Mr. Hamilton, Mr. Forrester and a Foundation for Evolutionary Economics

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In his seminal 1953 book, David Hamilton [1999 (1953)] argues that classical economics,[1] which first came of age during the intellectual revolution of Isaac Newton, is based on the notion of Newtonian change while institutional economics, which first came of age during the intellectual revolution of Charles Darwin, is based on the notion evolutionary change. Indeed, Hamilton makes the case that this difference in the way that economic change is conceptualized defines the fundamental difference between institutional and classical economics. Newtonian change is seen by Hamilton as taking place within a given social and economic structure while Darwinian or evolutionary change is viewed by Hamilton as occurring when there is an alteration of a society's social and economic structure itself.

The purposes of this paper are to:

- honor Hamilton's extraordinary contribution to the history of economic thought during the fiftieth anniversary year of its publication.
- extend Hamilton's basic idea to seven additional schools of economic thought that are based, to some degree, on an evolutionary view of change.
- argue that system dynamics computer simulation modeling, a methodology created by Jay W. Forrester,[2] can be profitably used to add value to the eight schools of economic thought that adhere to an evolutionary view of economic change.

Place Figure 1 About Here

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[1] Hamilton includes classical economics, neoclassical economics, Keynesian economics, and "all those in the mainstream of economic thought" [Hamilton (1999, p. 5)] under this heading.

[2] The first paper in the field of system dynamics is Forrester (1956) while the first book is Forrester (1961). The current "cutting-edge" book in the field is Sterman (2000).

Eight Schools of Evolutionary Economic Thought

In the more then 225 years since Adam Smith first published the Wealth of Nations, economic thinking has evolved into a tree with many branches. Some of these branches lie close together and are interconnected while others have grown apart and, arguably, have very little in common. Figure 1 presents a selected genealogy of economic thought and economic thinkers from Francois Quesnay and the Physiocrats to the present day.[3] It maps out the intellectual lineage leading to eight schools of economic thought that are based, to some degree, on the notion of evolutionary economic change, and the routes leading to several prominent schools of economic thought that are based on a Newtonian view of economic change.[4] The schools that adhere to an evolutionary view of change are shown in the ovals in Figure 1 and include institutional economics, Post Keynesian economics, ecological economics, agent-based computational economics, behavioral economics, Austrian economics, radical political economics, and evolutionary economics. These are the schools that can benefit from David Hamilton's ideas and from the incorporation of system dynamics modeling into their paradigms.

By way of contrast, the schools presented in Figure 1 that adhere to a Newtonian view of change include supply side economics, the Chicago school, new classical economics, traditional (American) Keynesian economics, and new Keynesian economics. For methodological reasons it is unlikely that economists working within these schools would find system dynamics to be a useful tool for economic modeling.

Although a complete justification for each entry in Figure 1 is beyond the scope of this paper, a general interpretation of the figure's structure is as follows. Time unfolds from the top of the figure to the bottom while the Newtonian schools of economic thought lie to the bottom left and the evolutionary schools of economic thought lie to the bottom right. Additionally, the schools of thought that are more laissez faire-oriented and that rely most on deductive logic and the assumption of homo economicus in their paradigms lie farther to the bottom left of the

[3] This figure should in no way be thought of as a complete mapping of all prominent economists and schools of economic thought from Quesnay to the present. Instead, its very limited purpose is to suggest several representative routes leading to a set of modern-day Darwinian, and a set of modern day Newtonian, schools of economic thought.

[4] Each of these schools of economic thought or, in Kuhnian terms [Kuhn (1962)] "invisible colleges," is defined by a shared set of beliefs about how "proper" economic analysis is to be conducted. Many of these schools are also defined by a professional society, a professional journal(s), an internet discussion network, and an annual conference.

figure, while the schools of thought that are more oriented toward government participation in the economy and that generally rely on inductive logic and the concept of hetro economicus in their paradigms lie farther to the bottom right of the figure. Lastly, schools of thought that are seen as complementing one another are joined by links with arrowheads pointing in both directions. These links are included because it is quite common for hetrodox economists to hold memberships in, publish in the journals of, and attend the conferences hosted by, one or more schools of thought that are based on an evolutionary view of economic change.

Institutional Economics

In his book, David Hamilton [1999 (1953)] makes a compelling case that institutional economics separates itself from classical economics primarily via its evolutionary view of economic change. Drawing heavily from the work of Veblen, Ayers, and other prominent institutionalists of the twentieth century, he makes the case that human nature is active and goal-seeking and that humans act in culturally conditioned ways -- i.e., their actions are learned. According to Hamilton, cultural conditioning includes both ceremonial aspects of behavior (i.e., behavior based on influences such as custom, habit, myth and legend) and technological aspects of behavior (i.e., learned behavior based on facts). Moreover, he emphasizes that humans both act upon, and are acted upon by, their culture in a never-ending process of circular and cumulative causation. The result is an on-going evolutionary process with no predictable path or predetermined end.

Lineage. In Figure 1, the intellectual lineage leading to the present-day school of institutional economics begins with Quesnay and Smith and follows two principal routes. The first runs through Ricardo and Marx and then through the "American institutionalists" Veblen, Commons, and Mitchell. The last link in this route passes through Clarence Ayres, Galbraith, and Myrdal. The second or "thermodynamics/general systems" route runs through Ricardo and Marx, passes through Schumpeter (1976), and links with Boulding (1970, 1978, 1991), Georgescu-Roegen (1971), and Robert Ayres (1978). This route has also been influenced by the cybernetics of Norbert Wiener (1948). Figure 1 also shows, via two-way arrows, four schools of thought that directly complement institutional economics: Post Keynesian economics, behavioral economics, ecological economics, and evolutionary economics. An argument can be made, however, that a two-way arrow between agent-based computational economics and institutional economics should be included as well.

Links to System Dynamics. In a series of papers, Radzicki (1988, 1990a, 1990b), Radzicki and Seville (1993), and Radzicki and Sterman (1994) outline the similarities between system dynamics modeling and institutional economic analysis and propose a synthesis that would yield a method of evolutionary economic analysis that is superior to either of them in isolation.[5] Since the details of this "institutional dynamics" approach have been laid out in these papers, they will not be repeated here.

Post Keynesian Economics

For the past thirty years or more Post Keynesian economists have tried to precisely define the characteristics of their school of economic thought and demonstrate how it differs from, and is more useful than, much of traditional economics. Post Keynesian authors who have done a particularly good job in this area include: Eichner and Kregel (1975), Eichner (1979a, 1987), Davidson (1981, 1991, 1994), Lavoie (1992), Arestis (1992, 1996), and Holt and Pressman (2002).

According to Arestis (1992, pp. 88-89), Post Keynesian economics is based on the following five propositions:[6]

1. Economies expand over time in the context of history.
2. In a world where uncertainty is unavoidable, expectations have a significant effect on economic activity (particularly on investment spending).
3. Economic institutions (particularly oligopolistic mega-corps) and political institutions play a significant role in shaping economic events.
4. Realism in economic analysis is important.
5. Capitalism creates class-divided societies.

According to Eichner (1987) the primary goals of Post Keynesian analysis are to explain the:

1. uneven growth rate of an economy or why it deviates from its long-term secular growth path.[7]
2. difference in growth rates between economies.

To try and reach these two lofty, but crucial, goals Post Keynesian economists have developed a corpus of theory and a catalog of models, both mathematical and nonmathematical, that:

1. utilize a systems approach.[8]

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[5] Building on this work, Harvey (1994) utilizes some system dynamics tools to analyze the Veblenian dichotomy in Keynes' General Theory.

[6] See also Davidson (1981) and Sawyer (1989).

[7] In other words, one of the goals is to explain the interaction between the trend and the cycle in an economy. See Deprez and Milberg (1990).

2. represent the behavior of an economic system in a state of disequilibrium.
3. utilize a "comparative dynamics" approach that shows how the expansion of one economic system is affected over historical time relative to another by differences in specific variables.
4. attempt to represent the behavior of economic agents as it actually is (i.e., bounded or procedural rational) rather than as it might be in an idealized state (i.e., globally rational).[9]
5. are based on the notion that the distribution of income between the rich and the poor is crucial to determining time path of economy and should thus not be ignored or treated as a residual of economic activity.
6. present a clear relationship between macroeconomic theory and macroeconomic data.
7. explain macro behavior as resulting from micro structure and thus successfully unify macroeconomics and microeconomics.

Lineage. Figure 1 presents one direct route and two main "directions of flow," each incorporating several routes, that lead to the modern Post Keynesian school of economics. The direct route simply runs from Quesnay and Marx to Leontieff and then to the Post Keynesian school because input-output analysis is frequently used by Post Keynesian economists. On the other hand, the first main direction of flow runs through the Cambridge Post Keynesians (e.g., Robinson, Kaldor, Passinetti) and the founders of American Post Keynesian school (e.g., Weintraub, Davidson, Eichner, Minsky). This direction is traversed by way of Quesnay, Marx, and Kalecki or via Smith, Malthus, Keynes, Harrod, and Domar. The second main direction of flow runs through those economists who pioneered the "engineering systems" approach to economics such as Tustin (1953), Phillips (1950, 1954,

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[8] For example, Eichner (1979b) uses an engineering systems approach to produce a Post Keynesian short-period model. In it he utilizes engineering block diagrams (p. 47 and pp. 49-50), feedback loops (p. 43), and dynamic lags (pp. 45-46). He also talks of the model being somewhat like an electrical circuit. Similarly, Arestis (1992, pp. 110-114) presents a dynamic Post Keynesian macroeconomic model loaded with feedback loops and dynamic lags.

[9] See Lavoie (1994) and Earl (1989, 1990). Although Post Keynesian models often employ the concept of bounded rationality, they typically employ the concept of a single, homogenous, bounded rational “representative agent” and are built using a “top-down” construction. This is in stark contrast to agent-based computational modeling where a multitude of bounded rational, heterogeneous, economic agents interact with one another and the behavior of the system thus emerges from the bottom-up.

1957), Allen (1955), Goodwin,[10] and Leijonhufvud (1968).[11] This direction is traversed via: (1) Keynes directly, (2) early Keynesian business cycle theorists such as Harrod, Hicks and Samuelson, (3) Hayek, because Post Keynesians such as Kaldor had their thinking influenced to some degree by Austrian economics, and (4) Schumpeter, because Goodwin both taught, and was taught by, Schumpeter [see Goodwin (1993, p. 305)].

Figure 1 also presents four schools of economic thought that directly complement Post Keynesian economics: institutional economics, behavioral economics, evolutionary economics, and radical political economics. Among these schools, the one that appears to be most in harmony with Post Keynesian economics is institutional economics. Indeed, many Post Keynesian economists are so comfortable with institutional economics that they refer to themselves as "Post Keynesian Institutionalists" or "neoinstitutionalists."[12]

Links to System Dynamics. System dynamics is well suited for Post Keynesian economic analysis. It is a dynamic, disequilibrium approach to modeling complex systems that portrays human behavior and micro-level decision making as it actually is (i.e., bounded or procedural rational; goal seeking), rather than it might be in an idealized state.[13] To a system dynamicist, the macro behavior of a system is due to its micro structure.

Unlike much of Post Keynesian economics, however, system dynamics has a well-developed theory of the dynamic behavior of socioeconomic systems that draws from the fields of behavioral decision theory, psychology,

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[10] For an overview of Goodwin's life and work see Harcourt (1985).

[11] For more details about Leijonhufvud's relationship to Post Keynesian economics see Cottrell (1990). For more on Leijonhufuvd's engineering systems approach to economics see Cochrane and Graham (1976) and Aoki and Leijonhufvud (1976).

[12] Forstater (2001) argues that aspects of <u>both</u> the Post Keynesian and institutionalist traditions are <u>necessary</u> for a more comprehensive approach to economic policy than either tradition can offer in isolation. Similar ideas are offered by: Harvey (1994), Lawson (1994), Kregel (1990), Hodgson (1989), Wilber and Jameson (1983), and Eichner (1979a). For a discussion of the similarities and <u>differences</u> between the American institutionalists and the Post Keynesians see Gruchy (1987, pp. 147-150).

[13] For discussions about the use of bounded rational decision making in system dynamics models see Morecroft (1985, 1983) and Sterman (2000, 1988). Although many system dynamics models utilize a single (or small number of), bounded rational, represenative agent(s) and a "top-down" construction, this approach is by no means mandatory.

control theory, organizational behavior, and management science, and a very intuitive set of modeling tools and techniques that are used to capture the dynamic behavior of complex systems. Although, in the past, system dynamics has been used to model macroeconomic systems,[14] it has almost never been used to portray an economy from a Post Keynesian point of view,[15] or to study the role of the distribution of income in determining macroeconomic behavior.[16] As a result, it appears that there is great potential for insightful and creative work arising from the application of system dynamics modeling to Post Keynesian economics.

Ecological Economics

The field of ecological economics can trace its intellectual roots to the material value theories advocated by the Physiocrats and by classical economists such as Thomas Malthus [Bradley (1995, p.4)]. The Physiocrats believed that only agricultural production yields a surplus or net product and that the wealth of a nation is determined by the size of its net product. Moreover, they believed that a nation's economy entered a "natural state" when the flows between its various sectors (agricultural, industrial, and commercial) were in balance. To the Physiocrats, the net product associated with an economy's natural state was the maximum net product that was sustainable over the long-run. They represented this "natural" state of affairs via Quesnay's famous Tableau Economique. The Tableau, of course, is one of the intellectual forerunners of Wassily Leontieff's input-output analysis.

Modern ecological economics is concerned with the problems that arise from the interaction of economic and ecological systems such as sustainability, the distribution of wealth, global warming, acid rain, and species extinction [Costanza (1998, p. 1)]. Costanza (1998, pp. 2-3) argues that the fundamental question underlying all of ecological economics is whether or not the supply of ecological factors, such as the finite sources of individual resources in the world and the finite sinks for waste in the world, will ultimately limit economic activity (activity that is growing exponentially and represents the demands on the ecological factors).[17] If human innovation and

[14] Some examples would be Mass (1975), Forrester (1979), Sterman (1982), and Harvey (2002).

[15] Notable exceptions are Saeed and Radzicki (1993, 1994), which are early attempts at creating Post Keynesian macrodynamic models with system dynamics.

[16] A notable exception is Saeed (1988), who presents a system dynamics model in which the distribution of income over time significantly influences, and is influenced by, the behavior of a developing economy.

[17] Georgescu-Roegen (1971) argues that the second law of thermodynamics guarantees that economic systems have limits to growth [see also Mayumi (2002)]. Khalil (1990) provides a similar, but different, view.

advancements in technology can keep pushing out a system's limits to growth (without creating significant new problems), ecological and economic disaster can be avoided. If they cannot, problems (most probably on a global scale) will result.

