What Is Complexity Science? It is Really Order-Creation Science

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Complexity science appears to be problematic and inconsistent in accounting for processes of order-creation, as indicated by a review beginning with coarse-graining in quantum entanglement fields and ending with emergent order from social entanglement ties: A theory about the engine of order-creation at any of the several levels of order (atoms to social systems), or across the levels, is missing as a collective belief among complexity scientists. The classic concept of external (Bénard) energy-differentials (as control parameters) that cause emergence "at the edge of chaos" is frequently missing. The nature of the entanglement pool or "base"—more broadly the set of network ties among agents such as atoms, molecules, organisms, human actors—from which emergent order, is often ignored. The implications for the adaptive efficaciousness of subsequent emergence events, of the possibility in biological and social systems that prior emergence events could have fed back to irrevocably "corrupt" the entanglement or network "base," also are not considered. The interaction of Bénard, Darwinian and "rational" order-creation processes is barely considered. Finally, attention to the basic causal processes underlying emergent order largely has been ignored in most managerial and organizational applications of complexity science. The paper concludes by outlining essential problematics of order-creation science.

1 INTRODUCTION

"Order" and its synonyms means "…put persons or things into their proper places in relation to each other." Disorder, to natural scientists, means the 2nd law of thermodynamics, namely, inexorable dissipation toward entropy and randomness. Kauffman (1993) and Holland (1995) use the term, *order*, in the titles of their books, respectively *The Origins of Order* and *Hidden Order*. Mainzer (1997) titles his book *Thinking In Complexity*, but on page one he says: "…The theory of nonlinear complex systems…is an interdisciplinary methodology to explain the emergence of certain macroscopic phenomena via the nonlinear interactions of microscopic elements in complex systems." And then every subsequent chapter starts with a question about the emergence of order—in matter, life, brain, computer, and social systems. It is not by happenstance that our journal is titled *EMERGENCE*!

Views of order-creation have changed over the last century, as one might expect. Classical management theorists (Massie 1965) say order comes solely from the (rational?) thoughts and actions of owner/managers, captured nicely in the following quote attributed to Henry Ford: "*Why is it that whenever I ask for a pair of hands, a brain comes attached?*"[1] The Darwin-Wallace theory of natural selection (Darwin 1859) explains speciation in the biological world, that is: Why are there different kinds of organisms? Durkheim (1893) and Spencer (1898) also define order as the emergence of kinds, specifically, social entities. Half a century later, however, Sommerhoff (1950), Ashby (1956, 1962), and Rothstein (1958) define order not in terms of entities but rather in terms of the connections among them. Ashby adds two critical observations. Order (organization), he says, exists between two entities, *A* and *B*, only if the link is "conditioned" by a third entity, *C* (1962, p. 255). If *C* symbolizes the "environment," which is external to the connection between *A* and *B*, environmental constraints are what cause order (Ashby 1956). This results in his "*law of requisite variety*" (1956): For a biological or social entity to be efficaciously adaptive, the variety of its internal order must match the variety of the environmental constraints. Furthermore, he also observes that order does not emerge when the environmental constraints are chaotic (1956, pp. 131–132).

But what *causes* emergent order and self-organization? What is the underlying generative mechanism or *engine* of order-creation? How is the order-creation process inside firms linked to their competitive context? Science is about finding causes of phenomena (Pearl 2000, Salmon 1998). If you start with the Prigogine line of thought (updated in Nicolis and Prigogine 1989) and continue with Mainzer's development, it is clear that the only engine of order-creation considered in complexity science, so far, is the *Bénard Process*:

1. Negentropy becoming available because of the energy differential or adaptive tension existing between a system and its surroundings, and imposing upon microagents within the system, causes emergence; and
2. The 1st and 2nd critical values of *R*, the measure of tension, define the upper and lower bounds of the region of emergence (self-organization or complexity) sandwiched between the regions of order (slow change) and chaos (dysfunctional change).

Prigogine's basic argument is that the 1st and 2nd laws of thermodynamics would not exist if "order" has not been created in the first place. Darwin's process of natural selection is irrelevant if "order" has not been created in the first place. Complexity science—as a general explanation of emergent order—is problematic and inconsistent in accounting for the Bénard process, as is evident in the literature emerging from the physical, biological, and social sciences. Worse, attention to the basic causal process underlying emergence has largely been ignored in most managerial and organizational applications of complexity science.

