Reflections on the Foundations of System Dynamics and Systems Thinking

George P. Richardson
Rockefeller College of Public Affairs and Policy
University at Albany, State University of New York

Abstract: JW Forrester's original statement of the foundations of system dynamics emphasized four 'threads': computing technology, computer simulation, strategic decision making, and the role of feedback in complex systems. Subsequent work has expanded on these to expose the significance in the system dynamics approach of dynamic thinking, stock-and-flow thinking, operational thinking, and so on.

But the foundation of systems thinking and system dynamics lies deeper than these and is often implicit or even ignored: it is the "endogenous point of view." The paper will begin with historical background, clarify the endogenous point of view, illustrate with examples, and argue that the endogenous point of view is the *sine qua non* of systems approaches. What expert systems teachers and practitioners have to offer their students and the world is a set of tools, habits of thought, and skills enabling the discovery and understanding of endogenous sources of complex system behavior.

The fault, dear Brutus, is not in our stars, but in ourselves.
Cassius, in Shakespeare's *Julius Caesar* (1599)

Man is not the creature of circumstances.
Circumstances are the creatures of men.
Benjamin Disraeli, *Vivian Grey* (1827)

We have met the enemy and he is us.
Walt Kelly's *Pogo*, on the first Earth Day poster (1970)

Introduction: the Four Foundations

In his seminal article in the Harvard Business Review (1958), Forrester laid out his initial statement of the approach that would become known as system dynamics. He founded the approach on what were then four recent developments: advances in computing technology, growing experience with computer simulation, improved understanding of strategic decision making, and developments in the understanding of the role of feedback in complex systems.

He phrased the four foundations slightly differently in *Industrial Dynamics*, but the emphasis was much the same (Forrester 1961, 14):

- the theory of information-feedback systems
- a knowledge of decision-making processes
- the experimental model approach to complex systems
- the digital computer as a means to simulate realistic mathematical models

The slight change in the list of four here shows Forrester emphasizing an *experimental approach* to understanding the dynamics of social organizations that would presumably be enabled by iterative computer simulation.

Thus we have the familiar and enduring cornerstones of the system dynamics approach as they were expressed at the founding of the field. But within ten years Forrester expressed the foundation quite differently.

The Foundation Ten Years Later

In 1968 Forrester published his classic paper "Market Growth as Influenced by Capital Investment," now known throughout the field simply as the "market growth model" (Forrester 1968a). During that time he was working with former mayor of Boston John Collins and others on urban problems, resulting in his first non-corporate study, *Urban Dynamics* (Forrester 1969) and on his teaching text *Principles of Systems* (1968b). In all of these he began by presenting the structure of the approach he used, not as the four threads outlined above, but rather as a four-tiered structural hierarchy:

- 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
      - Detection of discrepancy
      - Action based on discrepancy

(Forrester 1968a, 83; Forrester 1969, 12; see also Forrester (1968b, 4-17)).

To current practitioners, the hierarchy looks very familiar, so familiar in fact that it is easy to miss its significance. It emphasizes feedback loops, of course, and the familiar levels (stocks) and rates (flows), all of which are the stock in trade of all system dynamics practitioners. Within rate variables it exposes the classic goal-seeking structure that exists in some form in all purposeful decisions people make.

However, in this hierarchy it is easy to miss the item that appears at the top of the list: the *closed boundary around the system.* But that phrase signals what may be the most significant part of the system dynamics approach for understanding complex systems. It signals Forrester's *endogenous point of view.*[1]

The Endogenous Point of View

Forrester initially phrased it this way:

> 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?" (Forrester 1968b, p. 4-2).

[1] "Endogenous" (from the Greek fragments "endo" and "gen", meaning "inside" and "production") refers to an action or object coming from within a system. It is the opposite of "exogenous," something generated from outside the system (http://en.wikipedia.org/wiki/Exogeny). Systems thinking and system dynamics center on *endogenous* phenomena.

The idea became summarized in his first principle of system structure, the principle of the closed boundary:

> In concept a feedback system is a closed system.[2] Its dynamic behavior arises within its internal structure. Any action which is essential to the behavior of the mode being investigated must be included inside the system boundary. (Forrester 1968b, pp. 4-1,2).

Consider the reach of these statements. They tell us to build models that are capable of deriving the dynamic behavior of interest solely from variables and interactions within some appropriately chosen system boundary. They tell us not to depend upon any exogenous forces to produce the dynamics of interest. Moreover, they suggest guidelines for *thinking*: they tell us to try to think of dynamics that way, to try to *understand* system dynamics as generated from *within* some conceptual, mental boundary.

In *Urban Dynamics* Forrester apparently felt the idea was sufficiently important to warrant a graphic of its own (Figure 1). He explained, "The closed-boundary concept implies that the system behavior of interest is not imposed from the outside but created within the boundary" (Forrester 1969, 12).

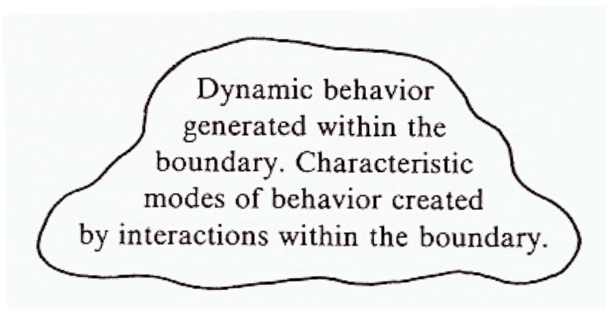

Figure 1: Figure reproduced from Forrester (1969, 13) symbolizing the closed-boundary concept.

Endogeneity and Feedback

The most salient aspects of the system dynamics approach are undoubtedly stocks and flows and feedback loops. These visible elements stand out and command our attention. But it is worth noting that feedback loops are really a *consequence* of the endogenous point of view.

Figure 2 illustrates the idea. On the left is a picture of some simple causal system, with causal elements tracing ultimately outside the system boundary. The dynamics of variables A through E are generated partly by interactions among them inside the system boundary but really stem mainly from variables P, Q, R, and S outside the boundary. The dynamics of this system are generated *exogenously* by forces outside the system boundary.

On the right of Figure 2 is an *endogenous* view, in which the dynamics of variables A through E are generated solely from interactions among those variables themselves, within the system boundary. We note from the figure that taking an endogenous point of view

[2] Forrester's use of the term "closed" means "causally" closed. His use is different from the the notion of a closed system in general systems theory, which refers to a system that is "materially closed," that is, does not exchange material or information with anything outside the system boundary. Forrester's "closed boundary" systems are, in general systems theory terms, "open systems" because they include little clouds representing sources and sinks of material outside the system boundary. See Richardson (1991, 298).

forces causal influences to form *loops*. Without loops, all causal influences would trace to dynamic forces outside the system boundary.[3] Feedback loops thus enable the endogenous point of view and give it structure (Richardson 1991, 298).

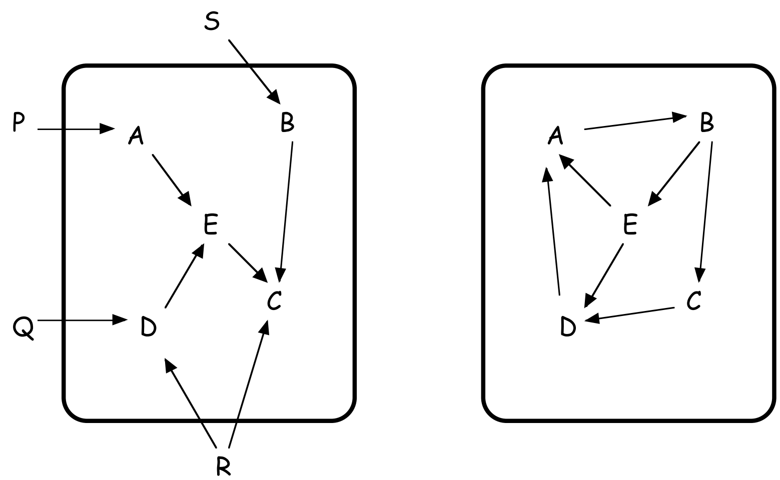

Figure 2: On the left is an *exogenous* view of system structure: Causality traces to external influences outside the system boundary. On the right is an *endogenous* view: Causality remains within the system boundary; causal loops (feedback) must result.

Endogeneity in Practice

Two examples from Forrester's early writings serve to show vividly what the endogenous point of view looks like in practice and why it is so crucial in thinking and modeling for policy analysis. Though the examples are very familiar to system dynamics practitioners, they deserve our attention here as we try to go deeply into the nature and significance of the endogenous point of view.

Market Growth as Influenced by Capital Investment
The first example, shown in Figure 3, is the famous market growth model mentioned above (Forrester 1968a). The figure vividly shows Forrester's endogenous point of view: Figure 3a shows a structure with no dynamic influences coming from outside the system boundary. The dynamics shown in the graph in Figure 3b stem solely from interactions among the variables shown and the balancing and reinforcing feedback loops they form together.

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[3] In practice, confronted with a view like the left side of Figure 2 one strives to expand the system boundary to draw in the influences that initially seemed exogenous and create a rich endogenous view.

