In Defense of System Dynamics: A Reply to Professor Hayden.

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Notes and Communications

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A Response to Professor Hayden

Abstract: In a 2006 paper, Professor Gregory Hayden argued that system dynamics is an inadequate tool for explaining the institutional systems principles of hierarchy, feedback and openness. The purpose of this paper is to show that many of Professor Hayden’s claims are either misguided or incorrect. The paper also reinforces the argument that system dynamics modeling can add significant value to traditional institutional economic analysis.

Keywords: system dynamics, heterodox economics, institutional economics, feedback, simulation

JEL Classification Codes: B4, B5, C6

In a 2006 paper in this journal, Professor Gregory Hayden argued that system dynamics is an inadequate tool for explaining the institutional systems principles of hierarchy, feedback and openness. The purpose of this paper is to show that Professor Hayden’s claims are, for the most part, misguided and, in some instances, patently incorrect. Moreover, we will reinforce the view that combining system dynamics with institutional economics can be a very powerful approach to heterodox economic analysis (Radzicki 1988a; 1990; 2003; Tauheed 2005).

Hierarchy

Hayden begins his criticism of system dynamics by discussing the notion of hierarchy in systems. He notes that “[h]ierarchies exist to ensure that . . . happenings [in complex systems] are happening as they should happen” and then reproduces a figure by Robert Boyer (2001), which purports to show the hierarchal nature of constitutionality and rulemaking. Hayden objects to Boyer’s figure because he feels it makes “hierarchy into a spatial order, rather than an institutional process . . .” (Hayden 2006, 528). Moreover, he objects to Boyer’s use of arrows with plus and minus signs in the figure because “[d]eliveries among institutions and organizations are not a matter of simple pluses and minuses” (529).
Up to this point in his paper, we have no quarrel with Hayden. However, we wonder why he believes that Boyer's figure is evidence that system dynamics is an inappropriate tool for incorporating hierarchy into institutional analysis. Boyer's figure is not a system dynamics model and, as far as we know, Boyer is not a system dynamicist. Indeed, the precise concepts that Boyer is trying to convey with his arrows and plus and minus signs are not clear to us, and he does not appear to be using the arrow and polarity nomenclature in the same way that a system dynamicist would. At the risk of stating the obvious, because a figure includes arrows with plus and minus signs does not make it a system dynamics model. To make a connection of this sort is a non sequitur of the highest order.

Hayden's critique of Boyer's model, however, does raise an important question. What, if anything, does the system dynamics approach to modeling have to say about system hierarchy? System dynamics models are almost always nonlinear, which essentially means that they, and the actual systems they represent, contain limiting factors. Stated differently, from a system dynamics perspective, nonlinear relationships typically define a system's approach to its limiting factors.

Conceptualizing and modeling systems as nonlinear is important to the issue of hierarchy because nonlinear systems must be studied and solved holistically. In other words, the behavior of a nonlinear system is due to both the behaviors of its individual parts and the particular connections and interactions among its parts. As such, nonlinear systems do not really consist of top-down hierarchies such as that described by Boyer, but are better categorized as complex interactive processes.

Another issue related to hierarchy in system dynamics modeling involves the recursive nature of continuous simulation on a digital computer. System dynamics models are solved by having the computer step through time and calculate the amount of "stuff" that has accumulated in each of a system's stocks at every step along the way. There is a defined past, present, and future in all system dynamics models and events unfold in the order that they do in the real world. In other words, in a system dynamics model "happenings happen as they should happen."

In fact, in spite of Hayden's major premise, the structuring of system dynamics models to represent hierarchical systems is technically unproblematic. The flows in a system dynamics model represent the decisions of the agents in the system under study and are indicative of the hierarchical arrangements that direct the happenings to happen as they should. These causal connections will typically consist of structures containing goals, current conditions, the gap between the goals and the current conditions, and the desired action (formal or informal) to bring the current condition closer to the goal. This is the essence of hierarchical structure, so when Hayden writes (2006, 530):

[Feedback is a form of inter- and intra-systemic control in which the performance of the system utilizes information, requirements, materials, violence, criteria, rules, evaluation research, inventories, semiotic signs, money flows, and other deliveries to guide a system. Hierarchy is one reason for feedback...
we not only agree that feedback has an appropriate use in institutional economics, but
assert that the only limit to using system dynamics to model hierarchical structures is
the modeler's skill and imagination, which applies to all modeling techniques. Any
and all of the items in Hayden’s list of deliveries can be modeled by system dynamics
structures.