Ecological economists employ holistic (i.e., systems) and interdisciplinary approaches to problem solving [Bradley (1995, p. 4)]. They recognize that both ecosystems and socioeconomic systems are constantly evolving and that solutions to problems created by their interaction must be based an evolutionary perspective [Bradley (1995, p. 3)]. They also recognize that an economy is part of a larger social system and that humans are motivated by social factors that go beyond those laid out in neoclassical economics. As a result, they search for solutions to problems that take into account the social structures and processes that are vital for human health and survival [Bradley (1995, p. 12)].

Lineage. In Figure 1, the intellectual lineage leading to the present-day school of ecological economics begins with Quesnay and Smith and follows three principal routes. The first runs through Malthus and then directly to Costanza and Daly (1992). The second runs through Quesnay and then through Leontieff. The third runs through Ricardo and Marx and then passes through Schumpeter. In terms of complementary schools of thought, both evolutionary economics and institutional economics are linked to ecological economics with a two-way arrow. An argument can be made, however, that a two-way arrow between ecological economics and agent-based computational economics should be added because the emergence and evolution of social structures such as property rights and environmental valuations and norms, that are crucial to avoiding “tragedy of the commons” and other non-sustainable dynamics, can be identified and studied.

Links to System Dynamics. System dynamics was first used for ecological economic analysis during the world modeling projects of the early 1970s [Forrester (1970), Meadows et al. (1972; 1992), Costanza (1989, p. 3)]. Today, it is regarded as a legitimate ecological economics modeling technique because its fundamental principles for socio-environmental-economic problem solving are the same as those adhered to by many ecological economists. More specifically, these principles are that a dynamic systems (feedback) approach should be applied to ecological economic problems, long-run/short-run trade-offs and significant delays should always be taken into account when examining the dynamics of an ecological-economic system, and most importantly, the ways in which limiting factors significantly influence an ecological-economic system's behavior must be taken into account. Other, more recent, uses of system dynamics in ecological economics include: Ford (1999), Ruth (1995), Jørgensen (1994), Maxwell and Costanza (1994), Bergh, and Straaten (1994), Bergh (1993), Costanza and Daly (1992), and Bergh and Nijkamp (1991).

Agent-Based Computational Economics

Agent-based computational economics is the application of complexity theory, the complex adaptive behavior paradigm, and the tools of "artificial life" or "artificial worlds" to economic problems.[18] It can be thought of as a blending of concepts and tools from evolutionary economics, cognitive science, and computer science [Tesfatsion (2000, p. 2)]. Potts (2000) lays out an elegant and sophisticated argument that agent-based computational economics represents the foundation of a new evolutionary microeconomics that can unite economists from many different schools of hetrodox economic thought.[19]

The goals of agent-based computational economics are to determine how complex disequilibrium behaviors and complex macro socioeconomic structures emerge and evolve from the very simple (and bounded rational) interactions among individual heterogeneous economic agents (a system's micro-structure), and from the interactions between these agents and the emerging macro-structure. More specifically, the goals are to (1) understand how global regularities such as trade networks, socially accepted monies, market protocols, business cycles, and the common adoption of technological innovations emerge, "bottom-up," from the local interactions of autonomous individuals, despite the absence of any top-down planning and control, and to (2) determine which alternative socioeconomic structures can be examined to determine their effects on individual behavior and social welfare [Tesfatsion (2001b)].

According to Lane (1993), any agent-based computational economic model has three main components: (1) a set of autonomous micro-level economic agents, (2) an environment within which the agents interact, and (3) a dynamic that specifies the rules of adaptive behavior for the agents. An agent-based modeler must specify an initial set of attributes for each agent that includes type characteristics, internalized behavioral norms, internal modes of behavior (including modes of communication, learning, and adaptation), and the amount and type of internally stored information about itself and other agents it is allowed to possess [Tesfatsion (2002, p. 56)]. The modeler must also specify the types of interaction (normally nonlinear) each agent can have with other agents and the environment.

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[18] See Tesfatsion (2001a, p. 1) and Tesfatsion's web site on agent-based computational modeling at: http://www.econ.iastate/tesfatsi/ace.htm.

[19] Physicist Stephen Wolfram (2002) argues that a particular type of agent-based modeling, cellular automata, represents a new paradigm in science that can be used to explain the evolution of a large portion of the world.

A key area of research within agent-based computational economics involves finding the best way to model the process by which individual agents learn and adapt. According to Tesfatsion (2002, p. 58), current techniques for modeling agent learning include: reinforcement learning algorithms, neural networks, Q-learning, genetic algorithms, genetic programming, "a variety of evolutionary algorithms that attempt to capture aspects of inductive learning," and algorithms that have been adapted for use in automated markets. Techniques that are used to represent the evolution of individual agents' learning methods (i.e., techniques that allow individual agents to "learn how to learn") include: classifier systems, adaptive toolkits, and evolvable neural networks.

When an agent-based computational model is simulated its initial conditions and dynamic produce a "history" or "time ordered sequence of states of the [artificial] world" [Lane (1993, p. 90)]. The question is "whether, and under what conditions, histories exhibit interesting emergent properties" (ibid.). Essentially, emergence is said to occur when patterns, including organized groups and hierarchies, arise at the macro level (i.e., at the level of the system as a whole) that are not derivable from an analysis of the capabilities of the individual agents (i.e., from analyses at the micro level).

Most agent-based histories are disequilibrium behaviors because the ways in which the individual agents interact locally (i.e., with the agents they encounter during the simulation) are continually recombined and revised. This leads to the continuous creation of niches that can be exploited by particular adaptations, which in turn lead to the creation of even newer exploitable niches, in a self-reinforcing sequence of "perpetual novelty" [Arthur et al. (1997, p. 4)].

Lineage. In Figure 1, there are several routes that lead to the present-day school of agent-based computational economics. The main route runs from John von Neumann and his work on self-replicating machines during the nineteen forties directly to the agent-based school; via John Nash and then Thomas Schelling [due to Schelling's (1978) path-breaking agent-based work on the emergence of racially segregated neighborhoods]; or via some of von Neumann's present-day followers such as John Holland [Holland and Miller (1991)], Stuart Koffman, John Miller (1998), W. Brian Arthur (1993, 1994), and Christopher Langton (1989).[20] Leigh Tesfatsion (1997, 2000, 2001a, 2001b, 2002), Robert Axtell, Joshua Epstein, Robert Axelrod and David

[20] Tesfatsion (1997) notes that Langton (1989) is responsible for establishing agent-based modeling as a distinct area of modern scholarly inquiry because he hosted the first artificial life conference at the Los Alamos National Laboratory during the late nineteen eighties.

Lane (1993) would also be legitimately included in this group. Most of these modern day researchers have ties to the Santa Fe Institute, an organization specializing in the study of complex systems.[21]

One of the leaders of the Sante Fe Institute, W. Brian Arthur (1988, 1990), has written extensively about being influenced by economists who emphasized the importance of positive feedback loops, increasing returns, and path dependency, in explaining evolutionary economic behavior. As a result, in Figure 1 links to Arthur run from Nicholas Kaldor (1981), Gunnar Myrdal, Paul David (1985), and Ilya Progogine (1993).

Links to System Dynamics. In a recent paper, Scholl (2001) outlined the strengths and weaknesses of both system dynamics modeling and agent-based computational simulation modeling, and identified the places where the techniques overlap and where they complement one another. His conclusion was that cross study and joint research between the two modeling traditions is long overdue.

The main difference between system dynamics and agent-based modeling is typically in the level of aggregation utilized by the researcher. Agent-based modelers start by specifying a set of heterogeneous decision rules for a relatively large number of individual agents that interact at the agent level, while system dynamicists usually start by specifying the decision rules for a relatively small number of aggregate or representative agents that interact via the system's overall feedback structure. Although an agent-based modeler knows the decision rules of the individual agents at the start of a simulation, he/she does not know the type of behavior that will emerge at the aggregate level as the system evolves. On the other hand, a system dynamicist typically knows the aggregate, system-wide, behavior that his/her model should generate at the start of a simulation, but does not know whether the decision rules he/she has given to the various representative agents in the model will generate this behavior.[22] As Scholl (2001) points out, agent-based modeling is thus the relatively weaker technique when a system's aggregate behavior is known and the object of the investigation, while system dynamics is the relatively weaker technique when the decision rules of the agents are known and the implications of the interactions of a large number of agents is the object of the investigation.

Scholl (2001) suggests that a good way to begin the cross study of system dynamics and agent-based modeling is by carefully analyzing models of the same phenomena created by each of the techniques. Sterman

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[21] http://www.santafe.edu/

[22] At times, a system dynamicist does not know the aggregate, system-wide, behavior that his/her model should generate at the start of a simulation, nor what type of behavior will emerge from his/her model. For an example of this, see the evolutionary system dynamics model presented below.

(2000, p. 896), on the other hand, acknowledges the similarities and differences between the two modeling traditions and poses several questions that are designed to advance the state of the art in both fields:

1. What principles should guide the choice of modeling method and level of aggregation?
2. How should modelers trade off the number of different agents they can represent in the model against the complexity of the individual agents?
3. What rules of interaction, level of rationality, and learning capabilities should be ascribed to the agents?

A very different way of combining system dynamics and agent-based modeling has been pioneered by John Miller (1998). In a 1998 paper he showed how hill climbing algorithms, and genetic algorithms that use the "genetic operators of crossover and mutation," can be used to run **A**utomated **N**onlinear **T**ests (ANTS) on system dynamics models [Scholl (1999, p. 7)]. These tests consist of computer searches over parameter sets from a system dynamics model that are aimed at maximizing or minimizing an objective function (e.g., maximizing an objective function defining product attractiveness or social welfare). As Sterman (2000, p. 887) notes, ANTS are very flexible tools that can be used to detect sensitive parameters and anomalous behaviors, find leverage points, and determine policy sensitivities, in system dynamics models.

<u>Behavioral Economics</u>

Behavioral economics involves the study of the ways in which human beings actually make their economic decisions. It combines insights, theory, and methods from economics and psychology to identify how actual human decision-making systematically deviates from the globally rational decision-making assumed in classical economic theory (e.g., profit and expected utility maximizing behavior), and to explain how this less-than-optimal decision-making is responsible for observable economic outcomes. Although many studies in behavioral economics are static and thus look at a single decision made by economic agents at a single point in time, increasingly they are evolutionary and examine a series of decisions made by economic agents over time. Of interest in studies of dynamic decision-making is how the economic agents' decisions are influenced through learning and adaptation.[23]

According to Mullainathan and Thaler (2000, p. 1), behavioral economists have identified three main factors that cause human decision-making to deviate from global rationality:

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[23] Some behavioral economists are turning to evolutionary psychology for insights into the learning and adaptation processes used by human decision makers. See Cosmides and Tooby (1994).

1. **bounded rationality**, which reflects the limited cognitive abilities and knowledge that constrain human problem solving.
2. **bounded willpower**, which explains why people sometimes make choices that are not in their long-run interest.
3. **bounded self-interest**, which explains why humans are often willing to sacrifice their own interests to help others.

Although burdened by their cognitive limitations, people (of course) still have to make economic decisions. Behavioral economists believe that human decision makers "satisfice" -- i.e., they do the best they can to achieve their goals by using simple rules and techniques to help them cope with complexity. Many of the most commonly used rules and techniques have been identified and cataloged by behavioral economists [see Kahneman and Tversky (1974)]. Unfortunately, the use of these rules and techniques often causes people to make poor economic decisions [Mullainathan and Thaler (2000)].

An important question first raised by Alchian (1950)[24] is whether or not some combination of market forces, learning, and evolution can make human cognitive limitations irrelevant.[25] In other words, if through an imperfect, adaptive, evolutionary process the firms and households that survive and prosper are those who have acted as if they had made their decisions rationally, the process by which they survived and prospered is irrelevant and the classical economic models are valid.[26] Behavioral economists reject this argument because the empirical evidence is overwhelming that non-rational agents survive and influence economic outcomes [Kahneman and Tversky (1974), Earl (1990), Rabin (1998), Mullainathan and Thaler (2000)].

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[24] See also Krugman (1996).

[25] Weibull (1997, p. 3) argues that evolution potentially closes the open-endedness of bounded rationality because it determines which bounded rational behaviors survive and prosper.

[26] An excellent example of this is provided by Rust (1987). According to Arthur (2000, p. 1), Rust examined the decision making of Harold Zurcher, the superintendent of maintenance at the Madison, Wisconsin Metropolitan Bus Company. Zurcher's job was to schedule the replacement of engines for the city's fleet of buses in such as way as to minimize maintenance costs and minimize unexpected engine failures. Rust then used stochastic dynamic programming to find an optimal solution to Zurcher's problem. When he compared his results to Zurcher's actual behavior, he found a fairly close fit.

Lineage. In Figure 1, the intellectual lineage leading to the present-day school of behavioral economics begins with Quesnay, Smith, and Ricardo and follows three principal routes. The first runs through Marx, to Dobb, Baran, Sweezy and Mandel, and then through some more modern-day radical political economists such as Sherman, Weiskopf, Bowles [Bowles, Ginits and Osborne (2001)], Foley (1997), and Marglin (1984). The second runs through Marx and then through Schumpeter, passes through Richard Day (1975) [see also Day and Eliasson (1986) and Day and Chen (1993)], and then through George Akerlof, Richard Thayler, and Robert Frank. The third runs through Veblen, Commons and Mitchell and then through Duesenberry and Simon (1957, 1979, 1984). It continues directly through Ackerlof, Thayler and Frank and also takes a side branch through Cyert and March (1963). This last route emphasizes the contributions to behavioral economics of the "Carnegie School" and the work of Herbert Simon. Indeed, Simon is considered to be the father of the field and frequently wrote that his thinking on bounded rationality was influenced by the work of John Commons [e.g., Simon (1979, p. 499; 1991, p. 87)].

Links to System Dynamics. Simply put, system dynamics modeling <u>is</u> behavioral economic modeling. Morecroft (1983, 1985) has spent considerable effort making this case while numerous studies by Sterman [e.g., Sterman (1989), Paich and Sterman (1993), Diehl and Sterman (1995), Kampmann and Sterman (1998)] have used system dynamics models to examine the effects of bounded rationality on dynamic economic decision making.

<u>Austrian Economics</u>

According to Kirzner (1987, p. 149), the term "Austrian economics" means different things to different economists. His list of contemporary interpretations of the term includes: (1) a school of economic thought that existed in Europe up until the 1930s, (2) a particular form of capital-and-interest theory, (3) libertarian ideology, (4) the work of Carl Menger, and (5) a body of theory that emphasizes the importance of uncertainty in economic decision making and thus a rejection of neoclassical economics. Kirzner (1987, p. 150) goes on to point out that the last interpretation of Austrian economics implies that the members of this school are sympathetic to historical and institutional approaches to economic analysis, which is considered by some economists to be "ironic or even paradoxical" given the original opposition of the Austrians to the German historical school.

A more specific list of the characteristics of the Austrian school can be found on the History of Economic Thought web site hosted by the Department of Economics at the New School University (2002). This list includes:

1. reliance on a "subjectivist" (hermeneutic) strain of marginalist economics.
2. dedication to pure theory, with an emphasis on "methodological individualism."

