The "0th Law" in Physical, Biological and Social Systems: Complexity Science vs. the Entanglement Trap—in Firms

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Bill McKelvey

The Anderson School at UCLA, 110 Westwood Plaza, Los Angeles, CA 90095-1481
tel 310/825-7796 fax 310/206-2002 mckelvey@anderson.ucla.edu

In trying to manage firms, executives confront emergent "*order*"—ranging from strong culture to ritualistic bureaucratic structure to informal organization—that may work for or against their intentions, whether aimed at near term cost control or strategic novelties. Compared to extant sociological views of emergent order, complexity science offers an explanation and normative approach that is multidisciplinary in its theory base, with better integration of the various dynamics involved. Prigogine's classic argument is that the 1st and 2nd laws of thermodynamics would not exist if "order" had not been produced in the first place. However, complexity science—as a general explanation of emergent order—is problematic and inconsistent as its literature has emerged from the physical, biological, and social sciences, thus making its application to the managerial setting problematic. Specifically its handling of reductionist and contextual causal generative mechanisms is hit-and-miss and there is no consistent phrasing, or even attention, what we might think of as the 0th law of thermodymics.

My review suggests that: (1) The complexity science "bridge" explanation between quantum entanglement and higher levels of order (atoms and above) is missing as a collective belief among complexity scientists; (2) The classic concept of external (Lorenz) energy-differentials (as control parameters) that cause emergence "at the edge of chaos" is frequently missing; (3) 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 emergence arises, is often ignored; and (4) Given the possibility in biological and social systems that *prior* emergence events could have fed back to irrevocably "tarnish" the entanglement base, the implications for the adaptive efficaciousness of *subsequent* emergence events also are not fully appreciated.

Primarily, I review explanations of how "order" (what Gell-Mann calls coarse-graining) emerges from the fine-grained structure of entanglement pools and higher-level networks, with special focus on the views of Gell-Mann, Cohen and Stewart, Prigogine, Mainzer, and Omnès. Once these views are integrated, it becomes clear that the adaptive efficacy of emergent structure in firms depends on the purity of the entanglement fields existing within a firm. The concept of "entanglement ties" is introduced to fill an operational hole in the sociological network literature. I conclude with some comments on difficulties executives might face in trying simultaneously to produce adaptively efficacious emergent structure *and* untarnished entanglement pools.

1 INTRODUCTION

What causes order? And, if order is caused, what causes it to emerge one way and not another? Complexity science is about what causes order. Entanglement is about what exists before order emerges in the physical world. 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 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. In fact, order doesn't exist without both.

The role of quantum entanglement as the precursor to emergent order is much discussed in physics (Gell-Mann 1994). And the proverbial primordial pool existing before the origin of life is much discussed in biology (Kauffman 1993). Particularly for the biological and social worlds, Long ago, Ashby made two observations. Order (organization), he says, exists between two entities, *A* and *B*, only if this relation is "conditioned" by a third entity, *C* (1962, p. 255). If *C* is viewed as the "environment" which is external to the relation between *A* and *B*, it follows that environmental constraints are what cause order (Ashby 1956). This, then, gives rise to his "*law of requisite variety*" (1956). It holds that for a biological or social entity to be efficaciously adaptive, the variety of its internal order must match the variety of the environmental constraints. Interestingly, he also observes that order does not emerge when the environmental constraints are chaotic (1956, p. ?).

Given that order already exists, the 1st law of thermodynamics holds that energy is conserved. The 2nd law holds that over time order, and the energy that causes it, dissipates into disordered randomness. What seems to be missing, and what complexity science is searching for, is a coherent statement of a 0th law of thermodynamics. This law would point to an environmentally imposed energy effect, broadly generalizable across the physical, biological, and social worlds, that sets what Gell-Mann (1994) calls "*coarse graining*"—emergent structure—into motion.

How close is complexity science to phrasing the 0th law. My review of some key sources in this paper suggests that work still needs to be done. As it stands, complexity science's emergent-order explanations play out differently in the physical, biological, and social worlds. Since these worlds are hierarchical—in that social entities are composed of biological entities that are composed of physical entities—the issue of upward vs. downward causality also arises. Natural selection is one way of explaining how order appears out of the primordial probabilistic soup—the *selectionist* explanation. An additional explanation of order-from-entanglement—completely nonselectionist—emerges from quantum theory—the *decoherence* explanation. 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. Gell-Mann (1994), focusing on coarse-graining, reviews how physical structures decohere from entangled atomic particles and/or wave packets. Drawing on recent quantum explanations (Omnès 1999), chaos theory

(Cohen and Stewart 1993), and complexity science (Mainzer 1994), I develop both reductionist (upward) and contextualist (downward) causal explanations of emergent order, emphasizing especially emergent dissipative structures (Prigogine 1962, Nicolis and Prigogine 1989). Specifically, I detail the process by which emergence arises from entanglement in the complexity region. This occurs in the so-called region at "the edge of chaos"—between the 1st and 2nd critical values of an imposed field created by energy-differentials in the natural world—what I have elsewhere termed "*adaptive tension*" in firms (McKelvey 1999c).

My discussion of entanglement, decoherence, coarse-graining, and causal explanations drawn from complexity science begins with review of explanations about how "order" or "coarse-graining" emerges from the fine-grained structure of entanglement pools and higher-level networks, with special focus on the views of Gell-Mann, Omnès, Cohen and Stewart, Prigogine, and Mainzer. This is the search for the 0th law and shows that a coherent statement of it does not yet exist. Given this review, it becomes clear that the adaptive efficacy of emergent structure in firms depends on the purity of the entanglement field(s) existing within a firm in addition to the law of requisite variety. Given this, the paper then focuses on (1) the joint importance of entanglement *and* adaptive tension as co-produces of effective emergent structure; (2) an elaboration of adaptive tension control parameters; and (3) the interaction of selection and decoherence as causes of coarse-graining. I pay special attention to forces that act to cause either the biological or physical process to dominate in firms. The concept of "entanglement ties" is introduced to fill an operational hole in the sociological network literature. I conclude by discussing difficulties executives face in trying simultaneously to produce adaptively efficacious emergent structure *and* untarnished entanglement pools.

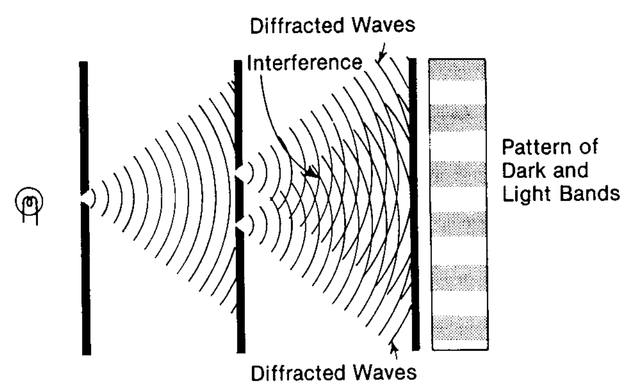
2 ENTANGLEMENT, DECOHERENCE, GELL-MANN

2.1 THE COPENHAGEN INTERPRETATION

In the classic "two-slit" experiment, a light source shoots photons at the panel holding the slits. What shows up on the viewing screen is a pattern of dark and light bands indicating that the photons travel as waves because, after passing through the two slits they interfere with each other—doubling their strength in the light bands and canceling each other out in the dark bands (Figure 1). But if a detector is located at one of the slits, what hits the screen no longer appears as interfering waves but rather as particles. Further, if the detector is placed at only one slit—and thus seemingly causing the wave to collapse into a particle, this same behavior occurs at the other slit, even though there is no detector—"spooky action at a distance," as Einstein put it. The so-called spooky action occurs with electrons, photons, and atoms and holds true even if the photon detectors are widely separated. Virtually any book on quantum mechanics will start with a description of this kind of experiment. This set in motion the now "traditional" view of quantum mechanics where an observer's detector collapse wave packets and, thereby, creates the observable world of classical physics (Gribbin 1984, Fine 1986, Shimony 1978, Mermin 1985, Mills 1994, Cohen, Hilpinen and Renzong 1996).

In response to this effect, during the course of his classic debate with Niels Bohr, Albert Einstein uttered three memorable phrases: "God does not play the dice." "Is the moon there when nobody looks?" and "I cannot seriously believe in…spooky actions at a distance" (Mermin 1985, pp. 38–39). Superficial interpretations of the debate define Bohr (along with Werner Heisenberg and Max Born) as anti-realists and Einstein as a realist, though later analyses reveal this a misappelation (Dainian 1996, Folse 1996). In fact both Einstein and Bohr had both realist and anti-realist goals, though Heisenberg remained a staunch instrumentalist (Folse 1996). The real difference is this: Einstein held out for an ontology that recognized quantum theory as incomplete without "*separability*," and "*locality*," that is, the accounting for rules governing individual particle behaviors—the so-called "hidden variables" approach. Bohr believed that the inability to define particle spin, state, or momentum independent of measurement effects (Heisenberg' uncertainty principle), prevented theories based on particle attributes or the realists' hidden variables.

Figure 1. The "Two Slit" Experiment †



† (Reproduced from Gribbin (1984, p. 16)

Though the debate continues (Cohen, Hilpinen and Renzong 1996), and neither side is easily dispatched (Shimony 1978, Fine 1986), most physicists now accept Bell's theorem and its supporting experiments (Shimony 1978, Mermin 1985, Zuoxiu 1996, Omnès 1999). An accessible description of the essence of Bell's theory and a way of running the "*gedanken*" thought-experiment—otherwise known as the Einstein, Podolsky and Rosen (1935) "EPR" experiment—are given by Mermin (1985). Common to all realist hidden variable arguments is the idea that particles come with "*instruction sets*" determining their "local" behavior. Absent the instruction sets, quantum theory, over and over again, predicts the probability of local particle behaviors in the experiment to be $p = .5$. If instruction sets exist, however, probabilities other than .5 should prevail. Results show $p = .5$ in the experiments. Thus, particle instruction sets do not exist; quantum theory is to be believed; and notions of "locality/separability" vanish—the moon is not there when nobody looks! Bohr was right; Einstein was wrong.

