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EVOLUTIONARY ECONOMICS: AT THE CROSSROADS OF BIOLOGY AND PHYSICS

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EVOLUTIONARY ECONOMICS AT THE CROSSROADS OF BIOLOGY AND PHYSICS

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Abstract

For almost a century, evolutionary economics has been based to a significant extent on analogies derived from biology. At the same time the discipline suffered from lack of analytical rigor. Recently, advances in thermodynamics and information theory have provided a new foundation for evolutionary studies in biology and economics alike. As a result, the body of studies in evolutionary economics that imports concepts from thermodynamics and information theory to develop new analogies is growing. This paper surveys recent trends in evolutionary economics at the crossroads of biology and physics, and argues to supplant analogies derived from either of the two disciplines. Albeit powerful means to crystallize thought about evolutionary processes in economic systems, analogies from biology have tended to plaster over the many differences between biological and economic processes that are essential to economic systems. Similarly, thermodynamics and information theory cannot provide a non-anthropocentric evaluation of economic processes. Yet, the concepts and measures available from physics can be used to improve our understanding of economic evolution if properly placed into the context of socioeconomic processes. The paper delineates the realm for non-analogy based applications of concepts from physics for the assessment of economic processes in light of discontinuities and emergent complexities.

Key Words: Evolutionary Economics, Analogy, Biology, Nonequilibrium Thermodynamics, Information Theory, System Theory, Modeling.

EVOLUTIONARY ECONOMICS
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1. Introduction

The need for economics to embrace evolutionary change rather than portrait economies as mechanistic systems has long been recognized. Reference is frequently made to turn-of-the-century economists such as Thorstein Veblen who asked "Why is economics not an evolutionary science?" (1919, p. 56) and Alfred Marshall who remarked "that in the later stages of economics better analogies are to be got from biology than from physics" (1898, p. 314). These references are then accompanied by condemnations of contemporary mainstream economics as being static and lifeless (Boulding 1981, Georgescu-Roegen 1981, Norgaard 1985). Yet, there is considerable debate on how to interpret and best draw on concepts developed in biology and ecology to improve our understanding of economic processes (Barham, 1990, Khalil 1993). This paper contributes to that debate by investigating methods used to better understand and assess quantitative and qualitative changes of economic systems.

For the purpose of this paper, two broad directions of research in evolutionary economics are distinguished. First, evolutionary economics is replete with analogies derived from biology and ecology to interpret economic change. So many compelling arguments have been made using analogies that it would be a major oversight if not at least some of them were discuss in more detail. I will do so in the next section.

Recent advances in nonequilibrium thermodynamics, bifurcation theory, and systems theory highlight the role of small disturbances for a system's trajectories (Prigogine and Stengers 1987). Seemingly negligible events may irreversibly alter a system's development path. The notion of equilibrium as a goal for system development loses its meaning in a setting of constant flux. The concepts and mathematical tools developed to understand nonequilibrium systems have been making inroads into biology and ecology for decades. The second direction of research in evolutionary economics discussed in this paper has been following this path (Rosser 1991). However, the economists' fascination with these new tools has again often resulted in analogies rather than thorough analysis (Artigiani 1987).

There lies the danger ahead for evolutionary economics to close the circle that started with neoclassical economics, freely borrowing concepts from physics in a search for equilibrium, the ensuing fascination with biological and ecological concepts to discuss evolutionary change, and the subsequent return to analogies from physics, this time, however, in the name of evolutionary change. To provide a physical basis for understanding economic change, the third section of this paper presents some relevant concepts from nonequilibrium thermodynamics, bifurcation theory, and systems theory.

It has been argued that biology and thermodynamics can only provide analogies and identify problems but cannot supply answers to economic or technological problems (Saviotti and Metcalfe 1991). In this paper, I strongly disagree, though I admit that much of the discussion digressed towards establishing and defending semantics for classification of phenomena that are perceived as relevant in the context of economic evolution (Khalil 1990, Resnick and Wolff 1994). Further pursuit of evolutionary analogies is likely to add little to our ability to analyze the processes in action and may even stultify scientific progress. It is no surprise that the discipline of evolutionary economics remains in its infancy with respect to the sophistication of tools used in empirical analyses as long as its adherents cling to the use of analogies.

Problems in evolutionary economics are further aggravated by the fact that biologists and ecologists themselves do not have a unique evolutionary theory to offer, albeit their differences may seem at first glance small from an economist's perspective. Ironically enough, some popular texts in evolutionary biology make use of *mechanistic* analogies, leading many to identify evolution with mechanistic feedback processes that govern a system's development. Take, for example, Dawkins' elegant portrayal of Darwinian evolutionary theory (1987, p. 5) as a blind watchmaker:

> "All appearances to the contrary, the only watchmaker in nature is the blind forces of physics, albeit deployed in a very special way. A true watchmaker has foresight: he designs his cogs and springs and plans their interconnections, with a future purpose in his mind's eye. Natural selection, the blind, unconscious, automatic process which Darwin discovered, and which we now know is the explanation for the existence and apparently purposeful form of all life, has no purpose in mind. It does not plan for the future. It has no vision, no foresight, no sight at all."