3. adherence to a theory of alternative cost which reduces all goods and factors, by "imputation," to the subjective valuation of consumer goods.
4. the adoption of a monetary over-investment theory of the business cycle.
5. support for anti-cyclical monetary policy and a free banking system.
6. a general political, economic and philosophical defense of laissez-faire economic policy.
7. the adoption of a time-theoretic approach to economic theory.
8. a belief that the markets are time consuming, disorganized, competitive processes driven by the learning and discovery of specific actors operating in a state of disequilibrium, rather than merely existing as an array of anonymous equilibrium positions.
9. an emphasis on uncertainty and information in economic decision making.
10. a concern with the psychology of economic actors, in particular, the supremacy of strategic, self-interested behavior when facing other agents and/or political and social institutions.
11. a belief in the importance of competitive markets and a price system in organizing a decentralized morass of economic agents with limited knowledge into a harmonious order.

To this list can be added:

12. a mistrust of the use of mathematics for economic analysis.
13. a vision of the entrepreneur as the driving force behind economic activity.

Of particular importance to Hamilton's concept of Darwinian change are characteristics 7–11, as they imply an evolutionary approach to economic analysis.

Lineage. In Figure 1, the intellectual lineage leading to the present-day school of Austrian economics begins with Quesnay, Smith and Ricardo and works its way to Carl Menger via Say and Mill. This route continues via Menger's most prominent disciples Böhm-Bawerk and Wieser to Mises and then to his student Hayek.[27] From Hayek, the route extends to the more modern-day Austrians such as Israel Kirzner (1987, 1997) and Murray Rothbard and finally to the school itself. A two-way arrow is shown between the Austrians and agent-based computational economics because many of Mises' and Hayek's beliefs are in harmony with central tenets of

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[27] Böhm-Bawerk taught both Mises and Schumpter. In addition to Hayek, Mises taught Oskar Morgenstern, Gotfried Haberler and Fritz Machlup. Hayek's monetary over-investment theory of the business cycle was significantly shaped by Wicksell [see New School University (2002)].

agent-based modeling. Indeed, Vriend (2002) lays out a strong case that Hayek was essentially an agent-based computational economist.

Caveat. Although the Austrian school has some clear evolutionary elements in its body of theory, it is somewhat hard to classify in Figure 1. More specifically, its focus on individual behavior, the entrepreneur, the efficiency of market processes, and the creation of policy through logic and theory, suggests that it should lie to the bottom left of the figure (where it is, in fact, positioned). On the other hand, its nonequilibrium (evolutionary) market process theory and its focus on dynamic decision making suggest that it should reside more to the bottom right of the figure. Since, as mentioned above, economists sometimes have trouble even agreeing on a definition for the Austrian school, this observation will merely be noted for the record.

Links to System Dynamics. Although, to date, system dynamics has not been used for Austrian analysis, this does not mean that it cannot add value to it. As will be discussed below, system dynamics modeling involves, among other things, mapping out the mental model of a decision maker so that the computer can trace out its dynamic implications. This is necessary because, due to cognitive limitations, humans are unable to accurately think through the evolution of their own mental models. Because Austrian economists reject (traditional) mathematical modeling and instead rely on logic for their analyses, system dynamics can, in principle, be used to trace out the evolutionary implications of their theories. Following Vriend (2002), the same thing can be said for agent-based computational modeling.

Radical Political Economics

In her essay on radical political economy in the New Palgrave Diane Flaherty (1987, p. 36), paraphrasing Bronfenbrenner (1970, p. 747), notes that there is "no simple generalization that can characterize the diverse and at times inconsistent principles and theories that comprise radical economics" and that "it is easier to establish what radical economists do than what radical economics is." With this caveat, however, she pushes forward and argues that radical political economists are united by their concern over the persistence of imperialism and inequality (which generates class conflict), and in the belief that traditional economics either cannot, or will not, provide solutions to these problems.

Much of radical economic theory has been directed toward reformulating classical Marxian analysis in an effort to explain and overcome modern imperialism and class conflict. Three areas in which the reformulation is most active are: (1) the labor theory of value, (2) the causes of crises in capitalist economies, and (3) the appropriateness of Keynesian and Sraffian analysis to radical political economics [Flaherty (1987, p. 36)].

Labor Theory of Value. The literature on the labor theory of value is vast and ranges from alterations that attempt to preserve the flavor of Marx's original theory while simultaneously explaining stylized facts observed in modern economies [e.g., Morishima (1973) and Shaikh (1977)], to its complete removal from radical theory, while simultaneously preserving class analysis [e.g., Lange (1935), Robinson (1942), and Steedman (1977)].

Crises Theories.[28] Reformulations in crisis theories range from those that focus on monopoly capitalism, its mark-up pricing power and imperialistic behavior, and the subsequent crises that arise from the increases in surplus value it generates [e.g., Baran and Sweezy (1966)], to those that see crises as being caused by fragile financial institutions [e.g., Foley (1982)], or those that define crises as downturns in the economic long wave or Kondratiev cycle [New School University (2002)]. The latter crisis theories blame long wave downturns on factors such as the dynamics of profit and accumulation rates [e.g., Mandel (1969, 1980)] or the evolution of "social structures of accumulation" [e.g., Bowles, Gordon, and Weisskopf (1983)].

Integrating Keynesian and Sraffian Theory. The debate over the place for Keynesian and Sraffian theory in radical analysis is actually a struggle over the irreducible core of radical political economics [Flaherty (1987, p. 38)]. Those radical economists who favor a synthesis between Marx and Sraffa or Marx and Keynes see the core as consisting of class exploitation and the evolving historical relationship between those who produce and those who appropriate surplus. This view, however, is not dependent upon the labor theory of value and, in fact, some radicals [e.g., Steedman (1977)] believe that the labor theory of value can be subsumed into Sraffa's neo-Ricardian system. Those radicals who favor a synthesis between Marx and Keynes belief that traditional Marxian theory does not include a consistent theory of effective demand. Economists such as Marglin (1984) therefore have incorporated Keynesian demand principles into reformulated Marxist models [Flaherty (1987)].

From its origins in anti-Hegelian dialectics to its modern-day ventures into agent-based computational modeling [see Bowles, Gintis and Osborne (2001) and Foley (1997)], radical political economic methodology has clearly been historical and evolutionary in nature. In fact, due to Marx's influence, radical political economy may very well be the intellectual home of Darwinian economic change [see Hodgson (1993, 1994)].[29]

Lineage. In Figure 1, the intellectual lineage leading to the present-day school of radical political economics begins with Quesnay and Smith and follows two principle directions of flow. The first runs through Marx, the older generation of western radical economists such as Dobb, Baran, Sweezy and Mandel, and finally through the

[28] For an overview of Marxian crisis theories see Shaikh (1978).

[29] For a system dynamics view of Marx and his dialectic process see Richardson (1991, pp. 71-73).

younger generation of western radical economists such as Howard Sherman, Weisskopf, Bowles, Gintis, Melissa Osborn, and Duncan Foley. The second principle direction of flow runs through Sraffa and the neo-Ricardians. It consists of several distinct routes including a Leontieff route, a Kalecki route, and a route that passes through Mrs. Robinson. Two-way arrows indicating complementary schools of thought run between radical political economics and evolutionary economics, Post Keynesian economics, and agent-based computational economics. A two-way arrow should probably be placed between institutional economics and radical political economics, even though their respective theories of evolutionary behavior are significantly different [see Dugger and Sherman (1997)].

Links to System Dynamics. In addition to a shared focus on evolutionary change, an obvious link between system dynamics and radical political economics is the economic long wave or Kondratieff cycle. The system dynamics national model generates, among other behavior modes, a 40-60 year macroeconomic cycle or long wave [Forrester (1979)]. This cycle occurs primarily because of self-ordering in the capital sector of the model economy. More specifically, both the goods sector and the capital sector must order plant and equipment from the model's capital sector. This results in a self-reinforcing process in which capital is used to produce more capital. The result is a period of enormous overbuilding of capacity in the system followed by a long period of depreciation and reduced accumulation of capital. The cycle repeats when the model economy's stock of plant and equipment falls below its desired level and capacity constraints begin to hinder production.

Evolutionary Economics

In this paper, the evolutionary economics school is considered to be a "catch-all" that includes any economists doing work considered "evolutionary" that does not explicitly fit into one the seven other evolutionary categories. Examples of economists who fit into this group include (but are not limited to) those who analyze evolutionary economic dynamics via historical essays and data analyses [e.g., Schumpeter [1976 (1942)], Boulding (1970, 1978), David (1985), Rostow (1990, pp. 428-441)], neo-Schumpeterian economists who use a variety of techniques to model structural economic change [e.g., Iwai (1984a, 1984b), Hanusch (1988)], thermodynamic economists who view evolution as a "far from equilibrium" phenomenon [e.g., Allen (1988), Prigogine (1993), England (1994)] or as a "transition to thermodynamic equilibrium" phenomenon [e.g., Georgescu-Roegen (1971), Ayres (1978)], and those who try to apply "punctuated equilibrium" theories from biology to economic problems [e.g., Tushman and Romanelli (1985), Sastry (1997)].

Lineage. In Figure 1, the intellectual lineage leading to the present-day school of evolutionary economics begins with Quesnay and Smith and follows several routes. The first runs through both Marx and Schumpeter and then through economic historians such as David (1985) and Rostow (1990). The second runs through Schumpeter and the neo-Schumpeterians such as Nelson (1995), Winter (1964), Witt (1992, 1993), Iawi (1984a, 1984b), Eliasson, Silverberg (1988), and Dosi [and Nelson (1994)]. The third runs through Schumpeter and then the far-from-equilibrium thermodynamicists [Prigogine (1993), Nicolis, Allen (1988)] and the punctuated equilibrium theorists [Tushman and Romanelli (1985)], and finally through England (1994), who notes that he was inspired by Boulding (1970, 1978, 1991), Georgescu-Roegen (1971), and Prigogine (1993). The fourth runs through Schumpeter and the classical thermodynamicists [Georgescu-Roegen (1971), Ayres (1978)], and then through England (1994), or directly to the school. Two-way arrows indicating complementary schools of thought are drawn between all of the other evolutionary schools except the Austrians.

Links to System Dynamics. As will be shown below, system dynamics modeling can be considered evolutionary in a variety of ways. It can thus, in principle, be used by any evolutionary economist who has an interest in formalizing his/her approach to structural change. Researchers who have used system dynamics to model, for example, the punctuated equilibrium phenomenon include Sastry (1997) and Sterman and Wittenberg (1999).

Caveats, Multiple Classifications and Omissions

Figure 1 is a modest attempt to trace the intellectual lineages leading to several well-known schools of economic thought that are based, to some degree, on an evolutionary view of economic change. It is by no means perfect or all-inclusive, and it omits some “obvious” evolutionary theorists or links between prominent evolutionary theorists. Moreover, a case can be made that some of the economists listed in the figure have been misclassified or that some of them should be given multiple classifications. All that can be said at this point is that the structure of Figure 1 can and should evolve as new information comes to light.

Perhaps the most obvious omission in Figure 1 is Alfred Marshall. As Hodgson (1993, 1994), Nelson (1995) and others have pointed out, there are clear and explicit references to an evolutionary brand of economics in Marshall’s Principles. Similarly, Weibull (1997, p. 4) points out that both Adam Smith and Thomas Malthus provided evolutionary explanations of economic phenomena in their writings.

Another glaring omission in Figure 1 is Thomas Sargent. Although he is clearly one of the founders of new classical economics, he has also written about applying agent-based computational modeling to macroeconomics [Sargent (1993)]. The exact position that Sargent should take in Figure 1 is thus not clear.

In terms of links between economists that have been omitted, Richard Day was a student of Leontieff and an admirer of Richard Goodwin, yet there are no arrows linking these men. Similarly, Nelson and Winter are said to have been significantly influenced by Alchian, but their paths do not cross in the figure [see Tesfatsion (2000), Nelson (1995)]. Other important links between economists are undoubtedly missing as well.

Examples of economists who could arguably be given multiple classifications in Figure 1 include Boulding and Georgescu-Roegen. These economists could easily be considered institutionalists and evolutionary economists.

Two Evolutionary Schools that Didn't Make the Cut

Two schools of economic thought that are not shown in ovals in Figure 1, and thus are not considered to be evolutionary in David Hamilton's sense of the term and/or are probably not amenable to system dynamics modeling, are new institutional economics and evolutionary game theory. Moreover, evolutionary game theory should probably not even be categorized as a school, but rather as a technique.

New Institutional Economics

According to Klein (1999, p. 456), the goal of new institutional economics "is to explain what institutions are, how they arise, what purposes they serve, how they change and how – if at all – they should be reformed." The term "new institutional economics" was coined by Oliver Williamson (2000), but its origins can be traced back to Ronald Coase's analysis of the firm [Klein (1999, p. 457)]. New institutional economics is often referred to as "transactions cost economics" because the transaction and its related cost, both inside and outside the firm, are seen as being the fundamental unit of economic analysis.

New institutional economics is considered to be an evolutionary form of economics because it assumes economic agents are bounded rational and that they evolve so as to minimize transactions costs and thus behave "as if" they were rational. It is thus a Darwinian "survival of the fittest" view of economic evolution.[30]

Despite its evolutionary flavor, new institutional analyses are typically static and nonmathematical. As a result, some new institutionalists have suggested that evolutionary game theory would be a useful tool of analysis [Ménard (2001)].

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[30] Dugger (1990) argues that although the economic agents in the new institutional economics may be bounded rational, they are not culturally rational – i.e., influenced by culture. In other words, he argues that the new institutional economics does not employ a holistic approach to economic problem solving, but instead follows a strict version of methodological individualism. Hodgson (1998, p. 176) points out that, an adherence to methodological individualism forces the new institutionalists to assume that the preference functions of individual agents are given.

Evolutionary Game Theory

Evolutionary game theory has become increasingly popular among economists since the mid-1980s. Unlike traditional game theory in which perfectly rational players, with perfect information, make a single strategic play of a game that leads to a stable equilibrium, evolutionary game theory assumes that the game in question is played multiple times by bounded rational players selected randomly from a large population, who have little or no knowledge about the structure of the game [Wiebull (1997, p. 1)].

During each play of an evolutionary game, the players adjust their strategies, adopting those that are deemed fittest, and discarding those that are not. Although this process is adaptive, there is no novelty or emergence because all of the possible agent strategies are initially specified at the start of the game.

An evolutionary game ends when an equilibrium is reached. Often the equilibrium is optimal, but some times it is not. The existence of sub-optimal equilibria in evolutionary games has called into question the notion that learning and adaptation ensure survival of the fittest solutions that are essentially optimal and reached "as if" the agents were behaving rationally.

Some Fundamentals of System Dynamics Modeling

System dynamics was originally created to help corporate managers better understand and control industrial systems. Today, system dynamics is used to address problems being experienced by <u>any</u> system that changes over time, be it a physical system, biological system, or socioeconomic system.