2.2 A VERY SHORT HISTORY OF QUANTUM THEORY

Over the past 65 years the Bohr Einstein debate and the classic two-slit experiment have been the subject of many philosophical discussions (Bohm 1951, Petersen 1968, Jammer 1974, Fine 1986, Cushing and McMullin 1989, D'Espagnat 1989, Healey 1989, Hughes 1989, Cohen, Hilpinen and Renzong 1996) and many complicated experiments (Gribbin 1984, 1995; Mills 1994, Omnès 1999). In recent years a complexity science perspective has been added (Mainzer 1994). With this broader historical background in mind, in looking for the 0th law I begin insert an "essence of quantum theory" by paraphrasing and quoting various passages from Mainzer's (1994, pp. 45–56) book so as to avoid tarnishing it by any interpretation I might add, recognizing that the few lines following are no substitute for reading Mainzer's book or other descriptions of quantum mechanics.

1. Around the middle of the 19th century Hamilton introduced what is now known as the *Hamiltonian function H*, where total energy is a function of kinetic and potential energy. Taking a pendulum, for example, at any point in its swing, one can reduce its force, if it were to hit something, to $F = H(q, p)$ where q is a position coordinate and p is a momentum coordinate—at any given position, q, the pendulum has a momentum, p. The advantage of a Hamiltonian function is that it allows one to summarize all of the interacting effects of, for example, the sun and all the planets and asteroids into one summary q and p. And, the orbital path of, say, a Mars lander, can then be calculated for any point on its trajectory from Earth to Mars, with errors, needless to say. For two adjacent photons or electrons you might think the Hamiltonian would appear as $E = H(q_1, q_2, p_1, p_2)$, but it doesn't. This is where quantum mechanics differs from the classical physics of moving bodies.

2. In 1900 Planck discovered that electromagnetic oscillations only occur in discreet lumps, know as *quanta*, such that $E = hv$, where v is the frequency of the oscillations and h is Planck's constant. de Broglie then proposed that particles of matter often behave as waves, giving rise to the classic particle/wave duality in physics. Coupled with Einstein's famous equation, $E = mc^2$, where m stands for mass and c the speed of light, we discover that the quantum state of an electron oscillates with a frequency $v = mc^2/h$—meaning that the actual value of an electron's quantum state at any given time is an oscillating value ranging from the peak to the trough of the wave's amplitude. Introducing his *uncertainty principle*, Heisenberg observed that, since any attempt to measure an electron's q would alter its p (or vice versa), an electron's Hamiltonian function would forever remain an uncertainty. This led to the Bohr Einstein debate, the Copenhagen interpretation that electrons can't be "*real*" since their "*locality*," that is, knowledge of both p and q at the same time, is unknown, and thence Einstein's famous question, "Is the moon there when nobody looks?"

3. This led quantum physicists to replace the Hamiltonian qs and ps with the so-called *Hamiltonian operator*, such that $E = H(q, p)$ becomes $E = H(x)$, where x is the operator reflecting the unseparable values of q and p. From this emerged Schrödinger's wave function, $\psi(x)$, where the probability of the quantum state at any given instant is defined as the squared modulus of its amplitude, $|\psi(x)|^2$. The causal dynamics of quantum states is determined by a partial differential question—Schrödinger's equation. But, because quantum states are indefinite, only statistical expectation values are possible.

4. "An essential property of Schrödinger's quantum formalism is the *superposition principle*[1] demonstrating its linearity. For example, consider two quantum systems which once interacted (e.g., a pair of photons leaving a common source in opposite directions). Even when their physical interaction ceases at a large distance, they remain in a common superposition of states which cannot be separated or located. In such an *entangled* (pure) quantum state of superposition an observable of the two quantum systems can only have indefinite eigenvalues. The superposition or linearity principle of quantum mechanics delivers *correlated* (entangled) states of combined systems which are highly confirmed by the EPR experiments" (Mainzer 1994, p 54; my italics). The Hamiltonian becomes $E = H(\psi(x_{ij}))$, where $\psi(x_{ij})$ is a *wave packet* consisting of the correlated wave functions of two interacting electrons or photons. For locality to occur, that is, for us to decompose $H(\psi(x_{ij}))$ back to $E = H(q_1, q_2, p_1, p_2)$, the wave packet has to be collapsed.

Why and how this short lesson on quantum mechanics becomes relevant to organization science will, I hope, emerge from the following approaches about how coarse-grain structures emerge.

2.3 GELL-MANN'S COARSE-GRAINING VIA QUANTUM HISTORIES

In a book written for popular consumption, Murray Gell-Mann (1994, Ch. 11) uses a few simple terms to explain the "Modern Interpretation" of how the world of objects and deterministic natural laws coexists with the probabilistic world of quanta. On page 147 he explicitly rejects the traditional interpretation of the two-slit experiment. On pages 152–153 he scoffs at Schrödinger's cat thought-experiment. It is not that we need to be experts on quantum theory here. But we do need to get beyond the observer-caused collapse of wave-packets. And, some key terms, like entanglement, interference, and decoherence, help us begin to talk about how order emerges from entanglement.

In terms of a Hamiltonian function, we know that knowledge about any moving object can be reduced to its position in a Cartesian coordinate system and its momentum. From Heisenberg's *uncertainty principle* we know that we cannot know both the position and momentum of an electron at the same time because the act of measuring one aspect alters the other. Now suppose there are two electrons that we would like to know about. In the Bohr Einstein debate, using the gedanken experiment, Einstein held that, since electrons are interchangeable and, thus, identical, one could, by using independent detectors and using different electrons, overcome the uncertainty problem. In essence, given

[1] When two waves of the same frequency and amplitude are "superimposed" their effect is (1) magnified if their peaks and troughs coincide, as in a laser; or (2) if the peak of one wave occurs at the same time as the trough of the other wave, they cancel each other out, as illustrated in the double-slit experiment.

knowledge of the position of electron A in detector α, one could by using electron B in detector β, learn the charge on B and then, since electrons are the same, presume that one then knows the charge on electron A as well. As noted above, we now know this is false logic—Bohr and quantum theory prevailed over Einstein's argument. Why? To pursue this, I take my lessons entirely from Gell-Mann's Chapter 11 on modern quantum theory.

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, with the coefficient ranging probabilistically between 0 and 1. 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, possibly a virtually infinite number. Presumably, correlations with nearer electrons dominate correlations with electrons, say on the other side of the galaxy but, still, correlations from the farther electrons filter through intervening neighbors to affect the neighborhood of the nearer electrons.

At any given time, in a sequence of time intervals, each electron has a *history* of effects from all the other electrons it is entangled with. Because of the many correlations, and the probabilistically differing quantum states of all the other electrons, each interaction history is likely unique. But quantum theorists do not attach a probability of occurrence to each history. Instead, they use a quantity, *D*(A, B) to record the relation between the quantum histories of two correlated electrons—thus *D* is always assigned to pairs of histories, A and B. If the two histories happen to be the same (unlikely) or are combined, *D* becomes a probability, between 0 and 1. If the histories are different, they are said to *interfere* with each other. Since most histories are unique, *D* is seldom a probability and so, as Gell-Mann says, "since the best that quantum mechanics can do in any situation is to predict a probability, it can do nothing in the case of histories that interfere with each other" (1994, p. 143). If histories almost always interfere, and thus *D* is almost never a probability, how can physicists predict with probability, let alone with what seems to most of us, virtual certainty? Gell-Mann refers to classical Newtonian, deterministic physics as "quasiclassical" physics" (p. 150) to recognize that even though natural physical laws seem deterministic and predictive, as more details are introduced, seemingly deterministic laws become probabilistic.

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 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 (not really probabilities, as Gell-Mann observes, but close approximations), 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. 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. In his view, it is important to realize that this happens whether you are actually at the track or see the race or not.

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. 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 correlation histories that become important do so because of the particular time and place—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—which is to say that we now have D(A, A) or D(B, B) or D(A & B, B & A) in Gell-Mann's terms, that is, similar histories; and (3) since the interferences among these few correlated histories disappear, they become truly probabilistic and, thus, we can talk reasonably of the probability that one horse will nose out another. In other words, a coarse-grained history is a class made up of equivalent fine-grained histories. As Gell-Mann puts it: "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, 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). 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. As Gell-Mann puts it, coarse-graining "*washes out*" the interferences among histories in the fine-grained structure (p. 145–146). To visualize (very metaphorically), imagine a large glass bowl filled with a billion tadpoles, the length of each representing the strength of the interference correlation between a pair of fine-grained quantum histories. At any given instant, some number of the tadpole length-axes line up exactly with it—some facing one way, some the opposite. This is a set of fine-grained histories. As a result of their being in line, they can be added up. These "decohere," and since they are in line, they become a vector, with a directional probability-effect equal to the average of their correlations.[2] When "summed over," the directional correlations of all the rest interfere with each other leaving them with no directional force. An "observer" is not required for this to happen.

In my reading of the 1994 book, Gell-Mann is some vague on what might cause some vectors to line up and therefore decohere. In traditional treatments it is, of course, the observer. The main clue that external causes or field effects are at work comes from his comments on pages 148–149 he talks about the decoherence of an object in orbit only in terms of how this process allows an observer, say on Earth, to see Mars. For him, Mars is a collection of wave-packets centered around a point-mass. Mars comes into view for humans on Earth because it is constantly bombarded by photons from the Sun. Since the Mars collection of wave-packets is large relative to individual photons from the Sun, the latter scatter off in random paths, develop quantum histories that interfere with each other, and thus sum-over and disappear. Absent the Sun, photons from the background radiation remaining form the Big Bang could accomplish the same thing.

For Gell-Mann, the reductionist's view, dominates. "…[C]hemistry is in principle derivable from elementary particle physics" (p. 112), but not determinism. Thus: "The laws of biology do depend on the laws of physics and chemistry, but they also depend on a vast amount of additional information about how those *accidents* turned out" (p. 115; my emphasis). By accidents Gell-Mann means "chance" events (p. 114). This is Gell-Mann's way of juxtaposing quantum theory and quasiclassical physics.