No doubt, a mechanistic view of evolutionary processes, at times fostered even in the name of complexity theory (Kauffman 1992), is very attractive to economists raised with the Newtonian paradigm. Its appeal stems, in part, from the fact that some of the tools used to describe complex systems on the basis of feedback processes can directly be brought to bear in evolutionary economic analyses. The system theory that underlies it is one of ordinary complexity; a simple teleology, such as growth and survival, is assumed (Funtowicz and Ravetz 1994).

There is more to evolutionary change than the potentially complex interactions of system components. Emergence of novelty cannot be explained with mechanistic tools. Entirely new species may emerge or new processes may be invented. The possibility and significance of fundamentally unpredictable events poses notable problems for a discipline interested in making predictions about the future. The ability to cause change is concomitant with the knowledge that resides in the system. Knowledge, in turn, originates from interacting with the environment, exchanging materials, energy and information. Section 4 relates material, energy and information flows to knowledge in order to better understand the evolution of economic systems. Concepts and measures developed in physics can be used to assess relationships between material and energy use, information flows and knowledge. Although these concepts are by themselves too basic to capture the richness of socioeconomic change, they provide a starting point for an assessment of evolutionary processes. In the final section I argue that in order to propel evolutionary economics towards empirical analysis requires case studies, experiments and modeling that capture the relationships among material use, energy transformation, information flows and knowledge generation. The respective models must treat the systems of their investigation not as being made up of “representative” individuals but as heterogeneous agglomerates whose evolution is determined by the interactions among its constituents.

2. Evolutionary Analogies

Over the years, evolutionary analogies have been used and refined to make us aware of the role of change at all levels of system organization. Analogies are powerful tools to crystallize thought about one system by employing language or concepts already established in another discipline for that discipline’s object of investigation. The use of analogies becomes even more appealing if there is significant overlap of the systems studied by separate disciplines. For example, humans and their interactions with the biological and physical environment are the result of biological evolution. They are also players in the economic system in which they interact with each other and their environment. The fact that both systems constantly change and that biologists and ecologist have already developed powerful ways of looking at the causes and effects of this change on a biological level begs for adoption of their language and concepts in economics.

Three examples of the use of evolutionary analogies are discussed here. The examples are not meant to represent the entire spectrum of evolutionary analogies but highlight their role in determining some directions evolutionary economics has recently taken. The first of these examples is concerned with evolution at the level of the individual, such as a firm, the second with larger systems, such as institutions or entire economies. Both of the first two examples deal with analogies derived from biology and ecology. The third example illustrates the use of analogies from physics at the system level. The latter are more recent, having been spurred by the works of Prigogine and his co-workers (Prigogine et al. 1972, Prigogine 1980, Prigogine and Stengers 1987) which already provided a major impetus for evolutionary research in biology and ecology (Yates 1987). The boundaries among each of these research avenues remains malleable.

Evolution at the Level of the Individual

The predominant use of the evolutionary analogy in economics can be found in the context of the behavior of individual firms. Firms are treated like organisms; their "genetic make-up" is given by their technologies, knowledge structures and organization, which enable them to survive in an ever changing socio-economic environment. Their "gene pool" is enlarged through acquisition or generation of knowledge. Acquisition may occur by imitating or merging with competitors, buying capital goods or hiring new employees. Knowledge is generated when new experience is gained as a result of imitations or mergers, through the execution of acquired capital goods, the integration of new employees into the organization, or active engagement in research and development activities. Firms with the ability to utilize their knowledge in the struggle to survive are considered the fittest if they are able to outperform their competitors. Loss of competition and "extinction" from the market place is thus considered a "natural" process resulting from each firm's characteristic, its interaction with other firms and its ability to respond to unforeseen, possibly random, fluctuation in their environment.

This view is frequently associated with studies by Nelson and Winter (1982), Silverberg, Dosi and Orsenigo (1988), Rahmeyer (1989), Silverberg (1990) and others who draw, at least partially, with their evolutionary modeling efforts on concepts developed by Schumpeter (1934, 1954). Extensive criticism of the failure to properly treat fundamental dissimilarities in the acquisition and maintenance of knowledge of the firm and of an organism can already be found in Penrose (1952). A more recent assessment of the scope and limits of the reduction of evolutionary behavior to the level of the individual firm is provided in Businaro (1983).

Of interest here are not the many pitfalls of superficially drawing analogies but the lack of consciously working out and building on the many differences in the evolution of organisms and firms to direct future research (Freeman 1992). Rather than exploring and learning from these differences, ever more efforts are made to extend the analogy of biological evolution and the evolution of the firm to the evolution of artifacts and innovations themselves (Boulding 1981, Lorenz 1984, Clark and Juma 1987). This tradition seems to have found its culmination in Faber and Proops (1990) who define evolution as "the process of the changing of something over time" (p. 16) in their search for a grand unifying theme to explain all change in the physical, biological and economic world. The perceived need to accommodate all possible sources of evolutionary change in one definition sacrifices concreteness and compromises the ability to develop meaningful instruments for empirical analysis.

Evolution at the System Level

Studies that utilize the evolutionary analogy at the systems level frequently concentrate on economic development (Dunn 1971, Boulding 1978) and the emergence, role and functioning of institutions (Tool 1988). Norgaard (1984a, 1984b, 1985, 1988, 1994) provides one refinement of these analogies by promoting a "coevolutionary" perspective of economic development. This view is based on a particular type of evolutionary change in which the evolution of closely interacting species occurs in response to the other species' evolution.