The system dynamics modeling process is aimed at creating a mapping of a decision maker's mental model (consistent with any available numerical data or written information) so that it is made precise and its underlying assumptions are stated and open to inspection by others. In addition, since a system dynamics model can be simulated on a computer, the modeling process enables the dynamic behavior inherent in a decision maker's mental model to be accurately revealed. Through an iterative process of mental model extraction, simulation, and reflection, a decision maker's thinking can be made strategic and learning and understanding can take place.

It terms of economic methodology, system dynamics modeling is a pattern modeling process [Radzicki (1988, 1990a)]. With proper refinement, an insightful system dynamics model can be transformed into a real typology called a "generic structure." A generic structure is a model that captures the fundamental causal relationships that appear in a variety of pattern models within a particular category. When properly parameterized, a generic structure can mimic the behavior of any pattern model within its category. Examples of insightful generic structures include Forrester's (1968) <u>Urban Dynamics</u> model, which can mimic the behavior of many different cities, and Homer's (1987) model of the diffusion of new medical technologies, which has been reparameterized to explain the history of cardiac pacemakers, the antibiotic clindamycin, artificial skin, and silicon gel breast implants.

Over the years, system dynamicists have identified a large number of regularities that appear in their pattern models and generic structures, and/or that define proper modeling practice. These regularities form the core of the system dynamics paradigm and can be thought of as a set of "principles of systems." The most fundamental and important of these principles is that the stock-flow-feedback structure of any system causes its dynamic behavior. Of course, this principle is identical to the notion of circular and cumulative causation, which is one of the core ideas in hetrodox economics.

Group Model Building

System dynamics modeling is also frequently used by groups of decision makers (e.g., the senior managers of a company, a city council, a committee of experts assembled to recommend a solution to a problem) to help reach a shared understanding of how and why the system they are studying behaves the way it does, and to reach an agreement on policy initiatives. Over the years, system dynamicists have developed techniques for group knowledge elicitation and group model building that have proved to be quite effective in helping decision makers reach a consensus.[31]

Learning Laboratories

Sometimes an insightful system dynamics model is turned into a “learning laboratory" that invites decision makers or "players" to run a system dynamics model in a gaming environment. More precisely, the learning laboratory simulates its underlying system dynamics model for a small number of periods, pauses, and waits for the player to respond to the unfolding scenario by altering some features (the structure) of the model. After the alterations, the learning laboratory again simulates the model forward for a small number of periods, pauses, and the cycle repeats. Additional information pertaining to the model in particular, or to system dynamics modeling in general, is available from the learning laboratory to assist the player in his/her decision making during the simulation.

After a complete play of the game, the player can recall from the learning laboratory his or her decisions and try to determine why the scenario played-out as it did. Of course, if the player did not do “well,” he or she can play again and, hopefully, learn more about the dynamics of the system along the way.

[31] See Vennix, Andersen and Richardson (1997) and Vennix (1996).

Learning laboratories can be installed on a single computer or made accessible to many users via a CD or intranet/internet (world wide web) configurations. Making a learning laboratory accessible via the world wide web is particularly important when the results of a system dynamics modeling project are to be made available to people who did not participate in the project. Complementary material, such as simpler versions of the model that lead a player, step-by-step, to the final version of the model, is typically available in the learning laboratory.

The Building Blocks of System Dynamics Models

All dynamic behavior in the world arises because of two fundamental elements: stocks and flows. Stocks are receptacles that accumulate or add-up entities that flow into, or out of, them. Flows are mechanisms that move entities into, or out of, stocks. Stocks are depicted in system dynamics models by rectangular-shaped icons intended to conjure-up images of bathtubs, while flows are represented by icons resembling pipe and faucet assemblies that fill or drain the stocks. Identifying the important stocks and flows in a system experiencing a problem is a primary goal of system dynamics modeling.

A second important building block of system dynamics models is feedback. Feedback is the transmission and return of information. In a system dynamics model, information about the number of entities in a stock moves throughout the system and, eventually, returns to alter the flows that fill and/or drain the stock. This movement of information, from stock to flow and back to stock, creates a feedback loop.

Two types of feedback loops exist in system dynamics models: positive loops and negative loops. Positive loops represent self-reinforcing (usually destabilizing) processes and negative loops represent goal-seeking (usually stabilizing) processes.[32] The various positive and negative loops in a system dynamics model fight for control (i.e., dominance) of its behavior. If the model is nonlinear, the dominance of the loops can change over time and significantly alter the system's time path. As a result, identifying the important reinforcing and counteracting processes in a system experiencing a problem is another primary goal of system dynamics modeling.

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[32] From a system dynamics point of view, when Eichner talks about disequilibrium as being "a discrepancy between the system's current output state and some homeostatic condition, and Hamilton argues that human behavior is "active and goal seeking," they are describing negative feedback loop structures. Similarly, when Post Keynesians such as Eichner and Kaldor [see Setterfield (1998)] discuss the importance of "increasing returns" to the behavior of economic systems they are describing, from a system dynamics point of view, positive feedback loop structures. For a feedback view of the thinking of John Dewey see Richardson (1991, pp. 75-77).

A third important component of system dynamics models is their limiting factors. Limiting factors are the physical, financial, and/or psychological components of a system's structure that constrain its behavior. Identifying the important limiting factors in a system experiencing a problem is yet another primary goal of system dynamics modeling.

A final important component of system dynamics models is their nonlinear relationships. Nonlinearities typically define the approach of a system to its limiting factors. Since system dynamicists believe that evolutionary systems often operate near their limits, identifying a system's important nonlinear relationships is still another primary goal of system dynamics modeling.

Evolutionary Change and System Dynamics

Hamilton's concept of evolutionary change can be related to system dynamics modeling at three different levels: (1) at the level of the triple loop learning process, (2) at the level of the modeling process itself, and (3) at the level of an individual simulation run. Although each of these levels is distinct and can be analyzed in isolation, they should really be thought of as intertwined aspects of the system dynamics modeling method.

<u>Evolutionary Change as a Triple Loop Learning Process</u>

According to Sterman (2000, p. 15), the concept of learning as a feedback process goes back to the early days of the 20th century and the work of John Dewey. As shown in Figure 2 [modified from Sterman (2000, p. 18)] a basic adaptive or evolutionary learning structure consists of three feedback processes or loops. The first loop is a negative feedback loop that links the **real economic system**, **information feedback**, and **decisions**. It defines the process whereby economic agents observe the real economic system, compare their perceptions of it to various goals, and then make decisions that they believe will move the real economic system toward their goals.

Place Figure 2 About Here

The second loop links the **real economic system**, **information feedback**, **mental models & theory**, **decision rules (policies) that are conditioned by institutional structures, organizational strategies, & cultural norms**, and **decisions**. It defines the process whereby economic agents not only make decisions based on their perceptions of the actual economic system, but also by decision rules (policies) which are influenced by economic theory and their own mental models of the system. The agents' mental models and economic theory are themselves altered by information from the real economic system.

The third loop in Figure 2 links the **mental models** of the economic agents and economic **theory** to **information feedback** from the real economic system. The concept represented here is that information from the real economic system can alter economic theory and the mental models of the economic agents, and economic theory and the mental models of economic agents can feedback to alter the type of information collected from the real economic system.

It is well-known from behavioral economics that actual economic agents have severe cognitive and informational limitations that inhibit their rational decision making. In terms of Figure 2, this means that the cognitive and informational limitations interfere with the smooth working of the triple loop learning process.

Place Figure 3 About Here

Figure 3 [modified from Sterman (2002, p. 20)] lists some of the cognitive and informational limitations that interfere with each of the steps in the triple loop learning process. These limitations range from an unknown structure in the real economic system, to ambiguity in the information feedback process, to unscientific reasoning that can lie behind mental models and economic theory, to the inability to infer the dynamic behavior inherent in mental models and economic theory, to inconsistency in decision making.

Place Figure 4 About Here

Figure 4 [modified from Sterman (2002, p. 34)] puts forth the case that using system dynamics modeling (and thus adding a fourth feedback loop to the triple loop learning process) can help overcome many of the impediments to learning. A virtual economic system has, for example, a known structure, unambiguous information feedback, a means (a system dynamics learning laboratory that incorporates a structured approach to policy analysis) for applying disciplined scientific reasoning, a means (simulation) for tracing out the dynamic behavior inherent in mental models and economic theory, and a means for the consistent application of decision rules (all model changes are precisely executed by the computer).

The Modeling Process as Evolutionary Change

Although system dynamics models can help decision makers overcome the problems inherent in the triple loop (evolutionary) learning process, the question arises as to whether or not system dynamics models themselves are evolutionary. In other words, the question arises as to whether or not system dynamics models can change their structures.

An important way that system dynamics models change their structures is via the modeling process. Indeed, in the field of system dynamics the modeling process itself is seen as being more valuable than any particular model [see Forrester (1985)]. This is because modeling is an evolutionary activity -- i.e., a learning process. The structure of a system dynamics model is steadily adapted as the researcher participates in the modeling process. The researcher's mental model and any available data lead to an initial specification of model structure, which in turn leads to simulation. Inspection of a simulation run usually leads to mental model revision, new data collection, new model structure, and more simulation. This process is so open-ended that a system dynamics model is never considered "complete," but is always considered to be in its "latest stage of development."

Kolb's Model of Experiential Learning. According to Saeed (1998), an evolutionary theory of learning put forth by David Kolb (1984) is directly applicable to the system dynamics modeling process. As shown in Figure 5 [reproduced from Saeed (1998, p. 402)], Kolb believes that learning is a cycle is driven by four basic activities: watching, thinking, doing and feeling. Each of these activities is carried out either physically or cognitively. Further, the physical activities are carried out either passively or actively while the cognitive activities are carried out either concretely or abstractly.

Place Figure 5 About Here

According to Kolb, for the learning process to be effective, watching (a passive physical activity) must consist of the careful observation of facts leading to the recognition of organized patterns. These patterns must then drive thinking (an active cognitive activity), which creates a concrete experience of reality. The implications of concrete experiences must then be tested through doing (an active physical activity) or experimentation, which can be conducted mentally or with physical and/or mathematical tools. Finally, the results of experimentation must be translated into abstract concepts and generalizations through a cognitive process driven at the outset by feeling (an abstract cognitive activity). Of course, new abstract concepts and generalizations create a framework for watching, and a new cycle of learning can be initiated.

Kolb's Model and the System Dynamics Modeling Process. When an experienced system dynamicist creates a model he/she utilizes a set of skills, and undertakes an evolutionary process, that is strikingly similar to Kolb's model of learning. As shown in Figure 6 [reproduced from Saeed (1998, p. 405)], each of Kolb's four primary learning activities corresponds to a skill that a system dynamicist needs in order to build insightful models. Feeling corresponds to the model conceptualization skill, watching corresponds to the pattern recognition skill, thinking corresponds to the system identification skill, and doing corresponds to the experimentation skill.

Place Figure 6 About Here

During the modeling process, a system dynamicist will typically make at least five trips around Kolb's cycle [trip (a) through trip (e)] and utilize a modeling skill at each step along the way. The shift from one cycle to the next occurs when the modeler has moved from the abstract cognitive domain to the passive physical domain -- i.e., when he/she has learned enough from the preceding cycle to enable him or her to initiate the next trip through the cycle. The five trips around the cycle define a spiral converging into a coherent model that generates insights into system improvement.

<u>Evolutionary Change During Simulation</u>

Although system dynamics models can be used to overcome the impediments to the triple loop learning process and the system dynamics modeling process itself is evolutionary, the question remains as to whether or not system dynamics models themselves can exhibit evolutionary behavior during a particular simulation run. The answer to this question is "yes," but the details of the answer depend on the type of structural change being considered.

The simplest form of structural change that can be exhibited by a system dynamics model is shifting loop dominance. This phenomenon is a by-product of a model's nonlinear relationships and occurs when its dominant and/or active feedback structure shifts endogenously during simulation. A second type of simple structural change occurs when equations representing proposed policy changes are introduced into a system dynamics model. These additional equations represent new pieces of system structure and typically activate only at certain points during a simulation run.[33] A third type of simple structural change occurs when a system dynamics model is run in a gaming mode from within a learning laboratory. Evolutionary behavior occurs when the model is paused and the player alters some of its structural features.

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[33] For more on these first two types of structural change in system dynamics models and on the evolutionary effects of “intelligent logical” or “spiral” loops in system dynamics models see Merten (1988).

A more sophisticated set of evolutionary behaviors that can be exhibited by system dynamics models[34] has been put forth by Radzicki and Sterman (1994, p. 64). This list includes: (1) path dependency, (2) self-organization -- i.e., emergent behavior, and (3) chaotic behavior.

Path dependence. Path dependency essentially means that history matters. More specifically, path dependent system dynamics models get locked into a particular dynamical path they "choose" early in their evolution (usually by chance) because their future trajectories are critically influenced by the cumulative effects of their past decisions.

Self-Organization. System dynamics models that can self-organize undergo abrupt changes in their temporal structures via parameter changes or the amplification (via positive feedback processes) of any random shocks that are perturbing them.

Chaotic Behavior. System dynamics models that exhibit chaotic behavior are unpredictable and oscillate with periodicities and amplitudes that never repeat. As a result their behaviors are considered emergent.

An Example of a System Dynamics Model that Exhibits Evolutionary Behavior

Figure 7 presents a single sector of a simple system dynamics model that exhibits path dependent, self-organizing, behavior. The overall model consists of three virtual manufacturing firms producing nearly identical products (e.g., three different manufacturers of 19 inch color TVs) that are competing for market share within their industry. Although Figure 7 shows only the first firm, the other firms in the model are identical to this one in every possible way.[35]

Place Figure 7 About Here

At time zero, the overall industry demand in the model is divided equally between the three firms. Additional market share is won only through price competition -- i.e., the firm with the lowest price in any period wins more market share. Each firm can lower its price by either producing more and thus learning to produce more efficiently (i.e., via learning-by-doing), or by appropriating the production knowledge of its competitors through such methods as reverse product engineering, participation at trade shows, or the hiring away of a competitor's

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[34] Or any type of dynamic, disequilibrium, model that is classified as evolutionary.

[35] This model is an extension, from two firms to three, of a model originally presented in Radzicki and Sterman (1994). The complete model is available from the author of this paper.

employees. Because a firm can increase its economic power by producing more, the model also assumes that each firm can increase its ability to protect its knowledge base from appropriation by its competitors as its market share increases.

To provide a guide to the nomenclature of system dynamics, Figure 7 displays labels for some of the system's stocks, flows, feedback loops, and limiting factors. Inspection of the figure reveals that firm #1 has two stocks. The first accumulates the firm's production, the second accumulates the production knowledge it has appropriated from firms two and three.

Each of the stocks is changed, over time, by flows. Firm #1's stock of cumulative production is increased by its flow of production and its stock of appropriated production knowledge is increased by its flow of learning from its competitors.