There are various other old and new interpretations building on the observer-effect related to wave/particle duality. The "hidden variables" approach has been debunked many times over (Bell 1964, 1987; Gribbin 1984, 1995). Many alternative interpretations have been proposed to explain the experimental results—referred to as "desperate remedies" by Gribbin (1995). The Modern Interpretation holds that an experimental "system" is not just a photon, electron, or an atom, a slit, and a detector. It consists of all the molecules and particles in the mechanism emitting the particles, molecules/particles comprising the plate containing the slit(s), molecules/particles in the mechanism of the detector, molecules/particles in the surrounding housing. And why stop here with just the "experimental system?" After all, quantum changes are metered by Planck's constant and are very small: $h = 6.626 \times 10^{-34}$ joule/second. Thus, perturbations on the experimental system could come from anywhere in the room, building, Earth, and possibly even the entire Universe (Mills 1994, Gell-Mann 1994, Gribbin 1995). Given the latter possibility, Everett's (1956) approach is to base an explanation on multiple universes. Mills (1994), on the other hand, prefers a "watcher" outside the Universe whose "observations" collapse the Universe's wave packet and all other wave packets within. Views like these force physicists to think of multiple copies of themselves or a Godlike super observer—neither being very palatable. Gell-Mann avoids these "desperate remedies" by allowing any source of photons may act as a "detector/observer" and, thus, collapse wave packets, disrupt entanglement, or create Heisenberg uncertainty situations.

Roland Omnès[3] (1999) develops an interpretation that connects better with complexity science, the details of which space precludes discussion. First, he makes 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 Omnés's and Prigogine's treatment of time irreversibility (Prigogine and Stengers 1984). Second, noting that a gedanken experiment is open to quantum-level effects from more than just the immediate apparatus of the experiment, we get:

$$H = H_c + H_e + H_1$$

a total Hamiltonian where H_c is the Hamiltonian of the relevant "internal" variables of the experiment, 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). Third, Omnès shows that the dynamical suppression of the environmental interferences of the H_e Hamiltonian almost immediately produce a large decoherence effect (p. 203), thereby

[2] My use of vectors in this metaphor is parallel with Dirac's generalization of Schrödinger's wave superposition into vector superposition (Mills, 1994, p. 335).

[3] 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 history is merely a narrative of a time sequence of events—past, present, or future.") (pp. 138, 140)

negating the need of any kind of outside "observer." [*Put equations from p. 200–203 in Appendix.*] Fourth, 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). Finally, he notes that "…the only possibility of avoiding decoherence is to work with a nondissipative system, such as ordinary light or superconducting materials" (p. 207). Needless to say, given Omnès' analysis, since most objects in the Universe are not photons or superconductors, there is no need for observers, multiuniverses, watchers, or other weird methods of collapsing wave packets! Wave packet decoherence occurs rapidly and long before humans "observe."

Omnès' view is essential. His introduction of H_c is a more explicit replacement of the human observer effect with the forces of external energy fields. Decoherence and emergent coarse-graining, even in quantum theory, are now subject to the regular-to-chaotic forces of these fields. The latter result from the tension created by the "*Lorenz 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*.

3 COARSE-GRAINING AND COMPLEXITY SCIENCE

3.1 COHEN AND STEWART'S COARSE-GRAINING VIA CONFLATION

Jack Cohen and Ian Stewart also struggle with the relation between an observer's perception of coarse-grained structure and causes of such structure in the universe, saying, "the best way to simplify the perceived universe is to tune into a collapse of chaos in the real universe" (1993, p. 429). They take a selectionist approach (Campbell 1974, Hooker 1995), to the development of human capacities for perceiving coarse-grained structures that are reflections of naturally emerging coarse-graining. This view argues that for purposes of survival in a hostile world, humans evolve perceptions in line with coarse-grained structures, whether biological or physical, that slowly become more accurate over time. Thus: "In the real world, we find matching instances for all these [quasiclassical] theoretical concepts…. Because our brains evolved through complicity between their internal representation of reality and the external reality itself…they can recognize features, analogies, and metaphors, and see patterns in them…. Our prized laws of nature are not ultimate truths, just rather well constructed Sherlock Holmes stories. But those stories have been scrubbed and polished, over the centuries, until they capture very significant features of the way the universe works" (p. 435).

Cohen and Stewart (1993) refer to naturally occurring coarse-graining as "*emergent simplicity*" and "*the collapse of chaos*." Indeed, the title of their book is *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" (1993, 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. 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—the essence of statistical mechanics. 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 create observable 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 likely.

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 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).

Nowhere in the Cohen and Stewart framework is an observer or photon scattering needed to cause coarse-graining by collapsing wave-packets. Nor do they focus on externally imposed energy-differentials as parameters that control emergence. They do focus on the selectionist effect in biology and the chaos and energy minimization effects in physics at the level of atoms. Cohen and Stewart 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.

3.2 PRIGOGINE'S COARSE-GRAINING VIA NEGENTROPY

Gell-Mann's book aims at a quantum-based *Theory of Everything* (see also Barrow 1991, Weinberg 1994). And to reprise, recall the quote: "The laws of biology do depend on the laws of physics and chemistry, but they also depend on a vast amount of additional information about how those [chance] *accidents* turned out" (Gell-Mann 1994, p. 115; my emphasis). Cohen and Stewart attack the Theory of Everything from a *contextualist* rather than *reductionist* perspective, saying essentially that, though coarse-graining surely depends on quantum dynamics, the reductionist explanatory path is so long and convoluted that meaningful explanations are well nigh impossible, thus giving contextual explanations the advantage—even Schrödinger wouldn't use a wave function to explain the behavior of his cat. Further, recall that Gell-Mann's analysis offers no basis for coarse-graining other than collapses of wave functions caused by photon scattering, whereas Cohen and Stewart argue that coarse-graining is caused by statistical distributions, energy minimization, and spatial (niche) conflation.

At the heart of the bifurcation is the apparent gulf between the purely random entanglement of quantum histories (Gell-Mann) and the chaotic entanglement of atoms and higher-level microentities (Cohen and Stewart). Missing is the causal link (reductionist *or* contextual) between Gell-Mann's <u>random correlated quantum</u> histories and Cohen and Stewart's <u>chaotic correlated atom</u> histories. Oppositely, Cohen and Stewart do not explain how the highest level coarse-graining got started, since they distrust the standard reductionist causal argument, and Gell-Mann doesn't say how chaotic atomic movements might be caused by purely random quantum entanglements. While one might wish they were clearer about it, (1) there appears to be no explicit mention in Gell-Mann's quantum theory that quantum entanglements can be altered by the effects of external energy fields—coarse-graining is only made visible by photon scattering from external sources, no mention on possible corruption of the underlying fine-structure; and (2) though Cohen and Stewart distinguish between purely random and deterministically chaotic entanglement pools and though they mention energy reduction as part of crystallization emergence, they do not explicitly mention external energy fields as the cause of why atom entanglements might be chaotic whereas quantum entanglements are not.

We might be at an explanatory impasse, except for the idea of dissipative structures (Prigogine 1962; up-dated and made more accessible in Nicolis and Prigogine 1989). And recall that dissipative effects are the key to Omnès's theory of decoherence. Ilya 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 2nd 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. I simply note this in passing, since my main concern is the opposite, that is, the 0th law: What causes coarse-graining in the first place—in the form of dissipative structures—whether from a reductionist or contextualist perspective.

3.2.1 QUANTUM CHAOS

Could coarse-graining be the result of quantum chaos? Klaus Mainzer (1994) asks, "Is there chaos in the quantum world?" He starts his analysis from the same perspective as Gell-Mann. Thus, reminiscent of the gedanken (EPR) experiment, he starts with a situation where two quantum systems—photons—leave a common source going in opposite directions. Even at a distance with no physical interaction they "…remain in a common superposition of states which cannot be separated or located"—due to Heisenberg's uncertainty principle (p. 54). He then says: "In such an entangled (pure) quantum state of superposition an observable of the two quantum systems can only have indefinite eigenvalues. The superposition or linearity principle of quantum mechanics delivers correlated (entangled) states of combined systems which are highly confirmed by the EPR experiments" (p. 54). Mainzer then asks "…whether the existence of chaotic motion in classical Hamiltonian systems leads to irregularities in the corresponding quantum systems" (p. 55). He notes that, given the uncertainty principle, the "…tiny, but finite value of Planck's constant [*h*] could suppress chaos" (p. 55). Bohr's "correspondence principle" allows the *q*s and *p*s in Hamiltonian functions describing classical systems to be replaced "…by quantum systems (e.g., electrons or photons) described by a Hamiltonian operator depending on operators (for position and momentum) instead of vectors" (p. 53). Mainzer notes, in passing, one fundamental difference between classical and quantum systems is inescapable—to wit, exact predictions are replaced by probabilistic expectations. Gell-Mann, in using the "quasiclassical" descriptor, reminds us that with truly exact measures even classical deterministic natural laws become probabilistic—the more exact the measures the less exact the laws.

Given Bohr's correspondence principle, Mainzer says that chaos in classical Hamiltonian systems should be detected at the corresponding quantum level. Assuming that classical systems can be described as "…integrable, almost integrable, or chaotic…" (p. 56), Mainzer refers to "…calculations which show that the energy spectrum of a free quantum particle…, for which the classical motion is chaotic, differs drastically from that of a free quantum particle…, for which the classical motion is regular" (p. 56). The reason is that the integrable classic case exists in a field having a lower distribution of energy than does the field permeating the chaotic system. He concludes by citing two studies (Friedrich and 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" (p. 56; my italics). Given this, a reductionist can argue that the initially tiny quantum chaotic effects can accumulate to cause coarse-graining in atoms and, building from Cohen and Stewart, eventually in higher-level natural phenomena.

