Managing Coevolutionary Dynamics

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Coevolution is defined. Coevolutionary dynamics are further elaborated and related to the Law of Competitive Exclusion and the Red Queen Paradox. Coevolutionary and noncoevolutionary causes of change are noted. European and American views as to what causes order creation in systems are reviewed. Need for damping mechanisms to stop or control coevolutionary events is noted. Concept of coevolution does not make any sense with attention paid to damping mechanisms. Remainder of the paper focuses on how to manage 12 kinds of coevolutionary damping mechanisms.

1. INTRODUCTION

The term, coevolution, was coined by Ehrlich and Raven (1964), in biology. Kauffman (1993) observes that all "evolution" is really *coevolution*:

> "The true and stunning success of biology reflects the fact that organisms do not merely evolve, they *coevolve* both with other organisms and with a changing abiotic environment" (p. 237; his italics).

Nowhere is this point made more wonderfully than in Magoroh Maruyama's classic paper of 1963, where he studies the interaction of coevolution and mutation rates, drawing on the earlier work of Wright (1932).

The term has since seeped into organization science (Boulding 1968, McKelvey 1997; Lewin and Volberda's 1999 special issue). While not using the term, social psychologists have long noted the "coevolution" of member attitudes and group norms (Homans 1950), sociologists have observed the interaction of formal and informal systems in organizations—coevolution in effect, though they did not use the term (Scott 1998, Lazaric 2000). And certainly, economists have long noted the interaction between firms' behaviors in creating industries and industry effects on firms (Nelson and Winter 1982, Carroll and Hannan 1995), as well as coevolution of economic agents inside firms (Lazaric and Denis 2001). And, reflecting all those who study knowledge and learning in organizations, Marengo (1998, p. 227) quotes March (1991, p. 73) as saying, "a distinctive feature of the social context…is the mutual learning of an organization and the individuals in it." Founders of the Santa Fe Institute (for the study of complexity sciences), such as Arthur (1988, 2000) and Kauffman 1993), argue that coevolution is at the root of self-organizing behavior, constant change in systems, the production of novel macro structures, and associated nonlinearities. A good case—based on a rather considerable literature—has been made in the past decade that this line of reasoning holds across a wide variety of biological and social phenomena. Many writers applying complexity theory to improve the management of firms argue that complexity theory is a tool that can help managers manage better in a rapidly changing nonlinear competitive context (Goldstein 1994, McKelvey 1997, 2001a, forthcoming; Brown and Eisenhardt 1998, Anderson 1999, Kelly and Allison 1999).

A problem generally ignored in organizational applications of coevolution is that it approximates a mutual-causal, deviation-amplifying, positive feedback process (Maruyama 1963). Thus, A reacts to B; B reacts to A; the deviation-amplifying cycle repeats indefinitely until some damping mechanism halts it. In the Galapagos Islands, birds' beaks strengthen as nuts harden and the reverse. But if beaks get too heavy the bird can't fly and gets eaten; if nuts get too hard they don't germinate and reproduce; and so the coevolution is damped out. In biology, damping mechanisms ultimately prevail over all coevolutionary processes. But in the econosphere such is not the case. Maruyama anticipates, and Krugman (1996) shows, that coevolutionary processes give rise to cities and more specifically to the inverse power law relation between rank and population. McCain (2000) uses coevolution to explain the increasing dichotomous relation between rich and poor, strong and weak economies, between the G7 and the third world. Absent antitrust efforts, economists have long observed industries tending toward monopolists—Rockefeller's Standard Oil trust, and Gate's Microsoft—the larger the firm the more industry control; the more industry control the larger the firm. The Lewin/Volberda special issue (1999) focuses on firm-industry coevolutions. Recent organization studies also identify many instances of coevolution inside firms (Burgelman 1991, Baum and Singh 1994, Baum and McKelvey 1999, Lazaric and Denis 2001, Kaminska-Labbé and Thomas 2002). Maruyama actually uses a simple-rule, computational approach to scientific inquiry to illustrate coevolutionary dynamics, making the essential point that rule-based experiments are a far more efficient form of inquiry, given coevolution, than traditional scientific methods that try to uncover the simple-rules after emergent complexity has clouded the underlying causal elements.

But sometimes, perhaps even mostly, coevolution is damped out. The dotcom bubble-burst showed that as investors increasingly emphasized the apparent single rule of B2C internet success—burn cash to create web-based marketing approaches and consumers will buy—a stock market crash followed, damping the dotcom investment/stock returns coevolution. LeBaron (2001) shows that as investment rules coevolve toward a single super-rule, the market collapses, thus damping out the coevolution of the single rule and wealth creation.

Lazaric/Denis and Kaminska-Labbé/Thomas show that coevolving trends in firms mostly get damped out. The same is true for most of the coevolving trends studied over the years by many earlier social psychologists and sociologists. The role of resource constraints and record of damping mechanisms in population ecology is clear in biological and in industry applications—the coevolutionary damping of members of species or industries as they coevolve to more speedily and efficiently consume resources in the (also) coevolving resource niche—is well tracked (Odum 1971, Pianka 1994, Hannan and Freeman 1989, Carroll and Hannan 1995, Baum 1996).

The problem for scholars interested in the knowledge distribution and creation processes in firms, such as Watkins and Marsick (1993), Marquardt and Reynolds (1994), Prusak (1997), Marengo (1998), and Argote (1999), is that coevolution can just as easily lead toward groupthink (Janis 1972) as it does novelty. However, if coevolution in firms and industries is too soon damped out, then it can't have the nonlinear, positive feedback effect that complexity scientists see as the basis of significant new order creation—the engine that the Santa Fe complexity scientists count on is halted, and managers would seemingly have nothing to take advantage of or worry about. But this would imply strong damping mechanisms. If these normally accompany coevolution, they should be features surfacing broadly in empirical organization studies—as they already have in Burgelman (1991) and Kaminska-Labbé and Thomas (2002), should be worth theorizing about, and should have managerial consequences. Bottom line for theorists?—Should they pay more attention to the presence or absence of damping mechanisms affecting rates of coevolution in firms? Bottom line for managers?—Should they worry about having insufficient or overly strong damping mechanisms in their firms?

I also zero in on coevolutionary *rate* dynamics. As I argue elsewhere (McKelvey 1997), the study of "rates" in organizations is almost nonexistent. Again, recent work on this by Lewin, Long and Carroll (1999) stands as an exception. Consequently, I focus on both coevolutionary initiating and outcome dynamics. Primarily, I mention some twelve coevolutionary dynamics that managers need to be aware of. Given that coevolutionary processes have outcome properties similar to positive feedback, there is the possibility that their nonlinear dynamics could show unlimited growth and effect.

Consequently, I focus on damping mechanisms, arguing that on balance the problem most modern managers face is not that there are too many or two few coevolutionary effects, but rather that damping may suppress positive dynamics too quickly and not suppress negative dynamics quickly enough. Presuming that coevolution can by made more robust and speeded up, and damping mechanisms suppressed, a second problem emerges: managers might prefer coevolution proceed in some directions but not others. Steering—or what Bennis (1996) likens to "herding cats"—seems called for, but managers attempting doing this risk setting "command and control" processes in motion, which then set off additional coevolutionary trends in possibly unwanted directions.