Feedback

After discussing the concept of feedback and its appropriate use in institutional
economics, Hayden then defines negative and positive feedback. With respect to the
former he writes, “[n]egative feedback, thus, leads to the convergence of system
behavior towards some goal” (2006, 530). With respect to the latter he writes that
“[p]ositive feedback processes, in which positive feedback overwhelms negative
feedback, tend to be destructive to the system because a change in the original level of
the system provides an input for further change in the same direction” (530). While
Hayden’s description of positive and negative feedback processes is only a sidebar to
his main arguments, we feel compelled to make two points. First, although negative
feedback loops are indeed goal seeking, they can often destabilize systems and cause
them to oscillate if there are delays in their corrective actions. Second, positive
feedback loops need not be “destructive to the system.” In fact, they can form either
vicious or virtuous circles and can sometimes even work to stabilize systems.3 Path
dependent behavior,4 which can be either good or bad, bandwagon effects, and
increasing returns to scale are examples of processes that are generated by positive
feedback loops. What positive or negative feedback loops do depends on their
relationships to the other loops and states of the system.

Hayden goes on to note that “[t]he feedback concept comes from cybernetics . . .
[which] is mechanistic, based on physics, and very concerned with energetics - hardly
the base for studying feedback control in social systems” (2006, 530). Based on this
statement, it appears that Hayden believes that the feedback concept originated in
cybernetics. Moreover, the statement makes us wonder if Hayden is also implying that
the intellectual predecessor of system dynamics is cybernetics. If our interpretations of
Professor Hayden’s statement are correct, we’d like to call his attention to George
Richardson’s (1991) book Feedback Thought in Social Science and Systems Theory.5 In this
book Richardson traces, in egregious detail, the loop concept (which embodies both
the concept of feedback and the concept of circular causality) in the social sciences
from the golden age of ancient Greece to the present day, and identifies two distinct
threads. The first is indeed the cybernetic thread, which stems from the work of
Norbert Weiner and the Macy Foundation conferences of the 1940s and the second
is the servomechanism thread, which stems from the world of control engineering.
Richardson makes a compelling case that social scientists working within the former
thread view feedback as the mechanism of homeostasis and utilize it to address issues
mainly related to control and communication. Positive feedback processes are rarely,
if ever, utilized by researchers working within the cybernetics thread. Social scientists
working in the latter thread, on the other hand, focus on understanding the causal
relationship between a system’s feedback structure (both positive and negative loops) and its dynamic behavior. Richardson (correctly) places system dynamics squarely within the servomechanism thread.

Hayden next introduces Figure 2, “a digraph expression of part of a social fabric matrix for the management of the surface water of the Platte River in Nebraska . . .” (2006, 531) and offers it as an example of the proper use of hierarchy and feedback in institutional economics. He defines the “feedback control paths” in this figure to be “sets of institutional processes at work” (530).

We have no particular disagreement with Hayden over this figure beyond its fairly cluttered appearance. In fact, from a system dynamics point of view it would appear to be equivalent to a sector diagram of a system dynamics model, with the “feedback control paths” simply defining some of the main causal relationships between the model’s sectors. A sector diagram such as this can be created prior to the construction of a system dynamics model as part of the knowledge elicitation/brainstorming/model conceptualization process, or after the construction of a system dynamics model as part of the model’s documentation. In the former case, utilizing a social fabric matrix as a tool to elicit knowledge from experts and stakeholders, and to conceptualize a problem from a system’s perspective, as a precursor to building a system dynamics model is excellent practice. Indeed, Roderick Gill (1996) did just this in his efforts to solve problems in the Australian beekeeping industry using system dynamics.

Openness

Next, Hayden discusses the concept of openness and notes that it is a characteristic of all systems and thus needs to be recognized in institutional modeling. According to Hayden, openness means that systems exist within diverse environments with which they continuously exchange information, energy, materials, and ideas. Again, we have no quarrel with Hayden on this point as the concept of openness is intimately intertwined with system dynamics modeling.