First, I review explanations of how "order" in matter (what Gell-Mann calls coarse-graining) emerges from the fine-grained structure of the entangled (correlated) histories of pairs of agents. Then I consider biological systems, dissipative structures, the Bénard process, and order-creation in organizations. Following Mainzer

[1] Quoted in Hamel (2000, p. 102).

(1997), my analysis leads to the inescapable conclusion that complexity science is really order-creation science mistakenly characterized by a relatively extreme end state, complexity.

2 ORDER-CREATION THEORY IN COMPLEXITY SCIENCE

Coarse-graining. In a book written for popular consumption, Gell-Mann (1994, Ch. 11) uses a few simple terms to explain how 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.[2] 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. At any given time, in a sequence of time intervals, each electron has a *history* of effects from all the other electrons it has come in contact with. Because of the countless correlations, and the differing quantum states of all the other electrons, each individual history is likely unique. Consequently quantum theorists cannot attach a probability of occurrence to each individual electron's history. Instead, they use a quantity, *D*(A, B) to record the relation between the quantum histories of two correlated electrons over time—thus *D* is always assigned to *pairs* of individual electron histories, A and B. *Entanglement* occurs when the *correlated histories* of pairs of electrons are greater than zero. If the individual histories are correlated, they are said to *interfere* with each other. Since most histories are correlated with other histories, *D* is seldom a probability. If histories almost always interfere, and thus *D* is almost never a probability, the root question is: How can physicists predict with probability, let alone with what seems to most of us, virtual certainty?

Gell-Mann refers to the world of interference-prone histories as "*fine-grained*" structure. Thus, the quantum world is the fine-grained structure whereas he labels the world of quasiclassical physics as the *coarse-grained* structure. The question then arises, How does coarse-grained structure emerge from fine-grained—entangled—structure? 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.

How do the race probabilities emerge from the interference of 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 interference effects average out at approximately zero. Hence all the effects of the myriad tiny correlations among the details have no effect. 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—to become the coarse-grained structure—whereas all the other detail correlations are summed-over and their "interference" made irrelevant. When this happens, there are really three effects: (1) most of the history quantities, *D*, are ignored, that is, 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 wouldn't be in the same race at the same place at the same time.

Gell-Mann 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" (p. 144). Empirical researchers play this game every time they assume that the various effects not specifically hypothesized, or designed into the study as control variables, are randomized. That is, they neutralize each other and are, thus, summed over. The emergent coarse-graining process overcomes the interference-term effect by translating entanglement into probability, what Gell-Mann speaks of as "*decoherence*" (p. 146).[3] Recall that the *interference terms* are the myriad correlations between pairs of particles in the fine-grained structure. Coarse-graining results in the selecting out from the myriad the correlated histories of the same kind and the same level of relationship. Gell-Mann says coarse-graining "*washes out*" the interferences among histories in the fine-grained structure (p. 145–146).

Roland Omnès[4] (1999) develops an interpretation that connects better with complexity science. He makes a

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[2] I have double checked everything Gell-Mann says with the recent "modern interpretation" by Omnès (1999), whom Gell-Mann cites with approval. The Omnès treatment is more technical and treats in book-length what Gell-Mann covers in one chapter. Their views are consistent, but, for example, they do view the collapse of the collective wave packet(s) that is Mars in somewhat different ways. In addition, Omnès holds that decoherence in the universe is so pervasive and instantaneous that decoherence has happened long before any "observer" happens upon the scene—thus observers such as the "watcher" (Mills 1994) are superfluous.

[3] Omnès (1999, p. 75) defines decoherence as "the absence of macroscopic interferences."

[4] It is worth noting that Gell-Mann (1994) 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 [referring to James Hartle and himself] 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

strong association between irreversibility, dissipation, and decoherence, arguing that "…the essential character of decoherence appears to be irreversibility" (p. 196). He shows that decoherence is "…an irreversible dynamical process" (p. 206). Complexity scientists should note the parallel of Omnès's and Prigogine's treatment of time irreversibility (Prigogine and Stengers 1984). Omnès suggests a total Hamiltonian: $H = H_c + H_e + H_1$, where H_c is the Hamiltonian of the relevant "internal" variables of a system, H_e is the Hamiltonian of the environmental variables (potentially all other variables or degrees of freedom in the Universe) 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). He shows that the dynamical suppression of the environmental interferences of H_e Hamiltonian almost immediately produces a large decoherence effect (p. 203). He bases many of his statements on an axiom by the French mathematician Borel (1941) that: "one must consider that events with too small a probability never occur" (Omnès 1999, p. 84, 236). While probability mathematicians have to take vanishingly small probabilities into account, he summarizes Borel as saying, "…this kind of event cannot be reproducible and should be left out of science" (p. 84).