I begin by defining various kinds of coevolution. Next I turn to a discussion of various causal dynamics setting coevolutionary processes in motion. Following this, I discuss coevolutionary outcome effects. The main body of the paper focuses on how to manage coevolutionary processes in organizations. I identify twelve potential damping mechanisms that could bring coevolution to a halt. These could be positive or negative in effect. Either way, managers could benefit from knowing more about how to speed them up or slow them down. I conclude with comments on how coevolution may be shifted from one outcome probability to another.

2. COEVOLUTION DEFINED

2.1. COEVOLUTION VS. MUTUAL CAUSAL VS POSITIVE FEEDBACK PROCESSES

Maruyama (1963) discusses *mutual causal* processes mostly with respect to biological coevolution. He also distinguishes between the "deviation-counteracting" negative feedback most familiar to general systems theorists (Buckley 1968) and "deviation-amplifying" *positive feedback* processes (Milsum 1968). Boulding (1968) and Arthur (1988, 1990) focus on "*positive feedbacks*" in economies. Negative feedback control systems such as thermostats are most familiar to us. An equally familiar positive feedback system emerges when a microphone is places near a speaker, resulting in the high-pitched squeal. In these two instances there is no adaptive *reaction*. In the first, temperature goes down and a furnace predictably comes on; room temperature rises and the furnace predictably shuts off. In the second, a sound wave from the speaker hits the mike; the mike sends it back to the speaker via the amplifier; and the speaker re-sends the sound to the mike, and so on. Since the process is instantaneous, the sound wave is shortened somewhat in each cycle and, therefore, shortens in frequency, producing the high-pitched squeal. In these cases the process is active, or activating, meaning that the response to the instigating action is predictable and causal—*a* happens; *b* happens; *a*' happens; *b*' happens, and so on.

Coevolution is different in that responses are reactively adaptive and frequently time-delayed. Clearly, viruses and bacteria are fast reactors, but still not at the causal speed of thermostats or the speaker/mike feedback loop. Even with fast reactors, however, the nature of the reaction is not predictive. Just exactly how a bacteria will adapt to an antibiotic is not predictable. We can, however, predict that coevolution will occur and some kind of adaptation will occur.

At the time of Maruyama's paper, the term coevolution had not been coined; Ehrlich and Raven came up with it in 1964. "Mutual causal" is really a misleading term to use in referring to evolutionary processes since they are reactive and not predictive-causal. "Positive feedback" is also inappropriate for the evolutionary context, and specifically for Arthur's application to economics, since it implies more positive mutual causality than what occurs in economies, where innovation and evolving systems are reactive. But then, economists are programmed to see the world like Newtonian physicists (Mirowski 1989, 1994; Colander 2000, Stanley 2000). For the study of organizations, coevolution really is the most appropriate term. But we have to remember that it is reactive. It is not predictive as to the specific nature of reactive content. We need to try to delineate circumstances where the process of coevolution may be predicted, but we cannot allow ourselves to be seduced into thinking that the nature of coevolutionary reactions is predictive. And, of course, coevolution is inherently nonlinear. Significant coevolutionary reactions and developments may be instigated by very small initiating events, as noted by Maruyama (1963), Gleick (1987), and Ormerod (1998).

2.2. VERTICAL AND HORIZONTAL

Lichtenstein and McKelvey (2002) detail the interaction of horizontal and vertical coevolution. Briefly, given appropriate stimuli, individuals (agents) may start acting to form *horizontal* networks. As the networks develop, the agents may mutually influence each other, thereby starting inter-agent coevolution. These coevolutionary interactions may then develop into groups, together with emergent group norms. These groups-with-norms, in turn, recursively influence the agents, setting up coevolutionary dynamics between the coevolving agents and groups-with-norms. All this is horizontal coevolution.

Vertical coevolution begins when several groups emerge and become groups under a higher level agent—could be another group or an individual (perhaps even a manager). At some point the higher level group or individual becomes institutionalized with its own set of norms, guidelines, rules, and so forth. Typically scientists even create a new discipline and new language to study the higher-level phenomena. Following this, supervenience is possible where downward influence emerges. At this point, vertical coevolution emerges as the lower-level agents (groups) influence upwards and the higher-level agents influence downwards. Lichtenstein and McKelvey conclude by arguing that inverse power functions are possible outcomes, as is predicted by the complexity logic of the Santa Fe Institute (Brock 2000).

2.3. RELATIONSHIPS

There are various kinds of coevolution. Maruyama mentions four; I add another:

1. *Coevolution between mutation (change) rate and environment*. The more we develop antibiotics, the faster the bacteria change; the faster they change, the faster the antibiotics in their environment change; and so on. The more the Internet develops the more people develop Internet skills; the more they develop their skills the faster the Internet develops, and so on.

2. *Predator/prey coevolution*. The faster rabbits can run, the faster the foxes have to run; the faster the foxes run, the faster the rabbits run, and so on. The faster large firms buy up start-up firms, the faster start-ups and IPOs materialize; the more start-ups and IPOs there are, the more large firms can buy them up, and so on.

3. *Supernormal coevolution*. In the American culture, for example, people who are good-looking and/or smart tend to be more attractive sexual partners; the more this is true, the more they reproduce offspring who are good-looking and/or smart; the more that supernormal people comprise a population the faster they will multiply, and so on. The more that firms see MBAs as preferred, the more MBAs will be hired; the more MBAs are hired, the more they will tend to prefer hiring additional MBAs, and so on.

4. *Inbreeding and population size*. The more inbreeding there is within in a small population (between cousins, for example), the more different and isolated the population's gene pool will become; the more restricted and different the gene pool, the more rapid the rate of differentiation by inbreeding [this is the basic logic of Eldredge and Gould's (1972) concept of punctuated equilibrium (which I note that Maruyama anticipated nearly ten years earlier)], and so on. The more a small discipline uses its members as referees the more narrowly restricted are the ideas in their papers—the more intellectually inbred it is; the more restricted are the ideas (the more inbred), the more narrowly the membership allowed into the population, and so on.

5. *Symbiotic coevolution*. The more the tick-birds eating ticks on a hippo give warnings of approaching predators, the more the hippos survive; the more that they survive and multiply as hosts, the more the ticks, and tick-birds survive, and so on. The more that a large firm hires surrounding suppliers, the more they survive and grow; the more that the suppliers survive and grow, the easier it is for the large firm to survive and grow in its competitive context, and so on. The more a business school's reputation depends, say, on its finance group, the more it attracts finance-oriented MBAs; the more the school attracts finance-oriented MBAs, the more finance faculty members it needs and the better its finance reputation grows; the better its finance reputation gets the more high-quality finance MBAs are attracted, and so on.

6. *Micro-Macro Coevolution*. For many people, coevolution is only between a population and its environment. This is the classic Ehrlich and Raven (1964) level of analysis. This level also characterizes all of the articles in the Lewin and Volberda (1999) special issue about organizational coevolution. Kauffman's (1993) analyses, however, ranges from DNA, RNA, and protein sequences, to molecules, to cells, to genetic regulatory networks, to organisms and species—from micro to macro coevolution. Chapters in the Baum and Singh (1994) and Baum and McKelvey (1999) books range from micro to macro coevolution. Burgelman's (1991) study is at the micro coevolutionary level. Lichtenstein and McKelvey (2002) recognize emergent coevolutionary dynamics at several social levels. A firm's ability to efficaciously *macro*coevolve with competitors depends on how its internal *micro*coevolutionary processes are progressing.