> "Coevolutionary explanations have been given for the shape of both the beaks of hummingbirds and the flowers on which they feed, the behavior of bees and the distribution of flowering plants, the biochemical defenses of plants and the immunity of their insect prey and the nature of numerous other closely interacting species or subcomponents of ecosystems. The concepts can be broadened to encompass any ongoing feedback process between two evolving systems including the interaction and evolution of social and ecological systems" (Norgaard 1985, p. 385).

Although intriguing in many respects, the establishment of analogies of biological co-evolution and socioeconomic change is prone to at least two points of criticism, notwithstanding the fact that the co-evolutionary concept is surrounded by much controversy even in biology (Futuyma and Slatkin 1983). First, Norgaard's plea for a coevolutionary perspective on economy-environment interactions is based on a giant leap spanning from interactions of organisms and their biotic environment to the development of economic systems. Unfortunately, the analogy of changes in interactions among animals and plants with their biotic environment and changes in economy-environment interactions is never explored in detail and remains rather dubious. Second, Norgaard's reference to an ecosystem dissolves economy-environment boundaries while it attempts at the same time to explain interactions between the economic system and its environment and to propose institutions governing these interactions (Ruth 1993).

On a more fundamental biophysical level, analogies between economic and ecological processes have been drawn under the heading of industrial metabolism (Ayres 1989a, 1989b, 1989c) and industrial ecology (Graedel and Allenby 1995). Here, the use of materials and energy and the release of waste products by economic processes are likened to the use of materials and energy by organisms for their maintenance and growth, and the excretion of waste products into the biogeochemical cycle. Ayres outlines interdependencies of changes in the atmosphere, geosphere and biosphere over geologic time, noting the ensuing improvements of organisms in their efficiency to utilize materials and energy. He concludes that

> "it is increasingly urgent for us to learn from the biosphere and modify our industrial metabolism, the energy- and value-yielding process essential to economic development. Modifications are needed both to increase reliance on regenerative or sustainable processes and to increase efficiency both in production and in the use of by-products" (Ayres 1989a, p. 23).

With its emphasis on the role of material and energy for change in the economic system and its interaction with the environment, the concept of industrial metabolism provides a stepping stone from the traditionally biology and ecology oriented evolutionary analogies to the use of concepts from physics for the understanding of socio-economic change.

Evolutionary Analogies from Physics

One school of thought in evolutionary economics contrasts the mechanistic, reversible treatment of economic processes by reverting to analogies from modern physics and chemistry, where randomness, discontinuities and irreversibilities play a major role. Emphasis is placed on nonlinearity of system processes and nonequilibrium system states rather than linearity and equilibrium (Nicolis and Prigogine 1977, 1989).

Nonequilibrium systems can be nonliving systems, such as tornadoes or lasers, and living systems, such as cells, organisms or entire ecosystems. Nonequilibrium systems are capable of developing new structures when externally applied gradients, such as temperature gradients or gradients in material composition, are increased. For example, if temperature gradients are sufficiently high, the typically slow upward movement of warm air and subsequent cooling are ineffective means to take advantage of and degrade these gradients. The formation of tornadoes enables a more efficient means of sucking in cold air over large areas and dissipating the energy. Their structures are easily discernible and are being maintained as long as the gradients are sufficiently large.

Development of new structures in response to changes in gradients in a system's environment can be observed not only in nonliving systems but also in living systems (May and Oster 1976). The analogy of discontinuities in physical and socioeconomic structures prompted application of the same mathematics in the social and economic context (Day 1982, 1983, White 1985, Wagenhals 1986). Recently, it has been argued that

> "it is clear that acceptance of nonequilibrium thermodynamics as a cornerstone of economic inquiry leads one to a certain kind of metaphorical vision. Not the vision of a lukewarm cup of coffee that has settled to the temperature of the surrounding room [...] but [...] a living thing of beauty that continuously seeks to maintain and reproduce itself through history. That metaphor is the appropriate starting point for a dialog between natural and economic science [...]" (England 1994, p. 221).

Based on the analogy of selforganization in physical, chemical and biological systems, inferences are made with regard to the sustainability of natural resource use and population growth (England 1994) to the role of revolutions in an historical and socio-economic context (Artigiani 1987), trading of assets, and effects of technology on the efficiencies of production and trade (Reiss 1994).

Presented with perhaps one of the greatest challenges and opportunities to counter the traditional, mechanistic view of economic processes, some evolutionary economists seem to have fallen into the same trap as early neoclassical economists who have freely adopted concepts and tools from classical physics to draw elaborate analogies instead of seriously considering the uniqueness of economic processes. Properly understanding core concepts and limitations of nonequilibrium thermodynamics is an important prerequisite for moving evolutionary economics beyond analogies towards a science in its own right. The following section attempts a brief outline of these concepts. Their relationship to economic processes is discussed afterwards.

3. Thermodynamics and Evolutionary Processes

Which are the concepts of thermodynamics that are essential for our understanding of evolutionary processes? How can we build on these concepts to assess evolutionary change in a system? Where do these concepts fall short? These are the questions this section intends to answer. Once delineated, the answers will be used to elucidate directions for evolutionary economics to go beyond the use of analogies from biology and physics by establishing relationships among material, energy and information flows, knowledge, and evolution of the economic system.