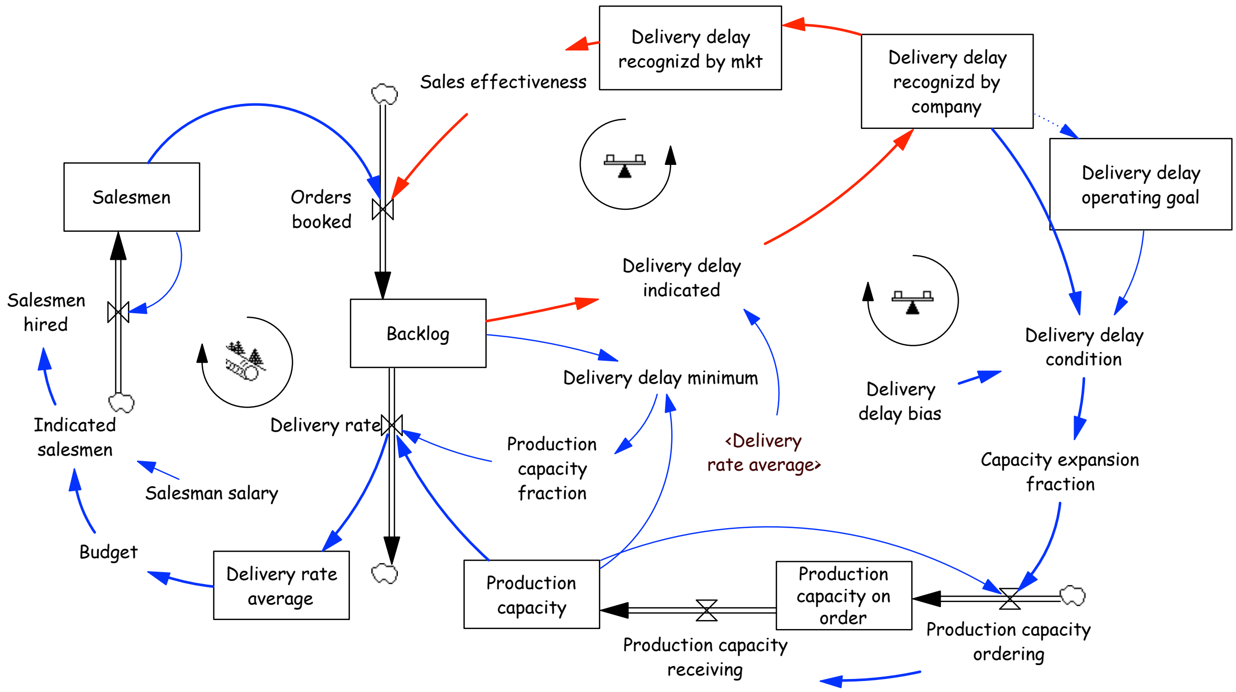
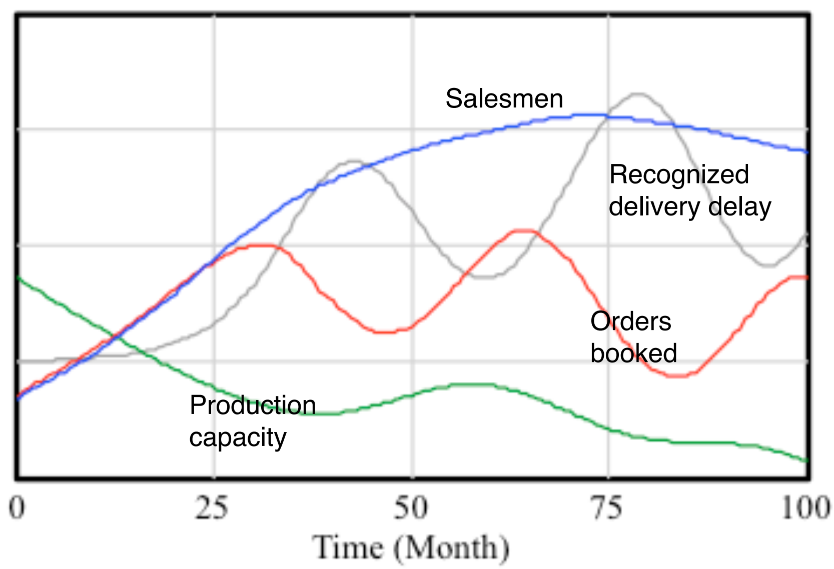


Figure 3a: The structure of Forrester's market growth model (Forrester 1968a).

Figure 3b: The behavior generated endogenously by the market growth model.



Forrester developed this model to illustrate a potential source of corporate poor performance: the internal operating policies of the company itself. To make the story most vivid, he set the company represented by the model in a potentially infinite market: there is no external market cap in the model that might limit corporate growth, production capacity, the size of the salesforce, or the amount of orders booked per month. Yet the dynamics shown in Figure 3b show a company in which production capacity is declining, orders booked have a pronounced oscillatory and eventually declining pattern, and the size of the sales force appears to peak and decline, even though there is no external limit to the size of the market the salesmen might reach. In an unlimited market, the company is going out of business.

The key to these dynamics is the policy the company is using to determine when to add production capacity. The policy (captured in the "Delivery Delay Condition" in the right of Figure 3a) says to add capacity when the delivery delay for the company's product exceeds a target, the Delivery Delay Operating Goal. If that goal is based on past performance, as is the case in this simulation, then it tends to slide upward as the actual delivery delay rises. As orders booked rise, the delivery delay initially rises, putting pressure to expand capacity, but that pressure depends on a comparison of the delivery delay recognized by the company and its target delivery delay. Since that target is based on past performance, it, too, is rising slightly, relieving somewhat the pressure to expand capacity. In this simulation, the sliding delivery delay target never generates enough pressure in the delivery delay condition to expand capacity, and the company proceeds to lose market share. It is likely that corporate decision makers in such a setting would believe the causes of the declining sales trace to an overall declining market, when in fact (in this model) that market is potentially infinite.

There are three key insights here that should inform our understandings of the endogenous point of view:

- First, we see in Figure 3a an unmistakable "closed boundary around the system" that Forrester put forward explicitly in this article to describe his approach. There are no causal links coming from outside. There is a hint of "roundness" to the picture that would be characteristic of such a closed causal boundary and the feedback structure it forces.

- Second, the dynamics generated by the model come from interactions of the variables inside the model boundary. There is no declining market cap coming from outside to inhibit growth. We see that the self-contained loop structure shown in Figure 3a is sufficient, by itself, to generate the observed dynamics.

- Third, we see that Forrester designed the model to tell the endogenous story of declining sales in the most vivid way possible: he put the company in a potentially infinite market. One might well argue no company exists in such a market, and so the model is unrealistic and invalid. But the potentially infinite market takes away all possibility that the declining sales can trace to anything other than an endogenous source. This is modeling for endogenous insight and understanding.

Think how extraordinarily difficult, if not impossible, it would be to reach these potentially crucial policy-related conclusions without an endogenous perspective, or to put it more forcefully, without an endogenous *bias* in one's point of view.

This endogenous perspective is neither well understood nor accepted by many practitioners and scholars. The second classical Forrester example provides a dramatic illustration.

Urban Dynamics

The 1960s was a period of urban renewal in the United States. Many policies were implemented in efforts to halt central city decay and return old cities to the economic vibrancy of their earlier days. Forrester engaged in conversations with a group of urban experts including John Collins, former mayor of Boston and past president of the National League of Cities. The book *Urban Dynamics,* and the model on which it was based, emerged from those conversations (Forrester 1969, vii-x).

Figure 4, reproduced directly from the book, shows how Forrester chose to frame the study. The perspective he took, and the model he built, viewed an archetypical city in a large and essentially uninteresting environment. Significantly, the model did not include suburbs around the city, or the transportation networks linking it to its environment (and it was criticized for such glaring omissions). In fact, the environment around the city generated no dynamic influences whatsoever on the modeled city, and the city was presumed to be small enough in the world setting not to affect its environment. In reality, there might be external economic cycles, political and social movements, cultural changes, and so on, affecting the city and its environment, but Forrester chose explicitly to ignore all those exogenous dynamics. The dynamics of interest were urban dynamics *relative to* the environment outside the city. They were to be insistently, undeniably *endogenous* dynamics generated by the city itself.

