Journal of Bioeconomics 6: 65–96, 2004

Toward a 0th Law of Thermodynamics: Order-Creation Complexity Dynamics from Physics and Biology to Bioeconomics

BILL MCKELVEY
The Anderson School at UCLA, 110 Westwood Plaza, Los Angeles, CA 90095-1481, USA
(mckelvey@anderson.ucla.edu)

Synopsis: The evolutionary economics part of bioeconomics has its origins in attempts to justify why only rational firms survive, or to introduce dynamics into economic orthodoxy. To the extent that these views persist, this aspect of bioeconomics appears outdated. A more recent view is that the most significant dynamics in bio- and econospheres are *not* variances around equilibria. Instead order is now seen to be due to the interactions of autonomous, heterogeneous agents energized by contextually imposed tensions induced by energy differentials. While Darwinian selection is still an important process at the tail end of the order-creation process, other natural forces surrounding the biosphere are seen as causing the more significant changes in biological entities over the millennia. This view is set forth within the framework of thermodynamics. It also calls for a change away from the definition of science rooted in the equilibrium mathematics of Newton's orbital mechanics. This new message from natural science is about rapid-fire dynamics calling for a fast-motion science of order-creation *before* the equilibria of the 1st Law of Thermodynamics take hold. The 2nd Law of Thermodynamics is seen to dominate the 1st Law as the root cause of change. The possibility of a 0th law – of agents' self-organization toward order creation – is considered. Key works by Prigogine, Ashby, Lorenz, Haken, Kelso et al., Salthe, Gell-Mann, Mainzer, Omnès, and Kauffman are reviewed. Nine premises – tracing the path toward an emerging 0th law – are discussed, with some variance also evident. The view of Kelso et al. most easily leads to a one-sentence statement of a possible 0th law of order creation that could offer something of value to bioeconomists.

Key words: thermodynamics, equilibrium, complexity, order, self-organization, evolutionary economics, synergetics, biology

1. Introduction

The evolutionary economics aspect of bioeconomics originates in attempts by Spencer (1898), Alchian (1950), and Friedman (1953) to use Darwinian selectionist theory to justify why only rational firms survive. Samuelson (1947) and Friedman (1953) draw on the mathematics of classical physics, its 1st Law of Thermodynamics (the conservation of energy law), and the centrality of equilibrium, to turn economics into a predictive science (Mirowski 1989, Witt 1999). To get economics out of its equilibrium-centric stance, Nelson & Winter (1982) use Darwinian selectionist theory to introduce dynamics into economic 'orthodoxy'. Now, Salthe (1993), Rosenberg (1994), Eldredge (1995), and Kauffman (2000) all recast Darwinian selectionist theory as an equilibrium-based theory as well. They conclude that the most significant dynamics in the bio- and econospheres are not variances around equilibria. While Darwinian selection is still important at the tail end of the order-creation process, the 'self-organization biologists' (Van de Vijver et al. 1998) see other natural forces surrounding the biosphere as causing the more significant changes in biological entities over the millennia. Self-organization biology stands as a logical additional component of bioeconomics.

Order in the bio- and econospheres, is now seen as the interactions of heterogeneous agents such as particles, atoms, molecules, organisms, people, and firms (Salthe 1993, Cowan 1994, Epstein & Axtell 1996, Kauffman 2000). In his book, *The Origins of Order*, Kauffman (1993, pp. 29–30) argues that when a system's complexity reaches a certain point, spontaneous order creation by the agents dominates order creation via Darwinian selection processes. The question is: *How and when does order emerge from the random actions of these agents?* Kauffman's assertion that order creation is spontaneous, however, glosses over a variety of theories emerging over the years that zero in on how probabilistic tendencies toward order creation emerge from the random interactions of autonomous heterogeneous agents. In several of these theories the agents are energized by contextually imposed tensions induced by energy differentials. This view is set forth within the framework of equilibrium thermodynamics (Prigogine 1955, Haken 1977, Salthe 1993, Depew & Weber 1995, Mainzer 1997). The 2^{nd} Law of Thermodynamics is seen to dominate the 1^{st} Law as the root cause of change. It also appears there is a search underway for a '0^{th} law' of order creation.[1]

I begin with a critique of the evolutionary/selectionist part of bioeconomics. Then, searching for a possible 0^{th} law, I piece together ideas from the European and American schools of complexity science, going from quantum physics through biology and into the econosphere. I extract nine premises that offer bioeconomists a view of order-creation dynamics *before* 1^{st} Law equilibria and Darwinian selection take hold. New order is seen to emerge at phase transitions. I present a metaview of how theorists in each field explain the emergence of probabilistic tendencies presaging order-creation at the point of phase transition. My treatment would not do justice to details in each discipline; if it did, it would lose its multidisciplinary perspective. My terms rest on familiar definitions broadly applicable across several disciplines, rather than being technically construed within the details of a single discipline; they are consistent with treatments of terms in the more cross-disciplinary works by Salthe (1993), Auyang (1998), Kauffman (2000), and Chaisson (2001).

2. Critiquing the evolutionary part of bioeconomics

Building on Spencer (1898), Alchian (1950), and Friedman (1953), among others, Nelson & Winter (1982) bring the most comprehensive treatment of Darwinian selectionist theory into orthodox economics. The essentials are: (1) genes replicate with error; (2) variants are differentially selected, altering gene frequencies in populations; (3) populations have differential survival rates, given existing niches; and (4) coevolution of niche emergence and genetic variance.[2] Orthodoxy develops the mathematics of thermodynamics to study the resolution of supply/demand imbalances within a broader equilibrium context. It also takes a static, instantaneous conception of maximization and equilibrium. Nelson & Winter introduce selection as a dynamic process over time, substituting routines for genes, search for mutation, and selection via economic competition.

Rosenberg (1994) observes that Nelson & Winter's book fails because orthodoxy still holds to energy conservation mathematics (the 1^{st} Law of Thermodynamics), the prediction advantages of thermodynamic equilibrium, and the latter framework's roots in the axioms of Newton's orbital mechanics, as Mirowski (1989) reports. Also, whatever weakness in predictive power orthodoxy has, Nelson & Winter's approach fails to improve it. Therefore, economists have no reason to abandon orthodoxy since, following physicists, they emphasize predictive science (Friedman 1953). Rosenberg (1994, p. 398) goes on to note that biologists have discovered that the mathematics of economic theory actually fits biology better than economics, especially because gene frequency analysis meets the equilibrium stability requirement for mathematical prediction. He notes in addition that two other critical assumptions of mathematical economics, infinite population size and omniscient agents, hold better in Darwinian selectionist aspects of biology than in economics.

Hinterberger (1994) critiques economic orthodoxy's reliance on the equilibrium assumption from a different perspective. In his view, a closer look at both competitive contexts and economic actors uncovers four forces working to disallow the equilibrium assumption:

1. Rapid changes in the competitive context of firms does not allow the kinds of extended equilibria seen in biology and classical physics.
2. There is more and more evidence that the future is best characterized by 'disorder, instability, diversity, disequilibrium, and nonlinearity' (p. 37).
3. Firms are likely to experience changing basins of attraction – i.e., the effects of different equilibrium tendencies.
4. Agents coevolve to create higher-level structures that become the selection contexts for subsequent agent behaviors.

Hinterberger's critique comes from the perspective of complexity science. Also from this view, Arthur et al. (1997, pp. 3–4) note that the following characteristics of economics counter the equilibrium assumption essential to predictive mathematics:

1. 'Dispersed Interaction' – dispersed, possibly heterogeneous, agents active in parallel.
2. 'No Global Controller or Cause' – coevolution of agent interactions.
3. 'Many Levels of Organization' – agents at lower levels create contexts at higher levels.
4. 'Continual Adaptation' – agents revise their adaptive behavior continually.
5. 'Perpetual Novelty' – by changing in ways that allow them to depend on new resources, agents coevolve with resource changes to occupy new habitats; and

6. 'Out-of-Equilibrium Dynamics' – economies operate 'far from equilibrium,' meaning that economies are induced by the pressure of trade imbalances, individual to individual, firm to firm, country to country, etc.

After reviewing all the chapters, most of which rely on mathematical modeling, the editors (Arthur et al. 1997, p. 12) ask: '... In what way do equilibrium calculations provide insight into emergence?' Most chapters miss the essential character of complex adaptive systems stylized in the list of six characteristics – heterogeneous agents in far-from-equilibrium systems.

The foregoing critiques have at their heart the question whether order-creation in the phenomena studied moves fast or slow relative to the equilibrium assumptions made by the classic mathematical sciences studying 1st Law energy translations. In the only textbook on complex system dynamics, Bar-Yam (1997) divides degrees of freedom into *fast*, *slow*, and *dynamic* time scales. At the time scale humans experience– 'dynamics' in Bar-Yam's terms – applications of thermodynamics to the phenomena of classical physics and economics assume that slow processes are fixed and fast processes are in equilibrium, leaving thermodynamic processes as dynamic. Thus, in the study of the thermodynamics of steam engines, the slow motion forces of geology and condensed matter physics are assumed fixed and the fast motion forces of quanta and chemical bonding are assumed in equilibrium. Bar-Yam (1997, p. 90) says: 'Slow processes establish the [broader] framework in which thermodynamics can be applied'. Now, suppose we speed up slow motion geological processes so that they appear dynamic at the human time scale – say to a rate of roughly one year for every three seconds. Then about a billion years goes by per century. It is like looking at a 3.8 billion year movie in fast-motion. At this speed we see the dynamic effects geological changes have on biological order – the processes of Darwinian evolution go by so fast they appear in equilibrium.

Taking the fast-motion view, we then discover that bioevolution occurs in a very thin layer sandwiched between two giant Bénard (1901) convection cells[3] – one in the earth's geology of lava plumes and tectonic plate sinks, speculated about by Salthe (1993, p. 107), and wonderfully analyzed and illustrated in Gurnis (2001), and one in the atmosphere (Lorenz 1963). The first is the engine creating the biosphere's geological context – rising and sinking continents, plate subductions, ocean trenches, volcanoes, mountain ranges, rivers, lakes, valleys, shifting landscapes, and ultimately the biological punctuations analyzed by Eldredge & Gould (1972). The second creates the climate on the earth's surface via heat, deserts, wind, storms, rain, floods, and so on. In fast-motion, *order* in the biosphere results from the joint effects of both giant Bénard processes, not from Darwinian gradualism. This is what underlies the various authors' views in the *Evolutionary Systems* anthology edited by Van de Vijver et al. (1998).