3 BASIC DYNAMICS

3.1 INITIATING EVENTS

Maruyama observes that initiating events may be random and insignificant. This is the same as the "butterfly" initiating event fabled in chaos theory (Gleick 1987). Maruyama also notes that even after coevolutionary processes have started, additional randomly occurring events can send them off into still other unanticipated deviation-amplifying directions.

What are the necessary and sufficient conditions for coevolution to occur? (1) Heterogeneous agents must exist. "Agents" has become a general term; agents may be quanta, particles, molecules, biomolecules, genes, chromosomes, organelles, organs, organisms, species, language concepts, organizational processes, people, groups, firms, populations, and so on. (2) Agents must have adaptive/learning capability and (3) be able to interact and mutually influence each other. (4) There must be some kind of higher-level constraint, adaptation to which motivates the coevolutionary process. And (5) there needs to be the initiating event. An initiating event could occur in any one of the "related dynamics" mentioned in the following section.

Can coevolution not happen? Clearly, if any one of the five essentials is missing, coevolution won't happen. Complexity scientists are fond of talking about the "boiled-frog effect"—if you put a frog in cold water and very slowly bring it to a boil, the frog will not jump out and cooks to death. But, if you drop it into boiling water, it jumps out immediately. Given the boiled-frog effect, many scholars hold to the idea that *absent* some kind of dramatic phase transition, tipping point, or rather significant initiating event, coevolution of any significance will not materialized. Or, there could be damping mechanisms so strong and so immediately applied that any beginning coevolutionary process is immediately stopped. European complexity scientists (Haken, Kaye, Cramer, Mainzer, Prigogine, etc.) are quite clear on the idea of an instigating phase transition. The American (read Santa Fe) complexity scientists seem much less prone to hold out for the phase transition effect. Thus, Per Bak's complexity cascades can occur given a miniscule initiating event, as long as there is connectionism among the heterogeneous agents (Brunk 2000). But, if miniscule initiating events were all that was required—if the Santa Fe view actually was true in firms—then we would not see boiled-frog effects, organizational change would occur all the time, organizations would always be successfully adapted to environmental change, and no permanently failing organizations would exist (Meyer and Zucker 1989). On the other hand, there is lots of evidence that small behavioral effects can lead to informal group formations of considerable significance (Roethlisberger and Dixon 1939, Homans 1950).

3.2 RELATED DYNAMICS

Coevolutionary dynamics visible in organizations would interact with the following constraints and dynamics:

1. *Contextual constraints*. Defined as any resource that is competed over by more than one population or set of agents. We may define these in terms of Porter's (1980) drivers: technology, markets, competitors, suppliers, costs, etc. But, not just economic drivers. There could be coevolution aimed at gaining power, status, reputation, visibility, information. A "resource" is anything that has to be shared, or poses a constraint of some kind that causes agents to react to each other. Any change in resources could lead to the following dynamics.

2. *Law of Competitive Exclusion.* Fisher's Theorem (1930) in biology holds that the faster the internal mutation/change rate the more likely species will evolve into new niches—into new resource pools. Given this, the faster are coevolutionary dynamics, the less likely species or industrial populations will be held hostage to the Law of Competitive Exclusion. Thus, if a weaker species is about to lose out to a dominant species, the weaker one migrates, via mutation and selective replacement, into a different resource pool (but see # 4 below). By Porter's (1985) strategic program, firms initially avoid the Law of Competitive Exclusion by competing on cost vs. product differentiation. Eventually, if two firms compete on cost, and one dominates, the other may aim its product line at a different market so as to avoid head-to-head competition. Agents that remain in competition with the dominant population are selected out; those that mutate/migrate into a different habitat survive and, via the process underlying punctuated equilibrium—mentioned above, multiply and become new populations.

3. *Red Queen "Evolutionary" Paradox.* The Red Queen Paradox essentially presumes coevolution. In a changing world, populations have to maintain "competitive" rates of coevolution among member agents just to stay even—otherwise they get hit with the Law of Competitive Exclusion. A population has to coevolve faster than competing populations to have sustained competitive advantage. Absent damping mechanisms, and given several competing populations in a niche, The Red Queen Paradox effect means that there is a general tendency for microcoevolution to speed up. Therefore, it appears that sustained competitive advantage, especially in a world of changing taste, technology, and globalization, is fundamentally a function of advantage resting on being able to speed up microcoevolutionary development and, relatedly, management of damping mechanisms.

4. *Niche Separation*. Odum (1971) observes that niches don't just sit their waiting to be occupied. Rather the definition of a niche—as a pool of relevant resources—coevolves in its elaboration in conjunction with the elaboration of the characters describing newly forming species. The Internet didn't just exist, with people subsequently starting to use it; the Internet's attributes coevolved with the skills and preferences of its users. Under circumstances where the Law of Competitive Exclusion begins to dominate, pressure mounts in favor of niche separation and, then, the beginning of the coevolution of niche and species characterization. Coevolution into a new niche temporarily stops further coevolution—until other players enter the new niche as well. Given that the niche/species combination is novel, and thus without significant competition, the niche separation process dominates the Red Queen Paradox. But, as competitors to the newly defined species/niche combination emerge, the Red Queen race begins to dominate, and when a winner emerges, the Law of Competitive Exclusion takes hold. Then the process starts all over again since there is now new motive toward niche separation.

5. In general, there is a cycling through the three kinds of dynamics, with each dynamic only temporarily in a dominating position. However, speeding up microcoevolutionary capabilities does lead to sustained competitive advantage.

Some constraints are not coevolutionary—see below

3.3 INTERNAL MECHANISMS OF CHANGE

Needless to say, the fundamental requirement for coevolution to occur is that the internal agents, within a driving context of some kind, have to meet the earlier mentioned defining attributes. Agents must be *heterogeneous*, *adaptive/learning*, *connected*, *interactive*, and *mutually influencing*. Take away any one of these characters and coevolution stops, as the biological record and many agent-based models show (Johnson 1998, Allen 2001, LeBaron 2001). Coevolution presumes that the agents compete for something—resources, attention, dominance, space, ideas, people, whatever.

Presumably, most technological, operational, functional, product, or bureaucratic processes in organizations are affected by other processes—are in some way competing for scarce resources. A change in the imposed constraint on one or more of these processes—in a well connected system—means changes in others as each adapts to the others. In Santa Fe terms, this means evolving change beginning in any part of a relatively well connected system, means that a Bakian complexity cascade begins (Brunk 2000). I note that absent connectivity, coevolution-based complexity cascades can't begin (Brunk 2000), and that if connectivity is too high, complexity catastrophe (defined below) occurs (Kauffman 1993, McKelvey 1999a,b).

Coevolution also presumes that some number of agents and/or agent groups (horizontally and vertically) respond to observed changes in other competing groups. Agents cannot coevolve against forces they remain unaware of. Presumably each agent has some *threshold level* of responsiveness. Neurons in the brain "fire" only after some level of signal reaches them via the synaptic links. Neurons are known as "*threshold gates*" because of this. Agents in general may be defined as behaving in a threshold-gate manner—the only question being, how high or low is the threshold. Cohen and Levinthal's (1990) *absorptive capacity* acts as a threshold gate. Thus, with the boiled-frog effect, a set of agents in a system may in fact be surrounded with all sorts of initiating events, but since none of the events rises above the threshold attention/response gates, coevolutionary reaction remains dormant.