Omnès' view is essential. His introduction of H_e recognizes that decoherence and emergent coarse-graining, even in quantum theory, are now subject to the regular-to-chaotic forces imposed upon these fields. The external force, and its nature, results from the tension created by the *Bénard energy-differentials* recognized by chaos and complexity scientists that foster negentropy and create emergent structure. In the simple Bénard cell, and in the atmosphere, an energy-differential causes energy transfer via bulk (current) movements of gas molecules rather than via in-place vibrations and collisions. More broadly, think of an energy-differential as producing coarse-graining among histories of the vibrating molecules—or among histories of bottom-level microagents in general. In this view, *the energy-differentials of complexity theory become the causes of emergent coarse-grained structure from entanglement pools*.

Collapse of chaos. Cohen and Stewart (1994) refer to naturally occurring coarse-graining as "*emergent simplicity*" and "*the collapse of chaos*." Their explanation of how coarse-grained structure emerges from fine-grained structure is the opposite of reductionism—thus, their explanation is the antithesis of Gell-Mann's. Gell-Mann's laws of nature, to Cohen and Stewart, are "Sherlock Holmes stories" scientists use to explain emergent simplicity. That they are predictive, especially in physics, is a fortuitous accident. In their view, "laws of nature are [coarse-grained] features. They are structured patterns that collapse an underlying sea of chaos [the fine-grained entanglement pool], and they are conditioned by context" (1994, p. 433). Their explanation is "*contextualist*" rather than reductionist. Their prime example is evolution (p. 418); really coevolution (p. 420). Cohen and Stewart see emergent order as resulting from several dynamics:

First, there is the emergence of feedback loops that join entities that otherwise could evolve separately. For example, Cohen and Stewart say that "DNA sequences live in DNA space, and in the absence of any other influences would wander around dynamically through the geography of DNA space, seeking attractors and settling on them. Similarly [for] organisms [that] live in creature space…." They, too, can evolve independently "…seeking attractors and settling on them" (p. 419). Both DNA and organism could evolve independently of each other. *But*, it is the joining of these two spaces by feedback loops—the coevolution of hierarchically related spaces—that counts. This parallels Omnès's coupling of H_c and H_c. More broadly, it is the interaction of heretofore independent spaces that are inherently conflicting, but coupled because of the effect of other influences, that causes coarse-graining (p. 414). Because the attractors in DNA space are likely to differ from those in creature space, once the feedback loop exists, novel structures are apt to emerge. In this example, and indeed all of the examples Cohen and Stewart give, the mechanisms for coarse-graining in biology are Darwinian selectionist processes.

Second, Cohen and Stewart argue that entanglement pools are seldom purely random—"…*really* random systems would not possess statistical regularities" (p. 233; their italics). Thus, emergent structure can follow from statistical features. Absent pure randomness, the correlated histories of quanta or higher level entities—molecules, genes, organisms, etc.—are distributed probabilistically, with the more probable correlations more likely to lead to emergent coarse-grained structure or the observation of same. Instead of Gell-Mann's dependence on photon scattering to create collapsed wave functions in purely random entanglement pools, they argue that many, if not most, pools are not purely random, and therefore coarse-graining is probable.

Third, Cohen and Stewart observe that many kinds of emergence do not stem from statistical distributions. "There is nothing statistical about π, the Feigenbaum number, the Mandelbrot set—or chlorophyll, DNA, or homeotic genes, for that matter…. Statistics is just one way for a system to collapse the chaos of its fine structure and develop a reliable large-scale feature. Other kinds of feature can crystallize out from underlying chaos—numbers, shapes, patterns of repetitive behavior" (pp. 233–234).