Thermodynamics is the discipline concerned with changes in the quantity and quality of energy. All change, whether physical, chemical, biological, or economic, is accompanied by energy flows. The evaporation of water from a puddle, the corrosion of metals, the maintenance of organisms, and the production and consumption of goods and services in an economy all result from, or lead to, energy flows across the system boundaries that delineate the puddle, piece of metal, organism, firm or consumer from its environment. The first law of thermodynamics tells us that the net amount of energy added to the system equals the net increase in its stored energy. The first law provides a simple yet powerful method for balancing energy inputs against outputs, accounting for waste heat generated in the process.

As a process occurs, the energy's ability to do useful work is reduced. This degradation in the quality of energy is captured by the second law of thermodynamics. Entropy is the concept most frequently invoked when measuring this change in energy quality. Entropy, a measure of disorder of a system, is said to increase in all natural processes. The state of maximum entropy is one in which there are no gradients in temperature, pressure or material composition between a system and its surroundings. In the absence of these gradients the system is unable to change, or exert change on its environment.

The need of living systems to compete for low entropy was already recognized by Boltzmann (1886) and discussed in more detail by Schrödinger (1944) who observed that living systems exhibit two fundamental processes. One of these is associated with the creation of "order out of order", and is manifest, for example, in the reproduction of DNA. The other is termed by Schrödinger "order from disorder" and is present in the creation of life out of disordered, randomly distributed atoms and molecules. The latter process has received considerably less attention in the literature, yet serves to link biology with the fundamental laws of thermodynamics (Schneider and Kay 1993).

The second law of thermodynamics seemingly violates the evolution of life as a process leading to increasingly complex structures. Reconciling the two phenomena of increasing entropy and increasing complexity, Schrödinger (1944) emphasizes that living systems are open systems that maintain their structure and function by using low-entropy energy from their environment. As a result, high entropy levels are created locally within the systems at the expense of the entropy budget of the surroundings. The net effect is a decline in total entropy. Systems that exchange mass or energy with their surroundings and temporarily maintain themselves in a state away from thermodynamic equilibrium and at a locally reduced level of entropy are called nonequilibrium systems.

Concepts developed in nonequilibrium thermodynamics are particularly suited for the analysis of changes in organization and complexity of open systems. The concept of entropy production, P, is central to nonequilibrium thermodynamics. If an open system is not in, but close to, its equilibrium position, the entropy generated inside the system per unit of time, d_iS/dt, is the sum of the products of the rates J_k and the corresponding n forces X_k (k=1:n) such that

$$P = \frac{d_iS}{dt} = \sum_{k=1}^{n} J_k X_k > 0 \tag{1}$$

for naturally occurring processes (Prigogine 1980). The rates J_k may characterize, for example, heat flow across finite temperature boundaries, diffusion, or inelastic deformation, accompanied by generalized forces X_k such as affinities and gradients of temperatures or chemical potentials.

In the steady state, the entropy production inside the open system must be accompanied by an outflow of entropy into the system's surroundings. Systems approaching the steady state are characterized by a decrease in entropy production, i.e. $dP/dt < 0$. Even though originally developed for non-living, physical systems, this "minimum entropy principle" serves as a cornerstone in many thermodynamic analyses of living systems (Johnson 1981, Gladyshev 1982, Schneider 1988).

Equation 1 holds only close to a local equilibrium. Far from equilibrium, it is typically not appropriate to assume the suggested linearity. There is considerable debate, in how far the "close-to-equilibrium" assumption can be maintained for the analysis of production and consumption processes in living systems, engineering systems or economies. If the corresponding systems are far from equilibrium, using equation 1 to assess system change may be circumspect at best.

In the nonlinear realm, systems can be characterized by a generalized potential, the excess entropy production. Excess entropy production is defined as

$$P_E = \sum_{k}^{m} \delta J_k \, \delta X_k \tag{2}$$

with δJ_k and δX_k as deviations from the values J_k and X_k at the steady state. Unlike for systems in, or close to, equilibrium the sign of P_E is generally not well defined. However, close to equilibrium the sign of P_E is equal to that of P (Glansdorff and Prigogine 1971).

Calculations of excess entropy production show decreases in P_E in open systems moving towards steady state. For example, an increase in temperature gradients in a far-from-equilibrium systems may trigger increasingly complex structures, as Bénard's experiments clearly demonstrate (Prigogine 1980). The evolution towards these structures is typically not smooth but accompanied by discontinuities and instabilities. In the critical transition point between stability and instability, a more complex structure emerges and $P_E = 0$ (Glansdorff and Prigogine 1971). Excess entropy production can therefore serve as a measure of changes in the structure and stability of a system. However, its applicability to real, living systems and especially to economic systems is severely limited by the lack of data sufficient for meaningful calculations (Ruth 1995).