The increasing use of agent-based models over the past decade has forced researchers to zero in on what the rules are that govern or guide adaptive agents. There are various ways that agents can change:

1. Biological agents can change by mutations with agents; by cross-over (when the genes of two sexually connecting agents are half-each passed on to offspring; and by random error at any point (Holland 1995).
2. Human agents may experience changes of varying kinds as the knowledge and skills of older agents are passed down to newer agents. Many aspects of this are detailed in Argote (1999).
3. Agents (even nonhuman ones)—as nodes in a system—may change by altering their intentions, strategies, goals, intelligence, fitness, and so on, through some kind of learning process (Argote 1999).
4. Contextual changes and *adaptive tensions* (McKelvey 2001a, forthcoming, uses adaptive tension instead of energy differentials for application to organizations) from outside the focal system may change what agents view as important. External events or actions of other agents could lower or raise the threshold gates, thus altering their absorptive capacity. Agents would become more or less responsive and, therefore, more or less likely to escape the boiled-frog effect.

3.4 NON-COEVOLUTIONARY CAUSES OF CHANGE

I have already mentioned the likelihood, based on Odum (1971), that there is coevolution between the development of population and niche characters. Not all changes, however, are coevolutionary with respect to agents. Many changes in the carrying capacity of the niche may not be coevolutionary. Order in the biological world is often a function of geological and, subsequently, climate changes that are clearly not changeable by a species. Gurnis (2001) discusses the geology of rising plasma, tectonic plate formation, and plate subduction in causing the rise and fall of continents. The subsequent creation mountains, plains, deserts, lakes, rivers, islands, and so on, sets these up as the instigators in the punctuated equilibrium theory (Eldredge and Gould 1972). This is a one-way effect—most species cannot cause changes in the geology of mountains, plains, and rivers, though elephants could conceivably wear down a mountain, too many plant feeders could destroy plant-life and make a plain subject to erosion, and beavers do, in fact, dam up streams (small rivers) and, thus, alter their geography.

Geological events may start coevolutionary processes but they are not influenced by biological coevolution. Some contextual changes—resources—do not coevolve. As mentioned, beavers can alter wetlands, which then may coevolve with the beaver population. Hippos can create mud wallows that, then, store moisture, alter the adjacent biosphere, attract wild life, predators of hippos, and thence alter the coevolution between hippos and their predators or other symbiotic partners.

Changes in Economic "Climate" are also possible. Many small and even large countries and their economies are subject to world events they have little control over. These events may instigate coevolution of various kinds within the countries, but within-country events "may" have little impact on the larger global events. I put "may" in quotes to remind us that very often seemingly minor events in very small countries can have global effects—the classic example being the shooting of the archduke in Austria that started the First World War.

4 OUTCOME EFFECTS

4.1 KINDS OF OUTCOMES

Earlier I distinguished between mutual causal processes, positive feedback, and coevolution. The key difference is that the first two, as Maruyama, Boulding, and Arthur use them, are predictive-causal, whereas coevolution is reactive-unpredictable. One of the key questions that complexity scientists face is the nature of knowledge limitation, given the unpredictable, nonlinear outcomes of coevolving agent processes. It is clear from the work by Juarrero (1998) that contextual constraints can narrow or expand the range of self-organizing outcomes. McKelvey (2001a, forthcoming) also discusses ways in which the management of contextual effects can steer coevolution in one way or another. Still, coevolution is essentially unpredictable:

1. *Nonlinear Effects*. Taken together, the chapters by Arthur and Brock in Colander's edited volume, *The Complexity Vision and the Teaching of Economics* (2000), join coevolution and inverse power laws as the two focal elements driving the nonlinearity effects so central to complexity science's view of phenomena, especially social phenomena. Whereas most scientific analysis, from Boltzmann on forward, focuseson the analysis of averages, the emphasis of power laws focuses our attention on the tails of distributions. Nowhere is this more clearly seen than in Gleick's discussion of chaos theory, Krugman's study of Zipf's Law applied to cities, and De Vany's (1997, 2001) analysis of the profits of movies and the effects of the superstars. Lichtenstein and McKelvey (2002) discuss possible power law effects stemming from emergent self-organization in firms.
2. *Complex Causality, Emergent "Macro" Structure, and New Hierarchical Contexts*. Lichtenstein and McKelvey (2002) review a variety of agent-based models in the organization literature that study the emergence of complex causality. The steps are: (a) emergence of initial

networks; (b) emergence of group properties; (c) emergence of hierarchical institutionalized properties; and (d) emergence of supervenience. The result of this is the emergence of both upward and downward causality. Whereas most earlier sciences were reductionist, focusing on only upward causality, systems theorists and holists have been telling us for half a century about the effects of downward causality (Buckley 1967, Cohen and Stewart 1994). It is clear that coevolution, resulting as it does in the emergence of macro structures, also results in the emergence of both upward and downward causality. This means that the study of coevolution requires more complicated views of causality that has been true in the past, especially in the more traditional sciences.

3. *Damping Effects*. In the biological world, at least, most coevolution is brought to a halt by damping mechanisms. Absent damping, coevolving species would deplete their niche resources. Each partner to a coevolving pair may also be coevolving with its predators and the latter help damping out the unlimted expansion of the initial coevolving pair. Population regulation effects also keep coevolution under control. Boulding (1968, p. 103) recognizes that in business/economic systems coevolutionary dynamics may constrained to operate between "floors" and "ceilings." In Section 5 I discuss a variety of damping mechanisms occurring in organizations.

4.2 BURSTS OF COEVOLUTION & NONLINEARITY

4.2.1 BURSTS

The interaction of coevolution and damping could lead to the appearance of "*bursts*" of coevolution and nonlinearity. Possibly damping mechanisms could emerge and coevolve with the coevolving parties almost instantly. More likely, coevolution of some kind results from an instigating event of some kind and then, only later, do damping mechanisms emerge, take hold, have an effect, or coevolve with the initially coevolving agents.

I visualize coevolution events as analogous to "bursts" of fireworks falling toward entropy. Some instigating event sets off a burst of coevolving agents—there could eventually be many of these as the many agents in a firm experience coevolutionary instigation effects rising above their threshold gates. All of these instigations progress like the fireworks bursts and then as damping mechanisms emerge, the bursts of coevolution and resultant nonlinearity dissipate.

The problem in organizations is that, unlike fireworks where the bursts fall down to the ground within seconds, organizational bursts of coevolution, complexity cascades, and nonlinearity could persist for quite some time—but probably not indefinitely because eventually resource constraints and gross imbalances hit. Boulding (1968) and Dechert (1968) describe a number of such imbalances in economies, as does McCain (2000). Some bursts could coevolve with the emerging damping mechanisms and, thus, stay ahead of them, much as bacteria stay ahead of developments in antibiotics—these could persist for a long time. And, the fact that they persist could be functional or dysfunctional.