The mathematical model of the natural sciences, born in the Newtonian era, has a stranglehold on orthodoxy (Mirowski 1989). Following the characterization of '*models as autonomous agents*' given in the anthology by Morgan & Morrison (2000), math models now are seen to affect the course of economics as much as do

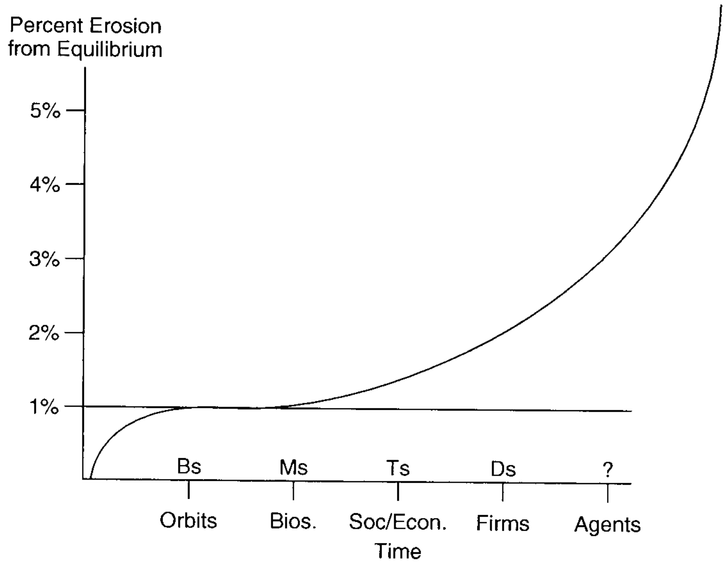

Figure 1. Rate of change away from precondition parameters.

theories and data. Figure 1 depicts the math model's increasing disconnection from phenomena prone to new order creation. Mathematical models increasingly misrepresent such phenomena in the bio- and econospheres, reading from left to right. As a rough estimate, the *Y*-axis represents the rate at which various phenomena move away from equilibrium – not wobble around some central tendency – but permanently change toward new order creation. The *X*-axis represents the amount of change by year. It is a log scale diminishing by three magnitudes per mark – thus, 1% new order creation in billions (planetary orbits) to millions (species) to thousands (socio/cultural/economic structures) of years; to 1% new order creation within a few years (firms), and finally 1% creations occurring in less than one year (single heterogeneous agents ranging from particles to molecules to biomolecules, to microbes, to human agents). The horizontal line, set at the 1% mark, represents a power function. Many readers probably would say that the *line* misrepresents the rate of erosion toward new order – preferring instead the *curve*.

What is missing from mature sciences, orthodoxy, and even much of evolutionary economics? The Arthur et al. (1997) characterizations of complex adaptive systems are what are missing: agent, nonlinear, level, coevolutionary, far-from-equilibrium, and self-organization effects. This becomes evident once we take a *fast-motion* view of most economic phenomena. The fast paced technology and market changes in the modern knowledge economy suggest such an analytical time shift for economic analysis is needed. If the classical physics based methods of orthodoxy are viewed through the lens of fast-motion science, Nelson & Winter's evolutionary economics shifts into Bar-Yam's fast motion degrees of freedom. Thus, changes they attribute to selection 'dynamics' slip into equilibrium. Following the path taken by Van de Vijver et al. (1998), dynamic analysis, therefore, must focus on agents' self-organization rather than Darwinian selection.

3. Order-creation theories

Mirowski's (1989) lengthy analysis shows how closely orthodox economics follows from the conservation-based thermodynamics of 19th century physics. He points to Fisher's (1926) equation of thermodynamic and economic primitives: particle ← → individual, space ← → commodity, energy ← → utility, and so on (p. 224). He calls Samuelson a 'true believer in ... the immutability of the laws of thermodynamics' (p. 378). Though Mirowski goes on to argue that Fisher '... and a great majority of neoclassical economists,' including Samuelson, are mistaken in their attempt to equate conservation of energy with economic phenomena, it is nevertheless clear from his analysis that orthodoxy is founded on the equilibrium principle at the heart of the 1st Law of Thermodynamics.

Nothing is more crucial to 19th century physics than the development of thermodynamics. Central to thermodynamics are its 1st and 2nd Laws. At the beginning of a book moving from the cosmos to the rise of complexity in nature, Chaisson (2001, pp. 16–17) settles on a simple definition of the 1st Law (the energy-conservation Law): '... [T]he sum of all energy is fixed.... Energy itself can neither be created nor destroyed, though its many forms may change.' Bar-Yam (1997, p. 61) says: 'the energy of an isolated system is conserved.' For example, a stock of energy (a tension or potential) in one kind of ordered structure flows at some rate and quantity into another – put water, coal, and fire into a steam engine and one gets smoke, steam, motion, friction, and heat. Under 1st Law energy translations, we observe order of one kind translating into order of another kind, with the energy translation accounted for via a mathematical expression.

Normal science accepts order as given in the universe except for the first few nanoseconds after the Big Bang (Field & Chaisson 1985). This leaves the thermodynamics of order translation as the defining dynamic of science. For half a century Prigogine (1955, 1962, 1997, Prigogine & Stengers 1984, Nicolis & Prigogine 1989) has been patiently reminding us that the 1st Law is time-reversible – the order and energy translation of classical physics runs in either order-translation direction. In the following review, time irreversible order creation, the role of the 2nd Law in order creation, and the meandering search for a 0th law of thermodynamics will become apparent.

I focus on the root question in complexity science: what causes order *before* 1st Law equilibria take hold? (Mainzer 1997). Also, how and when does order creation occur? And, is there a 0th – order creation – law? *Post-equilibrium* science limits itself to studying time-reversible, *post* 1st Law energy translations – how, why, and at what rate energy translates from one kind of order to another. It invariably assumes an underlying equilibrium. *Pre-equilibrium* science focuses on the order-creation characteristics of complex adaptive systems – some of which were described earlier in the six characteristics from the Arthur et al. (1977) chapter.

Quantum entanglement[4] as the precursor to emergent order is much discussed in physics (Gell-Mann 1994). And the primordial pool existing before the origin of life is much discussed in biology (Kauffman 1993). The Darwin/Wallace theory of natural selection (Darwin 1859/1964) explains speciation-based order in the biological world. Durkheim (1893) and Spencer (1898) also defined order as the emergence of *kinds*, specifically, social entities. Half a century later, however, Sommerhoff (1950), Ashby (1956, 1962), and Rothstein (1958) defined order not in terms of entities but rather in terms of the *connections* among them – as does Wolfram (2002).

Ashby (1962, p. 255) says that self-organized order exists between two entities, *A* and *B*, only if this relation is 'conditioned' by a third entity, *C*. By this definition, it is possible that not all links among entities comprising an economic system would be 'ordered' . This definition does, however, fit with Prigogine's (1955) and later views that order is a function of context – as will be in Section 3. If *C* is viewed as the 'environment' which is external to the relation between *A* and *B*, it follows that environmental constraints are necessary aspects of order creation (Ashby 1956). His '*Law of Requisite Variety*' follows. It holds that for a biological or social entity to be efficaciously adaptive, the variety of its internal order must match[5] the variety of its environmental constraints. He also observes that order does not emerge when the environmental constraints are chaotic (1956, pp. 131–132). Salthe (1985, p. 76) argues that any definition (description) of order that is not 'triadic' '. . . will be inadequate and of no interest to those pursuing complex phenomena.' 'Order' worth studying, in his view, has to consist of three levels at a minimum: a *focal* level (of interacting agents), a lower level (of interacting agents), and a *supervenient* level of environmental constraints. Order, thus, is a function of links, hierarchy, and contextual constraints.

How order emerges from the random actions of heterogeneous agents is the subject of Epstein & Axtell's (1996) *Growing Artificial Societies* and Wolfram's (2002) *A New Kind of Science*. They talk about 'bottom-up science' since the agents are the root phenomena of any science – how the agents at the very bottom create order from seeming randomness? Complexity theorists focus on what motivates individual agents to begin to shift from a disordered, disequilibrium state to produce some kind of collective, higher-level order (Cowan et al. 1994). Once this happens, interest turns to the mutual causal processes of coevolving agents (Arthur 1990, 2000), and then to coevolution of emergent higher level phenomena with lower-level agent behaviors.

In fast-motion sciences, and particularly in social science where agents' order-creation rates are – in terms of Figure 1 – within the few-year and intra-year ranges, self-organization questions and analyses may easily dominate, though not necessarily make meaningless, slow-motion science questions. And, of course, as the number of agents studied drops from billions to, say, the few hundreds of firms in the textile industry, or the couple dozen firms in the petroleum industry, or the few people in a start-up firm, analysis of coevolutionary agent behaviors and order-creation surely dominates the equilibrium methods of slow-motion science.[6]

Some readers may balk at my extension of the thermodynamics framework into social science. In fact, this framework has already been stretched from physicists' studies of motion, heat, electromagnetism and electrodynamics, into geology, biology, economics, and complexity science (Prigogine 1955, Cramer 1993, Salthe 1993, Mainzer 1997, Auyang 1998, Kauffman 2000). My exploration of order-creation theory stemming from the natural sciences is not to say that social scientists from Adam Smith to Henri Fayol, Durkheim, Spencer, Weber, and others have not also worried about order-creation in social phenomena. But in the spirit of the cross-disciplinary use of science-based analogies advocated in Khalil & Boulding (1996):

1. There could be significant lessons drawn from other natural science models of order-creation.
2. Given the limitations of economists' reliance on the math model from classical physics and Darwinian gradualist evolutionary theory from biology (both reflecting slow-motion science), lessons from fast-motion (complexity) science could be more instructive to social science theorizing.
3. Based on the message from the recent sandwiching of biological evolution between the atmospheric and geological Bénard processes, the question arises whether the Bénard engine of order-creation is the only engine, one of several equally viable engines, or the best engine available; and
4. Since most scientific analyses focus on energy translation theory within the framework of the 1st Law, I have tried to search for theories aiming at self-organization – order-creation – *before* the 1st Law.

Salthe (1993) notes that 'conservation' in material and nonmaterial systems is different – if you take money from me I lose it; if you take ideas from me I do not (but if I steal an idea from your R&D department and get it to market first, I get the value and you might not). While this might be an important distinction, it is not a deal-breaker. In beginning to wonder how people think about order creation before the 1st Law of Thermodynamics takes hold – the key question in this paper – nuances about energy conservation governed by the 1st Law do not seem so important given that the discussion is about what happens *before* the 1st Law takes hold.

Darwinian natural selection is the traditional way of explaining how order appears out of the primordial soup – the *selectionist* explanation in biology and the one imported into bioeconomics. A more recent view from biology is that self-organization – pre 1st Law processes – explains more order in the biosphere than Darwinian selection (Kauffman 1993, 2000, Salthe 1993, Van de Vijver et al. 1998) – the view of the so-called self-organization biologists. A more fundamental explanation of order-from-entanglement – completely nonselectionist – emerges from quantum theory – the *decoherence* explanation. I review theories of self-organization before 1st Law equilibria take hold – thereby introducing order creation via self-organization into bioeconomics. Throughout the following analyses, the driving questions are: *How do natural scientists explain agent-based processes leading to order-creation? How do they apply* *this thinking to social systems? Do they add value to social science thinking about order creation?*

3.1. Order creation in physics

One insight into how scientists think about order creation comes from physicists who worry about how the phenomena of classical physics emerges from the random interactions of quanta? Quanta are the ultimate in autonomous, heterogeneous agents, so let us start here.[7]

3.1.1. Quantum entanglement and context: Gell-Mann and Omnès

Gell-Mann (1994, Chapter 11) uses a few simple terms to explain how the world of objects and deterministic natural laws coexist with the probabilistic world of quanta. Electrons interact with one another such that the quantum state of the one is affected by the other – thus, over a series of time intervals, their quantum states are correlated. This is referred to as *entanglement*. The quantum state of a given electron is, thus, a function of its entanglement with all the other electrons it is correlated with. Over a sequence of time intervals each electron develops *correlated histories* with all of the other electrons it has come in contact with. Because of the countless correlated histories, no single, or even a few, histories dominate. Consequently quantum theorists cannot attach a probability of occurrence to the one or more correlated histories – the histories are confounded by their interaction with all the other electrons' histories. Since for quantum physicists, emergent probabilities are the beginnings of emergent ordering of matter, unless some force disrupts the entangled correlated histories, order creation is not forthcoming.

