EMERGENT ORDER IN FIRMS:
COMPLEXITY SCIENCE vs. THE ENTANGLEMENT TRAP

[Published in *Complex Systems and Evolutionary Perspectives of Organizations: Applications of Complexity Theory to Organizations*, Eve Mitleton-Kelly (ed.), Elsevier, Summer 2002.]

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April 25, 2002

ABSTRACT

Quantum theory concepts of correlated history and decoherence explain the emergence of structure (coarse-graining) out of fine-grained entanglement fields. Entanglement occurs when each quanta is somewhat correlated, over time, with all other quanta. Entanglement ties are proposed as alternatives to sociologists' weak and strong ties. Entanglement fields provide neutral starting points for efficacious emergence in response to adaptive tension. The adaptive efficacy of emergent structure in firms depends on the purity of the entanglement field(s) existing within them. The joint importance of uncorrupted entanglement and adaptive tension as co-produces of efficacious emergent structure is discussed, as are adaptive tension control parameters and the interaction of Darwinian selection and decoherence as causes of order-creation. Paper concludes by noting difficulties executives face in trying simultaneously to produce adaptively efficacious emergent structure and uncorrupted entanglement pools.

1 INTRODUCTION

Complexity science mostly asks: What causes order? (Mainzer 1997) Entanglement is about what exists before order emerges in the physical world. The Darwin/Wallace theory of natural selection (Darwin 1859) explains order (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.

Quantum entanglement, as the precursor to emergent order, is much discussed in physics (Gell-Mann 1994, Omnès 1999). And the spontaneous origin of life is much discussed in biology (Kauffman 1993). Long ago, Ashby made two observations particularly relevant to the biological and social worlds. *Order* (organization), he said, exists between two entities, *A* and *B*, only if this relation is "conditioned" by a third entity, *C* (1962: 255). If *C* is viewed as the "environment" which is external to the relation between *A* and *B*, it follows that connections become ordered only in the context of environmental constraints (Ashby 1956)—and disordered if the environment changes. This, then, gave 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.[1] Interestingly, he also observed that order does not emerge when the environmental constraints are chaotic (1956: 131–132).

Complexity science's emergent-order explanations play out differently in the physical, biological, and social worlds. Natural selection is one way of explaining how order appears out of the primordial 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 electrons and/or wave packets. Though selectionist theories pervade economics (Friedman 1953, Alchian 1950, Nelson and Winter 1982) and organization science (Kaufman 1975, Aldrich 1979, 1999; Weick 1979, McKelvey 1982, Baum and Singh 1994), decoherence theory is totally missing.

My discussion of entanglement, decoherence, and coarse-graining begins with a review of how order from coarse-graining emerges from the fine-grained structure of entanglement pools of quantum phenomena—all for the purpose of understanding the concept of *correlated histories over time* between pairs of electrons and how these affect emergence of higher-level structures. 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 2001, forthcoming). Clearly 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, I then focus on (1) the joint importance of entanglement

[1] Allen (2000) amends Ashby's law to the "law of excess diversity" to compensate for the probability that some portion of the potentially adaptively relevant routines a firm might have will prove irrelevant.

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 order-creation. 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 DEFINING ENTANGLEMENT

In the classic "two-slit" experiment, a light source shoots photons at the panel holding the slits. What shows up on the viewing screen are the well-known effects of wave superposition—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 causing the wave to collapse into a particle, this same behavior occurs at the other slit, even though there is no detector. 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?" [slightly paraphrased] and "I cannot seriously believe in…spooky actions at a distance" (Mermin 1991: 501–502). 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 increasingly complicated experiments (Gribbin 1984, 1995; Bell 1987, Mills 1994, Omnès 1999). In recent years a complexity science perspective has been added (Mainzer 1997). Key points in the "history" of quantum theory are:

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.