Fourth, Cohen and Stewart identify some kinds of

history is merely a narrative of a time sequence of events—past, present, or future.") (pp. 138, 140) emergence—specifically crystallography—as immune to the state of entanglement (p. 237). Recall that in Gell-Mann's view of quantum mechanics, the correlated histories of quanta result in purely random quantum states and a purely random entanglement pool. And, in his view, coarse-graining is only a function of photon scattering. In contrast, Cohen and Stewart see the correlated histories of atoms as following the rules of deterministic chaos—"since the motion of atoms is chaotic, their precise behavior *is* sensitive to initial conditions" (p. 236; their italics). They say: "Quantum systems don't exhibit chaos in the conventional sense, but any classical (that is, nonquantum) theory of large numbers of particles certainly does. Quantum systems aren't chaotic because the infinitely fine structures that are important for chaos are forbidden in quantum mechanics, thanks to the uncertainty principle" (p. 236). But then they say: "Quantum mechanics has its own form of small-scale chaos—genuinely random fluctuations, rather than the deterministic but effectively random fluctuations of conventional chaos" (p. 237). What emerges is a level-of-analysis effect: In their view, correlated histories of quantum states are purely random, but the correlated histories of atoms—and derivatively, all higher levels—are deterministically chaotic (p. 236).

Finally, they say: "Crystal lattices are not just immune to small-scale chaos; they are immune to most of quantum mechanics" (p. 237). Why? "The main thing we need to know is that physical systems tend to minimize their energy…. This argument in favor of an atomic lattice is independent of the shape of the atoms or their detailed properties; energy minimization is enough…. Crystal lattices are not just phenomena that emerge from quantum mechanics. They have a universal aspect; they will emerge from any theory sufficiently close to quantum mechanics that involves identical roughly spherical atoms and energy minimization. *This kind of universality is common to many, perhaps all, emergent phenomena*…" (p. 237; my italics).

Cohen and Stewart focus on the selectionist effect in biology and the chaos and energy minimization effects in physics at the level of atoms. They recognize that selection effects produce increasing complexity and increasing degrees of freedom. And though they don't use the term, still, in their view, biological organisms are emergent dissipative structures that, once formed, dissipate imported negentropy. In this sense, their "collapse of chaos" produces coarse-graining "far from equilibrium," to use Prigogine's phrase.

Dissipative Pressure. Prigogine uses dissipative structures to explain both the cause and disappearance of coarse-graining. Dissipative structures are shown to exist "far from equilibrium" and seemingly counter to the 2^{nd} law of thermodynamics—the "entropy" law holding that all order in the universe eventually reverts to purely random disorder and thermal equilibrium (Prigogine 1962). In this classic monograph, he develops a general theory of irreversibility, that is, entropy, demonstrating systematically the process whereby atoms and molecules showing different momenta and coordinates—the *q*s and *p*s in a Hamiltonian expression—reduce to a "…'sea' of highly multiple incoherent correlations" (1962, p. 8). Having translated the *q*s and *p*s into correlated histories, Prigogine, sets the stage for carrying his analysis across the seeming discontinuity between atoms and molecules and the lower-level correlated histories that Gell-Mann mentions in his analysis. Prigogine's analysis shows how the coarse-graining apparent in the universe can actually, and eventually, reduce to the random correlated quantum histories in the fine-grained structure.

Control Parameters. "Control parameters," as Mainzer (1997) uses the term, refers to external forces causing the emergence of dissipative structures in the region of complexity. He begins with a review of Lorenz's (1963) discovery of a deterministic model of turbulence in weather systems. A discussion of research focusing on Benárd cells follows. Here we discover that "*critical values*" in the energy (temperature, *T*) differential between warmer and cooler surfaces of the cell affect the velocity, *R*, of the air flow, which correlates with ΔT. The surfaces of the cell represent the hot surface of the earth and the cold upper atmosphere. The critical values divide the velocity of air flow in the cell into three kinds: (1) Below the 1^{st} critical value, 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 1^{st} and 2^{nd} critical values, heat transfer occurs via a bulk movement of air in which the gas molecules move between the surfaces in a circulatory pattern. We encounter these in aircraft as up- and down-drafts; and (3) Above the 2^{nd} critical value a transition to chaotically moving gas molecules is observed.

Prigogine's emergent dissipative structures form in the region of emergent complexity in between the critical values. Cramer (1993) observes that the three regions defined by the critical values define three kinds of complexity: *subcritical* →| 1^{st} |→ *critical* →| 2^{nd} |→ *fundamental*. His definitions appear in Table 1. The algorithmic compressibility characterizing all the laws of classical Newtonian science appears mostly in the subcritical region but also in the fundamental region of deterministic chaos. Mainzer (1997, p. 63) says, "mathematical symmetry is defined by the invariance of certain laws with respect to several transformations between the corresponding reference systems of an observer." Thus, symmetry dominates the subcritical region and to some extent also applies to the fundamental region. Furthermore, the invariant laws are reversible (Prigogine and Stengers 1984). But, as a control parameter causes *R* to move across the critical values, however, the consequence is symmetry breaking, at least in part, because the laws of classical physics do not remain invariant.

