, 1977, 1979; Sterman 1984).

3. Culbertson used Greek letters for some coefficients and time-dependent variables. For ease of reading I have substituted English letters throughout.

4. Culbertson gave complicated equations for g′ and d′ which I am omitting in favor of a verbal description of what they mean. Both of these switch coefficients are related to Y_{t-1} or Y_{t-2}, so additional feedback loops are present.

5. He derived the model in two equations, which he then combined into the following:

$$\begin{aligned} Y_t = {} & C_0 + I_0 + G_0 - (c_Y + i_Y)T_0 + f'h(M_0 - M_0 D) \\ & + [g_Y + (c_Y + i_Y)(1 - t_Y) + f'h(s_Y - m_Y)]Y_{t-1} \\ & + [g_A + c_A + i_A - t_A(c_Y + i_Y) + f'(s_Y - 1)](Y_{t-1} - Y_{t-2}), \end{aligned}$$

where

$$f' = \frac{c_R + i_R}{hm_R}; \quad c_R, i_R, m_R < 0; \quad f' > 0.$$

The interested reader can consult Culbertson (1968, p. 176) for the details. Here we merely note that the model is in the form of the generic model described in the text.

6. See section 3.3. For a discussion linking the mass-on-a-spring structure to employment, inventories and backlogs, see Richardson (1981, pp. 338–343).

7. For the deepest investigation that I know of of the nature of the feedback structure underlying oscillations, see Graham (1977).

8. See Meadows (1980).

9. For extensive bibliographies see Lebel (1981); Legasto, Forrester, and Lyneis (1980). For current publications see issues of *Dynamica*, the *System Dynamics Newsletter* (MIT), and the *System Dynamics Review*.

10. Hamilton et al. (1963); Roberts (1964); Forrester (1969); Meadows (1970); Forrester (1971); Meadows et al. (1972); Meadows and Meadows (1974); Meadows et al. (1974); N. Forrester (1972); Mass (1975); Levin, Hirsch, and Roberts (1975); Levin et al. (1976); Naill (1977); Choucri (1981); Boyce (1980); Gutierrez and Fey (1980). For others see Legasto, Forrester, and Lyneis (1980), pp. 259–261.

11. Forrester (1961, 1968b); Goodman (1974); Alfeld and Graham (1976); Coyle (1976); Coyle and Sharp (1976); Richardson and Pugh (1981); Roberts et al. (1983); Richmond, Peterson, and Vescuso (1987); Richmond, Vescuso, and Peterson (1987); Hanneman (1988).

12. These differences in what it means for a system to be "closed" suggest that Forrester's ideas progressed independently of the general systems movement. However, it should be noted that von Bertalanffy also referred to feedback systems as closed systems (von Bertalanffy 1951). I argued in section 3.2 that that determination conflicts with von Bertalanffy's own characterization, but the fact remains that superficially Forrester and von Bertalanffy (erroneously?) agree that feedback systems are "closed." To conclude that Forrester knew of von Bertalanffy's definitions of closed and open systems (and is therefore connected to him by the scholarly communications network), we would have to conclude that both Forrester and von Bertalanffy became confused in applying the concepts to feedback systems. For one of them to be confused is highly unlikely; the probability that both are confused on the subject is nil. I conclude that Forrester's development of the closed boundary idea in system dynamics is essentially independent of the general systems movement.

13. The decision-support work of Colin Eden and his colleagues in England is an interesting example (Eden and Harris 1975; Eden, Jones, and Sims 1979, 1983). In his more recent work, causal-loop diagrams or influence diagrams are used to bring out and improve the "cognitive maps" of people faced with a decision. In that usage the diagrams have a very transitory character, much as

in Weick's usage. Yet Eden's early work (Eden and Harris 1975) references authors in both feedback threads and makes extensive use of system dynamics analyses in which feedback diagrams aim to capture real, persistent, underlying causal structure. Eden's own use of the feedback concept seems to have evolved toward a flexible use of influence diagrams, mixing events and persistent pressures, as suits the cognitive maps of his decision support clients.