I will leave it to the reader to ponder whether Borel's theorem—that vanishingly small probabilities should be left outside of science—applies here or not. Actually, both views could apply. Thus, some miniscule probabilities could accumulate and then decohere to cause quantum-based chaos while most would simply be left out of scientific analysis. The only time they might become important is if and whether they have indeed accumulated to have effects at the level of quasiclassical physics analysis—meaning that they accumulated to have a real-world "chaos" effect.

3.2.2 EXTERNAL ENERGY-DIFFERENTIALS AS CONTROL PARAMETERS

Could coarse-graining be the result of external control parameters? "Control parameters," as Mainzer (1994) 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* (the so-called Rayleigh number), 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 1st 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 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. We encounter these in aircraft as up- and down-drafts; and (3) Above the 2nd critical value a transition to chaotically moving gas molecules is observed.

What is of primary interest to chaos theorists is the discovery of what Lorenz calls the "*strange attractor*." Lorenz describes the system using three differential equations with three rate-of-change variables: x = circulatory flow velocity, y = temperature difference between ascending and descending air flows, and z = deviation of the temperature differential from its equilibrium value. What Lorenz finds is that the state of the system does not settle at some equilibrium but instead oscillates between paths sometimes within the x, z plane and sometimes within the y, z plane, as shown in Figure 2. The state of the system is also is also very sensitive to initial conditions. As Cramer (1993), Kaye (1993), and Mainzer (1994) show, this basic discovery has been replicated across many kinds of phenomena.

Figure 2. The Lorenz "Strange Attractor" †

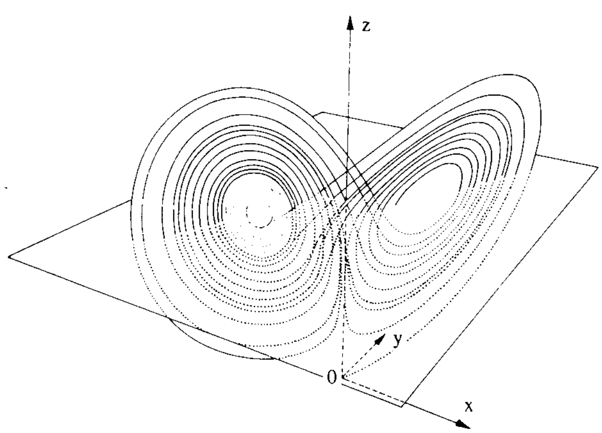


Fig. 2.21. Lorenz attractor

† Reproduced from Mainzer (1994, p. 59)

What is of primary interest to complexity theorists, however, is what happens in the region between the critical values, the region of emergent complexity where Prigogine's emergent dissipative structures form. Cramer (1993) observes that the three regions defined by the critical values define three kinds of complexity: *subcritical* →| 1st |→ *critical* →| 2nd |→ *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 (1994, 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 the *R* number 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) has observed, 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. 64).

3.2.3 Phase Transition at the 1st Critical Value

In the following three paragraphs, which I quote, Mainzer (1994, pp. 66–68) takes us through the phase transition at the 1st critical value.

> We start with an old [existing] structure, for instance a homogeneous fluid or randomly emitting laser. The instability of the old structure is caused by a change of external [control] parameters, leading eventually to a new macroscopic spatio-temporal structure. Close to the instability point we may distinguish between stable and unstable collective motions or waves (modes) [energy/vector forces]. The unstable modes start to influence and determine the stable modes which therefore can be eliminated. Hermann Haken calls this process very suggestively a 'slaving principle'. Actually, the stable modes are 'enslaved' by the unstable modes at a certain threshold.
>
> Mathematically, this procedure is well known as the so-called 'adiabatic elimination' of fast relaxing variables, for instance, from the master equation describing the change of probabilistic distribution in the corresponding system. Obviously, this elimination procedure enables an enormous reduction of the degrees of freedom. The emergence of a new [dissipative] structure results from the fact that the *remaining* unstable modes serve as order parameters determining the macroscopic behavior of the system….(my italics)

> In general, to summarize, a dissipative structure may become unstable at a certain threshold and break down, enabling the emergence of a new structure. As the introduction of corresponding order parameters results from the elimination of a huge number of degrees of freedom, the emergence of dissipative order is combined with a drastic reduction of complexity…. Obviously, irreversibility violates the time-invariance symmetry which characterizes the classical (Hamiltonian) world of Newton and Einstein. But the classical view will turn out to be a special case in a steadily changing world.

In the following bullets I trace out the order that Mainzer is describing 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.
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 other 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 in all but visible photons and superconduction, the decoherence processes occurs 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—too rapidly to measure, in fact. 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 Lorenz energy-differential figures centrally in Mainzer's treatment of complexity theory. Omnès does not refer explicitly to something akin to Lorenz energy-differentials, but he does focus on an external Hamiltonian. 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 photons do represent 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. No one argues that an externally existing or imposed Lorenz type energy-differential is *not* a cause of emergent order. I admit that at this stage, my review of the relevant literature is skimpy. It appears that we are at the cusp of saying that complexity science is about the 0th law of thermodynamics, that Prigogine was the early leader in this—got the Nobel Prize for it—and that it is really at the center of treatments such as those by Mainzer and Omnés. But it is clear that there is not universal agreement on the existence of the 0th law, *per se*, or that it even is relevant to complexity science. Further, while there is much discussion of complexity science and there are various complexity applications (see Cowan, Pines and Meltzer (1994), Belew and Mitchell (1996), or Arthur, Durlauf and Lane (1997) for example). And finally, there is no agreed upon phrasing of the 0th law. For our purposes at this conference, perhaps we could preliminarily agree that the 0th law holds that: *External constraints (to the system) in the form of Lorentz energy-differentials, in the context of an entanglement pool in some state of corruption from prior emergence, act as the generative mechanisms (causes) of order—where "order" is defined as the concurrent existence of both entities and environmentally constrained connections*.

4 ENTANGLEMENT IN FIRMS

If a 0th law can be phrased, a key test of its generality would be if it stretches from entanglement to firms. Aiming at firms, the starting questions become, What causes order in firms? If order is caused, what in firms might causes it to emerge one way and not another? The first calls for complexity science to be applied to firms. The second suggests that language developed in quantum theory about how coarse-graining emerges from entanglement could also be useful. But how could anything coming out of quantum mechanics have relevance to the study of firms? I begin by defining order in firms. Then I touch on the relevance of entanglement and quantum theory for organization science. Then I discuss entanglement dynamics as they might apply to managing firms.

4.1 EXPLAINING ORDER IN FIRMS

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, the behavior of which is 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); and (2) complexity catastrophe (Kauffman 1993, McKelvey 1999a). 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 will argue.

Where to look for developing a theory of "natural order emergence" in firms? Complexity science, of course.[4] 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. Going back to the roots of complexity science in Prigogine's work (Prigogine 1962), we see more accurately that complexity science is fundamentally aimed at explaining order creation (Cohen and Stewart 1993). As noted previously, most sciences explain existing order. The 2nd law of thermodynamics focuses on the inevitable disintegration of existing order. Complexity science aims to explain the emergence of order—the 0th law. Complexity science applications have now spread to the physical, life, social, and management sciences (Nicolis and Prigogine 1989, Mainzer 1994, Cowan, Pines and Meltzer 1994, Belew and Mitchell 1996, Arthur, Durlauf, and Lane 1997, Maguire and McKelvey 1999a, b).

4.2 A LANGUAGE TO DESCRIBE EMERGENT ORDER

Physicists have developed a language for talking about how order emerges from disorder at the quantum level. I think this language helps organization and complexity scientists more clearly discuss the intricacies of phase shifts at the 1st critical value and how natural order emerges in firms.

First, many authors of books applying complexity theory to management (reviewed in Maguire and McKelvey 1999b), use complexity theory in a loose metaphorical fashion in an attempt to help firms cope with an increasingly nonlinear, chaotic, rapidly changing competitive context, often by making a connection between the notion of "*empowerment*" stemming from the Organization Development literature (Maguire and McKelvey 1999a) and the "*emergence*" or "*self-organizing*" process central to complexity theory. Maguire and McKelvey, and many reviewers in Maguire and McKelvey (1999b), question the fruitfulness of this approach, arguing that it rests on misinterpretations of complexity theory. Entanglement and decoherence might offer additional insights even within this metaphorical discussion.

Second, quantum theorists have developed terms that, still in a metaphorical way, offer organization scientists a language with which to better pursue discourse about how order emerges from stochastically idiosyncratic individual behaviors. Perhaps a little less metaphorically, entanglement and decoherence offer an alternative source of order in firms that stands independently of emergent order based on Darwinian selectionist processes. Given that order in firms is now thought of mostly as resulting from the visible hand of top managers or the invisible hand of selectionist processes (McKelvey 1997), introducing a theory of order based on entanglement and decoherence could give organization scientists a significant new theoretical tool to use in explaining naturally emergent order in firms.

Third, physicists have learned to talk about and deal with particles lacking individuality because they are identical and, thus, interchangeable yet *also* existing in an infinite variety of stochastically idiosyncratic quantum states. Physicists and economists seem to have it both

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[4] 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.

ways. On the one hand, they assume microentities—electrons, photons, rational actors—are all identical and interchangeable. On the other hand, each is different—particles have an infinite number of quantum states and actors have an infinite variety of utility functions. For many scientists it is instrumentally convenient to assume uniformity—it simplifies the mathematics. Thus, instead of a planet with its millions of surface irregularities, rock, water, gas and other elements of different masses, bulging equator, and off-center center of gravity, etc., let's just assume a point mass. Instead of imposing all we know from behavioral decision theory (Camerer 1995) let's assume all actors attempt to maximize their utility function—again, for the mathematics.

Fourth, physicists are able to describe how the large, tangible objects and elements of the physical world around us emerge from, and coexist with, the entangled world of quantum states. Furthermore, this language also serves to describe how the seemingly precise and deterministically predictive natural laws explaining the behavior of these objects and elements can coexist on top of the entangled quantum world—remember, physicists are avowed reductionists (Weinberg 1994, Gell-Mann 1994). Again, physicists seem to have it both ways. On the one hand, they have become the hallmark science of both philosophers and the public because they have such accurate predictive success with their natural laws—which are invariant. On the other hand, from Max Planck's earliest papers/experiments on quantum theory, through Schrödinger's work on the wave function, and onto Gell-Mann and other's development of modern quantum theory (Hoddeson et al. 1997), they have wrestled with the problem of how the seemingly rock solid reductionist natural laws could work, given that ultimately they reduce down to the probabilistic quantum world.