Figure 7 also shows two primary feedback loops that affect the behavior of firm #1. The first is a positive loop that links firm #1's stock of cumulative production to its unit costs, and then to its price, product attractiveness, market share, firm-level demand, and flow of production. The second is a negative loop that links firm #1's stock of appropriated production knowledge to its unit costs, and then to its price, product attractiveness, market share, firm-level demand, flow of production, stock of cumulative production, and flow of learning. The positive loop is responsible for driving firm #1 down its learning curve via a self-reinforcing process – i.e., the more firm #1 produces, the more it learns how to produce efficiently, and thus the lower its price and the higher the demand for its product. The negative loop balances this growth process by reflecting the fact that firm #1 cannot learn from its rivals if it knows more about producing the product than they do and further that, if firm #1 is behind in production knowledge, it cannot close the information gap instantly but must instead learn over a given period of time.

Two other features of the model are of worth noting at this time. The first is that both the firm-to-firm learning rate and the attractiveness of firm #1's product are stochastic. This is shown by the die on the flow icon and the die on the random disturbance icon and reflects the fact that some factors important to learning and product attractiveness have not been explicitly modeled. The second is that the overall industry demand for the product, which is a limiting factor in the model, has a time sensitive trigger (shown by the clock face on the industry demand icon) that launches the evolution of the system by stepping up from zero units to four in time period #1.

Figure 8 shows the evolution of the market shares for each firm during four simulations of the model. In each case the relative market shares oscillate and the dominant firm does not emerge until at least the 25^{th} time period. Indeed, given that the simulations indicate that a firm can be all but out of business and then rise, phoenix-like, to dominate the market (e.g., simulation #3 for firm #3), the ultimate “winner” is not necessarily clear in any of the simulations.

Place Figure 8 About Here

What is clear from the simulations, however, is that the behavior of the model is emergent and path dependent. The time path each firm will take during any simulation run is not knowable from inspection of their micro structures and the dominant firm can be different from run to run. The model does a nice job of illustrating the importance of efficient production, learning by doing, learning from rivals, and of protecting proprietary production methods.

Conclusions

Fifty years ago, David Hamilton helped the economics profession understand the fundamental difference between classical and institutional economics, and helped establish a credible foundation for the concept of evolutionary change in economic theory. Although he confined his original evolutionary analysis to institutional economics, today his contribution is more relevant than ever due to the growth in the number of schools of economic thought that are based, to some degree, on an evolutionary view of economic change.

One of the reasons that evolutionary economists have had a somewhat difficult time significantly influencing policymakers and public opinion during the last fifty years has not been a lack of innovative ideas, but rather the relative lack of powerful mathematical tools to help them compete with their neoclassical colleagues. As evidence, consider Paul Samuelson's (1976, p. 847) comments about institutional economics that appeared in the 10th edition of his famous text-book:

> Forty years ago Institutionalism withered away as an effective counterforce in economics…Mainstream American economics…was therefore able, so to speak, to absorb and take over with superior analytical and econometric tools the descriptive tasks and policy formulations of the Institutionalists.

Today, the situation is very different. Tools such as system dynamics computer simulation modeling and agent-based computational economic modeling can be used to put David Hamilton's views on evolutionary economic change into action so that hetrodox economists can compete more successfully in the arena of public opinion. Let’s get to it!

Bibliography

Alchian, Armen A. 1950. "Uncertainty, Evolution and Economic Theory." Journal of Political Economy 58(June): 211-221.

Allen, R. G. D. 1955. "The Engineer's Approach to Economic Models." Economica 22: 158-168.

Allen, Peter M. 1988. "Dynamic Models of Evolving Systems." System Dynamics Review 4(1-2): 109-130.

Anderson, Phillip W., Arrow, Kenneth J. and David Pines, eds. 1988. The Economy as an Evolving Complex System. Proceedings Volume V. Santa Fe Institute Studies in the Sciences of Complexity. Redwood City, CA: Addison-Wesley.

Aoki, Masanao and Axel S. B. Leijonhufvud. 1976. "Cybernetics and Macroeconomics: A Comment." Economic Inquiry 14: 251-258.

Arestis, Phillip. 1992. The Post Keynesian Approach to Economics. Aldershot, UK: Edward Algar.

Arestis, Phillip. 1996. "Post-Keynesian Economics: Towards Coherence." Cambridge Journal of Economics 20: 111-135.

Arthur, W. Brian. 1988. "Self Reinforcing Mechanisms in Economics." pp. 9-27 in The Economy as an Evolving Complex System. Phillip W. Anderson, Kenneth J. Arrow and David Pines, eds. Proceedings Volume V. Santa Fe Institute Studies in the Sciences of Complexity. Redwood City, CA: Addison-Wesley.

Arthur, W. Brian. 1990. "Positive Feedbacks in the Economy." Scientific American (February): 92-99.

Arthur, W. Brian. 1991. "Designing Economic Agents that Behave Like Human Agents: A Behavioral Approach to Bounded Rationality." American Economic Review 81(2): 353-359.

Arthur, W. Brian. 1994. "Complexity in Economic Theory: Inductive Reasoning and Bounded Rationality." American Economic Review 84(2): 406-411.

Arthur, W. Brian, Steven N. Durlauf, and David A. Lane, eds. 1997. The Economy as an Evolving Complex System II. Proceedings Volume XXVII. Santa Fe Institute Studies in the Sciences of Complexity. Reading, MA: Addison-Wesley.

Ayres, Robert U. 1978. Resources, Environment and Economics: Applications of the Materials/Energy Balance Principle. New York: John Wiley and Sons, Inc.

Baran, Paul A. and Paul M. Sweezy. 1966. Monopoly Capital: An Essay on the American Economic and Social Order. New York: Monthly Review Press.

Batten, D. 2000. Discovering Artificial Economics: How Agents Learn and Economies Evolve. Boulder, CO: Westview Press.

Bergh, Jeroen C. J. M. van den. 1993. "A Framework for Modelling Economy-Environment-Development Relationships Based on Dynamic Carrying Capacity and Sustainable Development Feedback." Environmental and Resource Economics 3: 395-412.

Bergh, Jeroen C. J M. van den and Peter Nijkamp 1991. "Operationalizing Sustainable Development: Dynamic Ecological-Economic Models." Ecological Economics 4: 11-33.

Bergh, Jeroen C. J. M. van den and Jan van der Straaten. eds. 1994. Toward Sustainable Development: Concepts, Methods, and Policy. Washington, D.C.: Island Press.

Boulding, Kenneth E. 1970. A Primer on Social Dynamics: History as Dialectics and Development.

Boulding, Kenneth E. 1978. Ecodynamics: A New Theory of Societal Evolution. Beverly Hills, CA: Sage.

Boulding, Kenneth E. 1991. “What is Evolutionary Economics?” Journal of Evolutionary Economics 1(1): 9-17.

Bowles, Samuel, David M. Gordon, and Thomas E. Weisskopf. 1983. Beyond the Wasteland. New York: Anchor Press/Doubleday.

Bowles, Samuel, Herbert Gintis and Melissa Osborne. 2001. “The Determinants of Earnings: A Behavioral Approach.” Journal of Economic Literature 39(4): 1137-1176.

Bradley, Dennis. 1995. "Ecological Economics." http://www.fs.fed.us/eco/st21pl.htm.

Bronfenbrenner, Martin. 1970. “Radical Economics in America: A 1970 Survey.” Journal of Economic Literature 8(3): 747-766.

Cochrane, James L. and John A. Graham. 1976. "Cybernetics and Macroeconomics." Economic Inquiry 14: 241-250.

Cosmides, Leda and Jon Tooby. 1994. “Better than Rational: Evolutionary Psychology and the Invisible Hand.” American Economic Review 84(2): 327-332.

Costanza, Robert. 1989. "What is Ecological Economics?" Ecological Economics 6(1): 1-7.

Costanza, Robert and Herman E. Daly. 1992. "Natural Capital and Sustainable Development." Conservation Biology 6(1): 37-46.

Cottrell, Allin. 1990. "Reconciling Leijonhufvud and the Post Keynesians." Working Paper. Department of Economics. Wake Forest University. Winston-Salem, NC 27109.

Cyert, Richard M. and J. G. March. 1963. A Behavioral Theory of the Firm. Englewood Cliffs, NJ: Prentice-Hall.

David, Paul. 1985. “Clio and the Economics of QWERTY.” American Economic Review 75(2): 332-337.

Davidson, Paul. 1981. “Post Keynesian Economics: Solving the Crisis in Economic Theory.” pp. 151-173 in The Crisis in Economic Theory. David Bell and Irving Kristol, eds. New York: Basic Books.

Davidson, Paul. 1991. Controversies in Post Keynesian Economics. Brookfield, Vermont: Edward Elgar Publishing Company.

Davidson, Paul. 1994. Post Keynesian Macroeconomic Theory: A Foundation for Successful Economic Policies for the Twenty-first Century. Brookfield, Vermont: Edward Elgar Publishing Company.

Day, Richard H. 1975. “Adaptive Processes and Economic Theory.” pp. 1-38 in Adaptive Economic Models. Richard H. Day and Theodore Groves, eds. New York: Academic Press.

Day, Richard H. and Gunnar Eliasson. 1986. The Dynamics of Market Economies. Amsterdam: North Holland.

Day, Richard H. and Ping Chen. eds. 1993. Nonlinear Dynamics and Evolutionary Economics. New York: Oxford University Press, Inc.

Deprez, Johan and William S. Milberg. 1990. "Cycle and Trend in the Dynamics of Advanced Market Economies." Journal of Economic Issues 24(2): 513-521.

Diehl, Ernst and John D. Sterman. 1995. "Effects of Feedback Complexity on Dynamic Decision Making." Organizational Behavior and Human Decision Processes 62(2): 198-215.

Dosi, Giovanni and Richard R. Nelson. 1994. “An Introduction to Evolutionary Theories in Economics.” Journal of Evolutionary Economics 4(3): 153-172.

Dugger, William. 1990. "The New Institutionalism: New But Not Institutionalist." Journal of Economic Issues 24(2): 423-431.

Dugger, William M. and Howard J. Sherman. 1997. "Institutionalists and Marxist Theories of Evolution." Journal of Economic Issues 31(4): 991-1009.

Earl, Peter E. 1989. "Bounded Rationality, Psychology and Financial Evolution: Some Behavioural Perspectives on Post-Keynesian Anaylsis." in New Directions in Post-Keynesian Economics. J. Pheby, ed. Aldershot: Edward Elgar.

Earl, Peter E. 1990. ”Economics and Psychology: A Survey.” The Economic Journal 100(September): 718-755.

Eichner, Alfred S. 1979a. “A Look Ahead.” pp. 172-173 in A Guide to Post-Keynesian Economics. Alfred S. Eichner, ed. White Plains, New York: M. E. Sharpe, Inc.

Eichner, Alfred S. 1979b. "A Post-Keynesian Short-Period Model" Journal of Post Keynesian Economics 1(1): 38-63.

Eichner, Alfred S. 1987. The Macrodynamics of Advanced Market Economies. Armonk, New York: M. E. Sharpe, Inc.

Eichner, Alfred S. and Jan A. Kregel. 1975. "An Essay on Post-Keynesian Theory: A New Paradigm in Economics." Journal of Economic Literature 8(4): 1293-1314.

England, Richard W. 1994. "On Economic Growth and Resource Scarcity: Lessons from Nonequilibrium Thermodynamics." pp. 193-211 in Evolutionary Concepts in Contemporary Economics. Richard W. England, ed. Ann Arbor, MI: The University of Michigan Press.

Flaherty, Diane. 1987. “Radical Political Economics.” pp. 36-39 in The New Palgrave: A Dictionary of Economics. John Eatwell, Murray Milgate and Peter Newman, eds. London: Macmillan Press.

Foley, Duncan K. 1982. “The Value of Money, the Value of Labor Power and the Marxian Transformation Problem.” Review of Radical Political Economy 14(2): 37-47.

Foley, Duncan K. 1997. “Introduction.” in Barriers and Bounds to Rationality: Essays on Economic Complexity and Dynamics in Interactive Systems. Peter S. Albin, ed. Princeton, NJ: Princeton University Press.

Ford, Andrew. 1999. Modeling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems. Washington, DC: Island Press.

Forrester, Jay W. 1956. “Dynamic Models of Economic Systems and Industrial Organizations.” System Dynamics Group Memo D-0. Massachusetts Institute of Technology.

Forrester, Jay W. 1961. Industrial Dynamics. Waltham, MA: Pegasus Communications.

Forrester, Jay W. 1968. Urban Dynamics. Waltham, MA: Pegasus Communications.

Forrester, Jay W. 1970. World Dynamics. Waltham, MA: Pegasus Communications.

Forrester, Jay W. 1979. "An Alternative Approach to Economic Policy: Macrobehavior from Microstructure." pp. 80-107 in Economic Issues of the Eighties. Nake M. Kamrany and Richard H. Day, eds. Baltimore, MD: The Johns Hopkins Press.

Forrester, Jay W. 1985. “’The’ Model Versus a Modeling ‘Process.’” System Dynamics Review (1 and 2): 133-134.

Forstater, Mathew. 2001. "An Institutionalist Post Keynesian Methodology of Economic Policy with an Application to Full Employment." Working Paper #18. Center for Full Employment and Price Stability. University of Missouri - Kansas City.

Georgescu-Roegen, Nicholas. 1971. The Entropy Law and the Economic Process. Cambridge, MA: Harvard University Press.

Goodwin, Richard M. 1993. “My Erratic Progress Toward Economic Dynamics: Remarks Made at Banquet, Tuesday, April 18, 1989.” pp. 303-306 in: Nonlinear Dynamics and Evolutionary Economics. Richard H. Day and Ping Chen, eds. New York: Oxford University Press.

Gruchy, Allen G. 1987. The Reconstruction of Economics: An Analysis of the Fundamentals of Institutional Economics. New York: Greenwood Press.

Hamilton, David B. 1999 (1953). Evolutionary Economics: A Study of Change in Economic Thought. 2nd Edition. New Brunswick, NJ: Transaction Publishers.

Hanusch, Horst. ed. 1988. Evolutionary Economics: Applications of Schumpeter's Ideas. New York: Cambridge University Press.

Harcourt, Geoffrey C. 1985. "A Twentieth-Century Eclectic: Richard Goodwin." Journal of Post Keynesian Economics 7: 410-412.

Harvey, John T. 1994. "Circular Causation and the Veblenian Dichotomy in the General Theory: An Introduction to Institutionalist Method." Journal of Post Keynesian Economics 17(1): 69-89.

Harvey, John T. 2002. "Keynes' Chapter 22: A System Dynamics Model." Journal of Economic Issues 36(2): 373-381.

Hodgson, Geoffrey M. 1989. “Post-Keynesian and Institutionalism: The Missing Link.” pp. 94-123 in New Directions in Post-Keynesian Economics. J. Pheby, ed. Aldershot, UK: Edward Elgar.

Hodgson, Geoffrey M. 1993. Economics and Evolution: Bringing Life Back into Economics. Cambridge, UK: Polity Press.

Hodgson, Geoffrey M. 1994. "Precursors of Modern Evolutionary Economics: Marx, Marshall, Veblen, and Schumpeter." pp. 9-35 in Evolutionary Concepts in Contemporary Economics. Richard W. England, ed. Ann Arbor, MI: The University of Michigan Press.