Hayden goes on to criticize Boyer’s model for not including an environment and thus for not being open. However, he then says “[t]he same incorrect assumption is made for Forrester-type system dynamics computer programs” (2006, 532). Unfortunately, Hayden is misguided when he makes this statement. Although it is technically possible to create system dynamics models that are closed, the overwhelming majority of system dynamics models that are created of socioeconomic systems are open. Stated differently, the issue of whether or not it is “correct” to build a “closed” system dynamics model is problem specific. If the problem the model is addressing calls for a closed system, a closed system dynamics model should be created.

Figure 1 is a modified version of the well-known Bass (1969) diffusion model that is frequently used as a starting point for system dynamics models that capture the diffusion of new products or services into the marketplace. The dynamics of the model are fairly straightforward. The potential market for a new product or service is divided into two categories: households who have adopted the product or service and
households who have not. Over time, households move from one category to the other based on the impact of two factors: advertising and word-of-mouth. The former factor creates a negative feedback loop because households who decide to adopt the product or service due to the influence of advertising drain the stock of Non Adopters. The later factor creates a positive feedback loop as more households adopting the product or service means that more people are available to convince Non Adopters to come on board. The model also contains a negative feedback loop that contributes to the saturation of the market because more Non Adopters interacting with Adopters causes the stock of Non Adopters to drain more quickly.

In and of itself the modified Bass diffusion model of Figure 1 represents a “closed” system, as none of the households are allowed to interact with their environment. Figure 2 presents a simulation of the model. Over a ten-year time span all of the Non Adopter households simply move from the Non Adopter stock to the Adopter stock. The positive word-of-mouth feedback loop dominates the system until just before year five, when the system’s negative loops gain enough strength to control the system’s behavior. The adoption rate peaks at the point at which the switch in feedback loop dominance occurs.

Despite being materially closed, if the purpose of the modified Bass model is to convey some basic insights into the factors that influence the adoption of a new product or service, it can be argued that it is in some sense “legitimate” or at least that
it has some value or usefulness. Having said this, the model has several noteworthy problems including:

a) A lack of new Non Adopter households. This implies that the potential market for the good or service does not grow.

b) The assumption that existing Adopters use the good or service forever. This implies that the rate at which households discontinue using the product or service is not considered important to the purpose of the model.

c) The assumption that Adopters are not allowed to buy units of the good or service beyond their initial purchase.

Figure 3 presents an expanded version of the modified Bass diffusion model that addresses these deficiencies. It includes an Installed Base of the new product and flows that define the model's exchange of inputs and outputs with its environment. More specifically, the model:

a) Draws-in new Non Adopter households from its environment, presumably due to population growth or from people aging into new demographic cohorts that are likely to be interested in the new product.
As a consequence of these new flows across its boundary, the expanded version of the modified Bass diffusion model is a "materially open" system. Figure 4 presents a simulation of the model. It shows the market going through its initial adoption dynamics and then settling into a sustained rate of growth.

Continuing his discussion of openness, Professor Hayden notes that "because real-world systems are constantly open to their environments, equilibrium is not possible" (2006, 532). Again, we have no quarrel with this observation per se. However, it is clear that Hayden is making this point in an effort to attack system dynamics and, in doing so, reveals his confusion between properties of models and properties of real world systems.

Although system dynamicists believe that actual systems rarely, if ever, exist in a state of equilibrium, it is quite common in system dynamics to start a model in equilibrium and then knock it out with a shock from its environment so that its
"pure" (disequilibrium) response can be observed. Model testing is often undertaken in this manner because (a) it simply makes it easier to evaluate the response of the system to the shock and (b) a fundamental idea in system dynamics modeling is that the structure or "fabric" of a system (which includes the details of its institutions) is responsible for its behavior and thus the proper use of a model is for testing policies (i.e., changes to the system's structure) that are aimed at making the actual system robust. A robust system will respond "well" to shocks from its environment, regardless of the timing or direction of the shocks.