Finally, organization science is torn between approaches to inquiry resting *either* on thick, qualitatively rich descriptions of individuals and organizations (Geertz 1973) and related anti-normal science views held by Kuhnian relativists (Kuhn 1970, Feyerabend 1975, Suppe 1977) and postmodernists of varying kinds (Burrell and Morgan 1979, Lincoln 1985, Reed and Hughes 1992, Hassard and Parker 1993, Weick 1995, Chia 1996); *or* on methods of normal science stemming from the physical and biological sciences. Three things are important here. First, at the end of the 20th century most sciences now rest on the observation that all generalizations are probabilistic and rest on phenomena that, at the lowest level of analysis, are stochastically idiosyncratic (Schwartz and Ogilvy 1979, Nicolis and Prigogine 1989, Kaye 1993, Gell-Mann 1994, Mainzer 1994). Second, we need to thank postmodernists, geneticists, and quantum physicists for reminding us that the root phenomena, whether human, biological, or physical, are probabilistic and only problematically reducible to deterministic natural laws. Third, we need to remember, however, that the very process of qualitative "thick description" research is anti-scientific and anti-explanatory as defined by the institutions of science. Why? Because the focus on the entangled histories of individuals, in whatever setting, absent attempts to explain the emergence and impact of higher-level structure and process has no generalizable or lasting value from the scientific and pragmatic perspectives of discovering truthful theories about how organizations work that might be of some use to managers and other employees. Science only works if, in Gell-Mann's term, there is coarse-graining.

4.3 DECOHERENCE AND EMERGENCE IN FIRMS

Using complexity science, I have outlined the idea that quantum wave packets are collapsed by a variety of 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, or Mill's "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 have also developed a language that organization scientists can use to explain naturally emergent order in firms—again in an attempt to get past loose thinking about emergence at "the edge of chaos" and "far from equilibrium."

I can now remind organization scientists that the most fundamental message of complexity science—really a preliminary phrasing of the 0th law of thermodynamics: *Complexity theory applications to firms rest on environmental constraints in the form of Lorentz energy-differentials as causes of order defined as emergence of both entities and constrained connections*. The latter, when applied to firms, are best thought of as "*adaptive tension*" parameters (McKelvey 1999c). 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 complexity science colored review of entanglement, decoherence, and coarse-graining, uncovers the second fundamental problem in applying complexity science to firms—so far totally unrecognized. Before considering the existence of quantum chaos or the effect of external energy-differentials, natural scientists have long since stopped questioning the existence and reality of quantum entanglements—defined as correlated quantum histories. Here is the problem: *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 faulty results*.

The nature of the initial pool of entangled particles appears essential to the coarse-graining process. In the case of the traditional "scientist-as-observer," the fine-structure quantum states remain undisturbed, no matter what kind of coarse-graining one or more observers might construct, and no matter how many different constructions there are, or how they change over time, or in what sequence the changing constructions might appear. In Gell-Mann's view, coarse-grained structure emerges from entangled fine-grained structure as a result external influences, photon-caused or other. But whether the external energy fields, or coarse-graining emergence, corrupts the entanglement is unclear.

In contrast, 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 physical Newtonian 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. And 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.
5. To summarize, the logic sequence—in agent[5] terms—is as follows:
6. There is some level of correlation between the histories of all possible pairs of agents in the fine-grained structure.
7. Because each agent interferes with all the others, probabilities of how one agent affects another cannot be assigned—their destinies are, thus, entangled.
8. 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.
9. Coarse-graining can be a result of an photon scattering (Gell-Mann), quantum chaos (Mainzer), contextual chaos (Cohen and Stewart), or a field-effect caused by the energy-differential process of complexity theory (Prigogine, Mainzer).
10. 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.
11. 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.
12. 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.

4.4 THE ENTANGLEMENT PREREQUISITE

By implication from the foregoing summary, I conclude that for complexity science to work, the entanglement pool must not only contain a rich set of entanglements, but there also must be enough correlated histories of the same kind and magnitude that coarse-graining results in structures that emerge as probabilities relative to the fine-grained interference terms (correlations) among agents. Organization scientists should be quick to realize that the entanglement pool is somewhat analogous to Granovetter's (1973) "strength of weak ties" finding, with the proviso that the ties encompass a broad set of correlated substantive interests across agents within a firm. Weak ties parallel quantum entanglements in a couple of ways: (1) The weak ties an agent has with many other agents can "interfere" with the level of effort he or she puts into a particular tie and whether the particular tie will grow into a probability of meaningful action; and (2) Coarse-graining will not occur if: (a) there are not enough weak ties of randomly varying substantive contents to allow summing over to reduce the effects of the fine-grain structure to zero—that is, get rid of the interferences; and (b) if there are not enough weak ties having similar substantive contents for coarse-graining to cause the entanglement to decohere. Further, the pool of weak ties, as entanglements, then satisfies Ashby's (1956) "*requisite variety*" required for *efficacious* emergence to occur, presuming that the energy-differentials become imposed on the agent system either naturally or intentionally. I emphasize "efficacious" because we are not interested in just any old emergence, but rather in emergent structure fostering adaptation that enhances survival. In the case of competitive strategy (Porter 1980, 1985, 1996, McKelvey 1999c) we are interested in emergence leading to economic rents, defined as above industry-average levels of profit.

Since Granovetter's initial focus on weak ties, sociologists have reconfirmed, but also complicated his simple differentiation of weak vs. strong ties. Various studies showing confirmation are reported in Granovetter's (1982) review of weak tie research. Burt (1992) argues that what is important here are the "gaps"—what he terms "structural holes"—between social cliques and not necessarily the nature of the ties that bridge them. Thus, Burt's theory of social competition and emergent strategy is based on the holes

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[5] In agent-based computational models, an "agent" can represent any microstate, 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.

rather than the nature of the tie-bridges across them, though he admits that bridges are almost never composed of strong ties. Podolny and Baron (1997) develop a four-cell typology of kinds of ties based on two distinctions: (1) whether ties are person-to-person or (formal) position-to-position; and (2) whether the content transferred over the tie is about resources/information or about determinants of social identity. Emerging from this literature are the following kinds of network ties in firms:

1. **Face-to-face ties:** Strong ties based on frequent face-to-face meetings where "the entire bandwidth" of human interaction is captured (Nohria and Eccles 1992, p. 293).
2. ***Philos* ties:** Friendship ties based on social interaction and discussion of personal issues (Krackhardt 1992).
3. **Strong ties:** Frequent repeated ties (Granovetter 1973).
4. **Bridges across social gaps:** Any kind of tie—strong, weak, redundant, nonredundant—is a bridge between two social clusters and is capable of carrying information (Burt 1992).
5. **Weak tie bridges:** Defined as ties between clusters that are used, say, more than once a year but less than twice a week (Granovetter 1973, Burt 1992).
6. **Direct (weak) ties:** Infrequent ties that, nevertheless, occur directly between two individuals, whether or not they bridge between social clusters and whether or not virtual ties exist (Granovetter 1973).
7. **Indirect (weak) ties:** Ties someone has with all members of a social cluster by virtue of having access to all members via a chain of strong ties (Burt 1992).

None of the foregoing kinds of ties are "in motion" over time. Most sociological network research is static (McKelvey 1999a). Missing is the entanglement notion of correlated histories. Further, Uzzi (19xx) shows that that best advantage comes from an optimal mixing of weak and strong ties. But instead of having an optimal mix of clearly strong and clearly weak ties, consider one kind of tie that has some elements of both strong and weak and is missing other strong and weak attributes. In other words, instead of mixing black and white elements to produce gray, let's simply try to work with elements that are already gray. Thus:

> **Entanglement ties:** Defined as direct weak ties that are not so weak as to not have some kind of recognized, correlated "history" of interaction nor so strong as to have established a collective "pair-wise" bias against or predisposition toward specific organizational change possibilities.

I think it is possible to have entanglement present with direct weak ties occurring as little as once a year, as long as there is some evidence of interactive history. "History," here, means that the weak tie pair shows evidence metaphorically equivalent to particles or other kinds of agents influencing each other in some fashion. A once-a-year attendance at a gathering where the CEO gives a speech wouldn't qualify. But, if a listener followed the meeting with a couple of email interchanges with the CEO showing evidence of mutual influence, then a history would be established. Entanglement could also be present with strong ties as long as the history was not so strong that it was beyond interference from other entanglement ties the pair partners might have. Thus, as soon as a tie becomes strong enough to show evidence of bias, predisposition, or "groupness," then it is too strong to be counted as entanglement. From the literature, Friedkin's operationalization of both weak and strong ties fits entanglement: "Two scientists were said to have a weak tie if one reported talking with the other about his or her current work, but the other made no such report. Where both made this statement about one another the tie was defined as 'strong'" (1980, p. 120). Here the weak tie would not be entanglement because there is no correlated history. The strong tie is beginning to show correlated history, and thus entanglement, but it is not "strong" in my sense because there is no evidence of bias or predisposition.

4.4.1 Fostering Entanglement Ties

It follows from the foregoing discussion that the creation of efficacious emergent complexity in firms requires the requisite variety of entangled ties just as much as it requires an imposed adaptive tension. Given a population of agents in a firm, How to foster one or more entanglement pools? If entanglement-tie correlations do not have the necessary requisite variety, coarse-graining will not emerge, even if adaptive tension is imposed. If entanglement-tie pools are dominated by strong ties, emergent structure might be faulty with respect to efficacious adaptation.