Hodgson, Geoffrey M. 1998. “The Approach of Institutional Economics.” Journal of Economic Literature 36(1): 166-192.

Holland, John H. and John Miller. 1991. "Artificial Adaptive Agents in Economic Theory," American Economic Review 81(2): 365-370.

Holt, Richard P. F. and Steven Pressman. 2002. “What is Post Keynesian Economics?” pp. 1-10 in A New Guide to Post-Keynesian Economics. London: Routledge.

Homer, Jack. 1987. "A Diffusion Model with Application to Evolving Medical Technologies." Technological Forecasting and Social Change 31: 197-218.

Iwai, Katshuito. 1984a. “Schumpeterian Dynamics: Part I.” Journal of Economic Behavior and Organization” 5(2): 159-190.

Iwai, Katshuito. 1984b. “Schumpeterian Dynamics: Part II.” Journal of Economic Behavior and Organization” 5(3-4): 321-351.

Jørgensen, Sven Erik. 1994. "The Application of Global Models for Comparison of Different Strategies on Sustainable Living." Ecological Economics 11(1): 1-8.

Kahneman, Daniel and Amos Tversky. 1974. "Judgment Under Uncertainty: Heuristics and Biases." Science 185(September): 1124-1131.

Kaldor, Nicholas. 1981. "The Role of Increasing Returns, Technical Progress and Cumulative Causation the Theory of International Trade and Economic Growth." Economie Appliquee 34(4): 633-648.

Kampmann, Christian and John D. Sterman. 1998. "Feedback Complexity, Bounded Rationality, and Market Dynamics." Memo D-4802. System Dynamics Group. Massachusetts Institute of Technology.

Khalil, Elias L. 1990. "Entropy Law and Exhaustion of Natural Resources: Is Nicholas Georgescu-Roegen's Paradigm Defensible?" Ecological Economics 2: 163-178.

Kirzner, Israel M. 1987. "Austrian School of Economics." pp. 145-151 in The New Palgrave: A Dictionary of Econmics. John Eatwell, Murray Milgate and Peter Newman, eds. London: Macmillan Press.

Kirzner, Israel M. 1997. “Entrepreneurial Discovery and the Competitive Market Process: An Austrian Approach.” Journal of Economic Literature 35(1): 60-85

Klein, Peter G. 1999. "New Institutional Economics." pp. 456-489 in Encyclopedia of Law and Economics. Boudewijn Bouckaert and Gerrit De Geest, eds. Northhampton, MA: Edward Elgar Publishing.

Kolb, David A. 1984. Experiential Learning. Englewood Cliffs, NJ: Prentice Hall.

Kregel, Jan A. 1990. "The Integration of Micro and Macroeconomics through Macrodynamic Megacorps: Eichner and the 'Post-Keynesians.'" Journal of Economic Issues 24(2): 523-534.

Krugman, Paul. 1996. "What Economists can Learn from Evolutionary Theorists." A Talk Given to the European Association for Evolutionary Political Economy. http://web.mit.edu/krugman/www/evolute.html

Kuhn, Thomas S. 1962. The Structure of Scientific Revolutions. Chicago: The University of Chicago Press.

Lane, Dave A. 1993. "Artificial Worlds and Economics." Journal of Evolutionary Economics 3(2): 89-107.

Lange, Oskar. 1938. On the Economic Theory of Socialism. Minneapolis: University of Minnesota Press.

Langton, Christopher. ed. 1989. Artificial Life. Redwood City, CA: Addison-Wesley.

Lavoie, Mark. 1992. Foundations of Post Keynesian Analysis. Aldershot, UK: Edward Elger.

Lavoie, Mark. 1994. "A Post Keynesian Approach to Consumer Choice." Journal of Post Keynesian Economics 16(4): 539-562.

Lawson, Tony. 1994. "The Nature of Post Keynesianism and its Links to Other Traditions: A Realist Perspective." Journal of Post Keynesian Economics 16(4): 503-538.

Leijonhufvud, Axel S. B. 1968. On Keynesian Economics and the Economics of Keynes: A Study of Monetary Theory. New York: Oxford University Press.

Leijonhufvud, Axel S. B. 1993. "Towards a Not-Too-Rational Macroeconomics." Southern Economic Journal 60(1): 1-13.

Mandel, Ernst. 1969. Marxist Economic Theory. Two Volumes. New York: Monthly Review Press.

Mandel, Ernst. 1980. Long Waves of Capitalist Development: The Marxist interpretation. New York: Cambridge University Press.

Marglin, Stephen A. 1984. "Growth, Distribution and Inflation: A Centennial Synthesis." Cambridge Journal of Economics 8(2): 115-144.

Mass, Nathaniel J. 1975. Economic Cycles: An Analysis of Underlying Causes. Waltham, MA: Pegasus Communications.

Mayumi, Kozo. 2002. The Origins of Ecological Economics: The Bioeconomics of Georgescu-Roegen. London: Routledge.

Maxwell, Thomas and Robert Costanza. 1994. "Spatial Ecosystem Modeling in a Distributed Computational Environment." pp. 111-138 in: Toward Sustainable Development: Concepts, Methods, and Policy. Jeroen C. J. M. van den Bergh and Jan van der Straaten. eds. Washington, D.C.: Island Press.

Meadows, Donella H., Dennis L. Meadows, Jørgen Randers and William W. Behrens, III. 1972. The Limits to Growth. New York: Universe Books.

Meadows, Donella H., Dennis L. Meadows and Jørgen Randers. 1992. Beyond the Limits. White River Junction, VT: Chelsea Green Publishing Company.

Ménard, Claude. 2001. "Methodological Issues in New Institutional Economics." Journal of Economic Methodology 8(1): 85-92.

Merten, Peter P. 1988. "The Simulation of Social System Evolution with Spiral Loops." Behavioral Science 33: 131-160.

Miller, John H. 1998. "Active Nonlinear Tests (ANTs) of Complex Simulations Models. Management Science 44(6): 620-630.

Morecroft, John D. W. 1985. “Rationality in the Analysis of Behavior Simulation Models.” Management Science 31(7): 900-916.

Morecroft, John D. W. 1983. “System Dynamics: Portraying Bounded Rationality.” Omega: The International Journal of Management Science 11(2): 131-142.

Morishima, Michio. 1973. Marx's Economics. Cambridge, UK: Cambridge University Press.

Mullainathan, Sendhil and Richard H. Thaler. 2000. “Behavioral Economics.” Working Paper No. 00-27. Department of Economics. Massachusetts Institute of Technology.

Nelson, Richard R. 1995. "Recent Evolutionary Theorizing About Economic Change," Journal of Economic Literature 33(1): 48-90.

Nelson, Richard and Sidney G. Winter 1982. An Evolutionary Theory of Economic Change. Cambridge, MA: Harvard University Press.

New School University. 2002. The History of Economic Thought Website. http://cepa.newschool.edu/het/

Paich, Mark and John D. Sterman. 1993. "Boom, Bust, and Failures to Learn in Experimental Markets." Management Science 39(12):1439-1458.

Pearce, D. W. 1987. "Foundations of an Ecological Economics." Ecological Modelling 38: 9-18.

Phillips, A. William. 1950. "Mechanical Models in Economic Dynamics." Economica 18: 283-305.

Phillips, A. William. 1954. "Stabilisation Policy in a Closed Economy." Economic Journal 64: 290-323.

Phillips, A. William. 1957. "Stabilisation Policy and the Time-Forms of Lagged Response." Economic Journal 67: 265-267.

Potts, Jason D. 2000. The New Evolutionary Microeconomics: Complexity, Competence and Adaptive Behavior. Cheltenham, UK: Edward Elgar Publishing Ltd.

Prigogine, Ilya. 1993. “Bounded Rationality: From Dynamical Systems to Socio-economic Models.” pp. 3-13 in Nonlinear Dynamics and Evolutionary Economics. Day, Richard and Ping Chen. eds. New York: Oxford University Press, Inc.

Rabin, Matthew. 1998. “Psychology and Economics.” Journal of Economic Literature 36(1): 11-46.

Radzicki, Michael J. 1988. “Institutional Dynamics: An Extension of the Institutionalist Approach to Socioeconomic Analysis.” Journal of Economic Issues 22(3): 633-666.

Radzicki, Michael J. 1990a. "Methodologia Oeconomiae et Systematis Dynamis." System Dynamics Review 6(2): 123-147.

Radzicki, Michael J. 1990b. "Institutional Dynamics, Deterministic Chaos, and Self-Organizing Systems." Journal of Economic Issues 24(1): 57-102.

Radzicki, Michael J. and Donald A. Seville. 1993. "An Institutional Dynamics Model of Sterling, Massachusetts: Indicative Planning at the Local Level." Journal of Economic Issues 27(2): 481-492.

Radzicki, Michael J. and John D. Sterman. 1994. "Evolutionary Economics and System Dynamics." In: Richard W. England, ed. Evolutionary Concepts in Contemporary Economics. pp. 61-89. Ann Arbor, MI: University of Michigan Press.

Richardson, George P. 1991. Feedback Thought in Social Science and Systems Theory. Philadelphia, PA: The University of Pennsylvania Press.

Robinson, Joan. 1942. Essay on Marxian Economics. London: Macmillan.

Rostow, Walter W. 1990. Theories of Economic Growth from David Hume to the Present. New York: Oxford University Press.

Rust, John. 1987. "Optimal Replacement of GMC Bus Engines: An Empirical Model of Harold Zurcher." Econometrica 55(5): 999-1033.

Ruth, Matthias. 1995. "Thermodynamic Constraints on Optimal Depletion of Copper and Aluminum in the United States: A Dynamic Model of Substitution and Technical Change." Ecological Economics 15(3):197-213.

Saeed, Khalid. 1988. "Wage Determination, Income Distribution and the Design of Change." Behavioral Science 33(3): 161-186.

Saeed, Khalid. 1998. "Conclusion." pp. 398-410 in Towards Sustainable Development: Essays on System Analysis of National Policy. 2nd Edition. Khalid Saeed, ed. Brookfield, VT: Ashgate Publishing Company.

Saeed, Khalid and Michael J. Radzicki. 1993. "A Post Keynesian Model of Macroeconomic Growth, Instability, and Income Distribution." In Enrique Zepeda and José A. D. Machuca, eds., The Role of Strategic Modelling in International Competitiveness: Proceedings of the 1993 International Conference of the System Dynamics Society. Cancún, Mexico. July 19-25. pp. 435-443.

Saeed, Khalid and Michael J. Radzicki. 1994. "A Post Keynesian MacroDynamic Model." Working Paper. Department of Social Science & Policy Studies. Worcester Polytechnic Institute.

Samuelson, Paul A. 1976. Economics. 10th Edition. New York: McGraw-Hill.

Sargent, Thomas. 1993. Bounded Rationality in Macroeconomics. The Arne Ryde Memorial Lectures. Oxford, UK: Clarendon Press.

Sastry, M. Anjali. 1997. "Problems and Paradoxes in a Model of Punctuated Organizational Change." Administrative Science Quarterly 42(2): 237-275.

Sawyer, Malcolm C. 1989. The Challenge of Radical Political Economy: An Introduction to the Alternatives to Neo-classical Economics. Hemel Hempstead, Herts.: Harvester Wheatsheaf.

Schelling, Thomas C. 1978. Micromotives and Macrobehavior. New York: W. W. Norton and Company.

Scholl, Hans J. 2001. "Agent-Based and System Dynamics Modeling: A Call for Cross Study and Joint Research." Proceedings of the 34th Hawaii International Conference on System Sciences. I.E.E.E.. 0-7695-0981-9/01

Schumpeter, Joseph A. 1976 [1942]. Capitalism, Socialism and Democracy. 5th edition. London: George Allen and Unwin.

Setterfield, Mark. 1998. "History *Versus* Equilibrium: Nicholas Kaldor on Historical Time and Economic Theory." Cambridge Journal of Economics 22: 521-537.

Shaikh, Anwar. 1977. "Marx's Theory of Value and the 'Transformation Problem.'" In The Subtle Anatomy of Capitalism. Jesse Schwartz, ed. Santa Monica, CA: Goodyear Publishing Company.

Shaikh, Anwar. 1978. "An Introduction to the History of Crisis Theories." in U.S. Capitalism in Crisis. U.R.P.E., New York.

Silverberg, Gerald. 1988. "Modelling Economic Dynamics and Technical Change: Mathematical Approaches to Self-Organization and Evolution." pp. 531-559 in Technical Change and Economic Theory. Giovanni Dosi, Christorpher Freeman, Richard R. Nelson, Gerald Silverberg and L. Soete, eds. London: Pinter.

Simon, Herbert A. 1979. "Rational Decision Making in Business Organizations." American Economic Review 69(4): 493-513.

Simon, Herbert A. 1984. "On the Behavioral and Rational Foundations of Economic Dynamics." Journal of Economic Behavior and Organization 5: 35-55.

Simon, Herbert. A. 1991. Models of My Life. New York: Basic Books.

Steedman, Ian. 1977. Marx after Sraffa. London: New Left Books.

Sterman, John D. 1982. "A Dynamic Disequilibrium Model of Energy-Economy Interactions." International Journal of Energy Systems 2(3): 159-163.

Sterman, John D. 1989. "Modeling Managerial Behavior: Misperceptions of Feedback in a Dynamic Decision Making Experiment." Management Science 35(3): 321-339.

Sterman, John D. 1988. "A Skeptics Guide to Computer Models." pp. 133-169 in Foresight and National Decisions. Lindsey Grant, ed. Lanham, MD: University Press of America.

Sterman, John D. 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. The McGraw-Hill Companies, Inc.

Sterman, John D. and Jason Wittenberg. 1999. "Path Dependence, Competition and Succession in the Dynamics of Scientific Revolution." Organization Science 10(3): 322-341.

Tesfatsion, Leigh. 1997. "How Economists Can Get Alife." pp. 533-564 in The Economy as an Evolving Complex System II. W. Brian Arthur, Steven Durlauf, and David Lane, eds. Proceedings Volume XXVII. Santa Fe Institute Studies in the Sciences of Complexity. Reading, MA: Addison-Wesley.

Tesfatsion, Leigh. 2000. "Agent-Based Computational Economics: A Brief Guide to the Literature." Working Paper available at: http://www.econ.iastate.edu/tesfatsi/.

Tesfatsion, Leigh. 2001a. "Introduction to the CE Special Issue on Agent-Based Computational Economics." Computational Economics 18(1): 1-10.

Tesfatsion, Leigh. 2001b. "Guest Editorial: Agent-Based Modelling of Evolutionary Economic Systems." IEEE Transactions on Evolutionary Computation 5(5): 1-5.

Tesfatsion, Leigh. 2002. "Agent-Based Computational Economics: Growing Economies from the Bottom Up." Artificial Life 8(1): 55-82.

Tushman, Michael L. and Elaine Romanelli. 1985. "Organizational Metamorphosis: A Punctuated Equilibrium Model of Organizational Evolution." Research in Organizational Behavior 7:171-222.