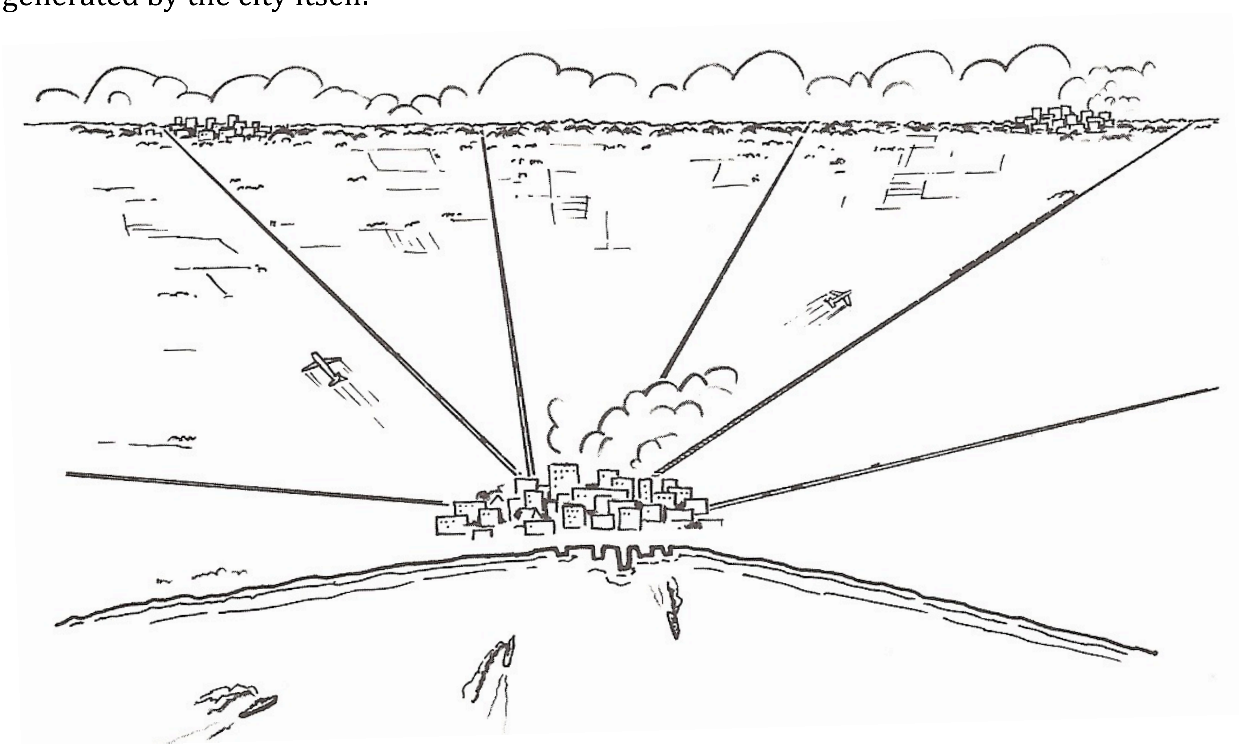


Figure 4: Forrester's picture of the conceptual setting of *Urban Dynamics* (Forrester 1969, 15).

To give a feel for what the *Urban Dynamics* model looks like, Figure 5a shows the structure of URBAN1, a simplified three-stock version created by Alfeld and Graham (1976).[4] To build toward understanding Forrester's more complex structure, Alfeld and Graham formulated URBAN1 to have single stocks of business and housing structures, where Forrester had three-stock aging chains of new structures, mature structures and aging structures. Forrester also disaggregated population into three linked stocks of underemployed, skilled workers, and managerial-professionals, while URBAN1 contains just a single stock of people. Forrester's model had about 150 equations; URBAN1 has 21.

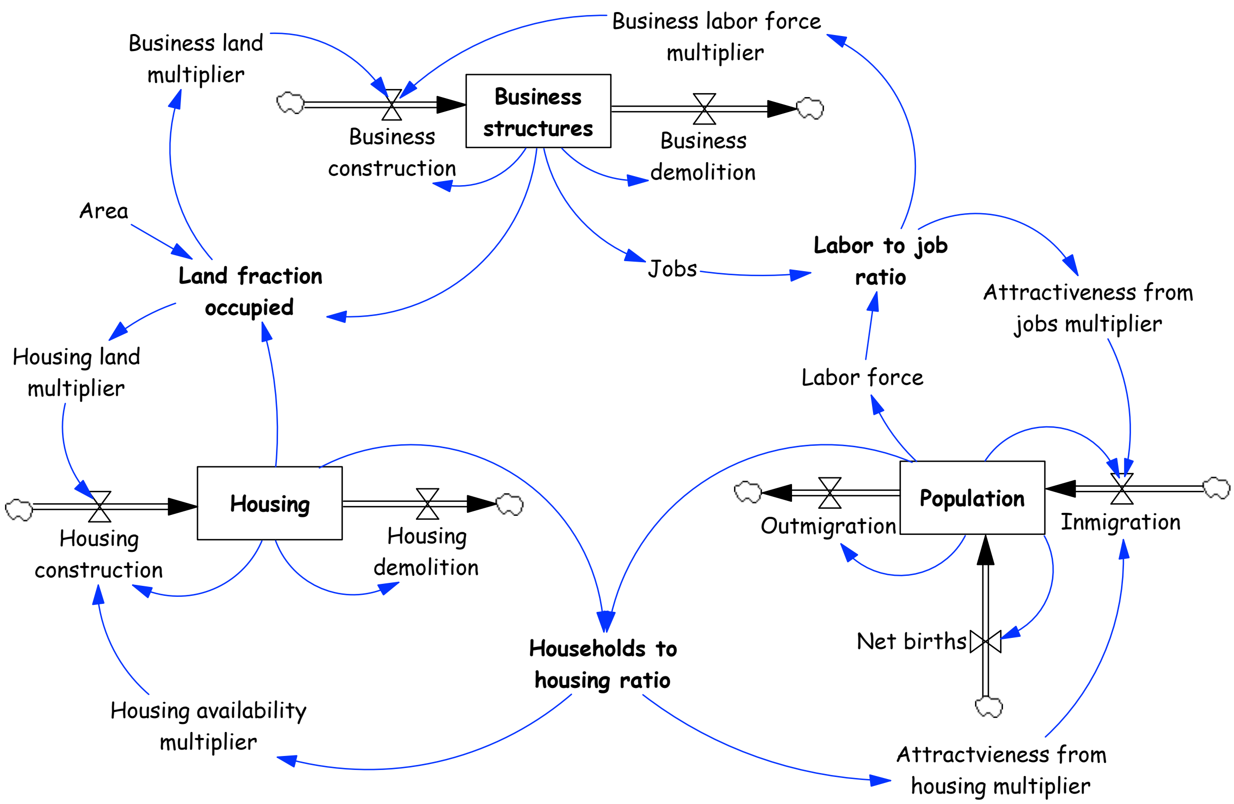
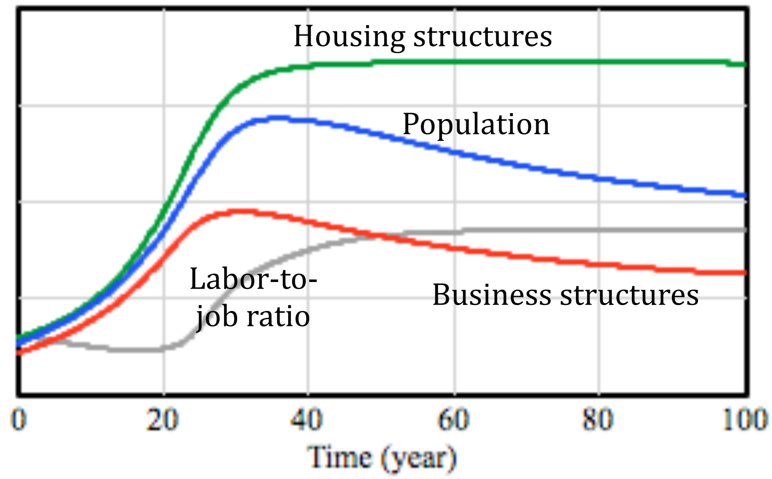


Figure 5a: The stock-and-flow feedback structure of URBAN1 (Alfeld and Graham 1976). This view hides the constants in the model in order to keep the picture simple and to emphasize visually its endogenous character.

In spite of the simplifications, the character of URBAN1 matches the *Urban Dynamics* model and it provides a marvelous introduction to the insights Forrester obtained. Figure 5b shows some of the key variables from the base run of the model.

[4] Alfeld and Graham's *Introduction to Urban Dynamics* remains one of the great teaching texts in the field. It builds from simple building blocks up to the complexity of Forrester's model, carrying the reader's understanding along in the process. URBAN1 appears about halfway through the text.

Figure 5b: Dynamic behavior of URBAN1, showing growth, stagnation, and decay of population and businesses, and high unemployment in the built-up city.



The figure shows a growth phase with low unemployment (indicated by the labor-to-job ratio) which turns rather quickly into a no-growth stagnation phase, followed by a long period of decline in population and business structures. During the stagnation phase, unemployment rises and remains high for the rest of the simulation.

Like the larger *Urban Dynamics* model, URBAN1 captures endogenously the dynamics of mature cities. The emergence of urban stagnation, the rise in unemployment, and the onset of urban decay come about without any external influences. Furthermore, the behavior of these urban models is astonishingly resistant to parameter changes. Figure 5c, for example, shows what happens when each business in the city is magically able to hire 30 percent more people at time 40, near the beginning of the urban decay phase, an incredibly successful jobs program. There is a sudden drop in unemployment, followed by a rise in population and a consequent rise in unemployment to the same level reached in 5b. The jobs program works in the short run and is then completely compensated for by a short term rise in the attractiveness of the city. One can also note that the city has fewer business structures by the end of this jobs program run: The period of lower unemployment raises wages and makes the city relatively less attractive for new businesses.

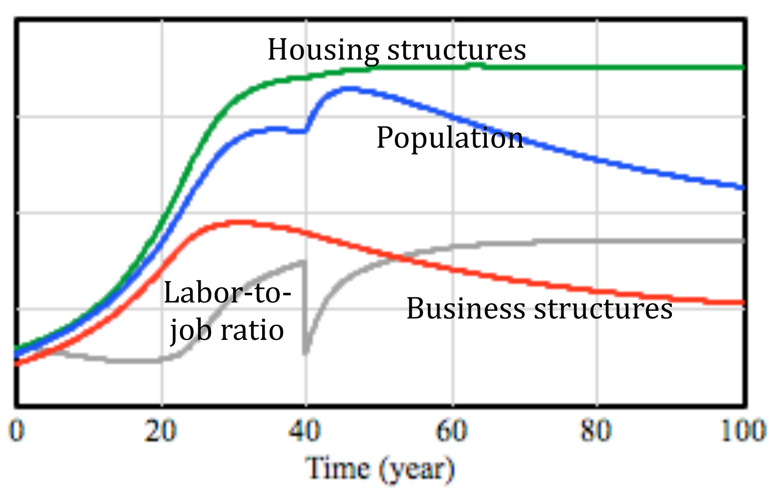


Figure 5c: The behavior of URBAN1 when a jobs program is instituted at time 40.