Figure 5 presents another run of the modified (open) Bass diffusion model. This time the system is started in equilibrium and knocked out in year four by an exogenous shock - in this case a sudden increase in the in-flow of new Non Adopter households from the environment. In this experiment the system responds by increasing the throughput of all of its flows until they balance at a new equilibrium. The simulation reveals that equilibria are indeed possible in open system dynamics models. Whether this sort of behavior is relevant or not depends on the purpose of the model and the particular issues the modelers are exploring when they reach this point in the model testing process. In addition, as stated above, the existence of such behavior certainly does not imply that the modelers believe that the actual system exists/can exist in a state of equilibrium. In fact, should there be a continuous supply of exogenous shocks to the system it will never reach a state of equilibrium at all.
Model Boundaries and Materially Closed Versus Causally Closed Systems

An important issue that is closely related to Hayden’s claim that system dynamics models are closed is that of specifying a model’s boundaries. This modeling task involves thinking hard about the elements of a real world system that should be included in, and excluded from, a model’s structure. The modeler is guided in this process by the goal of producing an endogenous explanation for a system’s problematic behavior. In other words, the modeler’s task is to identify the important feedback loops that are responsible for causing the system’s problems.\(^{13}\)

Professor Hayden is completely correct to note the importance of the open systems concept in contemporary evolutionary economics. Unfortunately, he appears to be confusing the concept of causally closed feedback loop (endogenous) explanations offered by system dynamics models with the notion of materially closed systems that do not exchange information, energy, materials, or ideas with their environments. The modified Bass diffusion models presented above, however, prove that the issue of open versus closed systems has nothing to do with feedback loops.

At this point we would like to cut Professor Hayden a little slack as he is not the first scholar to confuse causally closed and materially closed systems. No less a scholar than Ludwig von Bertalanffy, the father of general systems theory and the man behind the concept of materially open and closed systems, apparently made the same mistake.
According to extensive research by Richardson (1991, 122), von Bertalanffy:

may have confused the concept of a closed loop of circular causality with his own notion of a “closed system.” The latter is a system that exchanges no material or energy with its environment, an entirely distinct and independent idea from the notion of a closed sequence of causes and effects. Alternatively, [he] may have equated information with “material” and “energy,” and thus found information loops equivalent to materially closed systems.

Another source of confusion on this topic is, ironically, Jay Forrester, the father of system dynamics. Forrester (1968, 1-5-1-7) chose to classify systems as either “open” or “feedback” (i.e., “closed”). Again, according to Richardson (1991, 297-298):

The concept of the closed boundary signals the system dynamicist’s endogenous point of view . . . It also serves indirectly to show Forrester’s independence of von Bertalanffy and the general systems theorists . . . 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 [of a “feedback or “closed” system] 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 . . . . 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.”

**Fitting System Dynamics Models to Time Series Data**

Another problem that Professor Hayden has with the application of system dynamics to institutional economic analysis has to do with curve fitting. He writes (2006, 533):

Forrester systems literature emphasizes that models are to mimic databases, meaning that the coefficients are to be adjusted with the capabilities of the computer program until the model will reproduce historical database results for particular entities of interest . . . . If the goal is to juggle data and manipulate coefficients until a particular historical path is reproduced, what the nodes in the model are called or how they work in the real world is not a concern. It is coefficient adjustments that generate validity. The
coefficients are not adjusted because of statistical analysis or institutional theory, but, rather, to reproduce a database.

Unfortunately, Professor Hayden couldn't be more incorrect on this point, at least vis-à-vis proper system dynamics modeling practice. System dynamicists do not believe that it is profitable to think about models as being either "valid" or "invalid." Rather, they believe in building confidence in models along multiple dimensions. Peterson (1975, Appendix B), for example, provides a list of thirty-five tests to which a system dynamics (or any) model can be subjected. The more tests that a model can pass, the more confidence a system dynamicist has that the model can generate useful results that can be used to make an actual system perform better.

According to many system dynamicists one of the least powerful tests for building confidence in system dynamics models is fitting them to historical time series data. As Professor Hayden correctly suggests, this activity often becomes an exercise in curve fitting that yields no new policy insights. Indeed, no less a system dynamicist than Jay W. Forrester (2003, 5) warns against this practice in system dynamics in general, and in system dynamics modeling of economic systems in particular.

I believe there is much too much attention given in economics, and in system dynamics, to reproducing a specific historical time series. The dynamic character of past behavior is very important, but the specific values at exact points in historical time are not. Different random sequences in the past in the real economy would have produced different historical data sequences all with the same general character, just as would happen in a series of model simulations using different random inputs.

Pushing the preceding point further, Forrester (1992, 20) argues that system dynamics modeling produces a much richer form of economic analysis.