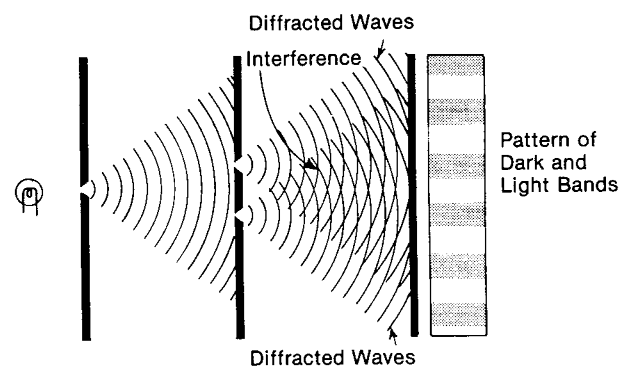
2. In 1900 Planck discovered that electromagnetic oscillations only occur in discreet lumps, known as *quanta*. Introducing his *uncertainty principle*, Heisenberg observed that, since any attempt to measure an electron's q would alter its p (or vice versa), an electron's Hamiltonian function would forever remain an uncertainty.

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.

4. Schrödinger's wave formulation includes wave *superposition*.[2] When waves appear superimposed, their individual states cannot be separated or located—they are *entangled* in a single wave packet. The process of detection—in the double slit experiment, for example—causes a wave packet to collapse and, therefore, the quanta, as particles, become visible—both after passing through the slit where the detector is *and also after passing through a* *<u>distant</u>* *slit having no detector*.

In the traditional interpretation of quantum phenomena, the visible world is somehow the result of the collapse of the countless billions of wave packets into particles of matter. The double-slit experiments show that, if an instrument is used to detect the passage of an electron through a slit, the wave packet is collapsed into a particle. Numerous theories have emerged to explain the "spooky action at a distance" and, further, what has caused all the wave packets in the visible universe to collapse into observable matter (Gribbin 1984, Fine 1986, Shimony 1978, Mermin 1991, Mills 1994, Cohen, Hilpinen and Renzong 1996).

Figure 1. The "Two Slit" Experiment †



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

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.[3] 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. The correlation of each quanta with all the others is referred to as *entanglement*.

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[2] 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.

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

The quantum state of a given electron at a given time 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 presumably 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 has come in contact with. Because of the countless correlations, and the differing quantum states of all the other electrons, each individual history is likely unique. Consequently quantum theorists cannot attach a probability of occurrence to each individual electron's history—its history is confounded by its interaction with all the other electrons' histories. Instead, they use a quantity, *D*(A, B) to record the relation between the quantum histories of two correlated electrons over time—thus *D* is always assigned to *pairs* of individual electron histories, A and B. *Entanglement* occurs when the *correlated histories* of pairs of electrons are greater than zero. If the two individual histories of a pair of electrons happen to be the same (unlikely) or are combined, *D* becomes a probability, between 0 and 1. If the individual histories are correlated, they are said to *interfere* with each other. Since most histories are correlated with other histories, *D* is seldom a probability and so, 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: 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—the more exact the measure, the more probabilistic the law!

Gell-Mann refers to the world of interference-prone histories as "*fine-grained*" structure. Thus, the quantum world is the fine-grained structure whereas he labels the world of quasiclassical physics as the *coarse-grained* structure. The question then arises, How does coarse-grained structure emerge from fine-grained—entangled—structure? He uses the metaphor of a race-track. As you get to your seat at the race track and consider the odds on your favorite horse to win, you eventually ignore all of the other factors that could affect the race—quality of horse feed and vets, the state of the track, sunlight, temperature, wind, swirling dust, flies, nature of the other people betting, track owners, mental state and health of the jockeys, and a hundred other factors that conceivably could affect the outcome of a race. All other times and the history of everything else in the universe is ignored. 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. The *context* of our interest in the winning horse causes us to sum-over all the other fine-grained correlations. The race-relevant correlations among all the fine-structure effects are focused on—to become the coarse-grained structure—whereas all the other detail correlations are summed-over and their "interference" made irrelevant. When this happens, there are three effects: (1) most of the history quantities, *D*, are ignored, that is, summed over; (2) the few correlated histories that become important do so because of the particular time and place—the context—meaning that the histories are similar and conjoined or the horses wouldn't be in the same race at the same place at the same time. This 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.