>>> Insert Table 1 about here <<<

As Prigogine (1962, Nicolis and Prigogine 1989) observes, in the region of emergent complexity are created emergent dissipative structures "far from equilibrium" as a result of importing energy into the system (at some rate) as negentropy. Though this process is nonlinear and not subject to symmetry, Cramer (1993) observes that once created, dissipative structures become subject to the symmetry and invariant laws of classical physics. The final state of dissipation, that is, of perfect entropy, is easily describable by a master equation from statistical mechanics; the probable positions of millions of particles subject to Brownian motion can be reduced to minimal degrees of freedom. In reverse, the creation of emergent dissipative structures is in fact a creation of degrees of freedom. As Mainzer puts it, "…complexity means that a system has a huge number of degrees of freedom" (p. 65).

Phase Transition. In the following bullets I trace out the order Mainzer 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—a coarse-grained structure in Gell-Mann's terms.
2. Just before the 1st critical value is reached (from below), unstable vectors (wave packets, modes, energy, forces, motions) appear along with the stable waves.
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 is crumbling, resulting in interference and entanglement. Consequently, coarse-graining is reduced.
4. The unstable vectors and their degrees of freedom disappear into a stochastic pool of Brownian motion. This leads to a vast reduction in degrees of freedom. Decoherence has nearly disappeard.
5. The last few unstable vectors remaining become *order parameters* acting to create the emergent dissipative structures as the system tips over the 1st critical value into the region of emergent complexity—meaning that the order parameters surviving across the complete phase transition are totally the result of a stochastic process.
6. At this juncture, order, complexity, and increased degrees of freedom emerge. The result is decoherence and emergent coarse-graining. This is where *context* has greatest impact.
7. The region of emergent 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 equal to, or even faster that the existing dissipative structures can reduce it, more dissipative structures will continue to emerge. Unless of course the energy-differential rises over the 2nd critical value. Then chaotic processes take over.

Mainzer teases out the fine-grained process events just before and after the phase transition at the 1st critical value. Recalling Omnès's (1999) argument, that decoherence processes occur more rapidly than can ever be measured, we realize that a physical system passes through the several states outlined in the bullets above very rapidly—perhaps too rapidly to measure. Nevertheless, we see that emergent structure is stochastically driven by the tail end of the disappearing unstable vectors. By this process, at the phase transition, most of the vectors simply disappear into entanglement. But the trace number at the end collapses the vectors (wave packets) thereby creating the order parameters governing the emergence of dissipative structures. This amounts to an explanation of emergent quantum chaos and the vanishingly small initial order parameters that, like the butterfly effect, eventually influence the forms of emergent dissipative structures of quasiclassical physics.

The Bénard energy-differential figures centrally in Mainzer's treatment of complexity theory. Omnès does not refer explicitly to something akin to the Bénard process, but he does focus on an external Hamiltonian and context. Ashby and Rothstein emphasize external environmental constraints as causes of order, but they do not define constraints in terms of anything looking like an energy-differential. The latter might be inferred vaguely in the background, perhaps, in the Cohen and Stewart treatment. And energy-differentials do not figure in Gell-Mann's photon scattering caused coarse-graining, though the photons do represent the context of an external energy source. But no mention is made as to whether they can appear below, between or above the 1st and 2nd critical values—though presumably, and perhaps rather obviously, back radiation could be below the 1st and an exploding star well above the 2nd. But Mainzer and Omnès argue that energy-differentials could or should be taken into account.

Mainzer views complexity science as an exploration of endogenously created nonlinearities operating in the context of control parameters and threshold effects. His analysis carries this theme across matter, life, mind (real and artificial), and into economic and other social systems. Whether firms are analogized as biological ecologies governed by Darwinian selection, as brains and distributed intelligence, as economies, or as networks of human and social capital Morgan (1997, McKelvey forthcoming-a), Mainzer's analysis applies. Following Schumpeter, Mainzer identifies innovation and technological change as the primary engine setting both the nonlinear and Bénard processes in motion and, thus, creating dissipative structures and emergent order. He specifically mentions Allen's (1988) discovery of these processes at work in urban development as a social system application. Allen's study of Atlantic fisheries (Allen and McGlade 1986, 1987) and recent analysis of knowledge management (Allen forthcoming) also instruct.