4.2.2 ORDER CREATION VIA COEVOLUTION: THE EUROPEAN VIEW

The world of complexity science scholarship seems to be divided into the European and American camps. The European group consists of Prigogine (1955, 1997), Haken (1977, 1983), Cramer (1993), Kaye (1993), Mainzer (1997), among others. The American group consists largely of those associated with the Santa Fe Institute. While one could gloss over the differences, I think it is worth not doing so. Certainly, a part of the "separation" is due to differing interpretations of the role of the 2nd Law of Thermodynamics. Prigogine (1997, p. 26) quotes Max Born as saying, "irreversibility is the effect of the introduction of ignorance into the basic laws of physics" and he quotes Gell-Mann (1994, 218–220) as essentially saying the same thing. Prigogine's entire body of work over 50 years is based on the Eddington's (1930) "arrow of time" and irreversibility. Further, it is clear that phase transitions, especially at the 1st critical value, are fundamental. Phase transitions are significant events that occur at the 1st critical of *R*, the Reynolds number (from fluid flow dynamics, Lagerstrom 1996). Phase transitions are, thus, dramatic events, far removed from (1) the almost meaningless random "butterfly" effects that set off "self-organized criticality" and complexity cascades (Bak 1996, Brunk 2000), and (2) the a periodic strange attractors of the chaos theorists (Gleick 1987).

The Europeans typically begin with Bénard cells. In a Bénard process (1901), "*critical values*" in the energy differential (measured as temperature, ΔT) between warmer and cooler surfaces of the container affect the velocity, R (the so-called Reynolds number), of the air flow, which correlates with ΔT. The surfaces of the container represent the hot surface of the earth and the cold upper atmosphere. The critical values divide the velocity of air flow in the container into three kinds:

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

Since Bénard (1901), fluid dynamicists' (Lagerstrom 1996) have focused on the 1st critical value, R_{c1}—the Rayleigh number—that separates laminar from turbulent flows. Below the 1st critical value, viscous damping dominates so self-organized emergent (new) order does not occur; above the Rayleigh number inertial fluid motion dynamics occur (Wolfram 2002, p. 996). Ashby, in his book, *Design for a Brain* (1952), describes functions that, after a certain critical value is reached, jump into a new family of differential equations, or as Prigogine would put it, jump from one family of "Newtonian" linear differential equations describing a dissipative structure to another family. Lorenz (1963), followed by complexity scientists, added a second critical value, R_{c2}. This one separates the region of emergent complexity from deterministic chaos—the so-called "edge of chaos." Together, the 1st and 2nd critical values define three kinds of complexity (Cramer

1993; see Table 1):

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

>>> Insert Table 1 about here <<<

4.2.3 AMERICAN VIEW

The Europeans seem to focus mostly on phase transitions at R_{c1}—the lower bound of the region of emergence complexity. American complexity scientists, in contrast, focus mostly on R_{c2}—the "*edge of chaos*" (Lewin 1992, Kauffman 1993, 2000). What happens at R_{c1} is better understood; what happens at R_{c2} is more obscure. The "edge of chaos" is clearly a Santa Fe reference point (Lewin 1992).

What sets off bursts of order-creation via coevolution? The American complexity literature focuses on coevolution, power laws, and *small* instigating effects. Gleick (1987) details chaos theory and its focus on the so-called—very small indeed—butterfly effect (the fabled story of a butterfly flapping its wings in Brazil causing a storm in North America), ever since the founding paper by Lorenz (1963). Bak (1996) reports on his discovery self-organized criticality—a power law event—in which small initial events can lead to complexity cascades of avalanche proportions. As I have already mentioned, Arthur's (1988, 1990) focus on positive feedbacks stemming from initially small instigation events. Casti (1994) and Brock (2000) continue the focus on power laws. The rest of the Santa Fe story is told in Lewin (1992). In their vision, coevolution is the "engine" of complex system adaptation.

Chaos theorists focus primarily on the discovery of what Lorenz calls "*strange attractors*." 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 a single equilibrium but instead oscillates between apparent equilibria, sometimes within the x, z plane and sometimes within the y, z plane, as shown in Figure 1. Lorenz also found that the state of chaotic systems is also very sensitive to initial conditions. The image in this figure is what gave rise to the butterfly in the "butterfly effect."

>>> Insert Figure 1 about here <<<

If one worries about overcoming the boiled-frog effect, then both visions are important—they are not really competing. Phase transition effects are significant enough to overcome the threshold gate effects characteristic of most human agents. This in turn requires the adaptive tension driver to rise above R_{c1}.[1] Once these stronger than normal instigation effects cross the threshold gates, then, assuming the other requirements (heterogeneous, adaptive learning agents, and so forth) are present, coevolution starts. Neither seems both necessary and sufficient by itself. Churchman and Ackoff (1950) would call phase transition and coevolution co-producers.

5 HOW TO MANAGE COEVOLUTION?

5.1 MANAGING RATES OF COEVOLUTION

Why do firms need to know how to manage *rates* of coevolution? As mentioned before, in the current world, there is reason to believe that sustained competitive advantage comes only with an ability to constantly speed up coevolution rates. This is based on Fisher's Theorem, mentioned earlier. There is a Red Queen Paradox effect with coevolution—one has to speed up coevolution faster and faster simply to stand still. In a changing world, faster is better—the Red Queen race! This obviously applies to firms in hyper-competitive (D'Aveni 1994), high-velocity (Brown and Eisenhardt 1998) environments. Speedy coevolution also implies an ability to initiate many "new experiments." Coevolution is still dependent on the operation of the basic elements of Darwinian selectionist theory: blind variation, selection, and retention (Campbell 1965, McKelvey 1982, 1994; Aldrich 1979, 1999).

There are two problems with coevolution: too little of it and too much of it. The Santa Fe complexity scholars see most of order creation stemming from coevolution. Coevolution produces nonlinear events in systems that we, and especially economists (Nelson and Winter 1982, Mirowski 1989, Colander 2000), might otherwise presume are trending toward equilibrium conditions. Since coevolution leads to new self-organized order creation, this can be the source of novelty, adaptation, and survival in a competitive, changing world. But nonlinearities are dangerous. Every gardener knows that just because a little fertilizer is good doesn't mean a lot is better. Bursts of coevolution and nonlinearity bring new order, but out of control they can be totally disruptive. And there is always the question, What kind of new order, functional or dysfunctional? If coevolution is good, How to speed it up? If it is bad, How to slow it down or stop it altogether?

Damping mechanisms are the methods of controlling the rate of coevolution, or shutting it down altogether. Managing coevolutionary damping mechanisms, then, seems required so as to speed up or slow down coevolution. Given a coevolutionary progression at some rate, there are also two problems with the associated damping process: it occurs too quickly or too slowly. Managers would like to know how to weaken damping mechanisms when coevolution is adaptive and how to strengthen them when nonlinear order-creations get out of hand.

5.2 MANAGING DAMPING MECHANISMS

Why manage damping mechanisms? Damping mechanisms themselves could coevolve with the focal

[1] Elsewhere (McKelvey 2001b), I review the slow convergence of many complexity scientists toward the realization that order creation in physical, biological, and social phenomena requires an R_{c1} induced phase transition. I see this as a search for the 0[th] law of thermodynamics, the so-called *order-creation law*.

agent coevolution. Or perhaps they don't coevolve fast enough. Damping mechanisms could appear willy-nilly, stopping some coevolutions and not others. Their timing seems random—damping mechanisms may occur too soon or too late. In a given firm, it would be difficult, off hand, to say whether they need to be encouraged or discouraged. They could shut down coevolution too soon or too late on their own. Damping mechanisms could, themselves, excessively self-organize on their own, at levels inappropriate to the strategic needs of a firm and, thus, themselves be out of control. Damping mechanisms may not be self-damping, or they may self-damp too soon or too late.