Gell-Mann says: "A coarse-grained history may be regarded as a class of alternative fine-grained histories, all of which agree on a particular account of what is followed, but vary over all possible behaviors of what is not followed, what is summed over" (p. 144). Empirical researchers play this game every time they assume that the various effects not specifically hypothesized, or designed into the study as control variables, are randomized, that is, 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).[4] Recall that the *interference terms* are the myriad correlations between pairs of particles in the fine-grained structure. Coarse-graining results in the selecting out from the myriad the correlated histories of the same kind and the same level of relationship. Gell-Mann says coarse-graining "*washes out*" the interferences among histories in the fine-grained structure (p. 145–146).

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[4] Omnès (1999: 75) defines decoherence as "the absence of macroscopic interferences."

3 COARSE-GRAINING AND COMPLEXITY SCIENCE

It is clear from Gell-Mann's race track metaphor that coarse-graining is a function of context. If a law enforcement authority went to the track looking for dishonest book-makers, then his or her emergent coarse-graining would be quite different. Coarse-graining is the result of external control parameters. This question returns to Ashby's idea of order created in the context of environmental constraints. "Control parameters," as Mainzer (1997) uses the term, refers to external forces causing the emergence of dissipative structures in the region of complexity. He begins with a review of Lorenz's (1963) discovery of a deterministic model of turbulence in weather systems. A discussion of research focusing on Benárd (1901) cells follows. Here we discover that "*critical values*" in the energy (temperature) differential, ΔT—the control parameter—between warmer and cooler plates of the cell affect the velocity, *R* (the so-called Reynolds number[5]), of the air flow, which correlates with ΔT. Suppose the plates of the cell represent the hot surface of the earth and the cold upper atmosphere. The critical values divide the velocity of air flow in the "cell" into three kinds: (1) Below the 1^{st} critical value, heat transfer occurs via conduction—gas molecules transfer energy by vibrating more vigorously against each other while remaining essentially in the same place; (2) Between the 1^{st} and 2^{nd}, heat transfer occurs via a bulk movement of air in which the gas molecules move between the surfaces in a circulatory pattern. We encounter these in aircraft as up- and down-drafts; and (3) Above the 2^{nd} critical value, a transition to chaotically moving gas molecules occurs.

Figure 2. The Lorenz "Strange Attractor" †

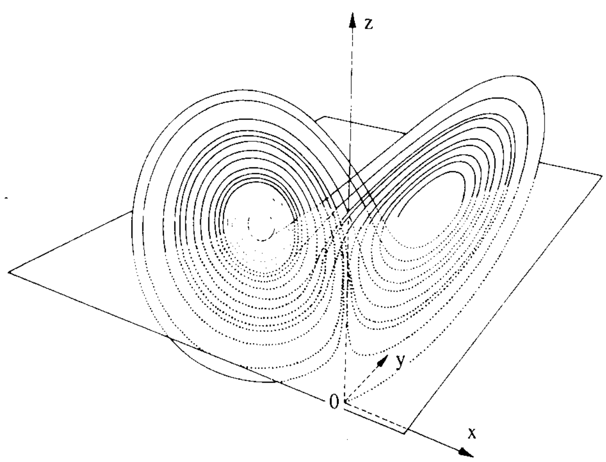

Fig. 2.21. Lorenz attractor

† Reproduced from Mainzer (1997, p. 59)

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 (Figure 2). The state of the system is also is also very sensitive to initial conditions. As Cramer (1993), Kaye (1993), and Mainzer (1997) show, this basic discovery has been replicated across many kinds of phenomena.