After a talk at a joint NATO/US conference on cities in Indianapolis, Indiana in 1971, William Dietel, now recently retired as president of the Rockefeller Brothers Fund, came up from the audience to discuss their future programs. From that meeting came initial funding for our work in applying system dynamics to behavior of economic systems . . . The approach is very different from the conventional econometric models, which are structured on the basis of macroeconomic theory with parameters drawn from statistical analysis of historical data and with a heavy dependence on exogenous time-series to drive the dynamics of the model. From the system dynamics point of view, econometric models are essentially curve-fitting exercises. They do not contain the essential feedback structures that create the kinds of dynamic changes that are seen in real economies.
To be fair, some system dynamicists disagree with Forrester and spend a great deal of their time fitting their models to historical time series data. However, unlike Professor Hayden’s assertions, their models adhere to both good system dynamics modeling practice and good statistical theory (Radzicki 2004). According to Homer (1997, 293):

Some system dynamics models are more effective than others in changing the thinking and actions of their audiences. In my experience, the models that prove most compelling to clients generally have two things in common: a potent stock and flow structure and a rich fabric of numerical data for calibrating that structure. Stock and flow structures focus attention on the intrinsic momentum of a situation and allow one to track movements of people and things in a clear and systematic way. Numerical data not only help to build a client’s confidence in a model, but can also materially affect the final structure and key parameter values of a model.

**Sector Diagrams and Causal Loop Diagrams**

The final area in which Professor Hayden criticizes the application of system dynamics to institutional analysis involves what he calls “the unique conceptualizations in the Forrester tradition” (2006, 532). He writes (533) that:

Jay Forrester developed his analysis for electrical engineering systems and applied it, along with the positive and negative charges of electricity, to social science problems . . .

This statement is factually incorrect and actually quite ridiculous. Forrester originally developed system dynamics solely for the purpose of improving policy making by managers of corporations.¹⁹ He never applied “positive and negative charges of electricity to social science problems” and, indeed, we’re hard-pressed to understand what Professor Hayden is talking about when he makes this assertion. Hayden (2006, 534) then continues:

Within most Forrester dynamics programs, there is the capability to attach any two entities in a program mapping and “tweak” the real or imagined connections with plus or minus charges to indicate influence, or support, or opposition, or causes, or whatever.

Again, this statement is filled with misunderstandings and inaccuracies. First, system dynamics software packages do not allow “any two entities” to be attached, willy-nilly. All system dynamics software packages contain rules that govern the proper attachment of icons on a computer screen – i.e., rules that govern proper equation writing and model construction that are consistent with fundamental “principles of systems.”²⁰ Second, a properly trained system dynamicist would never add “imagined” connections to a model of an actual system. Indeed, Forrester and Senge (1980, 212) write that:
Verifying structure means comparing structure of a model directly with structure of the real system the model represents. To pass the structure-verification test, the model structure must not contradict knowledge about the structure of the real system.

Having made this point, if Professor Hayden meant to say "perceived" instead of "imagined," he could have avoided the pejorative context implied by the latter term. In this case the modeling of "perceived" links would be good modeling practice whether one is constructing a system dynamics model or using some other modeling technique.

Hayden next criticizes a figure taken from a paper by Thomassin and Cloutier (2004, 499), in which they appear to present a first-cut causal loop (influence) diagram representing important aspects of the Canadian hog production system. Our interpretation is that this figure represents the authors' initial efforts to conceptualize the system from a feedback perspective and does not represent their final results. Indeed, from what they say at the end of their paper (501) it appears that Thomassin and Cloutier intend to extend their work by building an actual system dynamics model. If this is the correct interpretation of Thomassin and Cloutier's figure we have no particular objection to its presentation, as many system dynamicists utilize causal loop diagramming for brainstorming. Of course, a causal loop diagram is not itself a system dynamics model and, although some system dynamicists use this technique at the initial stages of a modeling effort, many do not.