Recognizing that the damping mechanisms coevolve with the focal agents' coevolution, what we know about coevolution could be instructive. The specific kind of damping mechanism appearing is unpredictable, except that we can predict that, given a coevolutionary process producing a nonlinear outcome, one or more damping mechanisms will materialize. The key question is, how far along is the coevolutionary nonlinearity before the damping mechanism takes hold? Damping could emerge too soon or too late, given management's desire for more or less of the nonlinearity. It seems clear that some kinds of damping need to be discouraged while others need to be encouraged. Thus, in many firms there are lots of damping mechanisms in place that stop innovation, risk taking, novelty, and so forth. These mechanisms need to be discouraged. But there are also may be coevolutionary processes that, while functional at modest strength or rate of growth, could also get out of hand. For example, having R&D oriented agent coevolutions that eventually get funding and produce ten new product concepts per year, two of which actually ramp up into marketable products could be acceptable; having a hundred such coevolutions, while still only having two per year ramp up, may be far too many. A damping mechanism seems warranted that would keep the number of research activities at a more appropriate level, while not stopping them altogether.

5.3 DAMPING MECHANISMS THAT CAN BE MANAGED

In this Section, I discuss a number of damping mechanisms that can be managed. Actually, each damping mechanism can be seen negatively or positively. Thus, there could be too much or too little agent heterogeneity in a given firm. To simplify, I always frame my discussion such that the coevolutionary process is a good thing to have and that, therefore, the damping mechanism is dysfunctional. But of course, in many firms it could easily be the reverse. I start with the obvious, well known ones and progress toward the less obvious.

5.3.1 LOSS OF AGENT HETEROGENEITY

Fisher's (1930) Theorem holds that having a faster internal mutation rate is the only way that biological species can avoid coming face-to-face with the Law of Competitive Exclusion. There are lots of more recent studies showing that as species lose the variety in their gene pool they lose their adaptive capability and go extinct. Some well known examples are the cheetah and California condor. Recent agent-based modeling studies of social phenomena show the same thing (Johnson 1998, Allen 2001, LeBaron 2001). In the econosphere, the history of Apple versus IBM/Wintel is a classic example. Apple insisted on closed architecture and enforced this by maintaining very tight control over their software development. In contrast, IBM, with its PC and choice of open architecture, give birth to Wintel, all the other programming sources that took advantage of the open architecture, and as they say, the rest is history—programming diversity easily won out over Apple's close architecture approach. Now, much of the antitrust concern against Microsoft focuses on its attempts to close off the diversity option. Many observers conclude that Microsoft is now going down the same path that Apple chose, much to the detriment of future software development.

Loss of agent heterogeneity is at the basis of Ashby's *Law of Requisite Variety* (1956). The agents subject to adaptive tension will not be able to respond constructively if they lose their heterogeneity of skills relative to the different kinds of adaptive uncertainties characterizing their external environment (Ashby's "variety"). Allen (2001) develops Ashby's Law into the *Law of Excess Diversity*." By this Allen makes the excellent point that since we don't know in advance which elements of "variety" are adaptively relevant there is always an underestimation of requisite variety. Thus, managers have to build in "excess" variety so that their firms have the necessary adaptive capability to respond to the various adaptive tensions imposed—given that some portion of this requisite variety will be irrelevant.

Connections among all the agents is a cornerstone of complexity, order creation, and novelty production via self-organization (Kauffman 1993, Arthur, Durlauf and Lane 1997, Brunk 2000). *But*, if all the agents are the same, there is no advantage to having them connected. Thus, the problem is, How to maintain agent diversity in the face of: (1) tendencies to form tight cliques that tend to produce group-think (Janis 1972); (2)tendencies toward strong command-and-control systems so as to assure reliability tend to produce organizational inertia, uniformity, and little change (Hannan and Freeman 1984); (3) corporate cultures that reduce heterogeneity (Martin, Sitkin and Boehm 1985); (4) selection tendencies that replicate the founding leader (Kets de Vries and Miller 1984); or (5) visionary charismatic leadership styles that tend to produce homogeneity (McKelvey forthcoming).

The foregoing "inhibitors" that act as damping mechanisms reducing agent heterogeneity are *emergent*: cliques, strong top-down leadership approaches, command-and-control (bureaucratic) structures, organizational cultures, and self-replicating selection processes, and so forth. Anything managers do to reduce the effects of these damping mechanisms will stop the lessening of agent heterogeneity. Examples of some of these "emergences" in action are described in Martin, Sitkin and Boehm (1985) and Siehl (1985).

5.3.2 LOSS OF WEAK-TIE FIELDS

Weak ties among agents create the conditions of novelty production and entrepreneurship (Granovetter 1973, 1982). Weak-tie "bridgers" across structural holes also create conditions of novelty production and entrepreneurship (Burt 1992). Many studies relate network structure to entrepreneurship (Aldrich 1999). Recently Uzzi (2002) presented preliminary results of his study of the emergence of the Broadway Musical industry. At several points in time he identifies "tipping points." *Before* these phase transitions there are progressions of the producers/directors most heavily involved toward the formation of tight cliques. *After* the tipping points there is invariably what I would call "weak-tie flooding." This is caused by the rapid influx of many new participants all of whom, because they are new, have weak ties among themselves and between all of them and the members of the pre-tipping point clique. Phase transitions separating periods of strong clique and strong-tie formation, followed by weak-tie flooding, also appear in Padgett's (2002) Medici Florence study. Implied, as well, in the Granovetter and Burt studies is the tendency of strong-tie cliques to produce group-think and agent homogeneity.

Novelty production and entrepreneurship require an emergent middle ground: (1) No weak ties and no novelty or entrepreneurship occurs; (2) Higher threshold gates and what would otherwise be weak-tie fields turn into non-weak-tie fields because there are no longer working connections; (3) As organizational cultures and/or groups emerge, or as functional or product specializations materialize, the tendency is for strong cliques to form. Strong cliques destroy weak ties because of strong ties within the clique. Once a clique forms, its boundary hardens leading to prejudice, "not invented here" attitudes, and diminished cross-boundary communications. The clique's collective threshold gate rises.

GE's "simple-rules" that, among other things: (1) prevent "best practice hoarding, so as to get good ideas out into the GE network and moved across boundaries;" (2) abstract these ideas to the point where they are broadly generalizable; (3) make resources available to people try new the ideas; (4) set up "popcorn stands" as places where new ideas can be safely tried out without damaging the rest of GE; coupled with (5) their policy of promoting successful managers into new positions where they might fail, all work to keep weak-tie construction and subsequent order creation active (Kerr 2000). GE's simple-rules act as damping mechanisms against organizational tendencies typically leading to weak-tie destruction. Burt's structural hole bridgers accomplish the same thing. As already noted, there are many damping mechanisms acting to stop weak-tip production—they are like bacteria in the human body. Out of control, they can kill. GE's simple rules are akin to organizational antibiotics introduced into the system to kill off the many, and constantly occurring, organizational weak-tie killing bacteria. The general question here is: How many mechanisms are there, like GE's that will work to dampen weak-tie destroying damping mechanisms—sort of meta-level damping mechanisms.

Clearly, weak-tie fields are closely coupled with agent heterogeneity. As weak ties become strong ties—to the point of strong clique formation—agent heterogeneity diminishes. As agents become more similar they will tend do more communicating with each other, thus destroying the weak-tie structure. Managers need to encourage the kinds of damping mechanisms that work to prevent the system from going toward no ties, higher threshold gates, or strong ties.