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 (Prigogine 1955, Nicolis and Prigogine 1989). Cramer (1993) observes that the three regions defined by the critical values define three kinds of complexity: *subcritical* $\rightarrow \lvert 1^{st} \rvert \rightarrow$ *critical* $\rightarrow \lvert 2^{nd} \rvert \rightarrow$ *fundamental*. His definitions appear in Table 1. The algorithmic compressibility characterizing all the laws of classical Newtonian science appears mostly in the subcritical region but also in the fundamental region of deterministic chaos. Mainzer (1997, p. 63) says, "mathematically, 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 position between the critical values, the consequence is symmetry breaking because the laws of classical physics do not remain invariant.

>>> Insert Table 1 about here <<<

As Prigogine observes, emergent dissipative structures, "far from equilibrium," in the region of emergent complexity are created as a result of importing energy into the system (at some rate) as negentropy (1955, Nicolis and Prigogine 1989).[6] 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 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

[5] Mainzer (1997: 58), as does Haken (1983: 254) incorrectly terms *R* the Rayleigh number. *R*, is really the Reynolds number—a measure of the rate of fluid flow, in our case it is a direct function of the energy difference, *T*. In fluid dynamics, at a specific level of *R*, fluid flow becomes turbulent. This "critical value" of *R* is termed the Rayleigh number, R_c (Lagerstrom 1996).

[6] Schrödinger (1944) coined negentropy to refer to energy importation.

means that a system has a huge number of degrees of freedom" (p. 65).

In the following three paragraphs, which I quote, Mainzer (1997: 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.

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.

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 vectors.
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 disappeared.
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 chaotic processes take over.

Mainzer teases out the fine-grained process events just before and after the phase transition at the 1st critical value. Recalling Omnès's (1999) argument, that in all but visible photons and superconduction, the decoherence processes occur more rapidly than can ever be measured, we realize that a physical system passes through the several states outlined in the bullets above very rapidly—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.

4 ENTANGLEMENT IN FIRMS

What causes order in firms? If order is caused, what in firms might cause 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 those of managers. Natural systems, such as informal groups, typically emerge as employees attempt to achieve personal goals in the context of a command-and-control bureaucracy. Open systems are in various ways defined by external forces. That all three exist goes unquestioned. What remains vague, however, are explanations about how they emerge, coevolve, come to dominate one another, and collectively impact organizational performance. Specifically, how do these three forces combine to produce the order we see in firms, where "order" is defined in terms of formal structure and process and other patterns of behavior within and by a firm?

McKelvey (1997) defines organizations as quasi-natural phenomena, caused by both the *conscious intentionality* of those holding formal office (rational systems behavior) and *naturally occurring* structure and process emerging as a result of coevolving individual employee behaviors in a selectionist context (natural and open systems behavior). Along this line, to date, two general order-causing effects in firms have already been identified: (1) selectionist microcoevolution (McKelvey 1997, 2001, forthcoming) coupled with complexity catastrophe (Kauffman 1993, McKelvey 1999a,c); and (2) more broadly, according to thick description researchers (Geertz 1973) and relativists or 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*.[7]

The question now is, What is the "engine" that sets these two (secondary) processes in motion? Increasingly, complexity science is seen as a promising place for developing a theory of "natural" order-creation in firms.[8] Management writers mostly emphasize chaos and complexity theories as a means of better understanding the behavior of firms facing uncertain, nonlinear, rapidly changing environments (Maguire and McKelvey 1999b). This view is somewhat off the track (McKelvey 1999b). Going back to the roots of complexity science in Prigogine's work, we see more accurately that complexity science is fundamentally aimed at explaining order-creation (Cohen and Stewart 1993, Mainzer 1997). Much of normal science focuses on equating energy translations from one form of order to another—working under the 1st law of thermodynamics. This is all in the context of existing order. The 2nd law of thermodynamics focuses on the inevitable disintegration of existing order. Complexity science aims to explain the emergence of order—it is really *order-creation science* focusing on the 0th law of thermodynamics (McKelvey 2002). Complexity science applications have now spread to the physical, life, social, and management sciences (Nicolis and Prigogine 1989, Cowan, Pines and Meltzer 1994, Belew and Mitchell 1996, Arthur, Durlauf, and Lane 1997, Mainzer 1997, McKelvey 1997, 2001, forthcoming; Byrne 1998, Cilliers 1998, Anderson 1999, 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 consider 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.