What is of interest at this point is not so much how to quantify changes in the structure and stability of a system. Rather, we need to be able to properly identify and measure gradients in the system's environment that are necessary for the system to develop towards higher complexity. We need to acknowledge, and preferably anticipate, the transition points in the change of complexity that are an inherent feature of far-from-equilibrium systems. Anticipating transition points in economic systems is not possible if we restrict ourselves to a purely physical analysis of economic processes based on the concepts discussed so far, or if we simply pursue analogies. Economic systems not only exhibit ordinary complexity that can, at least in principle, be assessed with thermodynamics, but also emergent complexity, the manifestation of novelty.

Recent advances in thermodynamics may help us explain emergent complexity from a physical perspective. Building on the work by Hastopulos and Keenan (1965) and Kestin (1966), Schneider and Kay (1994a) provide a statement of the second law of thermodynamics that does not draw on the definitions of entropy, entropy generation, and excess entropy production, and thus avoids the "equilibrium vs. close-to-equilibrium vs. far-from-equilibrium debate" that plagued for so long the application of thermodynamics to living systems. This restated second law of thermodynamics posits that systems that are moved away from equilibrium will counter the applied gradients. The system's ability to oppose further movement from equilibrium increases as the applied gradients increase. This new interpretation of the second law of thermodynamics provides a cornerstone in discussing teleology and assessing emergent complexity.

Evolution of life on earth occurred in a setting with considerable thermal and chemical gradients in which complementary molecules paired up long enough for chemical reactions to take place and to temporarily resist destruction (Rebek 1994). The resulting structures formed "chemical factories" that degraded solar radiation incident upon the primordial soup (Wicken 1978, 1979). In the process, new molecular structures are developed and later "fed upon" by the chemical factories, resulting not only in ever larger possibilities for recombination but also in ever more ways to degrade the incoming energy into waste heat.

Over time, the living systems that feed on the gradients in their environment and "excrete" high entropy should become stable — a hypothesis consistent with the findings by Prigogine and his coworkers and subsumed under the heading of *emergent stable dissipative structures* (Schneider and Kay 1994b). The emergence and evolution of life and the development of increasingly complex structures are thus explained as means for degrading externally imposed gradients. The teleology this applies, however, is not a simple one.

The fate of dissipative structures depends on perturbations imposed on the system by changes in the gradients of the system surroundings. When stability thresholds are exceeded, the system experiences a transition to a new structure and will offer a new "solution" to the problem of degrading gradients. Even small changes in the system's environment may thus lead to fundamentally different states of the system; new mechanisms — new species — may evolve in response to the externally imposed change (Ruth 1993).

Nonequilibrium thermodynamics tells us that changes in environmental constraints — gradients present in the environment — call for the response of the system to take advantage of, and degrade, those gradients. Since other populations are part of the environment, their response to changes in environmental constraints imposes new constraints. It is in this sense, that coevolution persists.

Bifurcation theory is the mathematics that deals with such discontinuities. From it, chaos theory and catastrophe theory emerged (Rosser 1991). Each of those, with a different focus, contrast markedly with the mechanistic world view by emphasizing the role of history in system development and the inability to forecast future trajectories on the basis of insufficiently known initial conditions. In this context, Heisenberg's uncertainty principle takes on a real meaning for the assessment of evolutionary change.

How can we model, let alone anticipate, system change if nonlinearities, bifurcation, chaos and catastrophe loom? Fortunately, the world is not permanently at the brink of chaos and catastrophe. Rather, system trajectories are often known over large domains (Gorshkov 1995). It is within this realm that we can make predictions, though the further we predict into the future, the less we can be sure to remain within this realm.

Systems such as biological populations consist of many individuals that may be characterized, for example, by their genetic make-up, phenotypic characteristics or their ability to learn. Deterministic models of system change have been built on the average individual in such a population, its interactions with others and the environment. Predictions with such models may safely be made for the short term if the majority of individuals are not too different from the average, and if environmental constraints on the system fall within the range of those experienced by the population in its immediate past. As mutations, changes in phenotypes or learning occur, the characteristics of the population are altered and the rules used to model the behavior based on the average are no longer valid (Allen and Lesser 1991, Allen 1994). I will return to this issue below.

The restated second law provides a direction for change of the overall system. Combined with knowledge of the *average* individual in a population and the rate at which non-average behavior affects mechanisms that determine change of the population, we can make use of thermodynamics to delineate the realm within which models and empirical analyses can contribute to the assessment of evolutionary processes. How we can build on this understanding and assess evolutionary change in the economy is discussed in the following section.

4. The Role of Materials and Energy in Generating Knowledge

The Sustenance of Economic Activity

What is so different in an economy from the physical and biological systems discussed above that limits the applicability of thermodynamics to economic processes? The descriptions physics can provide are basic, dealing with material and energy flows in response to gradients imposed on a system by the environment. When physical principles are applied to living systems, the systems typically are analyzed at either very fine or very coarse resolutions such as a cell under laboratory conditions or an entire ecosystem. Note the lack of concrete judgments that are possible about the demise of individual organisms or even populations that can be made by using thermodynamics. Yet, intermediate levels of organization, such as households and firms, are the most tangible in economic decision-making. Furthermore, the evolutionary concepts derived from physics are inapt in accommodating the conscious influences of humans that take place at that level. Thus, it seems prudent at the current stage of development of the concepts, to apply thermodynamics to larger entities in an economic system or entire economies than to decision making of individuals.