Once again, we see a number of crucial insights stemming from an endogenous modeling approach and an endogenous perspective on socio-economic dynamics:

- The dynamics of the city in these urban models do not depend upon dynamics outside the system boundary, in what Forrester conceptualized as a "limitless environment." All dynamics are generated from within. The suburbs are not causing urban decay; the cities in these models are doing it to themselves.

- The possibility that urban growth, stagnation, and decay have sources that trace to perceptions, interactions, and forces inside the city itself would never have emerged had Forrester expanded the system boundary to include suburbs, national urban policy, or national economic dynamics. The endogenous point of view was crucial for the insights we can derive from URBAN1 and the *Urban Dynamics* study. In fact, the choice of system boundary narrower than most would have taken proved to be the key to deep urban dynamics insights.

- Forcing dynamics to be endogenous forces causality in these models to be circular. Feedback loops in these models are consequences of the assumption of a closed causal boundary. Thus, the endogenous point of view provides the essential perspective capable of illuminating crucial compensating feedback effects that can conspire to defeat favorite policies.

- Feedback loops become crucially important for understanding urban policy. For example, the feedback loops containing the labor-to-job ratio here (see the upper right of Figure 5a) completely compensate for the simulated jobs program and render it useless in the long run.

How might thinking *exogenously* have affected conclusions emerging from these urban models? Consider just one: suppose, as a number of critics of various system dynamics studies have suggested, we chose to use time series data for urban population projections. Suppose the data-based projections were very carefully developed by sophisticated statistical tools and econometric methods, and suppose those projections were fed into URBAN1 in place of the endogenous stock of population. To make the implications easiest to see, let's suppose the base run of the model looks just as it did in Figure 5b. What would figure 5c look like? Sadly, population would not show a bump as it did in 5c because the sophisticated exogenous time series data would not be influenced in the slightest by the changing conditions in the model. We would not see the compensating urban migration effects we see in Figure 5c, and we would miss the crucial conclusion that population and business construction dynamics would naturally compensate for the jobs program. We'd probably think it was a long-term policy success, and we would be dramatically wrong.

Perhaps that conclusion is obvious here. We see the compensating loops in the upper right of Figure 5a rather easily, and we can easily understand the resulting dynamics and gain insight. But it may come as a surprise to learn that experienced modelers and some critics have been seduced by sophisticated statistical methods to think that time series data would improve the validity of dynamic models of social systems. The follow-on work to *World*

Dynamics (Forrester 1971) and the *Limits to Growth* (Meadows et al. 1974) provide an instructive example.

A Brief Observation from World Dynamics *and* Limits to Growth
In the decade following the publication of these model-based studies, many scholarly centers around the world worked to contribute model-based insights to the "global problematique" made famous by the Club of Rome. In a retrospective on those efforts, Forrester (1982) was forced to note rather critically that some of them held population exogenous, fed into the models as time series data, using the best estimates available for population data from sectors all around the world. He wrote to correct that tendency:

> Many recent world models, by letting population be exogenous, lose feedback from other variables back to population, and thus leave out the central dynamic factor driving world growth. The essence of world modeling is to find the high-leverage policies that will stabilize population in time to retain a satisfactory quality of life. ... If population is put back as an internal dynamic variable, more study will then be addressed to demographic change and to the underlying force that is threatening to drive the world into physical and social limits. (Forrester 1982, 102).

For example, improving health conditions on a global scale would lower infant mortality and increase average lifespans, thus increasing for at least two or three generations the population growth rate, resulting in a larger population to sustain materially and feed.

Continuing, he expressed his thoughts on the strengths of the system dynamics approach, mentioning specifically endogenous dynamics:

> ...Perhaps it is time to reintroduce system dynamics into world modeling: it lends itself to communicating with the public, dealing with long time horizons, choosing the appropriate level of aggregation, emphasizing policy choices, making all the variables endogenous,[5] joining the arena of political controversy, and drawing on the rich and diversified mental database. (Forrester 1982, 104).

In Forrester's view in this global modeling context, endogeneity and the feedback perspective it forces are crucial to responsible discussion of the global problematique and the reliability of potential national, regional, and global policy directions.

Endogeneity and Agency

We turn now to the question of *agency* in system dynamics: Who are the actors in the dynamics of a complex system and how do their perceptions, pressures and policies interact? Are you and I, or the groups we represent, part of the endogenous system structure responsible for the system behavior we perceive? Are we parts of the problem, or parts of the solution, or merely bystanders watching difficult dynamics play out over time?

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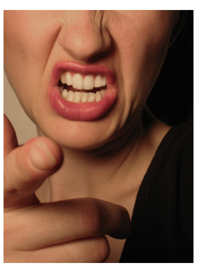
[5] Is this the first time he used the word in print?

The quotations at the beginning of this article illustrate that the question of the agents of endogenous dynamics has been with us for centuries. It is present in a number of current policy areas and is likely to bedevil future generations as well. Wisdom appears to side with inclusivity: certainly Cassius, Disraeli, and Pogo would have us believe that we are endogenous actors in the grand issues we face.

But others might have us believe differently. The following examples probe exogenous and endogenous points of view on problems of our time and the question of exogenous or endogenous agency in the problem dynamics. We'll conclude with an important framework for viewing such complex issues and a rich understanding of what systems thinking and system dynamics can contribute. For illustrations, we'll begin on a very homey note with personal relations, and move to big issues: global climate, terrorism, and floods.

Personal relations
Pam says Sam (at the right) is always mean to her. He says provocative, sometimes nasty things to her, argues with her, gets angry, puts her down, ...makes her feel bad. Pam thinks it's all Sam's fault; if he were nicer she'd feel a lot better.

We could characterize this as an *exogenous* view in interpersonal dynamics (the bold arrow below right).

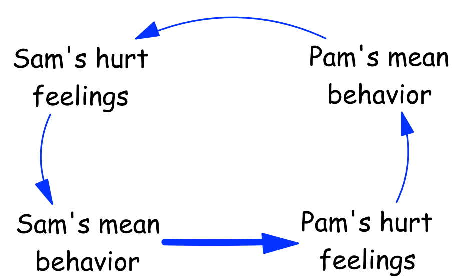


Pam (at the left), Sam's target, as maybe Sam sees her.

Something prompts Pam to consider whether she's part of the problem. Would an *endogenous* point of view would help in these interpersonal dynamics?

Maybe there's something that I'm doing that contributes to his behavior?!

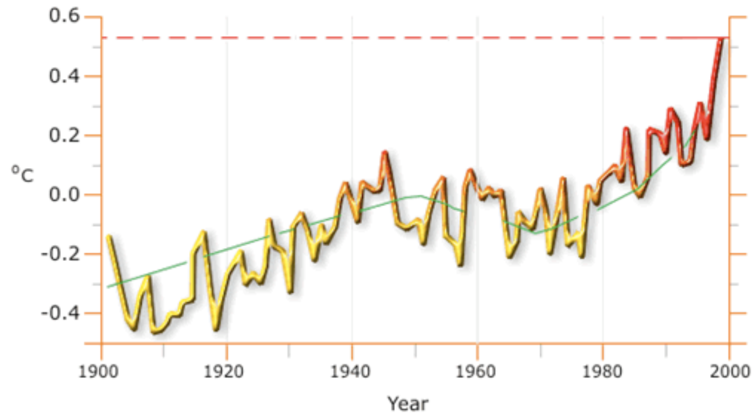
We're not sure in this example, but it's likely an endogenous point of view would help. It's probably not just Sam's behavior in isolation. Human interactions are just that — interactions. The thoughts and behaviors of each of us influence those arounds us, just as their thoughts and behaviors are influenced by us. To paraphrase Disraeli, sometimes we might tend to think we are creatures of circumstance (an exogenous view), but wisdom frequently suggests circumstances that surround each of us are creatures we help to create (an endogenous, feedback view).



Global Climate
Various groups in the United States, Europe, and the rest of the world are engaged in occasionally heated (!) conversations about global climate change. The data about global average temperature seems not to be at issue. Figure 6a shows 100 years of global temperature (relative to the 1961-1990 average) measured in degrees Celsius per year. The

figure shows that the global average temperature has been rising steadily throughout the 20th century, rising particularly sharply since 1970.

Figure 6a: One hundred years of global average temperature shown as deviations from the average temperature from 1961-1900, measured in degrees Celsius per year.[6]



That sharp rise coincides with a sharp rise in the global average atmospheric concentration of carbon dioxide, a significant heat-trapping gas (see Figure 6b).

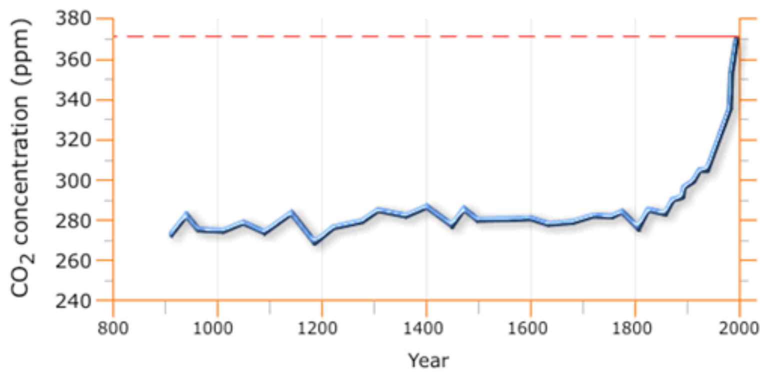


Figure 6b: Global average concentration of atmospheric carbon dioxide over the past thousand years, showing a dramatically sharp rise since 1900 (ibid.)