[7] See McKelvey (2002a) and Henrickson and McKelvey (2002) for further discussion of the "marriage" of postmodernist ontology and normal science epistemology.

[8] 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.

McKelvey (1999b) and Maguire and McKelvey (1999a), and many reviewers in Maguire and McKelvey (1999b), question the fruitfulness of this approach, arguing that it rests on misinterpretations of complexity theory. Still, 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-creation 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 (McKelvey 2002). 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 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. Organization scientists can have it both ways as well: (1) Use homogeneity assumptions and mathematics when searching for generalizable propositions within existing order regimes; (2) Use stochastic assumptions and agent-based models when studying order-creation—approaches I discuss elsewhere (McKelvey 1999a, 2000; Henrickson and McKelvey 2002).

Fourth, physicists 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 seem 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 others' 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) and postmodernists of varying kinds (Burrell and Morgan 1979, Reed and Hughes 1992, Hassard and Parker 1993, Chia 1996); *or* on methods of normal science stemming from the natural sciences. Three things are important. 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 1997, McKelvey 1997). 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, for many adherents, is tinged with an anti-science attitude (Gross and Levitt 1998, Koertge 1998, Sokal and Bricmont 1998). 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, to use Gell-Mann's term, there is coarse-graining—*and* propositions or laws explaining the origin and/or functioning of the macro structures.

4.3 DECOHERENCE AND EMERGENCE IN FIRMS

Using complexity science, I have outlined the idea that quantum wave packets are collapsed by external forces and particularly by imposed energy-differentials, following the Modern Interpretation. Not to have done this would have left entanglement—and the decoherence of it via the human observer, 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: *Complexity theory applications to firms rest on environmental constraints in the form of Bénard energy-differentials as the engines of order-creation—defined as the emergence of both entities and connections constrained by context*. The latter, when applied to firms, are best thought of as "*adaptive tension*" parameters (McKelvey 2001, forthcoming). Going back to the Bénard cell—the "hot" plate represents a firm's current position; the "cold" plate represents where the firm should be positioned for improved success. The difference is adaptive tension. This "tension" motivates the importation of negentropy and the emergence of adaptation fostering dissipative structures—assuming the tension lies between the 1st and 2nd critical values.

My review of entanglement, decoherence, and coarse-graining, modified by reference to complexity science, 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 maladaptive results*.

The nature of the initial pool of entangled particles appears essential to the coarse-graining process. In Gell-Mann's view, coarse-grained structure emerges from entangled fine-grained structure as a result external influences. Remove the external influence and macro structure disappears in the Bénard cell and coarse-grained quanta disappear back into wave packets. If energy-differentials are viewed as causes of coarse-graining, four critical differences appear:

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

To summarize, the logic sequence—in agent[9] terms—is as follows:

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

4.4 THE ENTANGLEMENT PREREQUISITE

For complexity science to work, the entanglement pool must not only contain a rich set of fine-grained entanglements, but there also must be enough more highly correlated histories that coarse-graining produces structures that emerge as probabilities relative to the fine-grained interference terms (correlation histories) 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 into coarse grained-structure. 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

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

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 forthcoming) we are interested in emergence leading to economic rents.

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 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 organizations:

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: 293).

2. ***Philos* ties:** Friendship ties based on social interaction and discussion of personal issues (Krackhardt 1992).

3. ***Simmelian Ties*:** Occurs when two people are strongly and reciprocally tied to each other and both have similar ties to at least one other person in common (Krackhardt 1999); similar to Luce and Perry's (1949) definition of a clique.

4. **Strong ties:** Frequent repeated ties (Granovetter 1973).

5. **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).

6. **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).

7. **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).

8. **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 ties are "in motion" over time. Most sociological network research is static (Wasserman and Faust 1994, McKelvey 1999a). Missing is the entanglement notion of correlated histories built up over time. Further, Uzzi (1999) 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. 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.