How to produce entanglement ties among pairs of agent-histories that are in "all," or at least many, substantive directions, i.e., satisfying the requisite variety law? Some alternatives are:

- Build up entanglement by creating denser networks of ties in the fine-grained structure.
- Bring in employees with diverse backgrounds (histories) and interests.
- Create diverse task and liaison groups, other meetings and social mixings—work related or not—where employees, more or less randomly, come together to share notes, ideas, perspectives and "connect" their histories.
- Create imposed field effects based on incoming stimuli that, opposite to adaptive tension, serve to create entanglement ties rather than emergent structure.
- Use stimuli and other actions to destroy obsolete coarse-grained structures so as to recreate viable entanglement pools. They do not talk about it in term of rejuvenating entanglement, but Baden-Fuller and Stopford (1994) do offer an approach toward decomplexification, that is, de-ordering.

Fostering entanglement pools is not easy because there are well known impediments. In general, anything that disrupts rebuilding the entanglement pools by retaining existing coarse-graining—that is, by retaining existing biased strong ties, or no bridge ties among biased, predispositioned cliques—is counterproductive. Strong egos, advanced specializations, and narrow functional perspectives all work against entanglement-tie formation, mostly by devaluing any kinds of more broadly defined ties. Perspectives and activities that work to create strong clique, group, or departmental boundaries—which are coarse-grained structures—also work against entanglement-tie formation (Ashkenas et al. 1995). Prejudices of any kind, physical distances, and poor communication skills or attitudes prevent entanglement ties. Strong existing *fields* that serve to maintain coarse-graining at the expense of fine-graining are important, the most obvious being strong cultures, whether imposed by upper management intentionalities, technological demands, or shared values (Martin and Frost 1996, p. 602), or by neurotic founding entrepreneurs (Kets de Vries and Miller 1984). A rash of recent books applying complexity theory to management (reviewed by Maguire and McKelvey 1999b) argue that strong command-and-control, that is, bureaucratic structures, impose "official" communication channels, sanctions, boundaries, and so forth, that warp entanglement pools. Strong path dependencies—whether leading to effective or ineffective behaviors—that serve to preserve some correlated histories at the expense of efforts otherwise going into broader and more random sets of entanglement ties disrupt entanglement. The dominance in a firm of particular kind of technological or market orientation can also work against entanglement. The existence of a particularly competent person in a firm can, by simply solving problems by him- or herself, can undermine any need for correlated histories, as Johnson's (1998) research indicates. From this, we can see that, in general, valuable human capital held by a few employees can undermine the need for emergent social capital, whether of the weak tie, entanglement tie or strong tie variety.

4.4.2 ENTANGLEMENT AND ADAPTIVE TENSION SEQUENCING

In Gell-Mann's (1994) treatment, focusing as it does on coarse-graining by the external photon streams, mutual causality is not a problem—the photon-stream's coarse-graining does not feed back to corrupt the underlying entanglement pool of correlated quantum histories. Since Cohen and Stewart focus on contextualism, and minimize the role of wave functions in causing what we see, what happens to the entanglement pool is irrelevant to their analysis. Coarse-graining from adaptive tension field effects can, however, feedback to alter social entanglement pools. McKelvey (1999c) develops an approach in which CEOs can draw on ideas from complexity theory to create adaptive tension fields in firms so as to foster regions of complexity "at the edge of chaos" in which emergent structures aimed to solve the adaptive tension problems will occur. But, from the foregoing discussion it should also be clear that "fields" also can work to create or disrupt social entanglement pools, potentially undermining the use of adaptive tension fields to foster efficacious emergence. It is possible that activities aiming to create entanglement and efficacious emergence work at cross purposes.

The basic principle is that untarnished social entanglement pools must be in place before identifying and setting up adaptive tension field effects and before efficacious emergence can take place. If coarse-graining emerges from fine-grain structure, and if fine-grain entanglement doesn't exist, then efficacious emergence cannot occur. Thus, entanglement ties must be in place before adaptive tension energy-differentials are imposed to foster coarse-graining. If agent properties and localities dominate over correlated histories, interrelations, and entanglement, then efficacious emergence is unlikely, or at best will be compromised, biased, fragile, or sterile.

In firms, however, it is likely that CEOs would want to progress, or evolve, from one set of adaptive tension field effects to others over the course of time. Is it realistic for CEOs to stop in between each adaptive tension field imposition aiming at altering coarse-graining to more or less reconstruct the fine-grained structure? How much effort should go into the interim re-creation of entanglement pools? Can this be accomplished quickly, if at all, given the impediments noted in the previous Section? The idea is *not* to inadvertently corrupt the creation of entanglement ties via the adaptive tension effects, otherwise the hoped-for outcome of the latter—emergent structures—are likely to be faulty adaptive mechanisms. In addition, the time periods necessary to accomplish fine-graining or coarse-graining could vary widely. The level of energy-differential or adaptive tension displacement required is uncertain, again causing timing problems. The time necessary to undo previous coarse-grained structures is uncertain, and difficult, as the resistance to change and strong culture literature suggests. In short, even though CEOs might be attempting a sequenced approach, the likelihood is that fields working to recreate entanglement and foster emergence don't just stop and start their effects with "on–off" clarity. The odds are that they could be in effect at the same time—working at cross purposes. Given all this, the sequential alternating approach seems dubious.

If alternating field effects is difficult, can fine- and coarse-graining, instead, take place simultaneously? Is it possible to impose fields simultaneously in firms, that aim to recreate both fine-grained and coarse-grained structures? I think the answer is, yes. On the one hand, adaptive tension effects are, by definition, aimed at moving a firm toward a more adaptively improved state relative to competitors and other forces and constraints in its competitive environment. As detailed in McKelvey (1999c), adaptive tension fields are created by promulgating information that says, in effect, "Our productivity, our product quality, our product portfolio is *this*… but it needs to be *that*…." In contrast, the five bullets listed previously, about how to produce entanglement, have nothing intrinsically to do with adaptive tension—*producing fine-grained entanglement <u>is</u> independent of producing coarse-grained emergent structure*. Though not necessarily easy, there is nothing really to prevent an employee, for example, from constantly trying to meet and talk to additional *other* "unentangled" employees while <u>at the same time</u> working on a team of like-minded—that is, having coherent correlated histories—employees working to solve an adaptive tension problem. "At the same time" is the key, however. Given 8 hours a day, trade-offs have to be made between fine-grained and coarse-grained activities. Writ large, entanglement and adaptive tension can be worked on at the same time. Writ small, given 8-hour days, developing entanglement could take time away from dealing with adaptive tension. But, using year-long intervals, both activities can be pursued simultaneously.

4.4.3 Social Entanglement Laws?

To sum it all up, neither entanglement nor adaptive tension separately are necessary and sufficient to foster efficacious coarse-grained emergent structure. Using Churchman and Ackoff's (1950) term, they are "*co-producers*" of coarse-graining, that is, jointly necessary and sufficient. It would appear that the following statement has the earmarks of a broadly generalizable natural law:

1. Two underlying generative processes, entanglement and adaptive tension (energy-differential)—within the critical value range—are both required to co-produce efficacious emergence.

Absent adaptive tension, nothing happens. Absent uncorrupted entanglement and the emergence, if produced, will likely be faulty and not adaptively efficacious. Though not said, the emergence is "at the edge of chaos" due to the need for the adaptive tension to lie within the critical values—the 2nd of which separates the region of emergence from the region of chaos. In some instances, however, a quickly identified human capital solution will arrest the emergent structure (Johnson 1999). And, more likely, in the real world, entanglement is never totally absent nor present.

2. The size and/or quality of the entanglement pool should match in requisite variety the complexity and multiplicity of the various tensions or energy-differentials imposed upon a firm.

It is clear from discussions by Rothstein (1958), Ashby (1956), and Buckley (1967) that entanglement in a firm is in a "requisite variety" relationship to its over all adaptive tension. The higher the tension and the more different dimensions of adaptive tension, the more critical and the larger and more different kinds of correlated histories—entanglement ties—are required in the entanglement pool(s).

3. Social entanglement ties are inherently unstable and deteriorate toward weak or strong ties over time because emergent structures (1) disrupt unbiased correlated histories; and (2) strengthen bias and predisposition, are self-perpetuating, and are self-reinforcing. Often the leave the residue of corrupted entanglement even after adaptive tension parameters have dropped below the 1st critical value.

4. Absent explicit attention to counteracting entanglement corruption, naturally occurring order in social systems is increasingly maladaptive over time—because of deteriorating entanglement.

While entanglement in quantum physics may tend toward equilibrium, social entanglement is inherently unstable because of feedback from prior emergent coarse-graining. Thus, over time, with sequentially occurring adaptive tension fields, the number of entanglement ties in a social system will decrease, being replaced by weak ties (pairs of agents stop having correlated histories) or biased strong ties (ties grow in strength to the point where they include bias and/or predisposition). Assuming that anti-corruption measures are ignored and that, therefore, entanglement slowly deteriorates, naturally occurring order is likely to be maladaptive. Further, over time, initially small emergent order formations will be self-reinforcing (Mark 1998), further disrupting the entanglement pool and leading to increased maladaptation.

5. Given naturally occurring entanglement deterioration, emergent complexity thwarts efficacious adaptation, absent imposition of parameters aimed at "purifying" entanglement.

Kauffman's (1993) argues that complexity, under conditions of complexity catastrophe, is an alternative source of order to that produced via natural selection forces. His theory rests on the idea that the adaptive landscape is turned into a "*rugged landscape*" by increasing complexity in ways that minimize the effects of natural selection. A rugged landscape consists of an increased number of lowered adaptive peaks, thereby resulting in the increased probability that adaptive searches will end on suboptimal peaks. Thus, Kauffman's logic chain is:

- *Complexity* ➔ *rugged landscape* ➔ *complexity catastrophe* ➔ *order based on complexity by default rather than natural section*.
- An entanglement-based theory logic chain suggests that:
- *Complexity* ➔ corrupted *entanglement ties* ➔ *maladaptive emergent structure* ➔ *self-reinforcing entanglement deterioration cycles* ➔ *order based on complexity-driven maladaptation rather than simply the neutralization of natural selection effects*.