Gell-Mann refers to the world of quantum histories as the '*fine-grained*' – zero probability – quantum structure. The world of classical physics is the *coarse-grained* structure – which is to say, the world of macro structure and material order as we experience it. The question then arises: how does coarse-grained structure emerge from fine-grained structure? To explain, he uses the metaphor of a race-track. As you get to your seat at the race track and consider the odds on your favorite horse to win, you eventually ignore all of the other factors that could affect the race – quality of horse feed and vets, the state of the track, sunlight, temperature, wind, swirling dust, flies, nature of the other people betting, track owners, mental state and health of the jockeys, and a hundred other factors that conceivably could affect the outcome of a race. All other times and the history of everything else in the universe is ignored – Gell-Mann calls this '*summing over*'. Everything about the horse loses importance except for when the tip of its nose crosses the finish line. The coarse-grained history of the race dominates all the other fine-grained histories of all the other possibly correlated factors.

How do the race probabilities emerge from the fine-grained structure? Gell-Mann says that when we 'sum over' all of the detailed factors left out – that are not the tips of the noses of the few horses in, say, the fourth race – the effects of the myriad tiny correlations among the details lose their effect. The key point here is that the *context* of our interest in the winning horse causes us to sum over all the other fine-grained correlations. The race-relevant correlations among all the fine-structure effects are focused on – and thus become the coarse-grained structure – whereas all the other detail correlations are summed-over and made irrelevant. When this happens, there are three effects: (1) most of the history quantities are ignored, i.e., summed over; (2) the few correlated histories that become important do so because of the particular time and place – the *context* – meaning that the histories are similar and conjoined or the horses would not be in the same race at the same place at the same time; and (3) since all the other history quantities disappear, the few correlated histories remaining become truly probabilistic. Gell-Mann (1994, p. 144) says: 'A coarse-grained history may be regarded as a class of alternative fine-grained histories, all of which agree on a particular account of what is followed, but vary over all possible behaviors of what is not followed, what is summed over'. Quantum theorists call the emergence of coarse-graining out of the fine-grain structure – i.e., the creation of probability by virtue of the destruction of entanglement – *decoherence*. Empirical researchers play this game every time they assume that the various interrelated effects not specifically hypothesized, or designed into the study as control variables, are randomized, i.e., neutralize each other and are, in effect, summed over.

> Gell-Mann's Premise: Contextual effects lead some correlated histories in the fine-grained structure to surface as the basis of probabilistic effects while the remaining histories sum over – their effects remaining randomized.

Omnès[8] (1999) connects quantum theory to Prigogine's (1955, 1962) view (to be developed shortly). He associates irreversibility, dissipation, and decoherence, arguing that '. . . the essential character of decoherence appears to be irreversibility' (p. 196). He observes that decoherence is an irreversible dynamic process (p. 206). His analysis concludes that only from the dissipation of energy can probability – coarse-grained structure – emerge from entanglement. The energy comes directly from environmental context. Thus, he proposes:

$$H = H_c + H_e + H_1 \tag{1}$$

a total Hamiltonian where H_c is pertains to the relevant 'internal' variables, H_e pertains to the environmental variables and H_1 a coupling of the two systems representing how the environmental variables affect, or are affected by, the internal variables (1999, p. 198). This further solidifies the connection between the environmental effects and the creation of probability out of entanglement. Omnès' view is essential. His Hamiltonian is an explicit connection of H_c – internal variables – with the *forces of external energy fields*. He connects the processes of decoherence and emergent quantum-level coarse-graining, with the dissipation of the tension created by the Bénard (1901) type energy-differentials recognized by chaos and complexity scientists.

Omnès's Premise: Externally imposed energy differentials cause decoherence – the emergence of coarse-grained structure from entanglement.

3.1.2. Coarse-graining via entropy gradients: Prigogine

Haken (1977, 1983, 1996), famous for his 'synergetics' movement, suggests a fundamentally different concept of how order emerges from the actions of autonomous, heterogeneous agents. But before continuing with the 'how' question, I need to discuss the 'when' question. This leads to Prigogine (1955, 1962) and the 2^{nd} Law, and then to Lorenz (1963).

Chaisson (2001, p. 17) says that the essence of the 2^{nd} Law is that every time there is an energy translation of any kind there is a price to pay in the form of a loss of energy. Bay-Yam (1997, p. 62) says: 'A system which is not in equilibrium must therefore undergo an irreversible process leading to equilibrium' – meaning that any system not in a state of equilibrium must move toward equilibrium and further, that there is a loss of energy in doing so. Loss of energy is termed entropy production – which, therefore, is set in motion by the juxtaposition of a high energy source (higher order) and an entropy sink (lower order or, alternatively, more randomness).

Prigogine (1997, pp. 16–20) observes that the 2^{nd} Law brings evolutionary theory into physics. Following Darwinian evolutionary theory, he argues that, just as biological evolution is irreversible, so is entropy production in physics. This is the foundation of his life-long focus on time-irreversibility. He draws on Eddington's (1930) one-way 'arrow of time,' which is simply the idea that while we easily see, in the Universe, that order readily dissipates into randomness, we do not see randomness dissipating into order.

Prigogine argues that, just as Darwinian evolution produces biological complexity[9] – as organisms failing to adapt to environmentally imposed tensions are selected out – so too does the process underlying entropy production. The tension between higher and lower energy (and associated states of order) creates an energy differential that initiates agent self-organization and resultant order creation. Prigogine terms these '*dissipative structures*' because they draw energy away from the already existing, larger, 'far-from-equilibrium' order or energy state. They speed up entropy production by reducing the energy of the higher ordered state and dissipating it into a lower order state – the more entropic condition. These externally imposed energy gradients are recognized by Omnès (1999) as essential even to the coarse-graining process at the quantum level.

Prigogine uses dissipative structures to explain both the cause and disappearance of coarse-graining at all levels of analysis in three ways:

1. The energy of an existing higher energy/order state is dissipated when negentropy[10] is imported into the newly created dissipative structure from the existing higher energy state. This process speeds up entropy production.
2. Within them, new dissipative structures conduct energy translations under the 1^{st} Law, and as a result, dissipate their own energy since entropy is created each time there is an energy translation.

3. Dissipative structures, once created, also exist 'far from equilibrium' and, therefore, conditions exist for the appearance of even more dissipative (sub)structures. Hierarchies of additional dissipative structures may result.

Swenson (1989) observes that order creation in the form of dissipative structures occurs to maximize the speed entropy production – i.e. his '*Law of Maximum Entropy Production*.'

Prigogine's Premise: Tension resulting from the energy differential between a high-order, far-from-equilibrium state and a more entropic state causes dissipative structures to emerge, thereby causing order-creation and speeding up entropy production.

3.1.3. Order-creation via external energy-differentials: Lorenz

The existence of an energy gradient is necessary but not sufficient. Lorenz (1963) introduces the deterministic chaos model of turbulence in weather systems built of Bénard cells. In a Bénard process (1901), '*critical values*' in the energy differential (measured as temperature, ΔT) between warmer and cooler surfaces of a container[11] affect the velocity, R (the so-called Reynolds number)[12] of the air flow, which correlates with ΔT. The surfaces of the container represent the hot surface of the earth and the cold upper atmosphere. The critical values divide the velocity of air flow in the container into three kinds:

1. Below the 1st critical value (the Rayleigh number), heat transfer occurs via conduction – gas molecules transfer energy by vibrating more vigorously against each other while remaining essentially in the same place.
2. Between the 1st and 2nd critical values, heat transfer occurs via a bulk movement of air in which the gas molecules move between the surfaces in a circulatory pattern – the emergent Bénard cells. We encounter these in aircraft as up- and down-drafts; and
3. Above the 2nd critical value, transition to the āperiodic behavior and strange attractors of deterministic chaos occurs.

Since Bénard (1901), fluid dynamicists' have focused on the 1st critical value, R_{c1} – the Rayleigh number – that separates laminar from turbulent flows. Below the 1st critical value, viscous damping dominates so self-organized emergent (new) order does not occur. Above the Rayleigh number inertial fluid motion dynamics occur (Wolfram 2002, p. 996). Lorenz, followed by complexity scientists, added a second critical value, R_{c2}. This one separates the region of emergent complexity from deterministic chaos – the so-called 'edge of chaos'. Together, R_{c1} and R_{c2} define

Table 1. Definitions of kinds of complexity by Cramer (1993)[a].

Below the 1st critical value '*Newtonian complexity*' exists where the amount of information necessary to describe the system is less complex than the system itself. Thus a rule, such as $F = ma = md^2x/dt^2$ is much simpler in information terms than trying to describe the myriad states, velocities, and acceleration rates pursuant to understanding the force of a falling object. 'Systems exhibiting subcritical [Newtonian] complexity are strictly deterministic and allow for exact prediction' (1993, p. 213) They are also 'reversible' (allowing retrodiction as well as prediction thus making the 'arrow of time' irrelevant (Eddington 1930, Prigogine 1997).

Above the 2nd critical value is '*chaotic complexity*'. Cramer lumps both chaotic and stochastic systems into this category, although deterministic chaos is recognized as fundamentally different from stochastic complexity (Morrison 1991, Gell-Mann 1994) since the former is 'simple rule' driven, and stochastic systems are random, though varying in their stochasticity. For random complexity, description of a system is as complex as the system itself – the minimum number of information bits necessary to describe the states is equal to the complexity of the system. Probabilistic distributions in stochastically complex systems allow some algorithmic compressibility. Thus, three kinds of stochastic complexity are recognized: *purely random*, *probabilistic*, and *deterministic chaos*. For this essay I narrow the label to deterministic chaos, at the risk of oversimplification.

In between Cramer puts '*emergent complexity*'. The defining aspect of this category is the possibility of emergent, simple, deterministic structures fitting Newtonian complexity criteria, even though the underlying phenomena remain in the stochastically complex category. It is here that natural forces ease the investigator's problem by offering intervening objects as 'simplicity targets' the behavior of which lends itself to simple rule explanation. Cramer (1993, pp. 215–217) has a long table categorizing all kinds of phenomena according to his scheme.

[a]For mnemonic purposes I use 'Newtonian' instead of Cramer's 'subcritical', 'stochastic' instead of 'fundamental', and 'emergent' instead of 'critical' complexity.

three kinds of complexity (Cramer 1993; see Table 1). Now we have arguments for both how and when.

$$\text{Newtonian} \rightarrow |R_{c1}| \rightarrow \text{Emergent} \rightarrow |R_{c2}| \rightarrow \text{Chaotic}^{13}$$

> Lorenz's Premise: The region of emergent complexity (self-organization of autonomous heterogeneous agents) is sandwiched between two critical values (the Rayleigh numbers, R_{c1} and R_{c2}) along the Reynolds energy gradient, R.

3.1.4. Quantum chaos: Mainzer

Generally, the European school[14] tends to start its complexity discussions with reference to phase transitions and Bénard cells (Prigogine 1955, Haken 1977, Nicolis & Prigogine 1989, Cramer 1993, Kaye 1993), focusing on the R_{c1} transition. The American (Santa Fe) school tends to start its discussions by reference to small random initial (butterfly) effects of chaos theory (Gleick 1987, Arthur 1990, Lewin 1992, Kauffman 1993, 2000, Bak 1996) and the 'edge of chaos'.[15] What happens at R_{c1} is better understood; what happens at R_{c2} is more obscure.[16]

Mainzer (1997) asks: 'Is there chaos in the quantum world?' Which is to ask, 'Can we have coarse-graining without the contextual input that Gell-Mann and Omnès focus on'? Mainzer suggests that '...the existence of chaotic motion in classical Hamiltonian systems leads to irregularities in the corresponding quantum systems'

(p. 55). Chaos in classical Hamiltonian systems may be detected at the corresponding quantum level. Mainzer (p. 56) cites two studies (Friedrich & Wintgen 1989, Friedrich 1994) using numerical models as well as laser spectroscopy that confirm '. . . quantum chaos is no illusion, but a complex structural property of the quantum world.'

Mainzer's Premise: Initially tiny quantum chaotic effects can accumulate to cause coarse-graining in atoms (even without contextual stimulation), and subsequently in higher-level natural phenomena.