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 correlated histories developed over time. "Histories," here, means that the weak tie pair shows evidence metaphorically equivalent to agents influencing each other in some fashion. It is to ask: What is the probability one can predict B's behavior given knowledge of A's? A once-a-year attendance at a gathering where the CEO gives a speech does not qualify. But, if a listener follows the meeting with some email interchanges with the CEO evidencing mutual influence, then a "correlated history" is established. Entanglement may also be present with strong ties as long as the history is not so strong that it is 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 illustrates 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: 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.

4.5 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 fine-grained 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 individual histories and begin to build correlated histories.
- Create imposed field effects based on incoming stimuli that,

opposite to adaptive tension, serve to create entanglement ties rather than emergent structure.

- Use field effect stimuli and other actions to destroy obsolete coarse-grained structures so as to recreate viable entanglement pools. They do not talk about it in terms 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 1999a,b) 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 creating 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.

4.6 ENTANGLEMENT AND ADAPTIVE TENSION SEQUENCING

In Gell-Mann's (1994) treatment, focusing as it does on coarse-graining by 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. Coarse-graining from adaptive tension field effects can, however, feedback to alter social entanglement pools. McKelvey (2001, forthcoming) 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" (such as culture, command and control structure, markets, technology, neurotic founders, etc.) also can work to create or disrupt social entanglement pools, potentially undermining the use of adaptive tension fields to foster efficacious emergence. Most importantly, it is possible that activities aiming to create entanglement and efficacious emergence work at cross purposes.

The basic principle is that uncorrupted 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, sterile, or maladaptive.

In firms, however, CEOs would want (or have) to progress, or evolve, from one set of adaptive tension field effects to others over 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 previously? 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 adaptations. 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 (forthcoming), 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 is 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, mitigate clique barriers, or bridge Burt's (1992) structural holes (a dissipative structure), while at the same time 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 eight 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 eight hour days, developing entanglement could take time away from dealing with adaptive tension. But, using year-long intervals, both activities could be pursued simultaneously.

4.7 SOCIAL ENTANGLEMENT PROPOSITIONS?

Summing up, neither entanglement nor adaptive tension separately are necessary and sufficient to foster efficacious coarse-grained emergent structure. Consider the following, seemingly broadly generalizable propositions:

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

They are "*co-producers*" of efficacious coarse-graining because they are both jointly necessary and sufficient (Churchman and Ackoff 1950). 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 1998). And, more likely, in the real world, entanglement is never totally absent or pervasive.

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.[10]

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 disrupt unbiased correlated histories, strengthen bias and predisposition, are self-perpetuating, and are self-reinforcing. Often they leave a 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 and shifting context.[11]

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 field effects 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.[12] 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 logic chain suggests that:

- Complexity ➔ corrupted entanglement ties ➔ maladaptive emergent structure ➔ self-reinforcing entanglement deterioration cycles

[10] As noted earlier (Note 1), Allen (2000) argues that Ashby's law of requisite variety should really be the "law of excess diversity," since not all of the potentially adaptively relevant routines a firm might have will actually be relevant.

[11] This effect could very well underlie Salthe's (1993) biological and/or social system senescence and Meyer and Zucker's (1989) permanently failing organizations.

[12] How Kauffman's rugged landscape and complexity catastrophe ideas apply to firms is detailed in McKelvey (1999a).

→ order based on complexity-driven maladaptation *in addition to* the neutralization of natural selection effects.

5 CONCLUSION

The classic double-slit experiments raise two fundamental questions in quantum mechanics: (1) Why does detecting collapse wave packets into particles? and (2) How does it accomplish this at the second slit where there is no detector? This discovery, replicated many times with photons and electrons, prompted Einstein's famous remarks: "God does not play dice;" Is the moon there when nobody looks?" and "I cannot seriously believe in…spooky actions at a distance." In producing their "Modern Interpretation" Gell-Mann (1994) and Omnès (1999) conclude that wave collapse is caused by forces external to the experiment, principally photons from the Sun and other more adjacent sources. In the course of developing this argument, they use key terms I introduce into this paper: *entanglement*, *correlated histories*, *decoherence*, and *coarse-graining*.