I do not use causal loops as the beginning point for model conceptualization. Instead, I start from identifying the system [stocks] and later develop the flow rates that cause those [stocks] to change. Sometimes I use causal loops for explanation after a model has been created and studied. For a brief overview presentation to people who will not be trying to understand the real sources of dynamic behavior, causal loops can be a useful vehicle for creating a general overall impression of the subject. (Forrester 1994, 252-253)

In sum, it appears that Professor Hayden doesn't understand that causal loop diagrams and, for that matter, sector diagrams are merely tools for conceptualizing and/or summarizing system dynamics models and that they are not, in and of themselves, system dynamics models. Moreover, it appears that he is confused about the plus and minus signs that often appear at the heads of arrows in causal loop and sector diagrams. These signs do not represent electrical charges but simply mean that the head-of-arrow variable moves in the "same direction" (plus sign) or "opposite direction" (minus sign) as the tail-of-arrow variable. Technically, each arrow ("causal link") connecting two variables in a causal loop diagram signifies cause and effect. A plus sign indicates that an increase in the variable at the tail of the arrow will cause an increase in the variable at the head of the arrow above what it would otherwise have been, and a decrease will cause a decrease below what it would otherwise have been. A
minus sign indicates that an increase in the variable at the tail of the arrow will cause a decrease in the variable at the head of the arrow below what it would otherwise have been, and a decrease will cause an increase above what it would otherwise have been. Mathematically, each causal link is a picture of a partial derivative, with the plus and minus signs indicating the signs of the derivative.  

**Examples of Best Practice**

Perhaps the biggest problem we have with Professor Hayden's paper is that he has chosen to support his harsh criticisms of the use of system dynamics in institutional analysis by pointing to examples that are 1) not system dynamics models, 2) represent the initial stages of a system dynamics modeling study (not the final results), and/or 3) do not represent the highest standards of system dynamics modeling. He ignores, for example, work such as Saeed's (2004) excellent study of the design of mitigation banking systems, Pavlov's cutting-edge work on the dynamics of illegal file sharing over the internet (2005), Pavlov, Radzicki and Saeed's (2005) work on instabilities in a superpower dominated economic system, and Nichols, Pavlov and Radzicki's (2006) model of administered pricing, all of which have appeared in this journal. Moreover, he ignores scores of other examples of excellent system dynamics practice that institutional economists would most likely find quite interesting such as:

- Lori Dauselsberg and Alex Outkin's (2005) work for Los Alamos National Laboratory (jointly undertaken with Sandia and Argonne National Laboratories) on the economic impacts arising from disruptions to the critical infrastructure of the United States.
- Tom Fiddaman's (2002) model of the economics of climate change.
- Andy Ford's (1999) models of economic/environmental issues and his work with Mike Bull (1989) on problems in the electric power industry.
- Jay Forrester's (1980b) national socioeconomic model.
- Roger Hall's (1976) model of the rise and fall of the old Saturday Evening Post.
- Luis Felipe Luna-Reyes and his colleagues' (2006) work on group model building via case studies.
- The Millennium Institute's many successes at helping to shape national development policies with its Threshold 21 model (e.g., Bassi 2007).
- Khalid Saeed's (1991) analysis of problems in developing countries.
Coupled with Hayden's clear failure to learn about the proper way to conduct a system dynamics study, his paper strikes us as an extremely ill conceived effort. In the future we urge him to take the time to learn the basics of system dynamics modeling before writing about it, and to circulate any papers in which he is critical of the field to experienced system dynamicists so that they can offer comments at the working paper stage.

**Conclusions**

Our analysis of Professor Gregory Hayden's objections to the use of system dynamics in institutional analysis has led us to conclude that they stem from both a misunderstanding of the details of proper system dynamics modeling and a failure to examine exemplary examples of system dynamics research. This is unfortunate because all of this information is publicly available and some of it has been published in the pages of this journal. We hope that our comments will help to set the record straight and will inspire other heterodox economists to consider using system dynamics, where appropriate, for institutional analysis.

**Notes**

1. By contrast, the behavior of a linear system is simply the sum of the behaviors of its parts. As such, a linear system can be broken down into its component pieces, the pieces can be studied in isolation, and the overall system behavior can be determined by aggregating the individual behaviors. See the discussion of the superposition property in Sterman (2000, 284) for more information on this topic.

2. This should not be confused with the notion of model super-sectors, sectors, and sub-sectors that although hierarchical, are merely conceptual tools for laying out the structure of a system dynamics model for an audience in an orderly fashion.