That is where the controversy begins. Some argue that human activity is at least partially responsible for the rise in global temperature because it is human production and use of fossil fuels that has pushed CO2 levels to dramatic heights. Others argue that current changes in global CO2 concentrations and temperature are simply part of a natural cyclic phenomenon that has been going on for millennia. Figure 6c, for example, shows 400 thousand years of data on temperature and CO2 and methane concentrations inferred from arctic ice core data. In each time series, the data show a vivid cycle with a period of about 100,000 years. Some argue we are simply in the most recent of these natural cycles.

[6] (Source of all graphs in Figure 6: http://www.landcareresearch.co.nz/research/globalchange/climate_change.asp#TempChange. For more graphs, data sources, and analysis see http://en.wikipedia.org/wiki/Temperature_record_of_the_past_1000_years.)

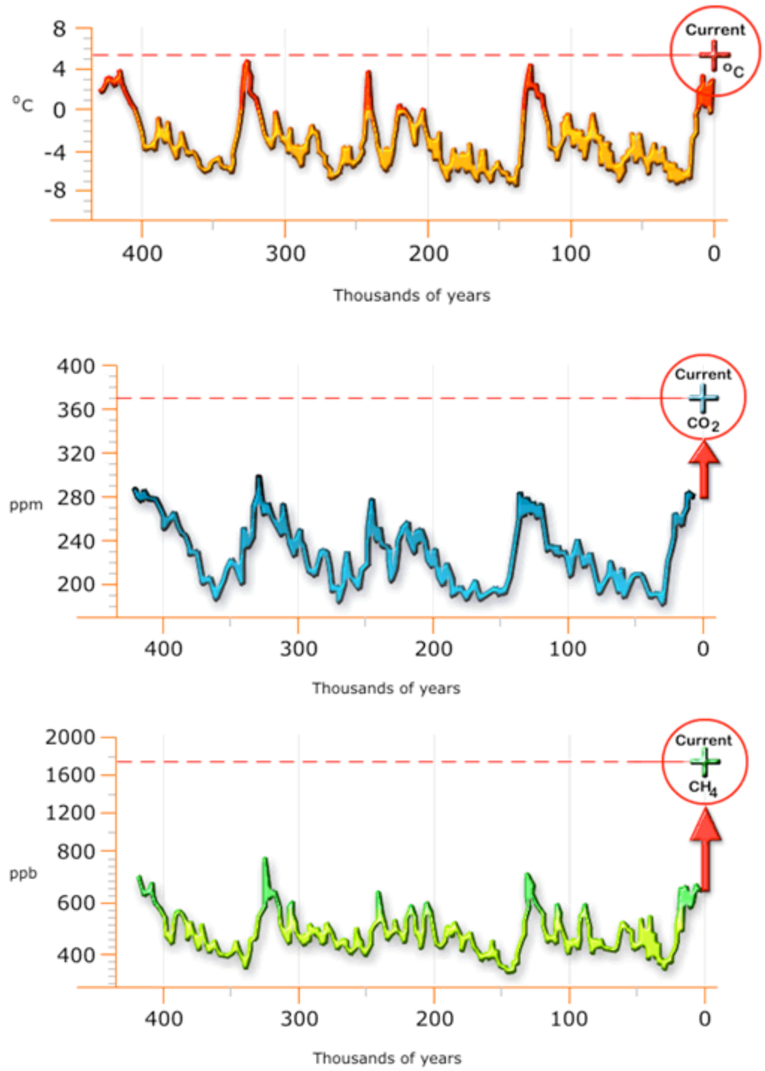


Figure 6c: Global average temperature and atmospheric CO2 and methane concentrations over the past 400,000 years, as inferred from Arctic ice core data (ibid.).

So there is an exogenous point of view on global warming, maintaining that current conditions are simply part of an exogenously generated cycle, and an endogenous view, holding that human activity in the form of the burning of fossil fuels is exacerbating temperature increases.

The exogenous view has some support in the mechanisms known as Malankovitch cycles (source: http://en.wikipedia.org/wiki/Milankovitch_cycles). Figure 7 shows the data supporting the theory that structural aspects affecting the intensity of solar radiation reaching earth are responsible for long-term ebbs and flows in the earth's incoming solar energy.

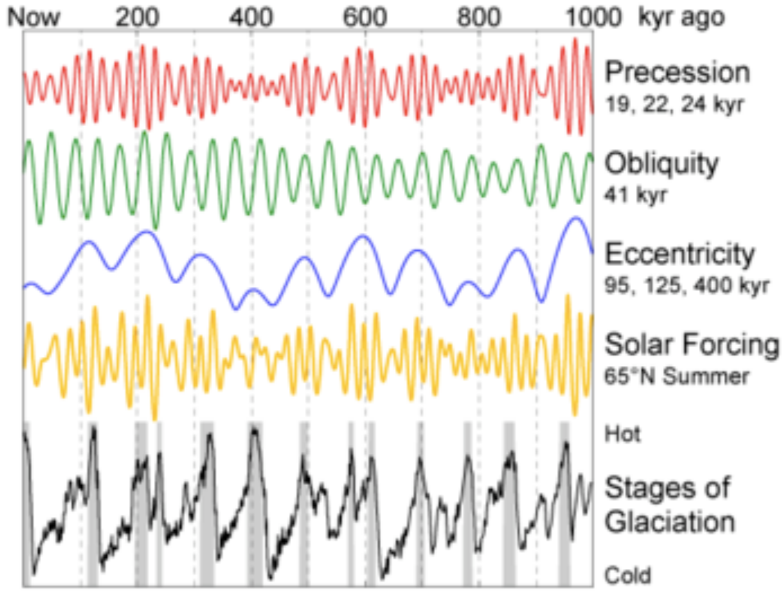


Figure 7 definitions:
Precession: a gradual shift in the direction of the earth's axis, which exhibits overlapping cycles from 19,000 to 24,000 year periodicities

Obliquity: the plane of the earth's orbit around the sun, which shifts in cycles of about 40,000 year periodicity

Eccentricity: the "ovalness" of the earth's orbit, which shifts from more circular to more elliptical and back in overlapping cycles from 95,000 to 400,000 year periodicities

Solar forcing: heat energy from the sun reaching earth, which exhibits long-term oscillatory patterns.

Figure 7: A million years of hypothesized data used by Malankovitch to suggest that earth's climate variations can be traced to structural aspects of earth's orbit and solar intensity. (Source: ibid.)

As Figure 7 illustrates, these Malankovotch cycles can apparently produce very long term oscillatory patterns in global temperature.

It is worth noting that both the exogenous and endogenous views on global climate change have a feedback structure underlying at least some of the dynamics (see Figure 8). The water and carbon cycles are influenced by atmospheric and ocean temperatures, and they in turn feed back to influence global temperatures via reflective effects from clouds and ice and heat trapping effects from water vapor and CO2 concentrations. Figure 8 shows four exogenous influences on interactions in the global climate system. Those who argue for a human role in rising global temperatures would emphasize fossil fuel use and human production of aerosols and greenhouse gases. Those who argue for a long-term natural cycle similar to the Malankovitch theory would de-emphasize those external forces and instead emphasize variations in solar energy reaching earth.