3.1.5. Order parameters at the 1st critical value: Haken

Haken (1977, 1983) begins by describing a number of physical systems in which a critical temperature, R_{c1}, causes a phase transition. He mentions magnetization, Bénard cells, lasers, cell formation in slime molds, chemical reactions such as Belousov–Zhabotinsky, predator/prey growth and decline rates, and even social change. Particularly, Haken focuses on a mathematics that allows him to predict how agents – whether atoms, organisms, or social actors – self-organize when the imposed external energy source exceeds R_{c1}.[17] Haken's analysis clearly pertains to Auyang's (1998) 'many-body' systems, such as physical matter, biological populations, and aggregate economies. Haken also applies his 'order parameter' theory to 'fewer body' social systems.

After discussing quantum chaos as a source of order creation, Mainzer, turns to the 'Bénard instability' (1997, pp. 57–66), and then to Haken's (1983) '*slaving*' principle and '*order parameters*'. In the following list, I trace out the steps that Mainzer (1997, pp. 66–68) describes and match his steps with Gell-Mann's coarse-graining process:

1. Start with an existing dissipative structure behaving according to a Newtonian Hamiltonian (system may be described by state and momentum variables) – a coarse-grained structure in Gell-Mann's terms.
2. Just before R_{c1} is reached (from below), the increased energy causes unstable (multidirectional) vectors (wave packets, energy, motions) to appear along with the stable vectors (these exert force in an unchanging direction).
3. As the unstable vectors multiply, they begin to *enslave* the stable vectors, thus eliminating the latter. Degrees of freedom are thereby reduced, as is complexity. Decoherence diminishes, resulting in a re-establishment of entanglement. Consequently, coarse-graining is reduced.
4. The unstable vectors and their degrees of freedom disappear into a stochastic pool of Brownian motion – entanglement. This leads to a vast reduction in degrees of freedom. Decoherence has nearly disappeared.
5. The last few stable vectors remaining become *order parameters* acting to create the emergent dissipative structures as the system tips over R_{c1} into the region of self-organized complexity – meaning that the few order parameters surviving across the completed phase transition are totally the result of a stochastic process.
6. At this juncture, order, complexity, and increased degrees of freedom re-emerge. The result is decoherence and emergent coarse-graining.

7. The region of self-organized complexity persists until the energy-differential is reduced by virtue of the continuing emergence of dissipative structures. That is, coarse-graining continues until the energy-differential is reduced. Of course, if the energy-differential is continuously renewed at a rate equal to, or even faster than the existing dissipative structures can reduce it, the more dissipative structures will continue to emerge.

With the foregoing steps, Mainzer teases out the process events just before and after the phase transition at R_{c1}. Recalling Omnès's (1999) argument, that the decoherence process occurs more rapidly than can ever be measured,[18] we realize that some physical systems pass through the several states outlined in the list above very rapidly – too rapidly to measure, perhaps. By this process, at the phase transition, most of the vectors simply disappear into entanglement. The few remaining vectors, by default, become the order parameters governing the subsequent emergence of dissipative structures. Thus, the emergent structure is stochastically driven by the few vectors remaining after all the others have been enslaved into randomness. This becomes an explanation of emergent order, in which the few post-transition order parameters, like the butterfly effect, eventually influence the vastly larger emergent dissipative structures of classical physics. Given that the order parameters are governed by external energy effects, it seems clear that external effects likely surpass the internal butterfly effects, thus reminding us of the importance of context.

> Haken's Premise: At the instability point forced by R_{c1} and, thus, after most degrees of freedom in complex systems have been enslaved by unstable vectors, the very few remaining vectors (the order parameters) govern the nature of subsequent self-organization.

3.2. Coarse-graining connected to bioeconomics

Haken's order parameters explain both the how and when of order creation. His enslaving process and control parameters suggest *how* coarse-graining occurs and his use of Prigogine's energy differential, coupled with Bénard's critical value, R_{c1}, identifies the conditions governing *when* order creation begins. Even more importantly, order parameters offer a means of generalizing from quantum physics to the bio- and econospheres. Energy differentials occur at any level, as do the order parameters and the process that creates them.

3.2.1. Order and control parameters in biology: Kelso et al. (1992)

Papers appearing in the many anthologies published by the Santa Fe Institute indicate, generally, that citations to Prigogine's 'dissipative structure' theory and Haken's 'order parameter' theory are almost nonexistent.[19] A mini-school at Santa Fe, that appears to combine European and American approaches, consists of Baskin et al. (1992), Goodwin & Kauffman (1992), Kelso et al. (1992), Mittenthal et al. (1992), and Newman (1992) formed by authors drawing from the work of Thompson (1917). In their elaborate chapter, 'Dynamic Pattern Formation: A Primer' , Kelso et al. (1992) integrate the dissipative *tension* from the physical world imposed on biological organisms and use Haken's order parameters as a means of theorizing about which of the countless external tension forces actually create biological order *before* Darwinian selection sets in. The key person in this synthesis is Scott Kelso, writing with a number of colleagues (see various references in Kelso et al. 1992).

Kelso et al. (1992) have the objective of identifying possible laws that would explain pattern formation among a number of biological fields, specifically with respect to Haken's order parameters and spontaneous self-organization arising from an imposed instability. Kelso & Schöner (1987) observe that numerous underlying mechanisms (material substrates) produce similar complex patterns. They specifically mention, for example, that the study of invertebrate pattern generation shows a 'uniform lack of common neuronal mechanisms' (Kelso et al. p. 399). The latter then conclude that: 'This fact, that many physical mechanisms may instantiate the same pattern, hints strongly of *universality*, that some underlying law(s) or rule(s) govern pattern formation' (p. 399, their italics). They focus on the '*instability*' occurring at R_{c1}. Haken (1983, p. 254), in a section on 'new variables,' starts using the Reynolds number, R, as a '*control parameter*' that 'can be manipulated from the outside', which in turn effects the emergence of the order parameters. Kelso et al. pick up on this to make a more explicit integration of Prigogine's dissipative structure theory and Haken's order and control parameters.

Boiled down, (1) *order parameters* are the devices that create 'enormous behavioral complexity' (Kelso et al. 1992, p. 401) from a very few initial degrees of freedom (after all the other degrees of freedom have been enslaved – as Mainzer describes it above), and (2) *control parameters*, R_i, are the various processes that move systems into the instability region just past R_{c1} and thereby set the instability (or phase transition) in motion (Haken 1983, p. 254). Haken only mentions altering ΔT, the energy differential. But there could be a number of contributing R_is, any one of which could heat up the hot surface or cool down the cold surface such that $R > R_{c1}$. If 'energy differential' is broadened to the 'adaptive tension' imposing on biological or social entities (McKelvey 2001), then one may delineate a considerable number of control parameters, any one of which might increase adaptive tension. Kelso et al. give the example of how an evaporating Lake Turkana created enough adaptive tension ($R > R_{c1}$) and subsequent rapid change leading to 'significant elevation of phenotype variance,' that developmental instability of mollusk species resulted. Thus, as the lake evaporates, water temperature could change, its level of chemical impurity could change, food supplies in the water could change, predator/prey ratios could change, etc. Any one of these could be the R_i that creates the instability and gives rise to new order creation.

I think this is a critical stage in the development of a possible 0^{th} law. Nowhere before (that I have found) have R_{c1}, order parameters, and the idea that one might use control parameters 'from the outside' to turn order creation on and off, been juxtaposed. After mentioning the Lake Turkana example, Kelso et al. (1992, p. 433) speculate that

'... speciation may be viewed as a self-organized pattern formation process'. Here, the situation, $R > R_{c1}$, is directly linked to speciation, i.e., order creation in biology over and above Darwinian selection – hence self-organization biology.

> Kelso et al.'s Premise: Control parameters, R_i, externally influenced, create $R > R_{c1}$ with the result that a phase transition (instability) approaches, degrees of freedom are enslaved, and order parameters appear, resulting in similar patterns of order emerging even though underlying generative mechanisms show high variance.

3.2.2. Order-creation in biosystems: Salthe

I mention Salthe (1993, 1998) in the heading, but this section builds on the work of Depew & Weber (1995), Swenson (1989), and Ulanowicz (1996). Depew (1986) is an early discoverer of the limitations of Darwinism – saying that '... Newtonian approaches to change involve only efficient causality and are limited to translational changes in the context of equilibria' (Salthe 1993, p. 25). Salthe also notes that Kampis (1991) says that mechanistic models are incapable of dealing with nonequilibrium-based change. Salthe's (1993) book is an in-depth reaction against the unrealism of what he calls the 'Baconian/Cartesian/Newtonian/Darwinian/Comtean' view of real-world phenomena (pp. 2–3) – the pattern of science laid down within the context of orbital mechanics. His Chapter Three makes it very clear that his analysis, like mine, is also framed in terms of the chaos theorists' nonlinear thermodynamics and very much in the shadow of Prigogine's theory of emergent dissipative structures under the governance of the 2nd Law.

Most relevant to bioeconomics is Salthe's *exclusion* of Darwinian selectionist theory as the primary explanation of order in the biosphere. 'Natural selection embodies the Newtonian spirit; it maintains the status quo unless perturbed by changes in external selection pressures' (1993, p. 199). He notes that Darwinian evolution fails to explain '*... convergent evolution, parallel evolution, iterative evolution, and ecological vicarage*' (p. 27; his italics). What does? Salthe's nonlinear thermodynamics (p. 106) starts with Prigogine's use of the 2nd Law, Bénard's critical values, and phase transitions. He also sets his theory in terms of Haken's order parameters (p. 107) and speculatively recognizes the Bénard process in the earth's geology and atmosphere (p. 107). Consequently his order-creation process is driven by the material surroundings of the biosphere – the truly novel changes in the latter are driven by geological and atmospheric effects. Salthe's definition of order builds on Ashby's – order-creation happens in the context of external constraints (p. 108) – as I noted earlier. Salthe says, in comparing 'organization' with 'order': '*Order* is a simpler notion; it is regularity, or predictability (Atlan 1978) – it is a local result of constraint (Bannerjee et al. 1990)' (p. 158; his italics and cites).

Like Prigogine's, Salthe's view is that new order emerges in the context of entropy production – new kinds of order speed up entropy production. Energy flow, from a large, highly ordered (energized) entity (the Sun) to a high entropy state (outer space) is the energy-flow engine that creates the context of new order creation (i.e., new entropy production dissipative structures). Thus, a substantial difference between supply and demand in a large economy provides a tremendous order imbalance that is resolved by the formation of smaller ordered entities – firms in this example.[20] Salthe's biology is beginning to look like Austrian economics and Schumpeter's (1942) phase transition induced 'creative destruction', except that Salthe emphasizes creation of the 'new' rather than destruction of the 'old', where old refers to the prevailing equilibrium, existing economic order, technology and market structures, and capital and labor dispositions.

Boiled down: order-creation, in Salthe's theory, results from energy flows much more than from Darwinian selection – the latter being a fine-tuning equilibrium process after a new species has emerged. What is especially important from my *fast-motion science perspective* is that dissipative structures (entropy production systems) have their own dynamics and follow rules of creation and destruction. Salthe proposes four 'phenomenological rules' that he also thinks of as possible laws of nature – 'These rules, then, will provisionally be taken here to apply, regardless of scale (being like laws of nature in that sense) to any dissipative structure' (p. 111). The rules are:

1. After an initial increase, there is an average monotonic decrease in the intensity of energy flow (flow per unit mass) through the system. The gross energy flow increases monotonically against a limit, just as
2. There is a continual, hyperbolic, increase in complicatedness (= size + number of types of components + number of organizational constraints), or, generally, an ever-diminishing rate of increase in stored information.
3. There is an increase in its internal stability (its rate of development slows down). ...
4. There is a decrease in its stability to perturbations, which eventually leads to [senescence and] recycling.