Once the appropriate level of analysis has been identified, the question becomes how to measure and assess evolutionary change. For physical and biological systems, measurement is typically done in terms of energy flows across system boundaries. For example, measurement of energy fluxes into and out of old growth forests in comparison to less complex ecosystems, such as plantations or barren ground, indicate that indeed the more evolved ecosystems possess a higher ability to degrade the gradients imposed on them (Luvall and Holbo 1991). Similarly, energy-flux based studies can be done for socioeconomic systems, as has been illustrated by Hannon et al. (1993) for the case of industrial and Amish agriculture. Judging the possible direction of evolutionary change in an economy, from these energy-based studies however, is difficult.

The relationships between energy flow into the economy and economic growth and development have long been recognized. The substitution of high-quality fuels such as coal, oil, natural gas and uranium, for animal and human labor, wood and other low-quality energy sources made possible the unprecedented expansion of economic activity since the industrial revolution (Cleveland et al. 1984, Hall et al. 1992). Long cycles in economic activity have been linked to break-throughs in energy conversion technologies (Ray 1983). Dramatic increases in the GDP/energy ratio in most countries during the second half of this century further elucidate the relationship of technological innovations, energy efficiency improvements and economic growth (Kaufmann 1992).

The relationships between material use and economic growth and development are less conspicuous. Although the role of material endowments and the availability of material processing industries, such as the presence of metal mining and manufacturing sectors, have often been cited as a contributor for long-term economic well-being (Hartwick 1978a, 1978b, Stern 1995) recent trends in material use seem to indicate a decoupling of material consumption and economic growth and development in industrialized nations (Larson et al. 1986).

Ever smaller amounts and more specialized materials are being used to generate a unit of output with the use of high-quality energy sources and advanced technology. At the same time, the quality of the output itself changed dramatically to meet the specialized needs of consumers. The increasing number of sophisticated services provided across the information super highway is virtually devoid of material inputs. Their presence further illustrates the decoupling of economic growth and development from material sources and the continued need for high quality energy, for example, to display, transmit, and reliably store and access data. Recent advances in computer hardware technology are in the direction of using biologically- rather than minerals-based media for data storage, capitalizing on natural processes to “synthesize” and store information and knowledge.

It is not only the change in the quantity and quality of inputs into economic processes that is fundamental to the evolution of the economy, but the fact that economic change feeds on itself. Can thermodynamics provide measures of change in material and energy inputs and economic output that are indicative of evolutionary processes? At what resolution is such a quantification valid and meaningful?

The concepts of information and knowledge can be defined from a thermodynamic perspective and linked to the material and energy sources used in an economy. They are general enough to encompass changes in output quality, technology, even changes in socio-economic characteristics that are concomitant with economic evolution.

Information and Knowledge

The relation between energy and information is fundamental in thermodynamics, having served to refute Maxwell's demon (Maxwell 1867, Leff 1990), and thus to confirm the validity of the second law of thermodynamics (Szilard 1929). The information concept has been adopted by Shannon (1948), Shannon and Weaver (1949) and Wiener (1948) in the context of communication theory. Information was defined in communication theory as a measure of uncertainty that caused an adjustment in probabilities assigned to a set of answers to a given question (Young 1971). Evans (1969) and Tribus and McIrvine (1971) formalized the connection between Shannon's work and thermodynamic information. Systems with lower entropy are more distinguishable from a reference environment by an observer, and thus, are able to convey more information to that observer than systems in equilibrium with their environment.

Recently, Ayres (1994) extended information concepts beyond the realm of thermodynamics, communication, and data processing. In his interpretation of the economy as an information transformation system, Ayres distinguishes three types of information, closely related to one another, and each measurable in terms of a common unit — bits. First, *thermodynamic information* is associated with chemical composition manifest in a system’s distinguishability from a reference state or reference environment. By the same token, geometric surfaces and patterns embody information by being distinguishable from each other. This second form of information is referred to as *morphologic information*. A third information concept is associated with control processes, and subsumed under the heading of *symbolic information*. Examples include the blueprints of machines and executable computer code.

Information concepts have found widespread application among engineers, are slowly penetrating thinking in biology and ecology and are now being taken up in the social sciences. Information concepts have been used to calculate the entropy of a machine (Berry 1972), the ability to process information as a function of information stored in a system (Moravec 1988) and, stressing the nonequilibrium character of systems, the order of a product (Berg 1988). Brooks and Wiley (1988) use it in the context of biological evolution. Recently, Spreng (1993) ranked economic activities by the relative importance of their output, measured by information, and compared over time various production processes by the information required to execute them. Chen (1994) investigates more closely the role of information as a factor of production. Ruth and Bullard (1993) go a step further by illuminating relationships among information, technology and material and energy use. Common to all these studies is the recognition of the fundamental role the concept of information can play in explaining the state and evolution of biological and economic activity. Its use is not by analogy but based on physical principles.

In contrast to information, knowledge comprises the ability for autonomous reproduction and change (Ruth 1995). Knowledge, as used here is equivalent to the concept of algorithmic information (Eriksson et al. 1987). In very general terms, knowledge is the result of information flows incident upon a recipient, that enable that recipient to generate new information. For example, gradients in material concentrations and temperature in the primordial soup enabled formation of simple structures that were not only distinguishable from their environment but also possessed the ability to change that environment. The emergence of catalytic RNA in a heterogeneous environment, in turn, not only led to change in the environment of these simple structures but, with chance, to the change of these structures themselves (Orgel 1994). Increasingly complex molecular structures evolved, functioning as the repositories of information flows and as generators of new information.