5 CONCLUSION

To better understand the course of emergent order in organizations, I have reviewed a number of well established views about causes of emergent order in physics and biology, particularly as viewed from the perspective of complexity science. Primarily, I review explanations of how "order" (what Gell-Mann calls coarse-graining) emerges from the fine-grained structure of entanglement pools and higher-level networks, with special focus on the views of Prigogine (1962, Nicolis and Prigogine 1989), Cohen and Stewart (1993), Gell-Mann (1994), Mainzer (1994), and Omnès (1999). This review suggests:

(1) The complexity science "bridge" explanation between quantum entanglement and higher levels of order (atoms and above) is missing as a collective belief among complexity scientists. The implication is that (a) reductionist (bottom-up) causes located in quantum entanglement are not clearly linked to higher-level coarse-graining; and (b) contextualist (top-down) causes located in higher levels do not appear to disrupt entanglement or clearly connect to quantum chaos, if it exists. Further, there is no explanation given for the highest level, "ultimate" instigating cause of top-down emergent coarse-graining, as it might be defined by the "collapse of chaos."

(2) The classic concept of external Lorenz energy-differentials (as control parameters) that cause emergence "at the edge of chaos" is frequently missing. The "collapse of chaos" discussed at great length by Cohen and Stewart should attend to the role of the Lorenz energy-differential and the phase shift and the 2nd critical value, but it does not.

Surely a hallmark of complexity science is the creation of the region of emergent dissipative structures when the Lorenz energy-differential lies between the 1st and 2nd critical values.

(3) 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 emergence arises, is often ignored. Though it may be the case in physics that entanglement pools "naturally" and continually remain in a homogeneous uncorrupted fine-structure state, this seem less likely in biology, and especially unlikely on social systems. Indeed, Mainzer states the case for quantum chaos, implying a corruption of entganglement.

(4) Given the possibility in biological and social systems that *prior* emergence events could have fed back to irrevocably corrupt the entanglement base, the implications for the adaptive efficaciousness of *subsequent* emergence events also are not fully appreciated. Once both reductionist and contextualist causal forces are admitted to the explanatory mix, there is the possibility of feedback such that emergent structure at t_1, for example, can corrupt the entanglement pool at t_2, with the result that emergent structure at t_3 is not as efficaciously adaptive as one might like. This is particularly relevant when complexity theory and entanglement notions are applied, in conjunction, in firms.

I have considered entanglement-applied-to-firms in the context of sociological research on "the strength of weak ties" (Granovetter 1973, Burt 1992). I found that none of the operational definitions of various kinds of ties identified by sociologists overlaps with what I define as an "*entanglement tie*." I conclude with a discussion of how managers might best manage the problem of trying to maintain pools of entanglement quality ties in their firms while at the same time drawing on complexity theory to create regions of emergence in their firms so as to foster the emergence of efficacious adaptive structures.

For more than 4 decades Prigogine has been working on what should really be identified as the ***Zero^eth^ Law of Thermodynamics***. But, if it actually exists across the physical, biological, and social worlds, my review shows that it has not been coherently defined as yet. The 1st law of thermodynamics essentially says that, given existing structure, energy is conserved. The 2nd law says that over time, order induced by higher energy states dissolves into randomness. The 0th law is what complexity science is all about—How does energy transform into order? The Lorenz energy-differential "cause" applies to weather, fluid dynamics, various chemical materials. This is at the core of much of "physical" complexity science. To what extent can this definition of the 0th "law" be applied to broader physical phenomena, to biological phenomena, and for us, to social phenomena. Is the Big Bang the 0th law in action. Is it a cause of order fundamentally different than energy-differentials? Einstein's theory of relativity shows an equation between energy and mass. Is energy (light) in his equation already ordered or is the theory of relativity also about the origin or order? Since light (visible, invisible frequencies) has wave structure, it is already ordered in this sense. Thus, the collapse of wave packets is not necessarily order creation. Following this, an entanglement field, as defined by Gell-Mann is already ordered at the fine-grain level. What causes fine-grain structure? Some kind of energy-differential?

In biology it is easy to note that the biological world is an open system with the Sun as the ultimate source of energy, though once wave packets collapse to produce the Earth and its chemicals, we see that the Sun is not the sole energy source—evidence of biological phenomena in ocean trenches suggests that life has evolved without the effect of the Sun. If we looked hard enough would we see that energy-differentials are a the heart of what Cohen and Stewart call "the collapse of chaos?" And of course there are levels of biological analysis. Kauffman's (1993) work on the origin of life is certainly built on the foregoing energy-differential view of the 0th law. Whether his view of emergence is broadly accepted as the root cause of biological order, I am in no position to say.

In the social world we are a long way from agreeing on the causes of "natural" order, that is, order that is not the direct result of people in positions of influence and authority being able to "dictate" order creation. But what is the root cause of the "order' that they contend with in most organizations? Does this order fundamentally follow from adaptive tension parameters between the critical values that are "felt" by individuals in an organization? It is one thing to suggest, as I do (McKelvey 1999c) that managers can use energy-differentials to foster emergence in their firms. It is something else again to actually find that energy-differentials have caused order that simply emerges from "natural" social interrelations.

What does seem clear to me is that my admittedly cursory review has not identified a set of complexity causes that can be brought together under the "0th law" in the coherent way that findings from analytical mechanics, electromagnetism, and thermodynamics were combined under the 1st and 2nd laws.

References

Arthur, W. B., S. N. Durlauf and D. A. Lane (eds.) (1997). *The Economy as an Evolving Complex System*, Proceedings of the Santa Fe Institute, Vol. XXVII. Reading, MA: Addison-Wesley.

Ashby, W. R. (1956). *An Introduction to Cybernetics*. London: Chapman & Hall.

Ashby, W. R. (1962). "Principles of the Self-Organizing System," in H. von Foerster and G. W. Zopf (eds.), *Principles of Self-Organization*. New York: Pergamon, 255–278.

Ashkenas, R., D. Ulrich, T. Jick and S. Kerr (1995). *The Boundaryless Organization*. San Francisco, CA: Jossey-Bass.

Baden-Fuller, C. and J. M. Stopford (1994). *Rejuvenating the Mature Business*. Cambridge, MA: Harvard Business School Press.

Barrow, J. D. (1991). *Theories of Everything: The Quest for Ultimate Explanation*. New York: Fawcett Columbine.

Belew, R. K. and M. Mitchell (eds.) (1996). *Adaptive Individuals in Evolving Populations*, Proceedings of the Santa Fe Institute, Vol. XXVI. Reading, MA: Addison-Wesley.

Bell, J. S. (1964). "On the Einstein Podolsky Rosen Paradox," *Physics*, 1, 195–200.

Bell, J. S. (1987). *Speakable and Unspeakable in Quantum Mechanics*. Cambridge, UK: Cambridge University Press.

Berger, J., C. L. Ridgeway, M. H. Fisek and R. Z. Norman (1998). "The Legitimation and Delegitimation of Power and Prestige Orders," *American Sociological Review*, 63, 379–405.

Bhaskar, R. (1975). *A Realist Theory of Science*. London: Leeds Books [2nd ed. published by Verso (London) 1997].

Bohm, D. (1951). *Quantum Theory*. Englewood Cliffs, NJ: Prentice-Hall.

Borel, E. (1937). *Valeur Pratique et Philosophie des Probabilités*. Paris: Gauthier-Villars.

Buckley, W. (1967). *Sociology and Modern Systems Theory*. Englewood Cliffs, NJ: Prentice-Hall.

Burrell, G. and G. Morgan (1979). *Sociological Paradigms and Organizational Analysis*. London: Heinemann.

Burt, R. S. (1992). *Structural Holes: The Social Structure of Competition*. Cambridge, MA: Harvard University Press.

Camerer, C. (1995). "Individual Decision Making," in J. H. Kagel and A. E. Roth (eds.), *The Handbook of Experimental Economics*. Princeton, NJ: Princeton University Press, 587–703.

Campbell, D. T. (1974b). "Evolutionary Epistemology," in P. A. Schilpp (Ed.), *The Philosophy of Karl Popper* (Vol. 14, I. & II), *The Library of Living Philosophers*. La Salle, IL: Open Court. [Reprinted in G. Radnitzky and W. W. Bartley, III (eds.), *Evolutionary Epistemology, Rationality, and the Sociology of Knowledge*. La Salle, IL: Open Court, pp. 47–89.]

Chia, R. (1996). *Organizational Analysis as Deconstructive Practice*. Berlin, Germany: Walter de Gruyter.

Churchman, C. W. and R. L. Ackoff (1950). "Purposive Behavior and Cybernetics," *Social Forces*, 29, 32–39.

Cohen, J. and I. Stewart (1994). *The Collapse of Chaos: Discovering Simplicity in a Complex World*. New York: Viking.

Cohen, R. S., R. Hilpinen and Q. Renzong (1996). *Realism and Anti-Realism in the Philosophy of Science*. Dordrecht, The Netherlands: Kluwer.

Cowan, G. A., Pines and D. Meltzer (eds.) (1994). *Complexity: Metaphors, Models, and Reality*, Proceedings of the Santa Fe Institute, Vol. XIX. Reading, MA: Addison-Wesley.

Cramer, F. (1993). *Chaos and Order: The Complex Structure of Living Things* (trans. D. L. Loewus). New York: VCH.

Cushing, J. T. and E. McMullin (eds.) (1989). *Philosophical Consequences of Quantum Theory*. Notre Dame, IN: Notre Dame University Press.

D'Espagnat, B. (1989). *Reality and the Physicist*. Cambridge, UK: Cambridge University Press.

Dainian F. (1996). "Niels Bohr and Realism" in R. S. Cohen, R. Hilpinen and Q. Renzong (eds.) *Realism and Anti-Realism in the Philosophy of Science*. Dordrecht, The Netherlands: Kluwer, 279–287.

Depew, D. J. and B. H. Weber (1995). *Darwinism Evolving: Systems Dynamics and the Genealogy of Natural Selection*. Cambridge, MA: Bradford/MIT Press.

Durkheim, É. (1893). *De la Division du Travail Social: Étude sur l'organization des Sociétés Supérieures*. Paris: F. Alcan.