Salthe (p. 154) observes that '... self-organization predictably involves some combination of an increase in size and an increase in internally generated constraints, as well as an increase in gross throughput' – rule no. 2. Though formulated in terms of the biosphere, these rules fit firms quite well (see Meyer & Zucker 1989) and are quite compatible with Austrian economics. Order-creation begins with entropy production tensions that create immature firms as newly ordered systems. This is a burst of new order. But eventually there is maturity and stability and the firm becomes less able to continue responding effectively (as a new order-creation entity) to novel perturbations from its competitive environment. Like fireworks in the sky, firms are bursts of order falling toward entropy.

> Salthe's Premise: The context of the bio- and econospheres creates the entropy production potential that gives rise to dissipative structures that themselves progress through immature, mature, and senescent stages of their own entropy production – that in turn creates irreversible order-creation conditions for lower scale dissipative structures, and so on in downward hierarchical progression.

3.2.3. Origins of bioeconomic order: Kauffman

Kauffman's 25 years of investigations into the origins of order – and life – are collected in his 1993 book, *The Origins of Order*. From his *NK* model, we learn that increasing complexity arising from the coevolution of autonomous heterogeneous agents eventually leads to a reshaping of a population's fitness landscape. Even though Darwinian selection continues, the differences between the adaptive peaks and valleys become so minute that improvement in adaptive advantage stops – his so-called '*complexity catastrophe*'. He also shows that if agents form some connections with agents outside the immediate population, what he calls '*coupled dancing*' emerges, which results in a relaxing of the catastrophe effect (his $NK[C]$ model). In Chapter Five Kauffman details the cellular automata (CA) origins of the *NK* model (Kauffman 1974, Derrida 1987[21]), and his claim that two kinds of complexity, *ordered* and *chaotic*, arise spontaneously. '*Such systems spontaneously exhibit order in the absence of outside work*' (1993, p. 191; my italics).

Given how the CA models work, Kauffman's 'spontaneous order creation' claim seems flawed. Kauffman sees the two complexities as separated by a '*phase boundary*' (p. 218). In the CA models there is a very narrow region, termed a '*boundary region*' or '*melting zone*', where, based on a control parameter, $R_{c1} < R_c < R_{c2}$, the CA system switches between the frozen and chaotic states (p. 206). Whether a CA system is frozen or chaotic depends on the proportion of CA cells that are '*forcing functions*' – cells' output effect on neighboring cells is (mostly) the same no matter what the input (pp. 203–206). First, a careful analysis of Kauffman's and Derrida et al.'s CA models shows that the CA models invariably follow the central limit theorem such that no matter how often the random draws occur, the distribution of forcing functions in a particular simulation run tends toward the same distribution. Second, the CA 'agents' in the models are always activated with rules prescribed by the model programmers. Take away these two conditions and there is no reason to expect spontaneous movement of the CA system from one state to another, whether ordered or chaotic. The fundamental difference is that for the 'Bénard theorists' the external stimulus (what Kauffman refers to as '*work*', is activated only if R rises above R_{c1} – agents are turned on only when this happens. In the Kauffman, Derrida and other models (mentioned in note 21) the agents are always 'on'. Hence there is obviously no need for them to be activated by outside *work* – the model's agents perform anyway.

Missing in Kauffman's 1993 book is any significant attention to Prigogine's theory about the role of the 2^{nd} Law and adaptive tension in order creation (for Kauffman's use of thermodynamics, see pp. 23–25). The phase boundary is present, but the increase in R and the transition across R_{c1}, which activates the agents, is missing. Kauffman's phase boundary is a *description* of the discontinuity between order and chaos, but it has no causal content, such as, if $R > R_{c1}$, a phase transition will occur. Thus, the engine that starts agent self-organization is missing. Only on page 567 does Kauffman recognize Prigogine's view that spontaneous order creation occurs in systems '. . . open to the flow of matter and energy' in far-from-equilibrium settings.

Kauffman (2000) takes up the problem of the missing engine in his *Investigations* book (2000). He asks: '. . . could there possibly be a 4^{th} law of thermodynamics for open thermodynamic systems, some law that governs biospheres anywhere in the cosmos or the cosmos itself?' (p. 2).[22,23] 'What principles, if any, underlie the spontaneous formation of self-reproducing systems?' (p. 35). Then, in the context of thermodynamics, he talks about the relation of energy to phase transitions. Starting with the 'work cycle' of Carnot's heat engine, Kauffman argues that a bioeconomic agent survives by completing work cycles not the least of which is earning a living (a bacterium swimming in the blood to find food; a firm acquiring materials, producing, and selling a product). From this basis he says: '... [for a work] cycle to operate at a finite rate, hence irreversibly, the autonomous agent must be an open thermodynamic system driven by *outside sources* of matter or energy – hence "food" – and the continual driving of the system by such "food" holds the system away from equilibrium' (p. 64). 'Work is the constrained release of energy' (p. 100).

Whereas Prigogine and Salthe rely totally on entropy production as the engine, Kauffman says: 'I claim that entropy is not yet adequate' (p. 105). He points out that to create order, agents have to complete a number of *tasks* to actually self-organize – tasks '... involving work, constraint, constraint construction, propagating work, measurements, coupling, energy, records, matter, processes, events, information, and organization' (p. 104) – all the things people in firms have to worry about. This is where Kauffman starts trying to escape the bonds of Newton's 1st Law, observing that we '... cannot pre-state the configuration space of a biosphere' (p. 125) given all the various tasks facing self-organizing agents. You can see that he and I are on the same page when he then says: 'You see, we have indeed been taught by our physicist friends to do science by prestating the configuration space in question' (p. 134) – which his analysis shows is an impossibility. In Chapter Seven he develops his conclusion that the biological and socioeconomic spheres (and even the universe) are decidedly nonergodic – meaning that they do not randomly spread out to occupy equally every possible adaptive space available. Of course, the nonergodic hypothesis is the opposite of the 2nd Law – the ergodic hypothesis. What drives nonergodicity? What drives phenomena to self-organize into clumps of order, into increased complexity and complication, into paths of increasing specialization and vulnerability to changing external conditions? Based on his conclusion that there exists in the universe an overwhelming drive toward nonergodicity, Kauffman, reasonably, worries more about limits on expansion into the '*adjacent possible*'.[24] His four 4th law candidates are (p. 160):

1. Communities of autonomous agents will evolve to the dynamical 'edge of chaos' within and between members of the community, thereby simultaneously achieving an optimal coarse-graining of each agent's world....
2. A coassembling community of agents, on a short time scale with respect to coevolution, will assemble to a self-organized critical state with some maximum number of species per community. In the vicinity of that maximum, a power law distribution of avalanches of local extinction events will occur. As the maximum is approached the net rate of entry of new species slows, then halts.

3. On a coevolutionary time scale, coevolving autonomous agents as a community attain a self-organized critical state by tuning landscape structure (ways of making a living) and coupling between landscapes, yielding a global power law distribution of extinction and speciation events and a power law distribution of species lifetimes.
4. Autonomous agents will evolve such that causally local communities are on a generalized 'subcritical–supracritical boundary' exhibiting a generalized self-organized critical average for the sustained expansion of the adjacent possible of the effective phase space of the community.

What Kauffman means when he says: '. . . entropy is not yet adequate' is *not* that the 'entropy imbalance engine' is not strong enough, but rather it is so strong that we on Earth and everywhere else should be totally buried in nonergodicity effects – *order* of all kinds everywhere. But his analysis in Chapter Seven shows this to be far from true. Hence, in his candidate laws he worries much more about what limits non-ergodicity. Kauffman uses Bak's (1996) '*self-organized criticality*' and power-law effects to define the dynamics of the limit process. He (p. 209) concludes by saying: 'I sense a fourth law in which the workspace of the biosphere expands, on average, as fast as it can in this coconstructing biosphere', subject to the criticality extinction process. In fact, in Kauffman's model, proliferation into nonergocity is virtually taken for granted. All four candidate laws are about limits to rampant nonergocity. The first candidate law simply states as a fact that agents evolve to the 'dynamical "edge of chaos"'. Again, as in his 1993 book, Kauffman assumes that *agents are always activated to self-organize*. Why is this so? Because his analysis in Chapter 8 – the Candidate Law chapter – is lifted right from the CA modeling part of his 1993 book.

One way to see what is important to Kauffman, and what is most relevant to what he calls the 'econosphere' comes from Chapter Nine. He says: 'We need a theory of the persistent coming into existence of new goods and services and the extinction of old goods and services. . . . The biosphere and econosphere are persistently transforming, persistently inventing, persistently dying, persistently getting on with it, and, on average, persistently diversifying' (p. 216). Does this happen equally in all the world's economies? He does not offer a theory about why there is more new order, or new order happening at a faster rate, in the US and China, say, than in India and Indonesia. Is this difference because the latter have too little 'persistent coming into existence' or too much criticality and extinction? Or, at the firm level, what makes some firms persistent sources of new goods and services (Collins & Porras 1994) whereas other firms in the same industry are candidates for extinction – Walmart vs. Wards being recent examples? He says: 'I am rather persuaded that adaptive systems can best exploit the trade-off between exploitation and exploration at a rough phase transition between order and chaos. Here power law distributions of small and large avalanches of change can and do propagate through the system as it adapts' (p. 222). This raises the problem of what value R_c is. If $R < R_{c1}$ or $R > R_{c2}$, then 'persistent coming into existence' breaks the Kelso et al. rule. Is it just by chance that the R_is just naturally cause $R_{c1} < R < R_{c2}$ in some economies, industries, or firms? The implication of Kauffman's statement 'The biosphere and econosphere are persistently transforming. . . .' implies that the R_is do cause $R_{c1} < R < R_{c2}$ all the time and everywhere. But surely the entire biosphere and econosphere cannot both be all the time and everywhere between R_{c1} and R_{c2}. In fact, there are *two* critical values, R_{c1} and R_{c2} defining the region of emergence; they would both have to all the time and everywhere serve to define a region of emergence so wide that all economic phenomena are within it. A tall order it seems to me.

> Kauffman's Premise: Since spontaneous self-organization always drives bio- and econosphere phenomena toward the dynamical edge of chaos, power law damping effects of self-organized criticality come into effect that lead to extinction events, thereby preventing the overwhelming triumph of nonergodicity into the 'adjacent possible'.

4. Conclusion

Representing a component of bioeconomics, Nelson & Winter (1982) have looked to biology, specifically Darwinian evolutionary theory, for a dynamic perspective useful for explaining the origin of order in economic systems. In doing so, this component of bioeconomics claims to stand in opposition to the tendency of economic orthodoxy to presume that all variance is simply movement around some central tendency. Leading biologists, such as Salthe (1993), Eldredge (1995), Ulanowicz (1996), Depew (1998), Weber (1998), Conrad (1998), and Kauffman (2000), among others – the so-called self-organization biologists – now argue that Darwinian theory is, itself, equilibrium bound and not adequate for explaining most of biological dynamics. Underlying this change in perspective is a shift to the study of how heterogeneous agents create order in the context of geological and atmospheric dynamics. Implicit in this change is a change from the slow-motion science of Newtonian classical physics – and its mathematics – to the fast-motion science necessary to see agent-level order-creation dynamics in action.