3. Jay Forrester (1980a, 14) likes to tell the story of a patent application he once submitted to the U.S. government, in which he described a hydraulic control device containing a positive feedback loop that worked to stabilize the system. The patent was initially rejected because the patent examiner did not believe a positive feedback process could add stability to a system. Of course, this was the characteristic that made the device innovative in the first place!

4. See for example Sterman (2000, Chapter 10) and Barnes, Gartland and Stack (2004).

5. Richardson originally did the research for this book as his Ph.D. dissertation at MIT. Jay Forrester supervised the dissertation.

6. For more detail on the cybernetic and servomechanism threads and their relationship to system dynamics see Radzicki (2009).

7. Actually, we agree with Hayden that cybernetics is not an appropriate methodology for institutional analysis. In fact, the focus in cybernetics on negative feedback processes and homeostasis is more consistent with orthodox economics because market-clearing behavior and equilibrium are both based on dominant negative feedback processes. The servomechanism perspective, on the other hand, in which dominant positive feedback loop behavior is common, is entirely consistent with institutional analysis. Increasing returns, path dependency, far-from-equilibrium phase transitions and the like (i.e., non-equilibrium, evolutionary, behaviors in which nonlinearities and limiting factors reign-in a system's behavior, not equilibrating forces) are processes driven by positive feedback. This is the type of feedback that economists such as Gunnar Myrdal were referring to when they wrote about "circular and cumulative causation."

8. Actually, Gill and Wolfenden (1998) later developed an "IDEaMaP" approach, which they argue is a superior knowledge elicitation process for system dynamics modeling.
9. Generally speaking, an open system is “dissipative” and a closed system is “Hamiltonian.” Systems of
the latter type do not exchange inputs and outputs with their environments. See Radzicki (1988b) for
some of the technical details surrounding dissipative and Hamiltonian systems.
10. An example of when a closed model may be appropriate is when a problem related to the evolution of
the universe is being studied in astrophysics.
11. See Sterman (2000, 323-347) for more on this model. Sterman extends it in several ways that
institutional economists should find interesting including the addition of learning curves, advertising
budgets, speculative demand, and various positive feedback processes associated with fads (e.g., the
social status of product ownership).
12. Both versions of the Bass model are available from the authors, in electronic form, ready to run on a
windows-based PC.
13. A classic example of a debate over where it was appropriate to set a model’s boundaries involves
Forrester’s (1969) Urban Dynamics model. This model was criticized for, among other things,
excluding the suburbs (i.e., the suburbs were the city’s environment - outside of the model’s
boundaries). In response to this criticism, the suburbs were added to revised versions of the model.
Surprisingly (to some) this expansion of the model’s boundaries did not lead to any policy
recommendations that were different from those generated by the original analysis (see Graham 1974;
and Schroeder 1975a and 1975b).
14. At the risk of stating the obvious, we are referring throughout this paper to instances of “proper
system dynamics modeling. It is unfair to use specific instances of improper system dynamics
modeling put forth by unskilled modelers (which typically means that they are untrained and/or
unexperienced) to criticize system dynamics in general. As in all fields of scholarly inquiry, instances of
improper practice occasionally make it through the refereeing process.
15. There is an extensive literature on model validity and building confidence in system dynamics models. See
especially Peterson (1975, Appendix B), Forrester and Senge (1980), Radzicki (1988a; 1990),
Barlas (1989; 1996), and Sterman (2000, Chapter 21).
16. An especially clever test for building confidence in system dynamics models is called a “reality check.” A
reality check is performed by a software tool that enables a system dynamicist to run tests on a
model that examines its robustness and conformity with the real world system. Reality checks have been
shown to uncover important problems with models that were very difficult to detect with
traditional methods. See Peterson and Eberlein (1994).
17. See for example the discussions in Forrester and Senge (1980), Saeed (1992) and Radzicki (2004).
18. Unfortunately, it is often necessary to fit models to historical time series data to convince policy
makers (or journal referees) to accept (and implement) model-generated results.
21. For a classic system dynamics modeling study of hog (and other commodity) production see Meadows
22. For a detailed analysis of the strengths and weaknesses of causal loop diagrams see Richardson (1986;
1997).
23. Instead of a plus and minus sign, many system dynamicists use an “S” and an “O” to designate “same”
and “opposite.”
24. An exception is when the dependent variable is a stock. See Sterman (2000, 139-141) for a discussion.

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Notes and Communications


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