An even broader extension of the Bénard process stems from Swenson's work (1989, 1998). His "law of maximum entropy production" holds that a "…*system will select the path or assembly of paths out of otherwise available paths that minimize the potential or maximize the entropy at the fastest rate given the constraints*…. The world will select order whenever it gets the chance—the world is in the order-production business because ordered flow produces entropy faster than disordered flow" (1998, p. 173, his italics). Consider the Big Bang as the ultimate heat source and outer space as the ultimate heat sink. At some point in time, every particle of matter in the universe will pass through the 1st and 2nd critical values of the Bénard process. Order-creation of dissipative structures is pervasive and inevitable. Galaxies, the Sun, and the Earth are all order-creations for maximizing entropy creation. Life on the surface of the Earth emerged in the context of the giant atmospheric and plate tectonic Bénard processes. Western civilization, including all its social systems, organizations, and firms, is a lesser order-creation device that, in fact, is so effective a dissipative process that it is rapidly depleting the resources upon which it depends. Innovations and new technologies create energy and resource disparities in economies—Bénard thresholds—that firms, as order-creations, emerge to dissipate the energy/resource differentials. Complexity science applications have now spread to the physical, life, social, and management sciences (Nicolis and Prigogine 1989, Cowan, Pines and Meltzer 1994, Belew and Mitchell 1996, Arthur, Durlauf, and Lane 1997, Mainzer 1997, McKelvey 1997, Byrne 1998, Cilliers 1998, Anderson 1999, Maguire and McKelvey 1999a, b), among many others. Complexity science is now pervasive and at its core are endogenous nonlinearities and the Bénard process.

3 EXPLAINING ORDER IN ORGANIZATIONS

Kinds of Order. Three kinds of order exist in organizations: rational, natural, and open systems (Scott 1998). Rational systems result from prepensive conscious intentionalities, usually by managers. Natural systems, such as informal groups, typically emerge as employees attempt to achieve personal goals in the context of a command-and-control bureaucracy. Open systems are in various ways defined by external forces. That all three exist goes unquestioned. What remains vague, however, are explanations about how they emerge, coevolve, come to dominate one another, and collectively impact organizational performance. Specifically, how do these three forces combine to produce the order we see in firms, where "order" is defined in terms of formal structure and process and other patterns of behavior within and by a firm?

McKelvey (1997) defines organizations as quasi-natural phenomena, caused by both the *conscious intentionality* of those holding formal office (rational systems behavior) and *naturally occurring* structure and process emerging as a result of coevolving individual employee behaviors in a selectionist context (natural and open systems behavior). With respect to the latter, two general order-causing effects appear in firms: (1) selectionist microcoevolution (McKelvey 1997, 1999a, c; forthcoming-a); and (2) complexity catastrophe (Kauffman 1993, McKelvey 1999a, c). More broadly, according to thick description researchers (Geertz 1973) and relativists and postmodernists (Burrell and Morgan 1979, Lincoln 1985, Reed and Hughes 1992, Hassard and Parker 1993, Weick 1995, Chia 1996), naturally occurring order in firms emerges from the conflation of the inherent stochastic idiosyncrasies of individuals' aspirations, capabilities, and behaviors—*the social scientists' analog of entanglement*, I argue.[5]

Where to look for developing a theory of "*natural order emergence*" in firms? Complexity science, of course.[6] Management writers mostly emphasize chaos and complexity theories as a means of better understanding the behavior of firms facing uncertain, nonlinear, rapidly changing environments (Maguire and McKelvey 1999b). This view is somewhat off the track (McKelvey 1999b). As demonstrated above, going back to the roots of complexity science in quantum physics and Prigogine's work, we see more accurately that complexity science is fundamentally aimed at explaining order-creation. Much of normal science focuses on equating energy translations from one form of order to another—working under the 1st law of thermodynamics. This is all in the context of the order within existing dissipative structures. The 2nd law of thermodynamics focuses on the inevitable disintegration of existing order. Also, I have argued that complexity science aims to explain the emergence of order—it is *order-creation science*.