To better understand the contribution that self-organization biology and fast-motion dynamics can make to bioeconomics, I have reviewed a number of well-established theories about causes of emergent order in physics and biology, some of which have been extended into the econosphere. I consider explanations of how '*order*' (what Gell-Mann calls *coarse-graining*) emerges from the fine-grained structure of entanglement pools and higher-level systems. The nine premises pertaining to order creation, order-creation and extinction, and extinction are:

(a) Order-creation:

1. Gell-Mann (1994): Contextual effects lead some correlated histories in the fine-grained structure to surface as the basis of probabilistic effects while the remaining histories are washed out – their effects remaining randomized.

2. Omnès (1999): Externally imposed energy differentials cause decoherence – the emergence of coarse-grained structure from entanglement.
3. Prigogine (1955): Tension resulting from the energy differential between a high-order, far-from-equilibrium state and a more entropic state causes dissipative structures to emerge, thereby causing order-creation.
4. Lorenz (1963): The region of emergent complexity (self-organization of autonomous heterogeneous agents) is sandwiched between two critical values (the Rayleigh numbers, R_{c1} and R_{c2}) along the Reynolds energy gradient, R.
5. Mainzer (1997): Initially tiny quantum chaotic effects can accumulate to cause coarse-graining in atoms (even without contextual stimulation), and subsequently in higher-level natural phenomena.
6. Haken (1977): At the instability point forced by R_{c1} and, thus, after most degrees of freedom in complex systems have been enslaved by unstable vectors, the very few remaining vectors (the order parameters) govern the nature of subsequent self-organization.
7. Kelso et al. (1992): Control parameters, R_i, externally influenced, create $R > R_{c1}$ with the result that a phase transition (instability) approaches, degrees of freedom are enslaved, and order parameters appear, resulting in similar patterns of order emerging even though underlying generative mechanisms show high variance.

(b) Order-creation and extinction:

8. Salthe (1993): The context of the bio- and econospheres creates the entropy production potential that gives rise to dissipative structures that themselves progress through immature, mature, and senescent stages of their own entropy production – that in turn creates irreversible order-creation conditions for lower scale dissipative structures, and so on in downward hierarchical progression.

(c) Extinction:

9. Kauffman (2000): Since spontaneous self-organization always drives bio- and econosphere phenomena toward the dynamical edge of chaos, power law damping effects of self-organized criticality come into effect that lead to extinction events, thereby preventing the overwhelming triumph of nonergodicity into the 'adjacent possible'.

If a 0^{th} order-creation law actually exists across the physical, biological, and social worlds, it has not been coherently defined or broadly agreed upon as yet. As my review indicates, it spreads across at least nine initial insights (the premises) about when and what kind of force precipitates order-creation by heterogeneous agents. There is not total agreement that an energy or tension differential, R, located between R_{c1} and R_{c2} is the key requirement – but no one explicitly disagrees with this view, except for Kauffman (1993, 2000) who side steps adaptive tension and 'work' from outside, insisting instead on spontaneous self-organization by agents, all of which are assumed activated. This is the Santa Fe view – self-organization, coevolution, positive feedbacks and complexity cascades are set off by small random initiating events (Arthur 1990, 2000, Bak 1996, Brock 2000, Brunk 2000) – Kelso et al.'s (1992) view being an exception. Their six concluding points (p. 433) on the dynamics of order creation come closest to a possible 0^{th} law:

> Control parameters, R_i, externally influenced, create $R > R_{c1}$ with the result that a phase transition (instability) approaches, degrees of freedom are enslaved, and order parameters appear, resulting in similar patterns of order emerging even though underlying generative mechanisms show high variance.

I ignore 'spontaneous' self-organization. One could take the Churchman & Ackoff (1950) approach and treat spontaneous instigation and phase transition events as '*co-producers*'. Most likely, small instigating events are ubiquitous in any system and do not need special signification in the proposed law. Any one or more of the 'tasks' Kauffman points to as elements of self-organization could be the locus of instigation once the agents are activated by $R_{c1} > R > R_{c2}$.

The 0^{th} law emerges from the complexity science of Prigogine (1955), Haken (1977), Nicolis & Prigogine (1989), Kelso et al. (1992), Cramer (1993), and Mainzer (1997). Their focus is on the Bénard process energy-differential that applies to weather, fluid dynamics, various chemical materials, the geology of the Earth, and various biological phenomena. The three laws form a causal circle. It seems clear that no one of them can exist without the other two:

1. The 1^{st} Law of Thermodynamics states that order translates from one form to another, with energy conserved – the 2^{nd} Law is an outcome of the order translation events.
2. The 2^{nd} Law states that over time, order induced by higher energy states dissolves into randomness – the 0^{th} law is an outcome of dissipating energy differentials.
3. The 0^{th} law states that, $R_{c1} > R > R_{c2}$ produces new order via agents' self-organization – the 1^{st} law is an outcome of order creation.

Does the 0^{th} law apply to bioeconomics? Equilibrium thinking and the 1^{st} Law are already endemic in economics. This automatically brings in the 2^{nd} and 0^{th}. Or, since bioeconomics is built partially on Darwinian thinking, and since this is now seen as equilibrium and fine tuning in the last frame of a 3.8 billion year long movie, again the 2^{nd} and 0^{th} laws are present by default. Durlauf (1997, p. 33) says: 'A key import of the rise of new classical economics has been to change the primitive constituents of aggregate economic models: while Keynesian models employed aggregate structural relationships as primitives, in new classical models individual agents are the primitives so that all aggregate relationships are emergent'. In this statement the 0^{th} law is brought in more directly. Schumpeter (1942) figured out the 0^{th} law in the econosphere decades ago. Besanko et al. (2000, p. 485), summarize his thesis as follows: 'Schumpeter considered capitalism to be an evolutionary process that unfolded in a characteristic pattern. Any market has periods of comparative quiet, when firms that have developed superior products, technologies, or organizational capabilities earn positive economic profits. These quiet periods are punctuated by fundamental '*shocks*' or '*discontinuities*' that *destroy* old sources of advantage and *replace* them with new ones. The entrepreneurs who exploit the opportunities these shocks create achieve positive profits during the next period of comparative quiet. Schumpeter called this evolutionary process creative destruction'. Remarkably, in 1942 Schumpeter writes about replacing evolution with phase transitions (well before Prigogine 1955) and replacing gradualist evolution with punctuated equilibrium (long before Eldredge & Gould 1972).

Many qualifications may be levied against my analysis. I simply try to clarify to myself the 'complexity science' that is being applied to social science. I take a 'strict constructionist' interpretation of what the various authors say, avoiding the gross metaphorical views many freelance writers and consultants lift from complexity science. Except for Lorenz, all of the authors whose premises I cite have extended complexity ideas from their own discipline into social science and the econosphere. I do not 'interpret' their application; they do it themselves. I have assumed that $R_{c1} > R > R_{c2}$, simply stated, always results in a phase transition, but I recognize that sometimes other variables may cause R to have to be higher than normal before it occurs. Do thermodynamics, the Bénard process, and phase transitions apply to social science? These authors think they do, but many others, including one of the referees of this journal, do not. Some may think that nonequilibrium thermodynamics of chaotic systems (Beck & Schlögl 1993), applies to social science, but I have not tried to do so. I have stayed away from deterministic chaos, dwelling instead on the region of emergent complexity/order just below 'the edge of chaos' as the Santa Fe scholars put it. Some see this boundary as imaginary; some see a major difference between the self-organizing agents in the complexity region and the linear differential equations driving the āperiodic behavior above the 'edge'; still others see it as needless, and temporary, excitement about over-determined equations (Kaye 1993, Beck & Schlögl 1993).

The application of the 0^{th} law across bio- and econospheres rests with Haken's control parameters, the first two words in the Kelso et al. premise stated above – and only in their premise – because they broadened Haken's R to R_i. The R_i adaptive tensions (McKelvey 2001) can appear in many different forms, from Jack Welch's famous phrase, 'Be #1 or 2 in your industry in market share or you will be fixed, sold, or closed' (Tichy & Sherman 1994, p. 108; somewhat paraphrased), to narrower tension statements aimed at technology, market, cost, or other adaptive tensions. Schumpeter observes (quote above) that entrepreneurs are particularly apt at uncovering tensions in the marketplace. The applied implication of the 0^{th} law is that economic development is a function of (1) *control parameters*, (2) *adaptive tension*, and (3) *phase transitions* motivating (4) *agents' self-organization*. Take away any of these and economic progress stops.

Why doesn't economic development happen all the time and everywhere? Kauffman essentially assumes that order-creation is a 'persistent coming into existence' all the time and everywhere – hence his focus on an extinction law – his 'candidate fourth law'. But order-creation or creative destruction does *not* happen in all economies, in all firms, in all divisions of a firm, among all agents worldwide. What turns this sort of activity on or off? One could say we already know the answer – entrepreneurs do not act because they cannot see the opportunities, capital is not available, or there are too many government restrictions, or the social norms are the sticking point, or people do not have the right kind of personality, and so on. Social scientists have focused on factors such as these for decades. If, as Durlauf suggests, agent behavior is the primitive underlying aggregate economic behavior, then surely any engine that turns on or off, or speeds up agent-produced order-creation becomes as central to economic development as is capital. All of the foregoing four factors are part of the context that the 0^{th} law says results in order creation. Availability of capital can speed things up or create greater impact. It is necessary but not sufficient. Thus in India, by this logic, the various social factors, in the past anyway, apparently, have seldom if ever combined in such a way as to produce $R_{c1} > R > R_{c2}$ actually impinging on more than a small percentage of agents.

Acknowledgements

I suppose it is purely by chance that I first presented this paper in Brussels 100 years after Henri Bénard's dissertation paper on 'Bénard cells', and completed all of the post copy-edit corrections a few days after Ilya Prigogine's death on May 28, 2003. Prigogine lived in Brussels most of his life. Surely, no two scientists' contributions are more fundamental to this paper. At the time of my Brussels presentation (at the *Workshop on Thermodynamics and Complexity Applied to Organizations*, EIASM, September 28–29, 2001), the paper was titled 'Social Order-Creation Instability Dynamics: Heterogeneous Agents and Fast-Motion Science – on the 100^{th} Anniversary of Bénard's Paper'. I wish to thank participants at this Workshop, as well as members of the *Center for the Study of Evolution and the Origin of Life*, UCLA, and participants at the *Evolution and Social Behavior Conference*, UCLA, for many helpful comments on earlier versions of this paper. I also wish to thank two anonymous referees, and especially Paul Zak, for suggestions, guidance, and encouragement. All remaining errors are my responsibility.

Notes

1. Another statement, 'Two bodies, each in thermal equilibrium with a third body, are in thermal equilibrium with each other . . . is sometimes referred to as the *0^{th} law of thermodynamics*' (Holman 1988, p. 5). Bar-Yam (1997) simply accepts it as the 0^{th} law. My contention is that a law about order creation should logically precede the 1^{st} Law of order conservation. Besides, Holman's so-called 0^{th} law is a transitivity – an obvious phenomenon hardly needing added recognition as a 'law'.
2. Witt (1999) calls for the translation of selectionist theory from biology to economics to occur at a more abstract level than the kind of direct analogical translation characteristic of, say, routines paralleling the function of genes á la Nelson & Winter (1982).
3. Consisting of a fluid between hot and cold surfaces; at some critical point in the temperature gradient between the plates, circular bulk movements of molecules will occur so as to reduce the temperature differential – an example of self-organization (Haken 1977).