From a thermodynamic perspective, the ability of living systems to degrade gradients in their environment is indicative of their ability to harness information flows from the environment and to apply the resulting knowledge in a changing environment. The presence of gradients stimulates emergence of new life forms that utilize and degrade the gradients. The environmental gradients, biological structures and resulting material and energy flows can all be assessed with thermodynamic concepts. As a proxy, the evolution of life is assessed by establishing taxa and measuring genetic diversity.

Humans receive a multitude of information flows from their environment, such as sounds and light of different frequencies, that are captured by sensory organs and become translated into stimuli to the brain where they trigger chemical processes. These processes may lead, for example, to the formation or maintenance of synapses in the brain, possibly contributing to its knowledge. The generated knowledge, in turn, may be told or transcribed, in the form of an historical account of a person's experience, a piece of poetry, a blue-print for a machine, a hymn or code of law. Each of these transcriptions is measurable in terms of information. For example, the piece of poetry can be compared to a random arrangement of letters, the hymn to random noise. In order to assess the evolution of the socioeconomic system we need to quantify the information flows that are generated from the accounts, rather than the information content of the accounts themselves. This will be difficult in real-world applications. Similar to the case of biological evolution, quantification of information storage in repositories such as libraries, data bases, capital equipment or the legal system must suffice.

It is important to recognize that information and knowledge as used here are physical concepts whose interpretation in an economic context requires special care. Thermodynamics cannot provide absolute, objective or non-anthropocentric measurement of system change. Rather, any thermodynamic analysis begins by defining system boundaries in space and time and by selecting a reference system to assess system change. Both of these processes require value judgment on the part of the human investigator (Denbigh and Denbigh 1985, Ruth 1993, Månsson 1990, 1991). By the same token, note the emphasis that is placed in communication theory on the uncertainty that resides with an individual observer. Again, it is impossible to define and measure information irrespective of invoking an observer. Thus, there is no non-anthropocentric method to measure the information content of a system, and the choice of information concept — and for that matter any thermodynamic concept — depends on the system of interest.

The descriptions of systems and the assessment of system change provided by thermodynamics are so compelling to serve as a basis for evolutionary economics *because* human value judgments only enter at the very beginning of the analysis when system boundaries and reference systems are defined. Once this first step has been taken, it becomes a straightforward exercise to calculate the information content, for example, of a piece of music. However, since anthropocentric judgments are excluded from the subsequent analysis, it is not readily obvious how to "value" the contribution a piece of music has to a listener within a specific historical, cultural or social context. The French and German national anthems contain virtually the same information when compared to random noise. However, they will be perceived quite differently by people in France, Germany, Great Britain or Zimbabwe, depending not only on the listeners' nationality but a number of other factors, such as the time in which they grew up.

Physics alone cannot provide the measuring rod when assessing the contribution of information and knowledge to evolutionary change in the economy. To move from the physical descriptions to assessments that are meaningful from an anthropocentric perspective requires that we build on the knowledge generated in disciplines that choose this perspective for their investigations. Here is where the disciplines of psychology, anthropology and economics can make their mark.

5. Modeling Information Transfer and Knowledge Generation in the Evolutionary Economic System

To briefly recast the main points in the previous section: thermodynamics provides means to account for (i) the quality and quantity of material and energy flows, information and knowledge, (ii) changes in structure and function of systems in response to gradients imposed on a system, and (iii) system-environment interactions. Thermodynamics does not immediately offer a connection to human value judgments with regard to material and energy flows, information, knowledge, or system change. To be able to apply the thermodynamic concepts of information and knowledge to the evolution of economic systems requires extensive research and case studies at various levels of organization, ranging from individual decision makers to large socio-economic systems.

With this discussion, we have seemingly digressed from the issues of nonlinearities, emergent complexity, novelty, and the ability of evolutionary economics to assess evolutionary processes. Let me return to them here and again make the connection to non-deterministic modeling already alluded to in Section 3. There, I stressed the need to specify system components and model their interactions to assess system change. If only the average behavior of system components is considered, the resulting model may help identify the role of nonlinearities and threshold effects for the system's dynamics but will be incapable of capturing emergent complexity.

What makes individuals different from each other is their ability to receive and disseminate information, generate knowledge, and thus their ability to bring about changes in the system. Nondeterministic system modeling that enables assessment of evolutionary processes must start with a group of individuals, each described by an endowment of knowledge, and interactions with other individuals. These interactions will be in the form of material, energy and information flows. As interactions occur, knowledge of each individual and in the system as a whole change, possibly altering the interactions among individuals and of individuals with their environment.

Of course, we will never be able to perfectly describe knowledge endowments, information flows, or interactions among individuals and of individuals with their environment, let alone fully anticipate all relevant environmental gradients imposed on the individuals. These caveats, however, stimulate, rather than limit, the application of nondeterministic models and extensive use of experimental approaches to economic evolution. Increased modeling and experimentation will improve our understanding of system processes and help us delineate the realms of likely system behavior. The following two examples illustrate the use of physical concepts in understanding the role of information and knowledge as a starting point for empirical analysis, experimentation and model development.