Decoherence and Emergence. Using complexity science, I have outlined the idea that quantum wave packets are collapsed by external forces and particularly by imposed energy-differentials, following the Modern Interpretation. Not to have done this would have left entanglement—and the decoherence of it via the human observer (Mermin 1991, or Mill's (1994) "watcher" of the universe—solidly in the hands of relativists and postmodernists who decry normal science because everything that is ostensibly and "objectively" detected by science is interpreted "subjectively" by the human observers—what we see is nothing more than the result of wave packets collapsed by subjective human observers. This would encourage the subjective, loose, metaphorical treatment of the term, entanglement, as it is applied to social systems.

I can now remind organization scientists that the most fundamental question of complexity science: **What**

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[5] See McKelvey (forthcoming-c) for further discussion of the "marriage" of postmodernist ontology and normal science epistemology.

[6] Sociologists have studied the process of emergent social order since Durkheim (1893) and Spencer (1898). For recent examples, see Ridgeway and Berger (1986, 1988), Berger et al. (1998) and Mark (1998). Ridgeway and Berger focus on power legitimation. For them, differentiation follows from the influence of forces external to the social system. Mark focuses on information effects. For him, however, differentiation can emerge in totally undifferentiated systems without the effect of external forces.

Causes Order-Creation? *Complexity theory applications to firms rest on environmental constraints in the form of Bénard energy-differentials as the engines of order-creation—defined as the emergence of both entities and connections constrained by context*. The latter, when applied to firms, are best thought of as "*adaptive tension*" parameters (McKelvey forthcoming-a). Going back to the Bénard cell—the "hot" plate represents a firm's current position; the "cold" plate represents where the firm should be positioned for improved success. The difference is adaptive tension. This "tension" motivates the importation of negentropy and the emergence of adaptation fostering dissipative structures—assuming the tension lies between the 1st and 2nd critical values.

My review of entanglement, decoherence, and coarse-graining, modified by reference to complexity science and ranging from quanta to social systems, uncovers the second fundamental question in applying complexity science to firms—so far totally unrecognized: **Emergence from What?** *Organization scientists and managers about to apply complexity science to firms cannot willy-nilly assume that entanglement exists uncorrupted in a given firm. Absent entanglement, altering adaptive tension parameters could produce maladaptive results*. The nature of the initial pool of entangled particles appears essential to the coarse-graining process. In Gell-Mann's view, coarse-grained structure emerges from entangled fine-grained structure as a result external influences. Remove the external influence and macro structure disappears in the Bénard cell and coarse-grained quanta disappear back into wave packets. If energy-differentials are viewed as causes of coarse-graining, four critical differences appear:

1. Given an initially "pure," uncorrupted, or untampered-with pool of entanglements, the first coarse-graining resulting from an imposed energy-differential could alter entanglement in an irrevocable fashion—whether in physical, biological, or social entanglement pools.
2. Whereas in the Newtonian physical world (Cramer's (1993) subcritical complexity) of quanta and molecules the energy-differential effect is time-reversible, in the biological and social worlds, as Prigogine would say (Prigogine and Stengers 1984), it is a time-irreversible process. Omnès includes the physical world as well.
3. As a consequence, especially in biological and social entanglements, any subsequent coarse-graining starts with some vestige of the prior coarse-graining effects remaining in the entanglement pool. This means that complexity science in the biological and social worlds is fundamentally different than in the physical world.
4. In the social world—and particularly in the world of firms—there is the possibility, if not actual advantage or necessity, of constantly managing to preserve or recreate one or more pools of fine-grained entanglements as primordial bases from which subsequent energy-differential caused coarse-grained structures emerge.

To summarize, the logic sequence—in agent[7] terms—is as follows:

1. There is some level of correlation between the histories of all possible pairs of agents in the fine-grained structure.
2. Because each agent interferes with all the others, probabilities of how one agent affects another cannot be assigned—their destinies, thus, are entangled.
3. Coarse-graining washes out interference terms in the fine-grained structure, which is to say, coarse-graining washes out entanglement and results in probabilities—and probabilistic natural laws—rather than interferences.
4. Energy-differentials—adaptive tension—impinging on agents can, therefore, cause coarse-graining and the creation of probable outcomes emerging from the pool of entangled agents.
5. In addition to causing coarse-graining, the likelihood that the energy-differential field effect will disrupt the entanglement pool so as to corrupt the "purity" of entanglement, so to speak, increases, going from physical to biological to social worlds.
6. Because of the feedback effect, the interrelation of entanglement and adaptive tension in social systems sets them apart from physical and to some extent biological systems—though I would not rule out the effect in physical systems. For example, in a Bénard cell, if one removes the energy differential the molecules revert to the conductivity state and it is if there had been no emergent structure. With organizations, however, successive emergent orders leave an accumulated legacy that usually does not disappear if the adaptive tension is removed—though it could easily deteriorate into a somewhat different coarse-graining.