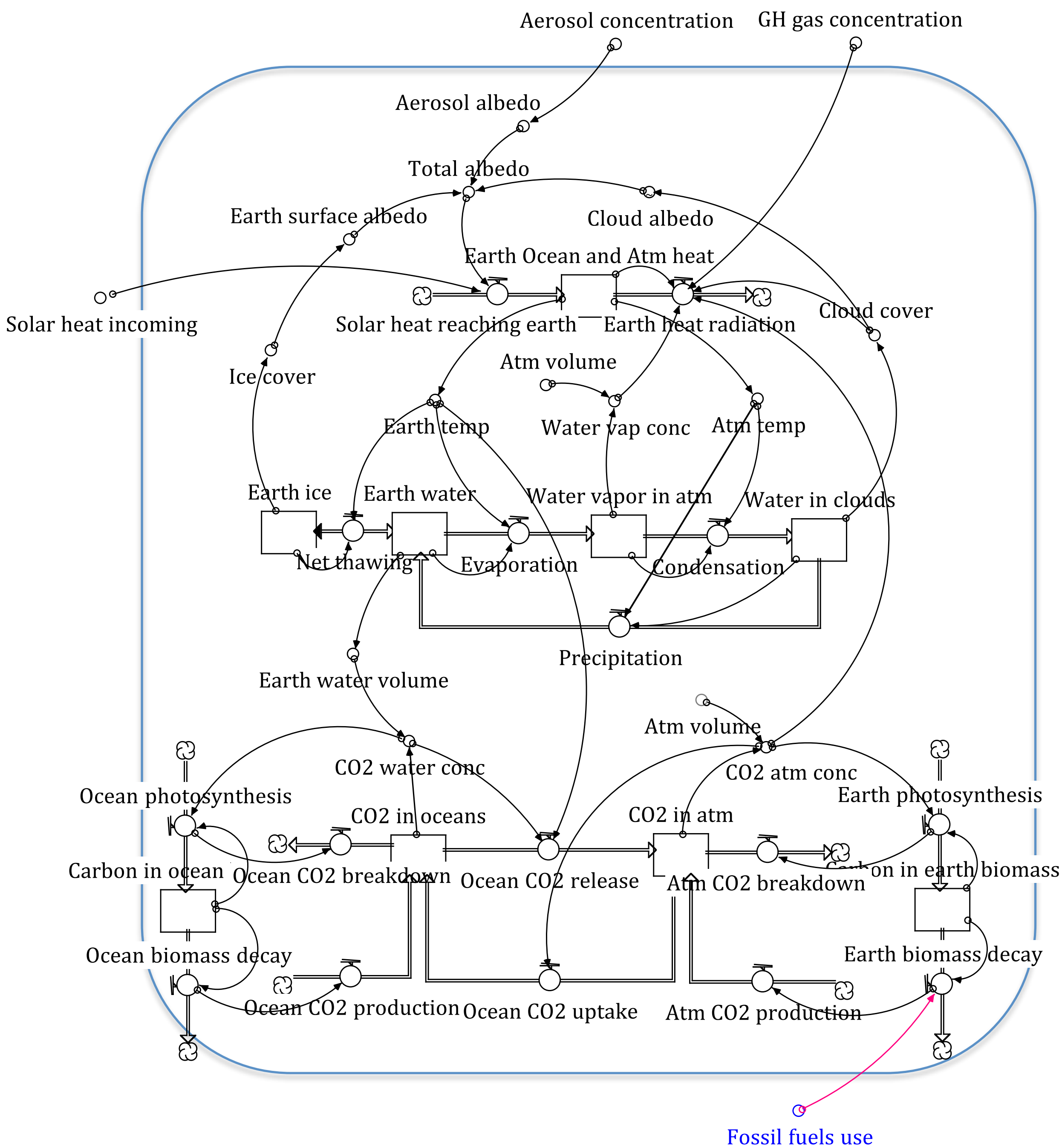


Figure 8: An overview of the water and carbon cycles and their feedback effects on global temperature, showing four exogenous influences. (Sources: Bernstein, Richardson, and Stewart (1994) and related work of the author. See also Fiddaman (2002).)

Thus, while balancing and reinforcing feedback interactions are present in all serious views of global climate dynamics, the global warming debate comes down to questions of agency and the implications for human action. Table 1 summarizes the points of view.

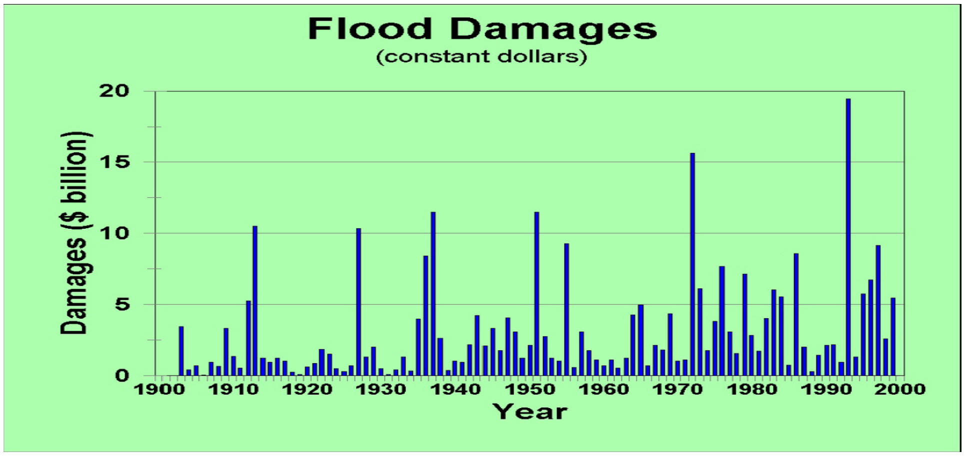
Global Climate	Perspective	Policy Implication
Exogenous view	We are in the warm phase of a 100,000 year cycle caused by exogenous, structural characteristics.	Adapt to the inevitable.
Endogenous view	Human activity is exacerbating the natural cycle.	Alter human habits to minimize the coming tragedies.

Table 1: Summary of exogenous and endogenous agency perspectives on global climate change.

Floods

The destruction caused by devastating floods along rivers and coastal waters provide another vivid contrast of exogenous and endogenous agency. Figure 9 shows the increasing costs of flood damages in the United States over the course of the 20th century.

Figure 9a: Annual costs of flood damages in the United States over the one hundred years from 1900 to 2000, showing an apparent tendency for costs to be increasing over time. (Sources: Deegan (2007), NOAA)



One obvious perspective on the increasing costs would hold that over the 20th century floods in the United States were becoming more frequent, or more severe, or both. Figure 9b captures that essentially exogenous perspective on flood damage.

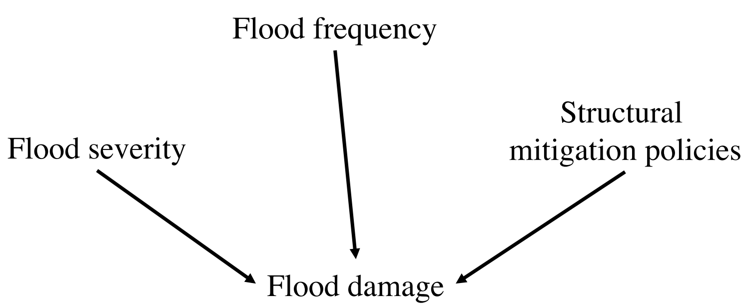


Figure 9b: An exogenous perspective on floods and flood damage, suggesting the reasonable conclusion that the main causes of flood damage are the random severity and frequency of floods.

However, Deegan's extensive analysis (2007) suggests another explanation, an endogenous view of the dynamics of flood damage that takes account of the human role in creating property vulnerable to flood damage. Citing Blaikie, Cannon, et al. (1994), he points out that "disaster occurs when hazard meets vulnerability." He then traces the dynamics of vulnerability to the interacting actions of the capacity of the local environment to withstand floods, development pressure, property tax needs, perceived risks of development, moral hazard, policy entrepreneurs, and other people pressures. Figure 9c shows an overview of the feedback structures he hypothesizes to be at work in the dynamics of flood-related property damage.

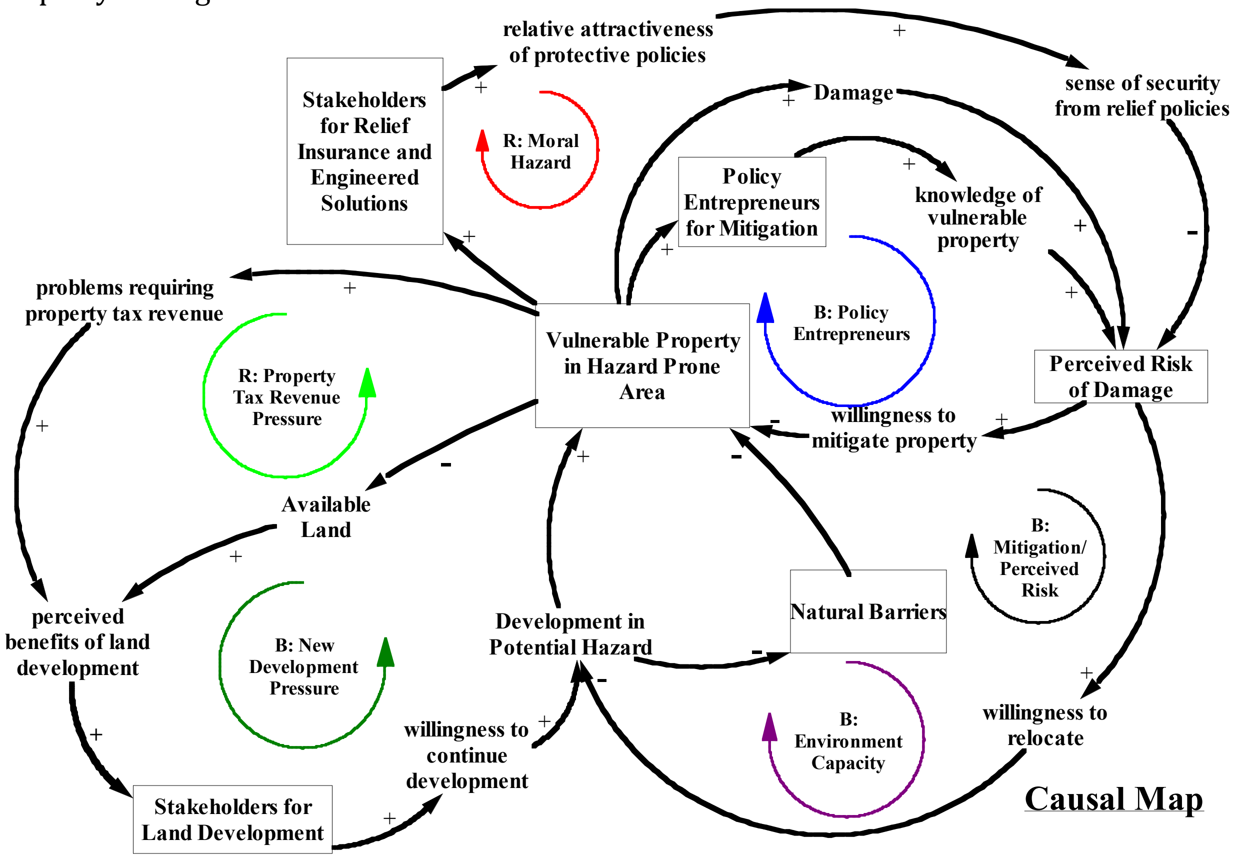


Figure 9c: Endogenous view of the dynamics of flood-related damage. (Source: Deegan 2007).