4. Preliminarily, think of *entanglement* as the interdependence of two particles or entities such that neither one can behave or be understood independently, and decoherence as the negation of the entanglement effect.
5. Allen (2001) argues that a 'Law of Excess Variety' is more appropriate, because in a rapidly changing world only some portion of the precursor set of internal states anticipated to have adaptive value will be relevant.
6. Hodgson (1994, p. 409), in a careful critique, writes that while 'methodological individualists' such as Hayek and von Mises (the Austrian School) did hold that '. . . all social phenomena . . . are explicable only in terms of individuals . . .' the individuals, in their view, did not evolve. This clearly separates their agents from the coevolving agents of the complexity scientists.
7. Elsewhere I show how correlated histories and entanglement relate to network sociology and management (McKelvey 2003).
8. It is worth noting that Gell-Mann (1994, pp. 138, 140) says of Roland Omnès as follows: 'Among those who have made especially valuable contributions are Robert Griffiths and Roland Omnès, whose belief in the importance of histories we share. . . . Hartle and I, like Griffiths and Omnès, make use of the fact that the questions always relate ultimately to alternative histories of the universe. (. . . A history is merely a narrative of a time sequence of events – past, present, or future.)' (pp. 138, 140)
9. This process is described in Bonner (1998), Kauffman (1993) and Salthe (1993), among many other sources.
10. Schrödinger (1944) coined negentropy to refer to energy importation.
11. My reason for emphasizing the 'container' is that, as Salthe (1993) points out, the container holds the scale of the system constant. If scale is allowed to increase along with ΔT, the transition from order laminar flows to turbulence (and thus new order) is negated.
12. Mainzer (1997, p. 58), as does Haken (1983, p. 254) incorrectly terms R the Rayleigh number. R is really the Reynolds number – a measure of the rate of fluid flow. In this case it is a direct function of the energy difference, ΔT. In fluid dynamics, at a specific level of R, fluid flow becomes turbulent. This 'critical value' of R is termed the Rayleigh number, R_c (Lagerstrom 1996).
13. For Kauffman (1993) it looks like: *ordered* $\rightarrow |R_{c1}| \rightarrow$ *complex* $\rightarrow |R_{c2}| \rightarrow$ *chaotic*. But, Kauffman really only talks about one phase transition – 'a phase boundary' (p. 218) – though he does talk about a 'boundary region' existing between order and chaos. For him, the 'region' – also called the 'melting zone' – appears to be defined by only one phase transition.
14. The European and American school characterizations of the complexity science literature are admittedly fuzzy sets.
15. Horgan (1996, p. 197) reports that the Santa Fe scholars now 'disavow' this phrase.
16. At the R_{c1} transition, in fluids for example, agents change their rules from viscous damping to inertial fluid motion. But at the R_{c2} transition, the conception changes from the agent self-organization view of complexity science to the linear differential equation view of deterministic chaos theorists, with no mention of whether or how the agents actually change their self-organizing rules.
17. Haken is bent on adding mathematical rigor to the study of self-organization. Consequently, he (1983, p. 194) says: '. . . we must not treat the external forces as given fixed quantities but rather as obeying by themselves equations of motion'. In this one step he has embedded his entire analysis in the equilibrium mathematics of the 1^{st} Law (orbital mechanics no less). Haken generalizes his mathematics from physics to chemistry to biology to economics and sociology (1983, 1996). *While I accept the logic of adiabatic elimination and the idea of most degrees of freedom in a complex system being successively randomized and thus enslaved by the order parameters, there is no basis – in biological and social systems – for accepting that the fluctuations of the order parameters themselves are, willy-nilly, governed by equations of motion.*
18. Omnès points out that this is true in all but visible photons and superconduction.
19. Goldstein (1993) manages to write a paper about 'nonlinear dynamics of pattern formation' in which he talks about 'dissipative dynamics' and the 'Rayleigh dissipation function' without ever mentioning the work of Prigogine or Haken, for example. Even more surprising is the omission of Prigogine and Haken's work in a 148 page chapter by Tagg (1995) about instabilities in fluid flows brought on by

changes in the Reynolds number and in which he even cites Bénard's original (1901) paper. Most egregious is a paper by Bennett (1988) in which he discusses irreversible self-organization resulting from dissipation in the context of the 2nd Law of Thermodynamics, without citing Prigogine, though he does cite van Kampen's (1962) paper on the statistical mechanics of irreversible processes – the subject of Prigogine's (1962) book. A recent exception is a paper by te Boekhorst & Hemelrijk (2000), who happen to be Europeans at the University of Zurich.

20. In Salthe's basic triadic hierarchy, context bears on agents only one level lower (i.e., at the same scale). Thus, if R is between R_{c1} and R_{c2} (environmental context = level 1), this adaptive tension causes self-organization among agents one level lower (level 2). Self-organization at level 2 either causes enough entropy production to reduce the tension imposed on level 2, or sets up an $R_{c1} < R < R_{c2}$ (at level 2) that causes self-organization among agents at the next lower level (level 3).
21. Also including: Derrida & Stauffer (1986), Derrida & Weisbuch (1987), Stauffer (1987a,b), Weisbuch (1991).
22. Physicists must surely cringe when outsiders start suggesting laws for them! But the problem is that thermodynamics (now infodynamics in Salthe's view) has become a general framework across many sciences, some of which are less hooked on the math of planetary mechanics and see more phenomena in action before the 1st Law takes hold. Since, physicists pay little attention to pre 1st Law order creation, or, like Haken (1977) or Auyang (1998) define it out of existence because it does not fit within the constraints of their math models, the tension imbalance in scientific explanation motivates others to step in to create theoretical structure. Thus, order-creation theory even governs the creation of order-creation theory!

,23. I will argue that the 1st and 2nd Laws are bracketed by the 0th and 4th laws. There is Schrödinger's 3rd Law that I am ignoring.

24. This is a key term for Kauffman (p. 142). Roughly put, suppose you have a space filled with 100 agents. The 'adjacent possible' space is filled with new agents, each of which is just one minimum adaptive step away from its counterpart in the original space.

References cited

Alchain, Armen A. 1950. Uncertainty, evolution and economic theory. Journal of Political Economy 58:21–221.

Allen, Peter M. 2001. A complex systems approach to learning, adaptive networks. International Journal of Innovation Management 5:149–180.

Arthur, W. Brian. 1990. Positive feedback in the economy. Scientific American, February: 92–99.

Arthur, W. Brian. 2000. Complexity and the economy. Pp. 19–28 in D. Colander (ed.) The Complexity Vision and the Teaching of Economics. Edward Elgar, Cheltenham, UK.

Arthur, W. Brian, Steven N. Durlauf & David A. Lane (ed.) 1997. The economy as an evolving complex system. Proceedings of the Santa Fe Institute, Vol. XXVII. Addison-Wesley, Reading, MA.

Ashby, W. Ross. 1956. An introduction to cybernetics. Chapman & Hall, London.

Ashby, W. Ross. 1962. Principles of the self-organizing system. Pp. 255–278 in H. von Foerster & G.W. Zopf (ed.) Principles of Self-Organization. Pergamon, New York.

Atlan, Henri. 1978. Sources of information in biological systems. Pp. 177–184 in B. Dubuisian (ed.) Information and System. Pergamon, New York.

Auyang, Sunny Y. 1998. Foundations of complex-system theories in economics, evolutionary biology, and statistical physics. Cambridge University Press, Cambridge, UK.

Bak, Per. 1996. How nature works: the science of self-organized criticality. Copernicus, New York.

Bannerjee, Satindranath, Peter R. Sibbald & Jack Maze. 1990. Quantifying the dynamics of order and organization in biological systems. Journal of Theoretical Biology 143:91–111.

Bar-Yam, Yaneer. 1997. Dynamics of complex systems. Addison-Wesley, Reading, MA.

Baskin, Arthur B., Robert E. Reinke & Jay E. Mittenthal. 1992. Exploring the role of finiteness in the emergence of structure. Pp. 337–377 in J.E. Mittenthal & A.B. Baskin (ed.) Principles of

Organization in Organisms. Proceedings of the Santa Fe Institute, Volume XIII. Addison-Wesley, Reading, MA.
Beck, Christian & Friedrich Schlögl. 1993. Thermodynamics of chaotic systems. Cambridge University Press, Cambridge, UK.
Bénard, Henri. 1901. Les tourbillons cellulaires dans une nappe liquide transportant de la chaleur par convection en régime permanent. Annales de Chimie et de Physique 23:62–144.
Bennett, Charles H. 1988. Dissipation, information, computational complexity and the definition of organization. Pp. 215–233 in D. Pines (ed.) Emerging Syntheses in Science. Proceedings of the Santa Fe Institute, Volume I. Addison-Wesley, Reading, MA.
Besanko, David, David Dranove & Mark Shanley. 2000. The economics of strategy, 2^{nd} edn Wiley, New York.
Bonner, John Tyler. 1988. The evolution of complexity by means of natural selection. Princeton University Press, Princeton, NJ.
Brock, William A. 2000. Some Santa Fe scenery. Pp. 29–49 in D. Colander (ed.) The Complexity Vision and the Teaching of Economics. Edward Elgar, Cheltenham, UK.
Brunk, Gregory G. 2000. Understanding self-organized criticality as a statistical process. Complexity 5:26–33.
Chaisson, Eric J. 2001. Cosmic evolution: the rise of complexity in nature. Harvard University Press, Cambridge, MA.
Churchman, C. West & Russell L. Ackoff. 1950. Purposive behavior and cybernetics. Social Forces 29:32–39.
Collins, James G. & Jerry I. Porras. 1994. Built to last. HarperCollins, New York.
Conard, Michael. 1998. Towards high evolvability dynamics. Pp. 33–43 in G. Van de Vijver, S.N. Salthe & M. Delpos (ed.) Evolutionary Systems: Biological and Epistemological Perspectives on Selection and Self-Organization. Kluwer, Dordrecht, The Netherlands.
Cowan, George. A. 1994. Conference opening remarks. Pp. 1–9 in G.A. Cowan, D. Pines & D. Meltzer (ed.) Complexity: Metaphors, Models, and Reality. Proceedings of the Santa Fe Institute, Volume XIX. Addison-Wesley, Reading, MA.
Cowan, George A., David Pines & David Meltzer (ed.) 1994. Complexity: metaphors, models, and reality. Proceedings of the Santa Fe Institute, Vol. XIX. Addison-Wesley, Reading, MA.
Cramer, Friedrich. 1993. Chaos and order: the complex structure of living things (trans. D.L. Loewus). VCH, New York.
Darwin, Charles. 1859/1964. On the origin of species by means of natural selection, Murray, London. [A Facsimile of the 1^{st} ed. with an Introduction by E. Mayr (Harvard University Press, Cambridge, MA.)]
Depew, David J. 1986. Nonequilibrium thermodynamics and evolution: a philosophical perspective. Philosophica 37:27–58.
Depew, David J. 1998. Darwinism and developmentalism: prospects for convergence. Pp. 21–32 in G. Van de Vijver, S. N. Salthe & M. Delpos (ed.) Evolutionary Systems: Biological and Epistemological Perspectives on Selection and Self-Organization. Kluwer, Dordrecht, The Netherlands.
Depew, David J. & Bruce H. Weber. 1995. Darwinism evolving: systems dynamics and the genealogy of natural selection. Bradford/MIT Press, Cambridge, MA.
Derrida, B. 1987. Valleys and overlaps in Kauffman's model. Philosophical Magazine B 56:917–923.
Derrida, B. & D. Stauffer. 1986. Phase transitions in two-dimensional Kauffman cellular automata. Europhysics Letters 2:739–745.
Derrida, B. & G. Weisbuch. 1987. Dynamical phase transitions in three-dimensional spin glasses. Europhysics Letters 4:657–722.
Durkheim, Émile. 1893 De la division du travail social: étude sur l' organization des sociétés supérieures. F. Alcan, Paris.
Durlauf, Steven N. 1997. Limits to science or limits to epistemology? Complexity 2:31–37.
Eddington, Arthur S. 1930. The nature of the physical world. Macmillan, London.
Eldredge, Niles. 1995. Reinventing Darwin. Wiley, New York.
Eldredge, Niles & Stephen Jay Gould. 1972. Punctuated equilibrium: an alternative to phyletic gradualism. Pp. 82–115 in T.J.M. Schopf (ed.) Models in paleobiology. Freeman, Cooper, San Francisco.