The root question in quantum theory expands, in complexity science, into a multidisciplinary concern about the engine that causes order-creation in matter, life, brains, artificial intelligence, and social systems (Mainzer 1997). And, needless to ask: Is there one primary engine working up and down the hierarchy of phenomena—from matter to social systems—or are there several and do they differ across disciplines—discussed in McKelvey 2002)? From all of this, I draw out two key elements that seem particularly relevant in the application of complexity theory to organizations: (1) the notion of correlated histories between pairs of agents, that is entanglement; and (2) the Bénard process as the main engine of order-creation so far discovered that applies across the hierarchy of phenomena—in addition to the Darwinian selectionist process, and human rationality, of course.

I conclude that it does not make sense to talk about emergence in organizations without worrying about: Emergence from what? In pursuing this argument, I introduce the concept of *entanglement ties* to separate the dynamics of quantum and complexity theories from the static (graph-theoretic-based) analyses of most sociological network analyses. My argument boils down to two aspects: (1) Without the Bénard process in operation, there is no reason to expect emergent structures; and (2) Without uncorrupted entanglement fields in organizations, there is little prospect for expecting adaptively efficacious emergent structures to appear. Corrupted entanglement fields in social systems are virtually guaranteed to appear, given the accumulated legacy of successive prior emergent macrostructures. The almost certainty of this eventuality separates order-creation studies in social systems from those in the biological world to some extent, and to a much greater extent in the physical world.

This conclusion raises the issue of how managers might best create the conditions of efficaciously emergent macrostructures in organizations. There are two tasks: (1) Making sure that entanglement pools are constantly being renewed so that corruptions (strong-tie cliques and the like) from prior emergent structures are eradicated or minimized; and (2) Creating the adaptive tension levels positioned within the critical values of the Bénard process. I consider the relative merits of trying to accomplish these tasks by sequential alternation as opposed to in-parallel. With a somewhat longer time perspective in mind, it seems more expeditious to think of trying to do both within the same time frame—recognizing that activities that seem in-parallel in a one-year time span may in fact appear to be alternating give a day-to-day perspective.

There is talk in some circles that complexity theory applications in social/organization science would be better off if ties back to the natural sciences were eradicated. There is talk that complexity theory is *loose rhetoric* that, no matter what the diverse meanings of the terms are—terms such as emergence, chaos, complexity, point and strange attractors, nonlinear, and so forth—complexity theory is useful simply because it gets managers to abandon deterministic machine-based views of organizations. I think both of these views rest on faulty logic.

As this paper demonstrates, and as I argue elsewhere (McKelvey 1997, forthcoming), lessons from natural science applications pertaining to:

1. shifts from instrumentally convenient homogeneous agent assumptions and statistical mechanics;
2. assumptions in favor of dynamics, heterogeneous agents, and agent-based modeling;
3. recognition of the inescapable importance of an uncorrupted entanglement field as a precursor to efficacious emergence; and
4. Bénard process driven efficacious emergence,

all are inescapable and offer considerable leverage to correct and make practically useful applications of complexity science to the management of firms. While loose rhetoric may be useful in getting managers to stop thinking of their firms as behaving like machines, stopping a "negative" is not the same as offering a "positive." A manager might reasonably ask, "Okay, so my firm isn't a machine! Now what do I do?"

I believe a careful review of physical and biological applications of complexity theory does add value to organizational applications, as I try to demonstrate in this paper. True, some natural world elements fall short of useful application in social systems, and some terms have to be carefully translated from natural science relevance to social science relevance. This does not mean loose rhetoric is the only recourse. Not at all! To avoid well known developments from the natural sciences is to risk putting energy into process reinvention, creating a confusion of unnecessary new terms, misapplying ideas already worked out, missing obviously advantageous approaches, and falling prey to the anti-science rhetoric of the postmodernists (Gross and Levitt 1998, Koertge 1998, Sokal and Bricmont 1998).

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