Tustin, Arnold. 1953. The Mechanism of Economic Systems. Cambridge, MA: Harvard University Press.

Weibull, Jörgen W. 1997. "What have we Learned from Evolutionary Game Theory so Far?" Working Paper 487. The Research Institute of Industrial Economics. http://swopec.hhs.se/iuiwop/papers/iuiwop0487.pdf

Wiener, Norbert. 1948. Cybernetics: Or Control and Communication in the Animal and the Machine. New York: John Wiley and Sons, Inc.

Wilber, Charles K. and Kenneth P. Jameson. 1983. An Inquiry into the Poverty of Economics. Notre Dame, IN: University of Notre Dame Press.

Williamson, Oliver. 2000. "The New Institutional Economics: Taking Stock, Looking Ahead." Journal of Economic Literature 38 (September): 595-613.

Winter, Sidney G. 1964. "Economic Natural Selection and the Theory of the Firm." Yale Economic Essays 4: 225-272.

Witt, Ulrich. 1992. “Evolutionary Concepts in Economics.” Eastern Economic Journal 18(4): 405-419.

Witt, Ulrich. 1993. Evolutionary Economics. London: Edward Elgar.

Wolfram, Stephen. 2002. A New Kind of Science. Wolfram Media, Inc.

Vennix, Jac A. M. 1996. Group Model Building: Facilitating Team Learning Using System Dynamics. New York: John Wiley and Sons, Inc.

Vennix, Jac A. M., David F. Andersen, and Richardson, George P. 1997. Special Issue on Group Model Building. System Dynamics Review 13(2).

Vriend, Nicolaas J. 2002. “Was Hayek an ACE?” Southern Economic Journal 68(4): 811-840.

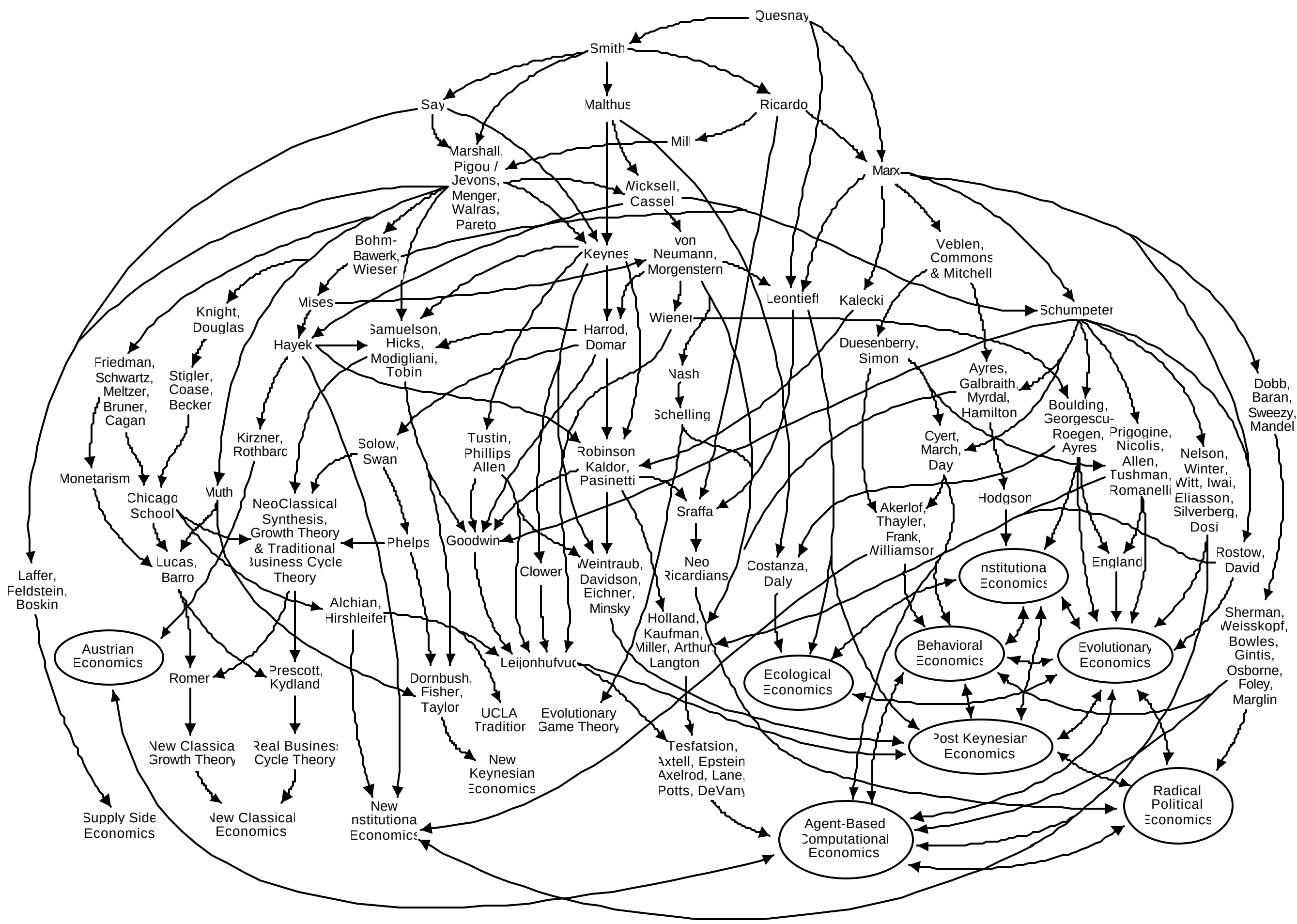

Figure 1: A Selected Genealogy of Economic Thought and Economic Thinkers from Francois Quesnay and the Physiocrats to the Present Day

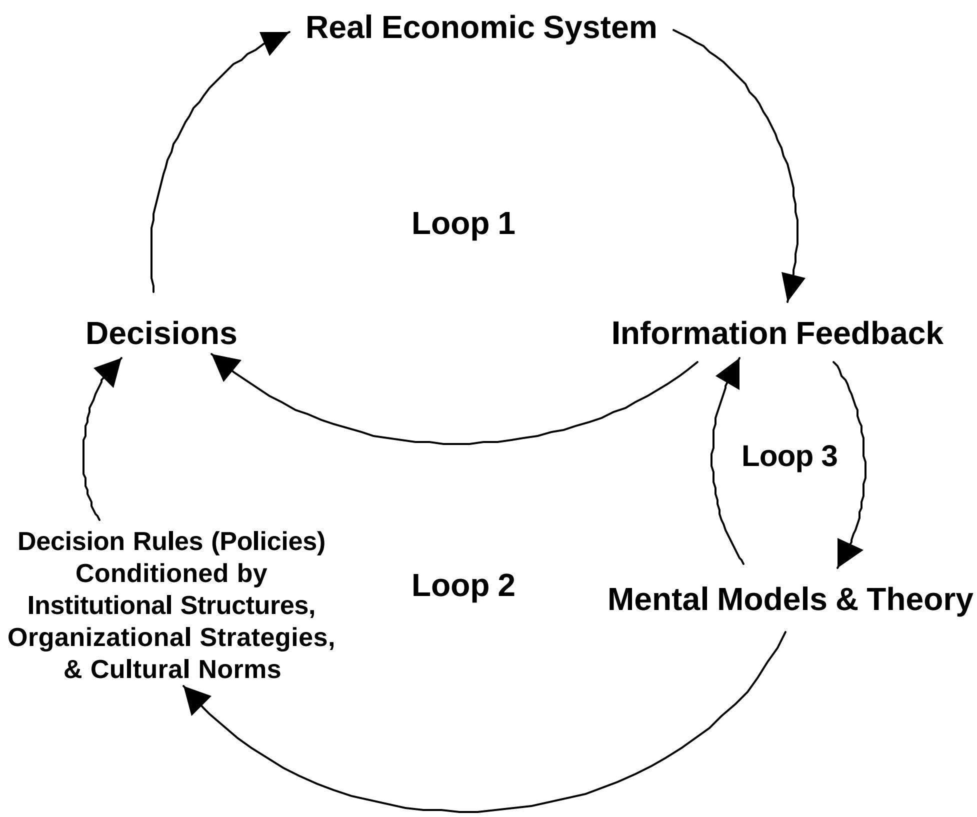

Figure 2: Evolution as a Triple Loop Learning Process

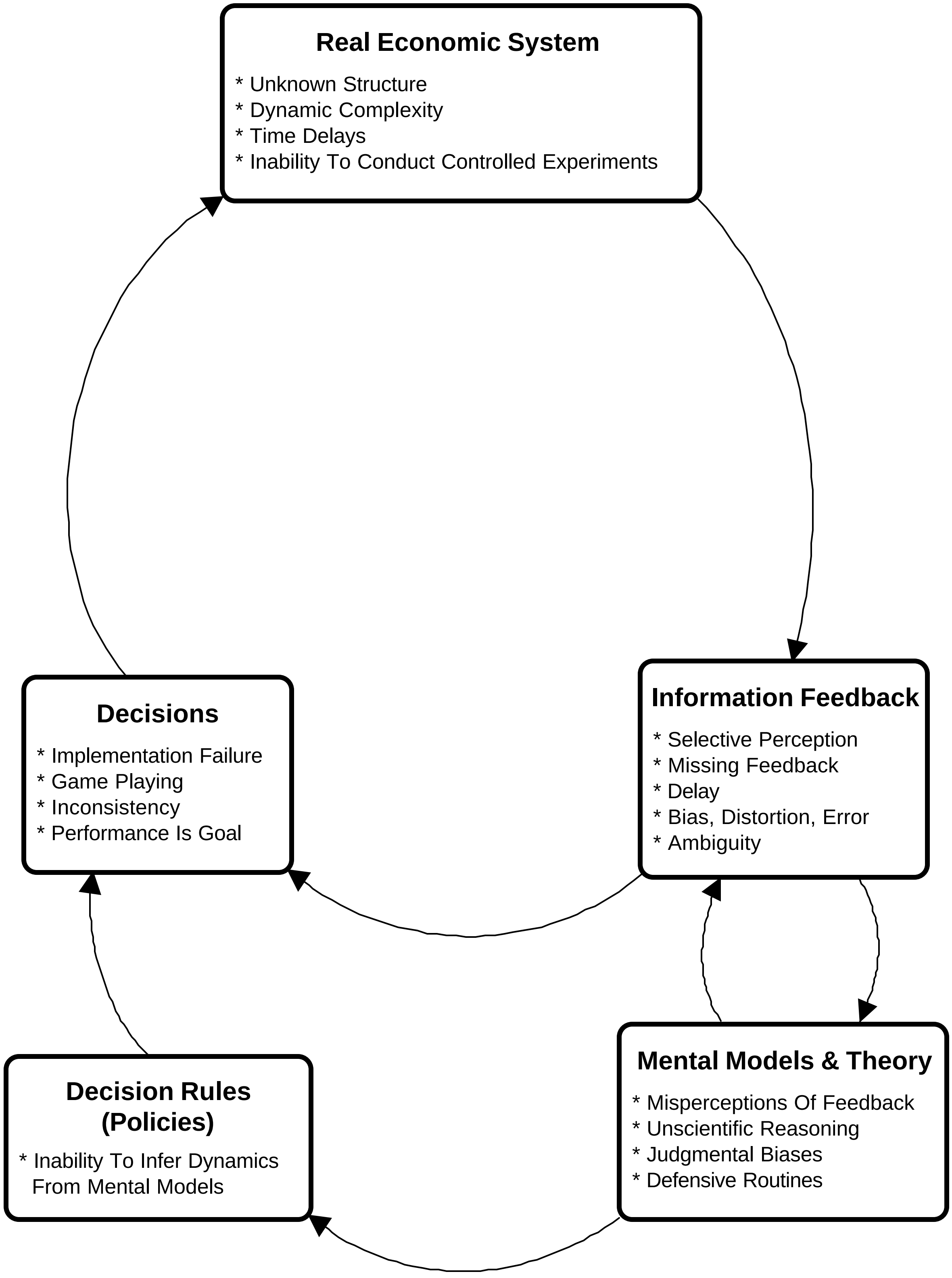

Figure 3: Impediments to the Triple Loop Learning Process

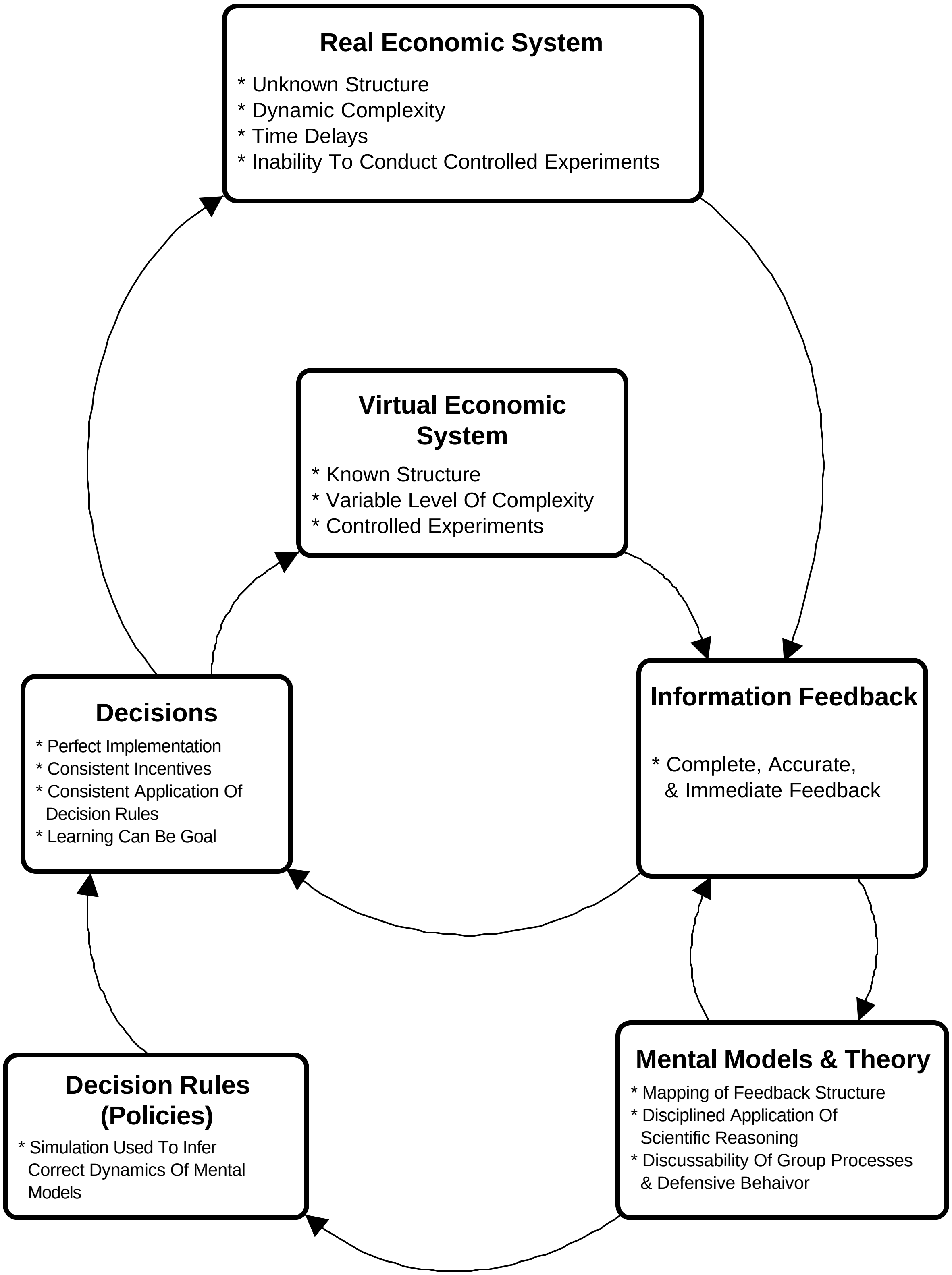

Figure 4: Idealized Learning Process in which System Dynamics is Used to Overcome the Impediments to the Triple Loop Learning Process