Eddington, A. (1930). *The Nature of the Physical World*. London: Macmillan.

Feyerabend, P. K. (1975). *Against Method*. Thetford, UK: Lowe and Brydone.

Fine, A. (1986). "Is Scientific Realism Compatible with Quantum Physics?" in A. Fine, *The Shaky Game*. Chicago, IL: University of Chicago Press, Chapter 9, 151–171.

Folse, H. J. (1996). "The Bohr-Einstein Debate and the Philosophers' Debate over Realism vs. Anti-Realism," in R. S. Cohen, R. Hilpinen and Q. Renzong (eds.) *Realism and Anti-Realism in the Philosophy of Science*. Dordrecht, The Netherlands: Kluwer, 2289–298.

Friedkin, N. E. (1980). "A Test of the Structural Features of Granovetter's 'Strength of Weak Ties' Theory," *Social Networks*, 2, 411–422.

Friedrich, H. (1994). "Chaos in Atomen," in K. Mainzer and W. Schirmacher (eds.), *Quanten, Chaos und Dämonen*. Erkenntnistheoretische Aspekte des physikalischen Weltbildes, Mannheim: B. I. Wissenschaftsverlag.

Friedrich, H. and D. Wintgen (1989). The Hydrogen Atom in a Uniform Magnetic Field," *Physics Reports*, 183, 37–79.

Geertz, C. (1973). *The Interpretation of Cultures*. New York: Basic Books.

Gell-Mann, M. (1994). *The Quark and the Jaguar*. New York: Freeman.

Granovetter, M. (1973). "The Strength of Weak Ties," *American Journal of Sociology*, 78, 1360–1380.

Granovetter, M. (1982). "The Strength of Weak Ties: A Network Theory Revisited," in P. V. Marsden and N. Lin (eds.), *Social Structures and Network Analysis*. Beverly Hills, CA: Sage, 105–130.

Gribbin, J. (1984). *In Search of Schrödinger's Cat: Quantum Physics and Reality*. New York: Bantum.

Gribbin, J. (1995). *Schrödinger's Kittens and the Search for Reality*. Boston, MA: Little, Brown.

Hassard, J. and M. Parker (1993). *Postmodernism and Organizations*. Thousand Oaks, CA: SAGE.

Healey, R. (1989). *The Philosophy of Quantum Mechanics: An Interactive Interpretation*. Cambridge, UK: Cambridge University Press.

Hoddeson, L., L. Brown, M. Riordan and M. Dresden (eds.) (1997). *The Rise of the Standard Model: Particle Physics in the 1960s and 1970s*. Cambridge, UK: Cambridge University Press.

Hooker, C. A. (1995). *Reason, Regulation, and Realism: Toward a Regulatory Systems Theory of Reason and Evolutionary Epistemology*. Albany, NY: State University of New York Press.

Hughes, R. I. G. (1989). *The Structure and Interpretation of Quantum Mechanics*. Cambridge, MA: Harvard University Press.

Jammer, M. (1974). *The Philosophy of QM*. New York: Wiley.

Johnson, N. L. (1998). "Collective Problem Solving: Functionality Beyond the Individual," unpublished manuscript, Los Alamos National Laboratory, Los Alamos, NM.

Kauffman, S. A. (1993). *The Origins of Order: Self-Organization and Selection in Evolution*. New York: Oxford University Press.

Kaye, B. (1993). *Chaos & Complexity*. New York: VCH.

Kets, de Vries, M. and D. Miller (1984). *The Neurotic Organization*. San Francisco, CA: Jossey-Bass.

Krackhardt, D. (1992). "The Strength of Strong Ties: The Importance of *Philos* in Organizations," in N. Nohria and R. G. Eccles (eds.), *Networks and Organizations: Structure, Form, and Action*. Cambridge, MA: Harvard University Press, pp. 216–239.

Kuhn, T. S. (1970). *The Structure of Scientific Revolutions* (2nd ed.). Chicago, IL: University of Chicago Press.

Lincoln, Y. S. (Ed.) (1985). *Organizational Theory and Inquiry*. Newbury Park, CA: Sage.

Lorenz, E. N. (1963). "Deterministic Nonperiodic Flow," *Journal of the Atmospheric Sciences*, 20, 130–141.

Maguire, S. and B. McKelvey (1999a). "Complexity and Management: Moving from Fad to Firm Foundations," *Emergence*, 1, (2), 19–61.

Maguire, S. and B. McKelvey (eds.) (1999b). Special Issue on Complexity and Management: Where Are We?" *Emergence* 1, (2).

Mainzer, K. (1994). *Thinking in Complexity: The Complex Dynamics of Matter, Mind, and Mankind*. New York: Springer-Verlag.

Mark, N. (1998). "Beyond Individual Differences: Social Differentiation From First Principles," *American Sociological Review*, 63, 309–330.

Martin, J. and P. Frost (1996). "The Organizational Culture War Games: A Struggle for Intellectual Dominance," in S. R. Clegg, C. Hardy and W. R. Nord (eds.), *Handbook of Organization Studies*. Thousand Oaks, CA: Sage, 599–621.

McKelvey, B. (1997). "Quasi-natural Organization Science," *Organization Science*, 8, pp. 351–380.

McKelvey, B. (1999a). "Avoiding Complexity Catastrophe in Coevolutionary Pockets: Strategies for Rugged Landscapes," *Organization Science*, 10, 294–321.

McKelvey, B. (1999b). Complexity Theory in Organization Science: Seizing the Promise or Becoming a Fad? *Emergence*, **1**, 3–32.

McKelvey, B. (1999c) "Dynamics of New Science Leadership: Strategy, Microcoevolution, Distributed Intelligence, Complexity," unpublished manuscript, Anderson School at UCLA, Los Angeles, CA.

McKelvey, B. (1999d). Self-Organization, Complexity Catastrophe, and Microstate Models at the Edge of Chaos. J. A. C. Baum and B. McKelvey, eds. *Variations in Organization Science: In Honor of Donald T. Campbell.* Thousand Oaks, CA: Sage, 279–307.

McKelvey, B. (1999e). "Toward a Campbellian Realist Organization Science," in J. A. C. Baum and B. McKelvey (eds.), *Variations in Organization Science: In Honor of Donald T. Campbell*. Thousand Oaks, CA: Sage, 383–411.

Mermin, D. N. (1985). "Is the Moon There When Nobody Looks? Reality and the Quantum Theory," *Physics Today*," **????**, 38–47.

Mills, R. (1994). *Space, Time and Quanta: An Introduction to Contemporary Physics*. New York: Freeman.

Morrison, F. (1991). *The Art of Modeling Dynamic Systems*. New York: Wiley Interscience.

Nicolis, G. and I. Prigogine (1989). *Exploring Complexity: An Introduction*. New York: Freeman.

Nohria, N. and R. G. Eccles (1992). "Face-to-Face: Making Network Organizations Work," in *Networks and Organizations: Structure, Form, and Action*. Nohria, N. and R. G. Eccles (eds.). Cambridge, MA: Harvard Business School Press, 288–308.

Omnès, R. (1999). *Understanding Quantum Mechanics*. Princeton, NJ: Princeton University Press.

Peterson, A. (1968). *Quantum Mechanics and the Philosophical Tradition*. Cambridge, MA: MIT Press.

Podolny, J. M. and J. N. Baron (1997). "Resources and Relationships: Social Networks and Mobility in the Workplace," *American Sociological Review*, 62, 673–693.

Porter, M. E. (1980). *Competitive Strategy: Techniques for Analyzing Industries and Competitors*. New York: Free Press.

Porter, M. E. (1985). *Competitive Advantage*. New York: Free Press.

Porter, M. E. (1996). "What Is Strategy?" *Harvard Business Review*, Nov.-Dec., 61–78.

Prigogine, I. (1962). *Non-Equilibrium Statistical Mechanics*. New York: Wiley Interscience.

Prigogine, I. and I. Stengers (1984). *Order Out of Chaos*: *Man's New Dialogue with Nature*. New York: Bantam.

Reed, M. and M. Hughes (eds.) (1992). *Rethinking Organization: New Directions in Organization Theory and Analysis*. London: Sage.

Ridgeway, C. L. and J. Berger (1986). "Expectations, Legitimation, and Dominance Behavior in Task Groups," *American Sociological Review*, 51, 603–617.

Ridgeway, C. L. and J. Berger (1988). "The Legitimation of Power and Prestige Orders in Task Groups," in M. Webster Jr. and M. Foschi (eds.), *Status Generalization: New Theory and Research*. Stanford, CA: Stanford University Press, 207–231.

Rothstein, J. (1958). *Communication, Organization and Science*. Indian Hills, CO: Falcon's Wing Press.

Schrödinger, E. (1944). *What is Life: The Physical Aspect of the Living Cell*. Cambridge, UK: Cambridge University Press.

Schwartz, P. and J. Ogilvy (1979). "The Emergent Paradigm: Changing Patterns of Thought and Belief," Analytic Report 7, Values and Lifestyle Program, Menlo Park, CA: SRI International.

Scott, W. R. (1998). *Organizations: Rational, Natural, and Open Systems* (4th ed.). Englewood Cliffs, NJ: Prentice-Hall.

Shimony, A. (1978). "Metaphysical Problems in the Foundations of Quantum Physics," *International Philosophical Quarterly* 8, 2–17.

Spencer, H. (1898). *The Principles of Sociology*. New York: D. Appleton & Co.

Suppe, F. (1977). *The Structure of Scientific Theorie*s (2nd ed.). Chicago: University of Chicago Press.

Uzzi, B. (19??).

Weick, K. E. (1995). *Sensemaking in Organizations*. Thousand Oaks, CA: Sage.

Weinberg, S. (1994). *Dreams of a Final Theory*. New York: Vintage/Random House.

Zuoxiu, H. (1996). "On the Einstein, Podolsky and Rosen Paradox and the Relevant Philosophical Problems," in R. S. Cohen, R. Hilpinen and Q. Renzong (eds.) *Realism and Anti-Realism in the Philosophy of Science*. Dordrecht, The Netherlands: Kluwer, 279–287.

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.