Deegan's simulation experiments are telling. In the base run, he simulates five identical floods ten years apart. The behavior of several key indicators are shown in Figure 9d. The important observation is that damaged properties (blue curve) does not show the same behavior after every flood. The causes for variable damages over time trace to the endogenous feedback structures outlined in Figure 9c which generate the dynamics of vulnerable property (red curve).

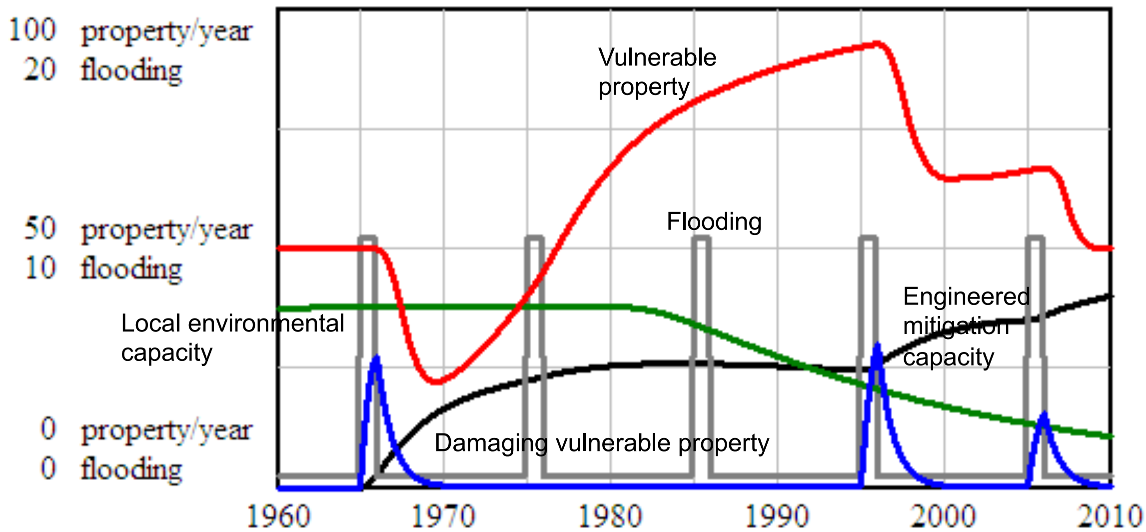


Figure 9d: Dynamics of four indicator variables Deegan (2007, chapter 5) showing what happens when the model is disturbed by five identical floods spaced ten years apart. The damage (blue curve) resulting from the five floods is different each time, dramatically illustrating the dominant role of human agency in property damage from floods.

Again, we have open-loop and feedback perspectives on the dynamics of flood damage. Table 2 summarizes these exogenous and endogenous points of view.

Flood Damage	Perspective	Policy Implication
Exogenous view	Floods happen sometimes; the greater the flood, the worse the damage.	When floods happen to occur, recover and rebuild.
Endogenous view	Damage occurs when hazard meets vulnerability; vulnerability is a result of people policies	Recognize human role in damage. Work with stakeholders to minimize vulnerabilities.

Table 2: Summary of exogenous and endogenous agency perspectives on flood damage.

We should observe that only in the endogenous point of view is there the empowering perspective that human behavior can have a significant policy role that could minimize future flood-related damage.

Terrorism

The dynamics of terrorism dominate the concerns of today's world. Figure 10a shows data on incidents in various regions of the world from 1970 to 2005 compiled by Gary Lafree and colleagues at the START Center at the University of Maryland.

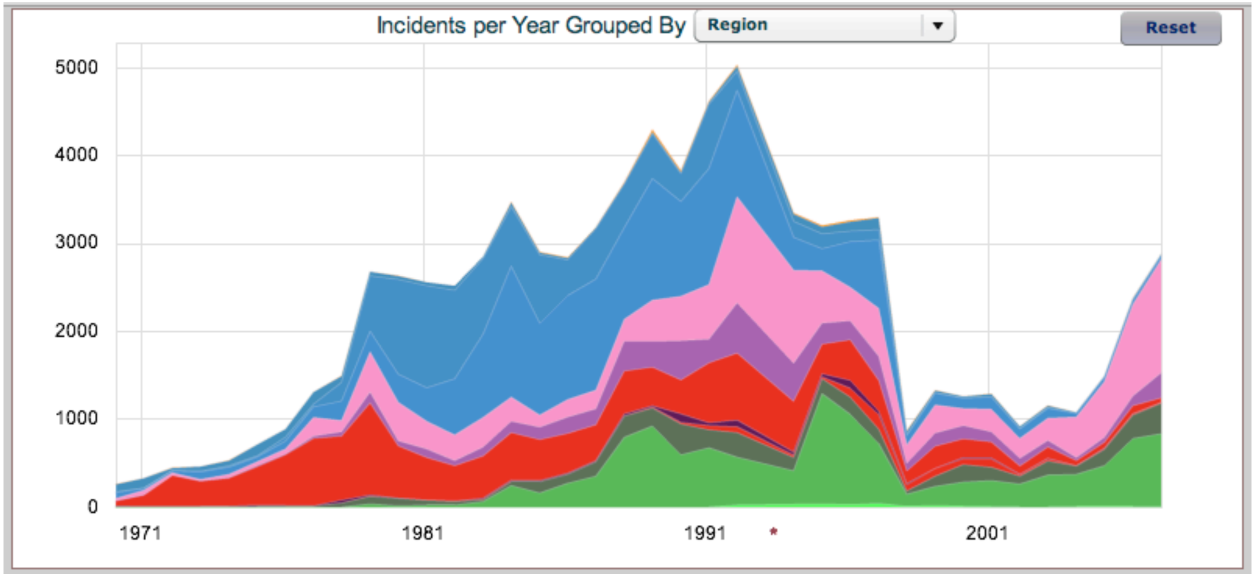


Figure 10a: Time series data on terrorist incidents world-wide. Colors distinguish regions in which attacks occurred. The dominant region in the 1980s was South America; the later emerging dominant regions are the Middle East (pink) and South Asia (green). (Source: http://www.start.umd.edu/gtd/features/GTD-Data-Rivers.aspx)

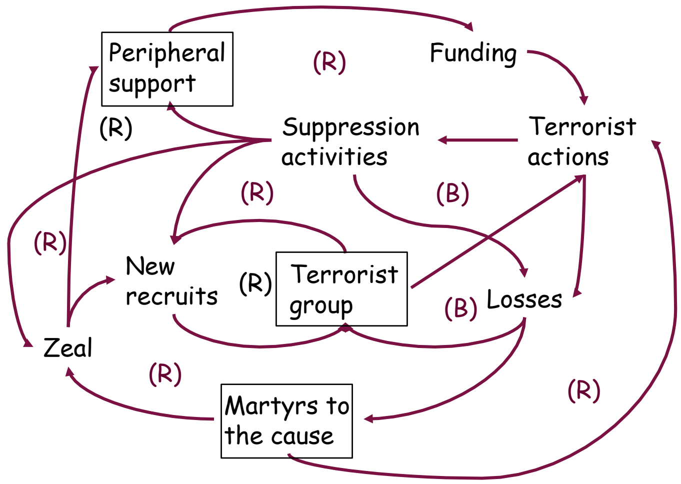
Even a very brief search on the internet can reveal a host of theories about causes of such terrorism incidents. Here is an arbitrary random sample:

- Ethnicity, nationalism/separatism, poverty and economic disadvantage, globalization, (non)democracy, Western society, disaffected intelligentsia, dehumanization, and religion
(excerpted from http://www.meteck.org/causesTerrorism.html)
- Marginalization, ethnicity and nationalism, religion, cultism, free flow of weapons, training of non-military personnel, no pure democracy present
(excerpted from http://www.helium.com/)
- Belief causes terrorism.
(http://nobeliefs.com/terrorism.htm)
- Foreign domination and control of Muslim resources, the hatred of the Western way of life. alienation. poverty and illiteracy. moral decadence of the West. the West's support for Israel.
(excerpted from http://www.wnd.com/news/article.asp?ARTICLE_ID=53842)
- Economic deprivations, political injustices, foreign occupation and denial of fundamental rights including the right to self-determination
("World must cooperate against terrorism: Qureshi," June 10, 2010 archive of http://www.dailytimes.com.pk/)

These examples and untold numbers of media accounts suggest that people have a tendency to think about terrorism in much the same open-loop terms that dominate most of our daily intuitive thinking. For the most part, the language focuses on exogenous sources and pressures. To be sure, one can begin to see interacting influences in words like "marginalization" and "foreign domination," but explicit loops of causal influence are extremely rare in online and printed analyses.

Consider how different a feedback view of the dynamics of terrorist cells might look.

Figure 10b: A feedback view of the dynamics of a hypothetical terrorist cell somewhere in the world, or perhaps an aggregate of linked terrorist cells



In Figure 10b, the Terrorist Group grows as new recruits are attracted to it because of the zeal they feel for their cause. The Group experiences loses as some of its members are killed or defect because of the dangers of Terrorist Actions. Those actions (suicide bombings, raids, improvised explosive devices, and so on) lead to efforts to supress terrorist activities and groups, which can lead to loses from terrorist groups but can also inflame passions, make it easier to recruit new terrorists, and contribute to Peripheral Support. That support can increase Funding and help to generate even more terrorist actions.