5.3.3 FAILING HUMAN CAPITAL (NODES)

As already noted, a key finding from the sociological network and complexity literatures is that connections among agents are critical to order creation. This is the *social capital* that Burt (1992) discusses. But so, too, are the capabilities of the nodes—in our case the *human capital* (Becker 1975). There is the possibility that a firm loses its capability of hiring high quality agents, the agents lose their capabilities, or they increase their threshold gates for one reason or another. Zucker and Darby (1996, Darby, Liu and Zucker 1999) find that one genius appropriately networked is superior to larger networks comprised of less talented agents. Not having stars or having isolated stars inhibits novelty production. Agents who lose their capability of absorbing new technical information—that is, absorptive capacity—lose novelty production capability (Cohen and Levinthal 1990). Threshold gates can rise: (1) Agents who get locked into hardened attitudes, perspectives, strategies, path dependencies, existing networks, prejudices, and so forth, become resistant to change; (2) Agents who lose their learning capability, who stop communicating with others, who stop listening, reading, being exposed to new sources of information, who lower their levels of awareness about what is going on around them, who become isolated, who start rejecting "not invented here" ideas, and so on, lose their adaptive capability, idea creation ability, and ability to introduce novel ideas to others. (3) Argote (1999) finds that one of the systematic inhibitors of adaptation is the failure of agents to know "who is good at what." There are two parts to this: agents may not be very good at doing things; other agents may not know who is good or not good at accomplishing various tasks. As already noted, (4) the absorptive capacity of agents is also critical (Cohen and Levinthal 1990). Finally, (5) some time ago Pfeffer (1978) observed that people in positions of authority are most likely to be the primary organizational change damping mechanisms simply because, since they are currently in positions of influence, they have the most to lose under conditions of change.

The forces just discussed are all damping mechanisms tending to make agents less responsive (1) to the external adaptive tension drivers that call for new order creation; and (2) to connections with other agents. All of these are well known. I mention them here simply to remind us all that adaptive coevolution in any complex system is still governed in some proportion by node responsiveness. This means that managers have to be aware of these damping possibilities and work to keep their agents responsive to potential coevolutionary influences. If a firm's agents are not interactively adaptive, coevolution, nonlinearity, and novelty production don't occur. In addition, as noted earlier, if its agents are not capable of offering the firm its *requisite* variety (Ashby 1956), coevolution toward efficacious adaptation is less likely.

5.3.4 SENESCENCE DUE TO LONGEVITY

Meyer and Zucker's *Permanently Failing Organizations* book (1989) details many examples of "senescence" coming to dominate firms—see also Baden-Fuller and Stopford (1994). Miller's *Icarus Paradox* book (1990) relates to senescence in the sense that it describes the many firms that become so specialized into narrow and increasingly resource-deficient niches that they fail. Much of the organization change and development literature speaks to the inevitable growth of change inhibiting systemic elements in organizations (French and Bell 1995). Much of the complexity-theory-applied-to-management literature focuses on the deleterious effects that strong command-and-control structures have on new order creation, novelty production, and entrepreneurship within firms (Goldstein 1994, Kelly and Allison 1999, Marion 1999, Sherman and Schultz 1998, Wood 2000).

Salthe (1993, 1998) is a biologist who sees self-organization as a far more dramatic order-creation process than Darwinian selection—which he puts into the "fine-tuning" role. He argues that the energy flows that work to produce order creation, novelty, and so forth, as we would expect from the European school of complexity science, would, in Kauffman's (1993) terms, work to slowly increase network complexity to the point where Kauffman's "complexity catastrophe takes hold. Complexity catastrophe thwarts natural selection processes. As order-creating energy flows create more and more order, internal stability sets in, and as Salthe emphasizes, the rate of further development slows down.

Salthe observes that "…self-organization predictably involves some combination of an increase in size and an increase in internally generated constraints, as well as an increase in gross throughput" (p. 154). Though formulated in terms of the biosphere, Salthe extends his logic to the econosphere. His view is compatible with Austrian economics. Thus, order-creation begins with entropy production tensions that create a start-up firm as a newly ordered system. This comprises the burst of new order. But eventually there is maturity and stability and the firm becomes less able continue responding effectively (as a new order-creation entity) to novel perturbations from its competitive environment. Like fireworks in the sky I mentioned earlier, firms are bursts of order falling toward entropy.

All of the tendencies described act as damping mechanisms that stop or slow down the coevolutionary agent self-organizing processes essential to adaptive order creation tend, over time, to create senescence: increased complexity—order creation itself can act as a damping mechanism to further order creation, bureaucratic command-and-control systems, niche specialization, all of the things resistance to change factors that OD people work to overcome. Leaving aside mention of more specific damping processes, simply the accumulative effect of the many order-creation forces in organizations is to, over time, create the conditions inhibiting the emergence of the kinds of coevolutionary nonlinearities that create adaptive novelty. Kauffman's complexity catastrophe effect is parallel to Salthe's senescence.

5.3.5 GROWING COMPLEXITY CATASTROPHE

I have already touched on Kauffman's (1993) complexity catastrophe concept as a significant damping mechanism. His theory, which is well known in biology, holds that as the number of links among agents increases there is some point where the probability of negative responses from newly contacted agents dominates. Once this happens a system's adaptive capability diminishes. This is the "*NK* model" part of Kauffman's theory—*N* indicates the number of agents; *K* the number of links an agent has with other agents *inside* the firm. He argues that the landscape over which agents search for more adaptive capability, consists of peaks and valleys. Two effects are possible: (1) agents can get trapped on suboptimal peaks; and (2) complexity increases have the effect of reducing the amount of adaptive capability possible (meaning that the peaks get lowered), to the point where even though Darwinian selection continues to take place, the difference between the peaks and valleys is so small that the order resulting is more a function of too much complexity than too little variation and selection. The *NK* model idea has been moved into organization science by Levinthal (1997), McKelvey (1999a,b), Rivkin (2000), and Yuan and McKelvey (2002). Rivkin, for example, shows that a moderate level of organizational/strategic complexity is the most optimal position for a firm to hold. Sorenson (1997) presents some empirical evidence from the computer workstation industry in support of the effects highlighted in Kauffman's model.

The main point of Kauffman's model is the realization that coevolutionary processes leading to increased order creation and increased complexity contain an automatic process that adds in an increasingly potent damping effect. In Kauffman's view, the adaptive efficacy of coevolutionary order creation is, thus, always brought to a halt as complexity increases. In any given firm, if complex order creation proceeds at a faster pace than efficaciously adaptive outcome effects, the firm will become overly complexified and therefore moribund before it becomes adaptive. Salthe's book (1993) was published at the same time as Kauffman's. Salthe's senescence effect, depending as it does on the proliferation of new order (structures) over time, is rather like Kauffman's complexity catastrophe. Both outcomes result from too much complexity, new order, new structures, however you choose to call it.