Given the definition of complexity science presented here, what should managers worry about? I don't have space for details (see instead McKelvey forthcoming-a, b), but some key elements are:

1. Before emergent order-creation has any chance of being efficacious, the uncorrupted entanglement pools from which order emerges have to already exist or be created. This creates initial conditions.
2. Goal-setting becomes a context identification process. This is a process of identifying which kinds of adaptive tension parameters should be the center of attention. Besides being identified, incentives for paying attention to them have to be put in place. A classic example is Jack Welch's "Be #1 or #2 in your industry or you will be sold." It defines context, an adaptive tension, and motivation all in one short phrase. This sets up the Bénard process.
3. Focus on enlarging the region of emergent complexity (order-creation). Some firms cycle between bureaucracy and chaos because the region of emergence is virtually nonexistent. Focus on lowering the 1st and raising the 2nd critical values. This increases the probability of Bénard processes and emergence.
4. Agency problems and other noxiants need to be avoided (via strange attractor management) so as to avoid emergence in directions clearly not in a firm's best interest.

4 CONCLUSION

My review suggests that:

1. A theory about the engine of order-creation at any of the several levels of order (atoms to social systems), or across the levels, is not obvious as a coherent collective belief among complexity scientists, but Mainzer's analysis is the most comprehensive available to date;
2. The classic concept of external (Bénard) energy-differentials (as control parameters) that cause emergence "at the edge of chaos" is at the heart of complexity science, but is frequently missing in much of the complexity science literature. Especially it is missing in organizational applications;
3. The nature of the entanglement pool or "base"—more broadly the set of network connections among agents such as atoms, molecules, organisms, human actors—from which emergence arises, is frequently unspecified as the initial condition. This concern is mostly missing in organizational applications;

[7] In agent-based computational models, an "agent" can represent any microentity, such as electrons, atoms, molecules, cells, organisms, species, language/process/conversation elements, individuals, groups, divisions, firms, etc. I use it in this "catch-all" sense here.

4. The implications for adaptive efficaciousness of *successive* emergence events, that is, of the possibility in biological and social systems that *prior* emergence events could have fed back to irrevocably "tarnish" the entanglement or network "base," also seems missing; and.

5. The interaction of Bénard and Darwinian and "rational" processes is barely considered.

The root question in quantudm theory expands, in complexity science, into a multidisciplinary concern about the engine that causes order-creation in matter, life, brains, artificial intelligence, and social systems (Mainzer 1997). And, needless to ask: Is there one primary engine working up and down the hierarchy of phenomena—from matter to social systems—or are there several and do they differ across disciplines? From all of this, I draw out two key elements that seem particularly relevant in the application of complexity theory to organizations: (1) the notion of correlated histories between pairs of agents—that is entanglement—as the initial condition; and (2) the Bénard process as the main engine of order-creation so far discovered that applies across the hierarchy of phenomena—and down into organizations—in addition to the Darwinian selectionist process, and human rationality, of course, that we already know about.

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Table 1. Definitions of Kinds of Complexity by Cramer (1993)

- '***Subcritical complexity***' exists when the amount of information necessary to describe the system is less complex than the system itself. Thus a rule, such as $F = ma = md^2s/dt^2$ 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 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 and Stengers 1984).
- At the opposite extreme is '***fundamental complexity***' where the 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. Cramer lumps chaotic and fundamental systems into this category, although deterministic chaos is recognized as fundamentally different from fundamental complexity (Morrison 1991, Gell-Mann 1994), since the former is 'simple rule' driven, and fundamental systems are random, though varying in their stochasticity. Thus, three kinds of fundamental complexity are recognized: ***purely random***, ***probabilistic***, and ***deterministic chaos***. For this essay I narrow fundamental complexity to deterministic chaos, at the risk of oversimplification.
- In between Cramer puts '***critical complexity***'. The defining aspect of this category is the possibility of emergent simple deterministic structures fitting subcritical complexity criteria, even though the underlying phenomena remain in the fundamentally 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, p. 215–217) has a long table categorizing all kinds of phenomena according to his scheme.