Of particular interest in an endogenous feedback view like Figure 10b is the stock called "martyrs to the cause." It is increased by terrorist deaths and decreases only when those deaths are no longer remembered. It has a very long time constant. Recall that the split between Shia and Sunni Muslims dates from 632, the year the prophet Muhammad died and a disagreement developed over who should succeed him. That's more than 1300 years ago, and it continues today in modern day Islam. The Armenian Genocide (a term disputed by modern day Turkey) occurred between 1915 and 1917, more than 90 years ago, yet is a source of current impassioned debate. William Wallace, a leader in the Wars of Scottish Independence, was found guilty of treason by the English and was executed in 1305. About 700 years later, in 2002, he was ranked #48 as one of the 100 Greatest Britons in a poll conducted by the BBC (http://en.wikipedia.org/wiki/William_Wallace). These few examples suggest that reinforcing loops containing "martyrs" are extremely worrisome sources of very long-term dynamics.

Thus, we have mixed exogenous and endogenous (feedback) views of terrorism. Table 3 sketches their characteristics and implications.

Terrorism	Perspective	Policy Implication
Exogenous view	Violent forces exist that threaten others, and they are growing.	Defend to prevent harm; attack to weaken or eliminate the violent forces.
Endogenous view	Violent forces interact with defenses and attacks to create the rising tensions we observe.	Defend to prevent harm; minimize behaviors that create nasty reinforcing loops; maximize creation of beneficial reinforcing loops; work toward cross-cultural understandings.

Table 3: Summary of exogenous and endogenous views of terrorism.

The Great Insight of Servomechanisms Engineering

As we saw in the first part of this paper, the early writings of Forrester suggest that the endogenous point of view is a crucial aspect of the system dynamics approach. And we have identified in the various examples described above at least some of the important societal implications of taking exogenous versus endogenous perspective.

But the importance of endogeneity can be very local and visceral, as this story told by Forrester from his student days suggests:

> One time as we were making feedback control systems with some high-powered applications — I think it was a 10-horsepower motor with a hydraulic control system to drive probably some kind of military gun mount. I remember one night I was working with it, and something went wrong. It had become unstable, and it began to go back and forth at the maximum speed that the 10-horsepower motor would drive it. Some of the hydraulic lines had broken, and it was spraying oil into the air, and I was trying to get it stopped. As I rushed over to try to turn it off, I slipped in the oil on the floor. What I remember is seeing the rainbows in the oil spray up against the lights… which is a lesson on oscillatory behavior.[7]

A lesson indeed. The story reminds us that Forrester was a servomechanisms engineer by training (and inclination). He studied electrical engineering and servomechanisms control with Gordon Brown, who founded MIT's Servomechanisms Laboratory in 1940 (Richardson 1991). Brown surely had experiences like Forrester's oily slip in mind when he wrote in his early servomechanisms text,

> A closed-loop control system is thus an error-sensitive system and, being such, it acquires certain peculiarities and idiosyncrasies which, in large measure, are the reasons for this book (Brown and Campbell 1948).

The story and the excerpt from the introduction to the servomechanisms text also remind us that "closed loop control systems" – feedback systems – often behave in counterintuitive,

[7] An excerpt from *Jay's Stories,* an unfinished, unpublished collection of stories Forrester has told and retold over the years, collected in interviews by the author in 2006-07.

unpredictable ways, as the young servomechanisms student Forrester was finding out. At the heart of that unpredictable behavior lies the great insight of servomechanisms theory, and by extension, system dynamics:

The act of trying to govern / manage / control generates system dynamics of its own.

The military gun mount goes haywire when its hydraulic control system overcorrects; a muscle trembles trying to hold a heavy weight; the speed of a steam engine under the control of a centrifugal governor oscillates as it "hunts" for the set-point; the inflation rate in the U.S. economy similarly oscillates under the efforts of the Federal Reserve Open Market Committee to keep it and the economy on an even and productive keel; the efforts of a government to dictate to its citizens generates rebellion; and so on. In each case, *the act of control generates dynamics of its own.*

That insight – and it is indeed a deep, profound insight – underscores the importance of the endogenous point of view in understanding the dynamics of social systems.

Choosing Points of View

As we think about the way natural and social systems play out over time, we have a choice of perspectives. We can view dynamics as arising largely from exogenous forces outside our purview and control, or we can see ourselves and the decisions we make as part and parcel of the ebb and flow of things. It also seems reasonable that reality has a similar "choice": the dynamics we are thinking about might come in reality from largely exogenous forces, or from predominantly endogenous interactions. Thus, we have a kind of two-by-two table, the *X/N matrix* in Table 4, a distant cousin of the Taylor-Russell diagram.

Table 4: The *X/N matrix*: eXogenous and eNdogenous perspectives contrasted with their corresponding "true" states of affairs that are mainly exogenous or endogenous, showing four possible (idealized) perception/reality combinations and their implications.

Predominant Mode of Analysis	True (Predominant) State of Affairs: Exogenous	True (Predominant) State of Affairs: Endogenous
Endogenous	Striving for understanding and leverage, but failing ☺😐	Achieving understanding and leverage ☺☺☺
Exogenous	Accepting fate, Predicting, Preparing 😐☹	Confused, Misguided, Misguiding ☹☹☹

Table 4 suggests four possibilities. In two of the cells we are “right.” The cell in the lower left of Table 4 represents those situations in which decision makers see the phenomena as largely exogenously caused, and in reality that is essentially the true situation. In the upper right, decision makers are taking an endogenous point of view of what are, in reality, essentially endogenously generated dynamics. The other two cells represent situations in which our perspective does not match reality very well, analogous to Type I and Type II errors in statistics. Perspectives and reality probably do not fall neatly into such discrete boxes, so we should think of these as something like “ideal types.”

In the lower left cell (exogenous view of exogenous phenomena), we see correctly that there is little that can be done to alter the future state of affairs, so our best course is to accept our fate, predict, and prepare for whatever we believe is coming. The expressions on the faces in the table suggest that even though this is a correct perception, we probably aren’t very happy about it.

In the upper left cell (endogenous view of exogenous phenomena) we are trying to find endogenous understandings but we will fail in such attempts because the situation is predominantly determined externally. So we are wrong, and our efforts at endogenous explanation and understanding are misguided. Yet for this author and perhaps most of us, the effort to find some endogenous aspects here give us hope for understanding and control (the “illusion of control”) and probably makes us feel better than we do in the lower left. So the faces are still mixed, but happier.

In the upper right (endogenous view of endogenous phenomena), we are taking the correct perspective for the situation, and we are potentially empowered by it. The situation is best understood in feedback terms, with the possibility of human agency in contributing to problems and solutions. We are seeing the endogenous aspects of corporate conditions, urban dynamics, global climate, or terrorism and the like from an endogenous perspective ,and we have the chance of influencing wisely how things will play out over time. That cell merits three very happy faces.

In contrast, the cell on the lower right (exogenous perspective on endogenous phenomena) is a dismal prospect, characterized by three very unhappy faces. Here we take the point of view that circumstances are largely caused by external forces, when in fact there are essentially correct endogenous, empowering explanations. In this cell we are destined to be confused and misguided, and we will misguide others.

If one were to recast Table 4 as a decision tree, the decision to take an endogenous point of view in all circumstances would have the highest net payoff, at least in terms of happy faces and the real feelings they represent. An endogenous point of view is potentially empowering, and that feels good to us.

The Foundation of Systems Thinking and System Dynamics

We began this exploration with the early thoughts of Forrester on the essential nature of the field he created. Through those early writings and a number of wide-ranging examples we have plumbed the nature of exogenous and endogenous points of view. We are now ready to try to expose the implications of these ideas and examples. The implications now appear to enable both a tight characterization or even definition of the field of system dynamics and perhaps an accurate characterization of *systems thinking* in general.

Our first implication is, by now, rather well established:

> *The endogenous point of view is a crucial foundation of the field of system dynamics.*

While we know that there are legions of systems thinkers, and they have their own special interpretations and contributions[8], it now seems very likely that they draw their deepest fundamentals from what we have been investigating. Could we capture a key aspect of all of them in the following sweeping characterization?

> *Systems thinking is the mental effort to uncover endogenous sources of system behavior.*

An appealingly concise characterization of the field of system dynamics results:

> *System dynamics is the use of informal maps and formal models with computer simulation to uncover and understand endogenous sources of system behavior.*

A potential corollary is important to the understanding of our field: Analyses that do not seek to uncover endogenous sources of system behavior are not really system dynamics applications. There may be formal models in a study, there may be stocks and flows, there may even be feedback loops, but without a strong endogenous character the analysis is missing a defining aspect of the system dynamics approach. Such analyses will be prone to miss crucial ramifying effects and intricate compensating mechanisms that an insightful endogenous perspective could reveal.

From this point of view, we can say quite clearly what system dynamicists do:

> *System dynamics practitioners use systems thinking, management insights, and computer simulation to*
> - *hypothesize, test, and refine endogenous explanations of system change, and*
> - *use those explanations to guide policy and decision making.*

This characterization of the system dynamics approach is true to the writings of the founder of the field and is reflected in the best work of its practitioners.[9]

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[8] See, e.g., Systems Thinkers, Systems Thinking (1994).

[9] See, e.g., http://www.systemdynamics.org/AwardRecipients.htm for a list of winners of the Forrester Award.

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