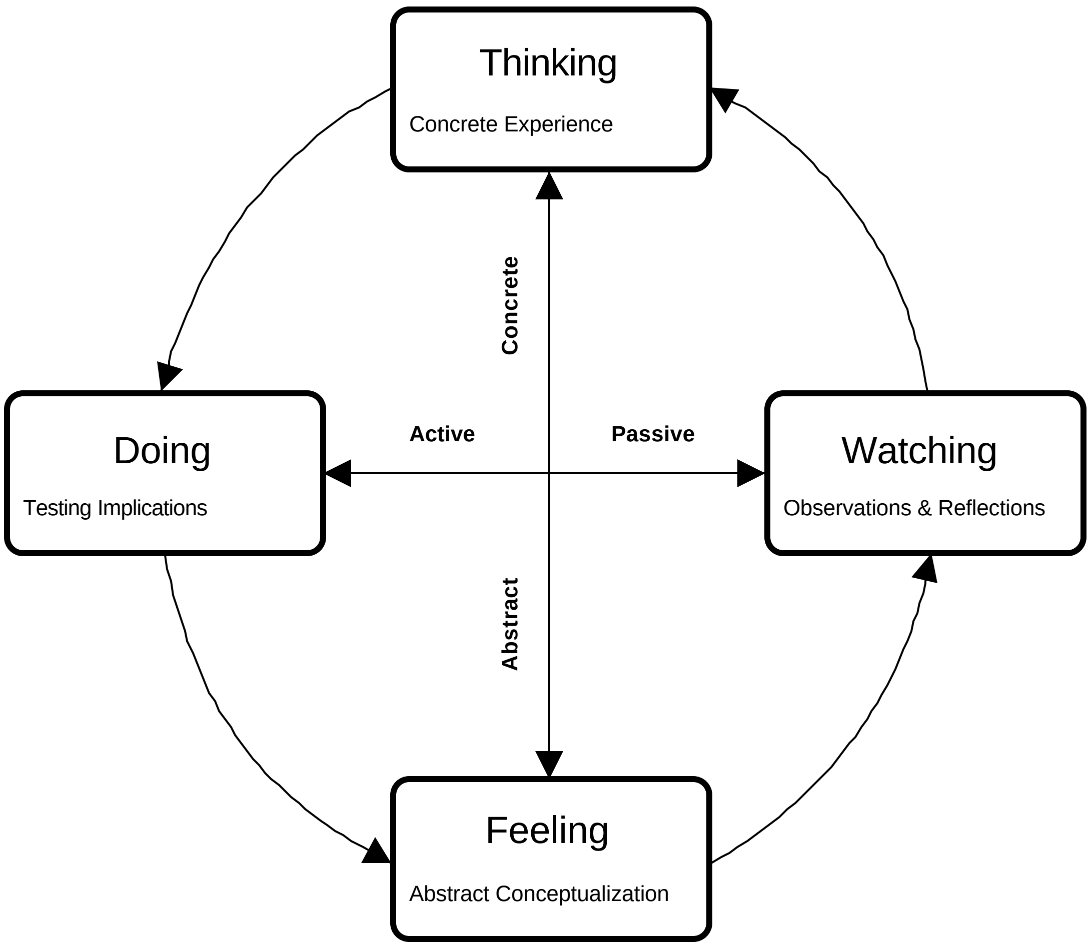

Figure 5: Kolb’s Model of Experiential Learning

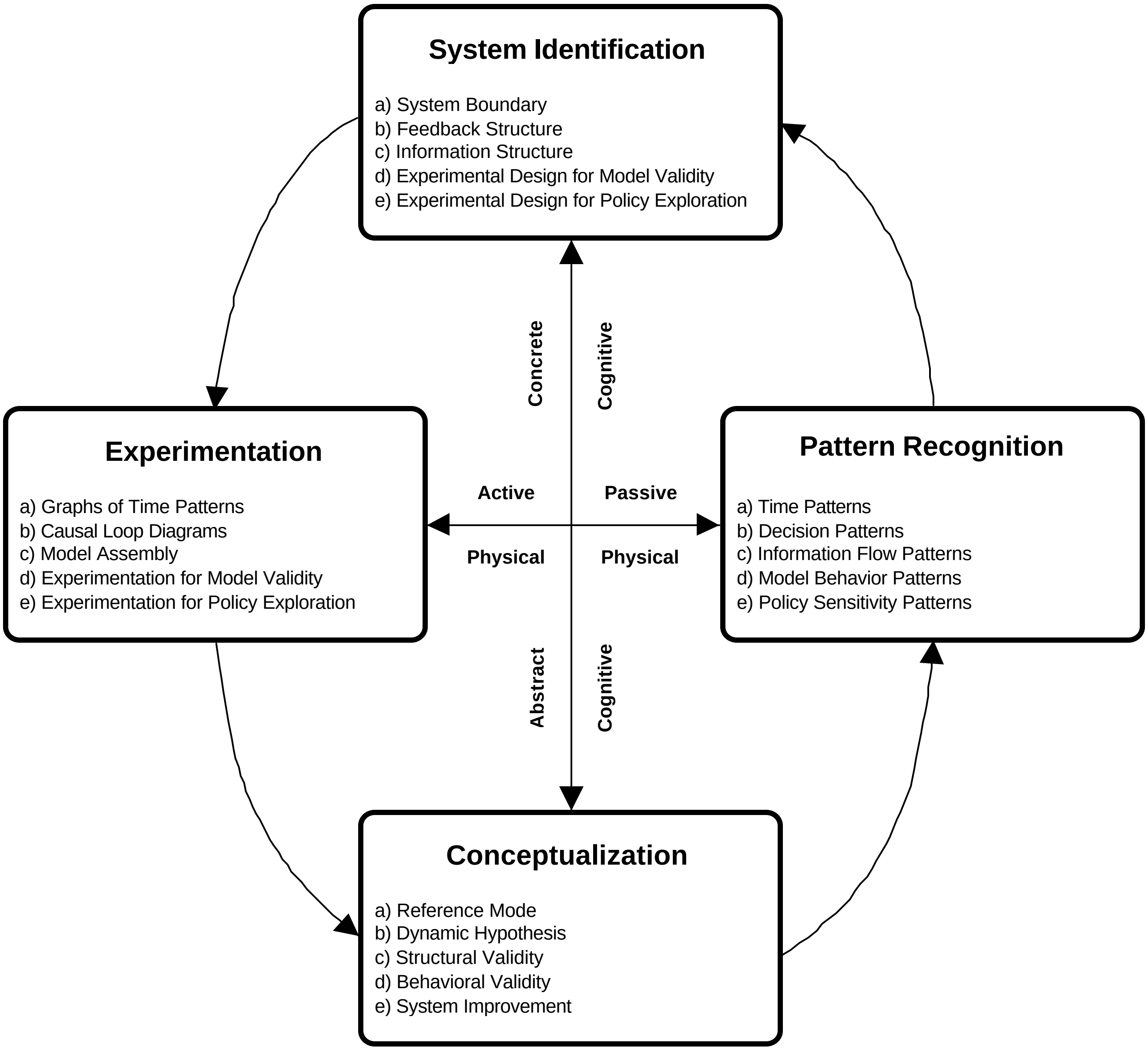

Figure 6: System Dynamics Interpretation of Kolb's Model of Experiential Learning

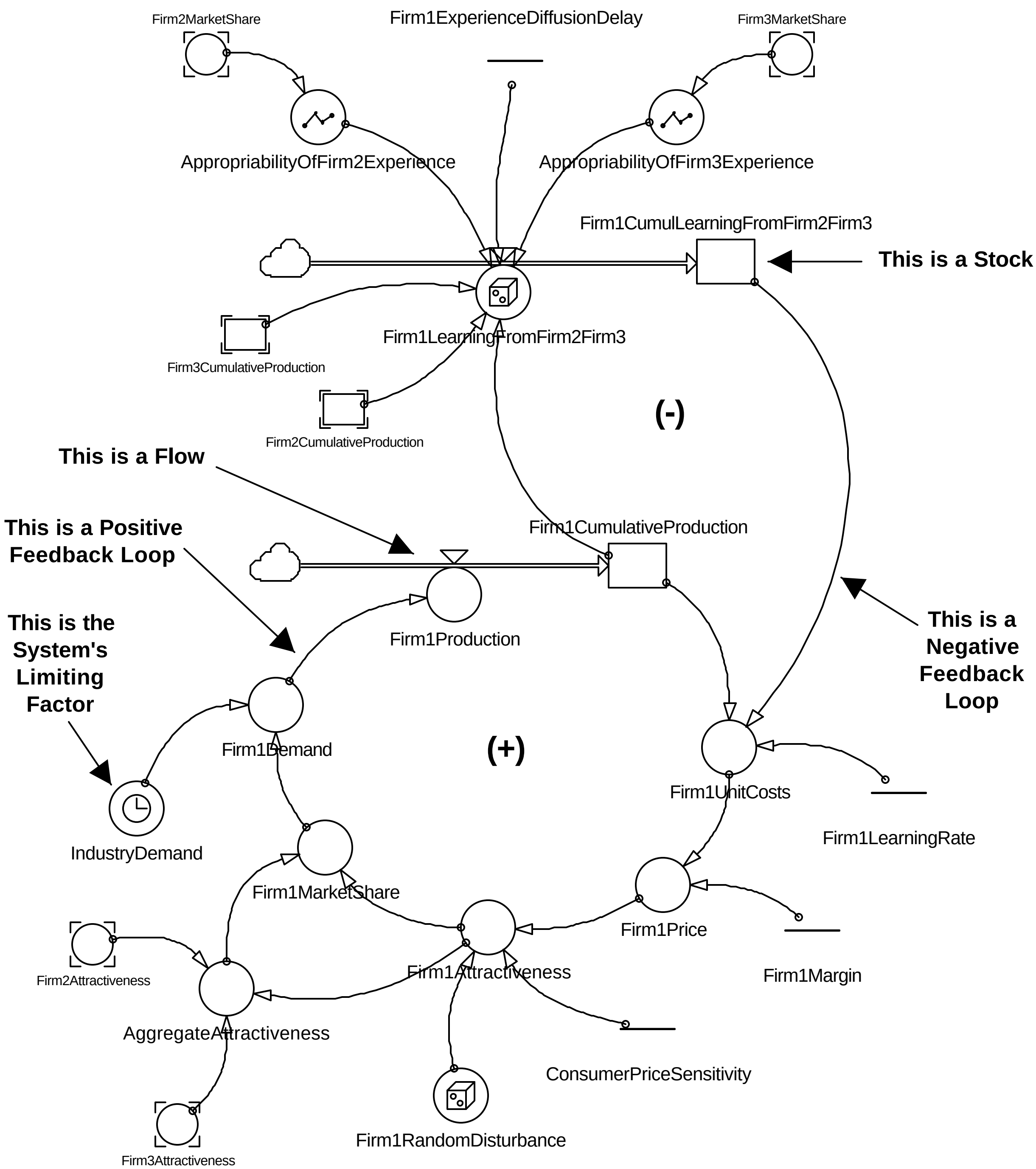

Figure 7: Firm #1 Sector from the Evolutionary System Dynamics Model

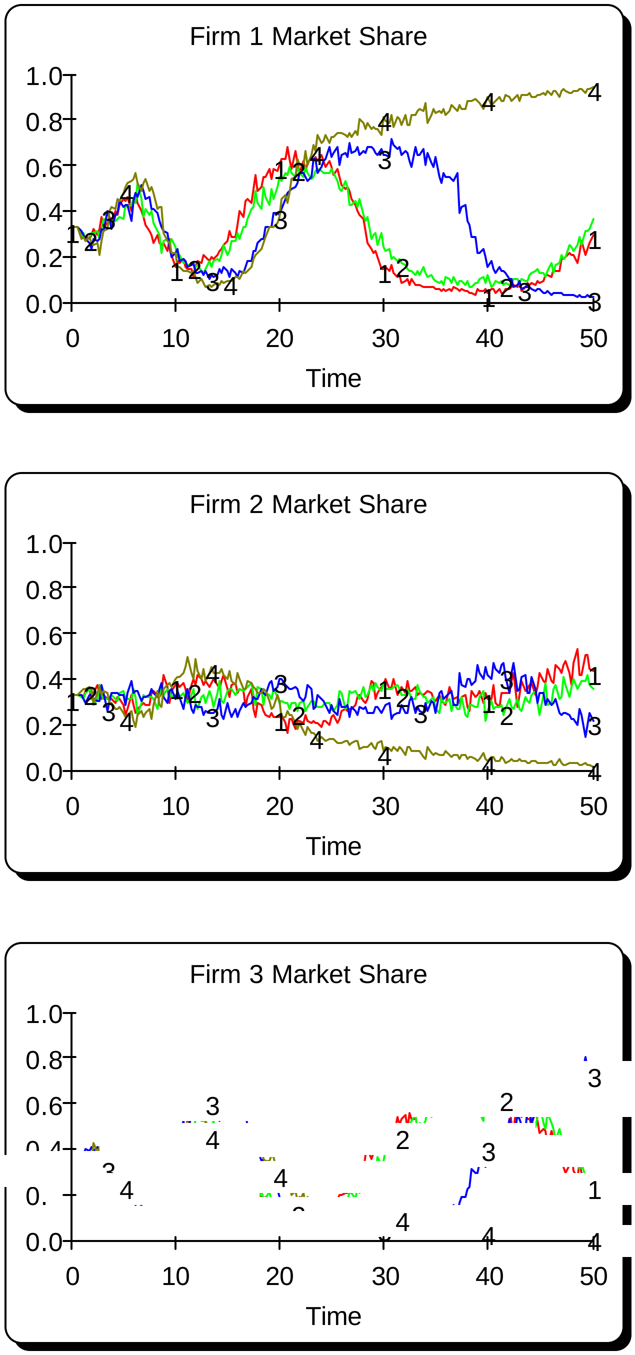

Figure 8: Four Simulations from the Evolutionary System Dynamics Model