First, consider a primitive society using materials that can be easily collected from its environment. The materials may be worked from less desired to more desired forms, making use of human and animal labor and low quality fuels such as wood or peat. Material outputs are slightly more refined than the inputs, thus giving value to the products. The undesired outputs, such as waste materials, are not fundamentally different in their thermodynamic state from the materials entering the production processes. For example, clay is extracted from the environment, shaped by hand and with the use of simple technologies, then dried in the sun or burnt in an oven. Bits of clay may be lost in the process in the form of shavings or in the water used when shaping the form. In either case, the waste products are not very different from the raw materials. The changes in the quality of energy are small. The production process is characterized by small information flows across the economy-environment system boundary. The contribution to the knowledge of the society, its ability to autonomously bring about change in its environment in the future, is also small but not negligible, as human history, following the advent of pottery, illustrates. Technologies are refined by observing the cause-and-effect relationships associated with the changes in states of materials and energy quality and by passing that knowledge on to the next generations in the form of verbal instructions or written accounts.

As knowledge increases, so does the ability to utilize a variety of materials and energy sources, and to produce increasingly specialized products from them. As a result, the ability to actively cause change in the physical, but also biotic and socioeconomic environment of the simple society, is enhanced. Trying to understand the rise and fall of societies in relationship to material and energy use, complexity of production and distribution of goods and services — in short, a society's knowledge — has a long history in anthropology (Cronon 1983, Debeir et al. 1986, Tainter 1988, Perlin 1989). Relating socioeconomic changes to the exchange of materials, energy and information in and among simple economies, and their relationship to knowledge, may seem a worthwhile endeavor for evolutionary economics (Samuels et al. 1994).

As a second example, consider a set of firms each endowed with a fixed amount of materials and energy, an initial stock of knowledge, embodied in their machines, workers, and organizational structures. Materials and energy are used by a firm to generate a desired output and undesired waste products. Some of these materials come from the firm's endowment, others are acquired from other firms. As production occurs, the state of materials and quality of energy change. Commensurate with these changes are information flows that may contribute to knowledge endowments. This is the classical learning-by-doing.

Since a firm interacts with its environment through the acquisition of materials and energy, the release of waste products, and the sales of desired output, information flows occur also across the economy-environment system boundary. Part of the environment are other firms that function as suppliers or recipients in the exchange of goods and services. With this exchange, their knowledge changes. For example, they may directly use these goods and services in their production processes, triggering learning-by-doing, or they may learn from observing material and energy flows and make inferences on the technologies of other firms which lead them to imitate their competitors.

Some of the interactions of firms with their environment occur through exchange of goods and services with final consumers. Some of the goods consumed contribute to the maintenance of their "organisms" while some of the services enlarge the knowledge of consumers. A third type of interaction of firms may be with government institutions such as those that collect taxes, oversee production processes or output. For example, emissions are measured at the smoke stack to arrive at a proxy for likely impacts on the structure and function of down-wind ecosystems and the health of humans. The information, derived from measurements of material and energy flows, provides the basis for taxing pollutants and inducing adjustments in material and energy use, technologies in, and organizational structure of, production processes. Again, information flows are used to alter the knowledge associated with material and energy transformations.

If markets are perfect, prices are the relevant surrogates for all information flows in the economic system. However, the very possibility of discontinuities and novelty preclude markets to convey all the information about all possible current and future states of the system. As a result, there is no possibility that these markets can ever generate perfect knowledge that enables decision makers to perfectly prepare for future states by making the necessary adjustments in the presence. Information itself becomes a good for which firms, consumers, and government are willing to expend scarce resources (Laffont 1989) and as a result alter the environment within which decisions must be made.

The exchange and contribution of information to knowledge can be measured in physical terms. Its value to the firm, consumer or government institution, however, must be made from an anthropocentric perspective. This is where experiments, games and simulations may enrich economics. Recent advances in computer modeling, for example, provide powerful means for developing nonlinear dynamic models of complex economy-environment interactions (Hannon and Ruth 1994, Ruth and Hannon in press). Large numbers of individuals, each endowed with their own characteristic stocks of materials, energy and knowledge, can be modeled to interact with each other and their physical and biotic environment. Allen and McGlade (1986, 1987) provide a simple application of such models to the evolution of fishing strategies and fisheries management. Ruth and Hannon (in press) model bargaining for goods and services by individuals with different strategies and knowledge endowments. With each new bid in the bargaining process, new information becomes available to the decision makers, possibly leading to the exchange of materials and energy and a contribution to their knowledge.

At the crossroads of biology and physics lies the insight that material, energy and information flows at, and across, various levels of system organization are essential for the generation of knowledge and evolution of a system. Concepts from physics can help assess the contribution of material, energy and information flows to the evolutionary process. However, the descriptions physics can provide are basic. To be able to assess the contribution of information flows and knowledge to the evolution of production, consumption and control structures in the economy requires evolutionary economics to engage in non-deterministic modeling, experimentation and in-depth case studies. As compelling as analogies may seem, they do not provide the rigor to develop evolutionary economics into a science and cannot be substitutes for measurements and models.

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