Epstein, Joshua M. & Robert Axtell. 1996. Growing artificial societies. MIT Press, Cambridge, MA.
Field, George B. & Eric J. Chaisson. 1985. The invisible universe. Birkhauser, Boston, MA.
Fisher, Irving. 1926. Mathematical investigations into the theory of value and prices. Yale University Press, New Haven, CT.
Friedman, Milton. 1953. Methodology of positive economics. Pp. 3–43 in M. Friedman, Essays in Positive Economics. University of Chicago Press, Chicago, IL.
Friedrich, Harold 1994. Chaos in Atomen. Pp. 208–219 in K. Mainzer & W. Schirmacher (ed.) Quanten, Chaos und Dämonen. Erkenntnistheoretische Aspekte des Modernen Physik. B. I. Wissenschaftsverlag, Mannheim.
Friedrich, Harold and Dieter Wintgen. 1989. The hydrogen atom in a uniform magnetic field. Physics Reports 183:37–79.
Gell-Mann, Murray. 1994. The quark and the jaguar. Freeman, New York.
Gleick, James. 1987. Chaos: making a new science. Penguin, New York.
Goldstein, Raymond E. 1993. Nonlinear dynamics of pattern formation in physics and biology. Pp. 401–424 in L. Nadel & D. Stein (ed.) 1992 Lectures in Complex Systems. Lectures at the Santa Fe Institute, Volume V. Addison-Wesley, Reading, MA.
Goodwin, Brian & Stuart A. Kauffman. 1992. Deletions and mirror-symmetries in Drosophila segmentation mutants reveal generic properties of epigenetic mappings. Pp. 269–296 in J.E. Mittenthal & A.B. Baskin (ed.) Principles of Organization in Organisms. Proceedings of the Santa Fe Institute, Volume XIII. Addison-Wesley, Reading, MA.
Gurnis, Michael. 2001. Sculpting the earth from inside out. Scientific American 284 (March):40–47.
Haken, Hermann. 1977. Synergetics, an introduction: non-equilibrium phase transitions and self-organizationin physics, chemistry, and biology. Springer-Verlag, Berlin.
Haken, Hermann. 1983. Synergetics, an introduction: non-equilibrium phase transitions and self-organizationin physics, chemistry, and biology, 3rd edn. Springer-Verlag, Berlin.
Haken, Hermann. 1996. Synergetics as a bridge between the natural and social sciences. Pp. 234–248 in E.L. Khalil & K.E. Boulding (ed.) Evolution, Order and Complexity. Routledge, London.
Hinterberger, Friedrich. 1994. On the evolution of open socio-economic systems. Pp. 35–50 in R.K. Mishra, D. Maaß & E. Zwierlein (ed.) On Self-Organization: An Interdisciplinary Search for a Unifying Principle. Springer-Verlag, Berlin.
Hodgson, Geoffrey M. 1994. Hayek, evolution, and spontaneous order. Pp. 408–447 in P. Mirowski (ed.) Natural Images in Economic Thought. Cambridge University Press, Cambridge, UK.
Holman, Jack P. 1988. Thermodynamics, 4th edn. McGraw-Hill, New York.
Horgan, John. 1996. The end of science. Broadway Books, New York.
Kampis, George. 1991. Self-modifying systems in biology and cognitive science: a new framework for dynamics, information, and complexity. Pergamon, New York.
Kauffman, Stuart A. 1974. The large-scale structure and dynamics of gene control circuits: an ensemble approach. Journal of Theoretical Biology 44:167–190.
Kauffman, Stuart A. 1993. The origins of order: self-organization and selection in evolution. Oxford University Press, New York.
Kauffman, Stuart. 2000. Investigations. Oxford University Press, New York.
Kaye, Brian. 1993. Chaos & complexity. VCH, New York.
Kelso, J.A. Scott & Gregor S. Schöner. 1987. Toward a physical (synergetic) theory of biological coordination. Springer Proceedings in Physics 19:224–237.
Kelso, J.A. Scott, Mingzhou Ding & Gregor Schöner. 1992. Dynamic pattern formation: a primer. Pp. 397–439 in J.E. Mittenthal & A.B. Baskin (ed.) Principles of Organization in Organisms. Proceedings of the Santa Fe Institute, Volume XIII. Addison-Wesley, Reading, MA.
Khalil, Elias L. & Kenneth E. Boulding (ed.) 1996. Evolution, order and complexity. Routledge, London.
Lagerstrom, P.A. 1996. Laminar flow theory. Princeton University Press, Princeton, NJ.
Lewin, Roger. 1992. Complexity: life at the edge of chaos. University of Chicago Press, Chicago, IL.
Lorenz, Edward Norton. 1963. Deterministic nonperiodic flow. Journal of the Atmospheric Sciences 20:130–141.

Mainzer, Klaus. 1997. Thinking in complexity: the complex dynamics of matter, mind, and mankind, 3rd edn. Springer-Verlag, New York.
McKelvey, Bill. 2001. Energizing order-creating networks of distributed intelligence. International Journal of Innovation Management 5:181–212.
McKelvey, Bill. 2004. Emergent order in firms: complexity science vs. the entanglement trap. Pp. 99–125 in E. Mitleton-Kelly (ed.) Complex Systems and Evolutionary Perspectives on Organizations. Pergamon, Amsterdam, The Netherlands.
Meyer, Marshall W. & Lynne G. Zucker. 1989. Permanently failing organizations. Sage, Newbury Park, CA.
Mirowski, Philip. 1989. More heat than light. Cambridge University Press, Cambridge, UK.
Mittenthal, Jay E., Arthur B. Baskin & Robert E. Reinke. 1992. Patterns of structure and their evolution in the organization of organisms: modules, matching, and compaction. Pp. 321–332 in J.E. Mittenthal & A.B. Baskin (ed.) Principles of Organization in Organisms. Proceedings of the Santa Fe Institute, Volume XIII. Addison-Wesley, Reading, MA.
Morgan, Mary S. & Margaret Morrison (ed.) 2000. Models as mediators: perspectives on natural and social science. Cambridge University Press, Cambridge, UK.
Morrison, Foster. 1991. The art of modeling dynamic systems. Wiley Interscience, New York.
Nelson, Richard R. & Sydney G. Winter. 1982. An evolutionary theory of economics. Belknap, Cambridge, MA.
Newman, Stuart A. 1992. Generic physical mechanisms of morphogenesis and pattern formation as determinants in the evolution of multicellular organization. Pp. 241–267 in J.E. Mittenthal & A.B. Baskin (ed.) Principles of Organization in Organisms. Proceedings of the Santa Fe Institute, Volume XIII. Addison-Wesley, Reading, MA.
Nicolis, Grégoire & Ilya Prigogine. 1989. Exploring complexity: an introduction. Freeman, New York.
Omnès, Roland. 1999. Understanding quantum mechanics. Princeton University Press, Princeton, NJ.
Prigogine, Ilya. 1955. An introduction to thermodynamics of irreversible processes. Thomas, Springfield, IL.
Prigogine, Ilya. 1962. Non-equilibrium statistical mechanics. Wiley Interscience, New York.
Prigogine, Ilya (with Isabelle Stengers) 1997. The end of certainty: time, chaos, and the new laws of nature. Free Press, New York.
Prigogine, Ilya & Isabelle Stengers. 1984. Order out of chaos: man's new dialogue with nature. Bantam, New York.
Rosenberg, Alexander. 1994. Does evolutionary theory give comfort or inspiration to economics? Pp. 384–407 in P. Mirowski (ed.) Natural Images in Economic Thought. Cambridge University Press, Cambridge, UK.
Rothstein, Jerome. 1958. Communication, organization and science. Falcon's Wing Press, Indian Hills, CO.
Salthe, Stanley N. 1985. Evolving hierarchical systems. Columbia University Press, New York.
Salthe, Stanley N. 1993. Development and evolution: complexity and change in biology. Bradford/MIT Press, Cambridge, MA.
Salthe, Stanley N. 1998. The role of natural selection theory in understanding evolutionary systems. Pp. 13–20 in G. Van de Vijver, S.N. Salthe & M. Delpos (ed.) Evolutionary Systems: Biological and Epistemological Perspectives on Selection and Self-Organization. Kluwer, Dordrecht, The Netherlands.
Samuelson, Paul A. 1947. Foundations of economic analysis. Atheneum, New York, NY.
Schrödinger, Erwin. 1944. What is life? The physical aspect of the living cell. Cambridge University Press, Cambridge, UK.
Schumpeter, Joseph A. 1942. Capitalism, socialism, and democracy. Harper & Row, New York.
Sommerhoff, Gerd. 1950. Analytical biology. Oxford University Press, London.
Spencer, Herbert. 1898. The principles of sociology. D. Appleton & Co, New York.
Stauffer, D. 1987a. On forcing functions in Kauffman's random Boolean networks. Journal of Statistical Physics 46:789–794.
Stauffer, D. 1987b. Random Boolean networks: analogy with percolation. Philosophical Magazine B 56:901–916.
Swenson, Rod. 1989. Emergent attractors and the law of maximum entropy production: foundations to a theory of general evolution. Systems Research 6:187–197.

Tagg, Randall. 1995. Instabilities and the origin of complexity in fluid flows. Pp. 231–379 in L. Nadel & D. Stein (ed.) 1993 Lectures in Complex Systems. Lectures at the Santa Fe Institute, Volume VI. Addison-Wesley, Reading, MA.

te Boekhorst, Irenaeus J.A. & Charlotte K. Hemelrijk. 2000. Nonlinear and synthetic models for primate societies. Pp. 19–44 in T.A. Kohler & G.J. Gumerman (ed.) Dynamics in Human and Primate Societies: Agent-Based Modeling of Social and Spatial Processes. Proceedings of the Santa Fe Institute. Oxford University Press, New York.

Thompson, D' Arcy Wentworth. 1917. On growth and form. Cambridge University Press, Cambridge, UK.

Tichy, Noel M. & Stratford Sherman. 1994. Control your destiny or someone else will. HarperCollins, New York.

Ulanowicz, Robert E. 1996. The propensities of evolving systems. Pp. 217–233 in E.L. Khalil & K.E. Boulding (ed.) Evolution, Order and Complexity. Routledge, London.

Van de Vijver, Gertrudis, Stanley N. Salthe & Manuela Delpos (ed.) 1998. Evolutionary systems: biological and epistemological perspectives on selection and self-organization. Kluwer, Dordrecht, The Netherlands.

van Kampen, N.G. 1962. Fundamental problems in the statistical mechanics of irreversible processes. Pp. 173–202 in E.G.D. Cohen (ed.) Fundamental Problems in Statistical Mechanics, Interscience, New York.

Weber, Bruce H. 1998. Emergence of life and biological selection from the perspective of complex systems dynamics. Pp. 59–66 in G. Van de Vijver, S.N. Salthe & M. Delpos (ed.) Evolutionary Systems: Biological and Epistemological Perspectives on Selection and Self-Organization. Kluwer, Dordrecht, The Netherlands.

Weisbuch, Gérard. 1991. Complex systems dynamics: an introduction to automata networks (trans. S. Ryckebusch). Lecture Notes Volume II, Santa Fe Institute. Addison-Wesley, Reading, MA.

Witt, Ulrich. 1999. Bioeconomics as economics from a Darwinian perspective. Journal of Bioeconomics 1:19–34.

Wolfram, Stephen. 2002. A new kind of science. Wolfram Media, Inc., Champaign, IL.