At the heart of Kauffman's theory are the "epistatic links" in biology. An epistatic link is one where there is no positive addition to fitness—the new link is a fitness dead end. In bureaucracy, this is like the situation where if one asks a bureaucrat for permission to do something new he/she says no, perhaps accompanied by the notorious phrase, "There is no reason for it [the "no"], it's just policy." If new links in an organization run into this kind of bureaucratic response, you can see how Kauffman's theory applies to firms. A manager should respond to this by trying to minimize the "epistatic link" possibilities in his/her firm so as to make sure that the adaptive fitness increase rate proceeds faster than the complexification rate. The GE "workout" technique—where managers have to either give an on-the-spot "no" to ideas presented to them face-to-face in the workout session, or else them have to say "yes" to the new ideas—is exactly aimed at countering the epistatic link problem. At GE, the nonbiologicl word for "epistatics" is "rattler" or "python." Rattlers are bureaucratic impediments that can be shot dead on the spot. Pythons are those that can't so quickly be unraveled. See Slater (2001, pp. 115–128) for a quick review of the GE workout technique. The advantage of the workout sessions is that they are "on the record," visible to facilitators and higher management, and are run systematically throughout GE.

5.3.6 LOSS OF COUPLED DANCING

Another approach to counteracting the damping effect of complexification comes from Kauffman's *NK*[*C*] model. In this part of his model, agents are allowed to make connections with other agents who, in our context, are outside departmental boundaries, outside a dominant local subculture, or outside the firm. The number of outside agents contacted is indicated by *C*. This is a way of assuring continued development and influence of weak-ties—ties to agents that are outside the "group-think" effects of a given corporate culture. Kauffman's model shows that the "*C*" effect raises the threshold at which the *K* effect—the number of epistatic links—becomes a damping mechanism.

As already mentioned, GE's simple rules are a good example of how one firm manages to counteract the *K* effect. Forcing people to stop hording new best practice ideas—getting them out on the GE network, and constantly moving successful managers around the firm into new positions is one way of keeping weak-tie production going. Both of these force idea sharing across departmental boundaries—increase the *C* effect. There is now a literature showing that firms taking the privacy approach to new technology development—specifically by relying on patents and secrecy—actually suffer damage in their adaptive improvement rate (Cohen ????). The alternative is to open up firm boundaries (increase the *C* effect) so that new ideas come into the firm at a rapid rate and so that the speed at which a firm adapts to new markets and technologies speeds up. This goes back to my earlier point about the coevolutionary Red Queen race—a firm has to coevolve faster and faster just to stay even with the competition. In summary, increasing the *C* effect is a second method for counteracting the damping effect of an increasing *K*. It would correct Salthe's senescence effect as well.

5.3.7 SEPARATION FROM CONTEXTUAL DRIVERS

In McKelvey (2001b) I review the principle ideas from a number of well known complexity theorists, focusing on the centrality of Bénard's classic paper (1901)—which was brought back into the chaos/complexity literature by Lorenz (1963). Bénard, a fluid dynamicist, develops his ideas in terms of energy differentials measured in terms of temperature. Thus, what are now called "Bénard cells" emerge from the self-organization of fluid molecules when the energy differential imposed on a fluid, for example as between the hot surface of the earth and the cold upper atmosphere, creates a bulk movement of the fluid. Thus, in the atmosphere, at a certain critical of temperature difference we see the bulk movement of an air current upward and another one downward. Together they form a giant circular motion. These currents are what cause the air turbulence we encounter on airplane trips. Bénard cells also appear in liquids and lasers (Haken 1983) and in the geology of the earth (Gurnis 2001). The concepts of energy gradients and critical values often appear in "Chapter 1" of complexity books (Nicolis and Prigogine, 1989, Mainzer 1997). As noted earlier, McKelvey (2001a, forthcoming) translates the energy differential giving rise to the critical value effect in natural science into "*adaptive tension*" as a more general concept relevant to social systems.

Remember that coevolution is set in motion when the agents involved are under pressure to adapt to some contextually imposed problem—this is the adaptive tension driver. Absent adaptive tension, in the European view especially, there is no reason to expect coevolution. Because of this effect, the adaptive tension driver is also the means by which coevolution is steered in one direction rather than others—coevolution is always in the direction of reducing the adaptive tension. The best view of adaptive tensions in the management strategy literature is given by Porter (1980) with his focus on industry drivers—existing industry competitors, potential new entrants, suppliers, buyers, and substitutes.

IQ is defined as the ability of an individual to deal with, or solve, problems. Following this analogy, McKelvey (2001a) introduces the idea of "corporate IQ" which is taken as a measure of a firm's ability to respond to adaptive tensions—note the plural. Needless to say, there are many kinds and amounts of adaptive tension facing firms.

To the extent that a firm loses contact with adaptive tensions imposing on it, and thereby fails to respond and adapt successfully to the tensions, *separation from adaptive tension* becomes an important damping mechanism—no tension, no adaptive coevolution. It is that simple. Managers can counter this effect by constantly working to assure that all the key players in their firms—perhaps even *all* employees—are constantly kept confronted by the *most relevant* adaptive tensions. Toyota has been doing this for years by confronting employees on the assembly line with how well they are doing relative to employees doing parallel operations at other plants. Some ideas about how to accomplish this are developed in McKelvey (2001a, forthcoming). Managers have the capability of steering coevolutionary self-organization by deciding which adaptive tensions are most important for people in their firms to confront.

The only complication to the foregoing occurs when there are many tensions floating around an organization that are not driven by the external environment, and thus do not steer the organization toward efficacious adaptation. One of the most egregious of these would be the tension on most agents created by a strong command-and-control structure, as has been noted by the afore cited complexity-applied-to-management books. It is also well known that employers respond to other tensions as well. There are personal psychological tensions described in terms of Maslow's (1954) "hierarchy of needs," McClelland's (1961) achievement, power, and affiliation needs, and so on. Roethlisberger and Dixon (1938) and Homans (1950), among many others, point to the tensions and emergent informal organizational behaviors arising from social needs.

These tensions set coevolutionary dynamics in motion, but often not in ways that are efficaciously adaptive. These coevolutions could result in increasing resistance to change. The exception occurs when the lower level participants are more connected with cues from the external environment, that is, more connected with the environmental tension drivers, than are the bureaucrats.

5.3.8 Disconnection from Adaptive Tension and Critical Values

One Jack Welch's favorite phrases, to his division presidents, is "Be #1 or 2 in your industry in market share or you will be fixed, sold, or closed" (Tichy and Sherman 1994, p. 108; somewhat paraphrased). This is a classic adaptive tension statement. The adaptive component is that "your sales are at "this" level and you have to get to be #1 or 2 in sales in *your industry*, not in anything else. The tension component is "Be # 1 or 2 or…you will be fixed, sold, or closed." Tichy and Sherman record the fact that this one statement caused a phase transition throughout GE (Chapter 5). In a giant firm where not much change was happening, the tension in this statement was above the 1st critical value and was definitely above the threshold gates of the relevant agents. This is just one broad statement. It could be decomposed into statements more relevant for specific divisions, technologies, markets, functions, products, costs, careers, geographical areas, kinds of job, positions of jobs in the hierarchy, and so forth.

McKelvey (2001a, forthcoming, p. 11) offers an extended discussion of how the key ideas of complexity science support the adaptive value of Welch's famous phrase. Some symptoms are mentioned that give some indication of which of Cramer's three kinds of complexity is present in a firm. Some that show evidence of emergent coevolution are:

1. Emergent social two or three person networks, informal or formal teams, groups, or other network configurations;
2. More effective networks within or across groups, more structural equivalence, better proportions of strong and weak ties, networks emerging between hostile groups—marketing with engineering, or with production, with suppliers, with customers, and so forth;
3. Emergent networks of any kind, networks that produce novel outcomes, new strategies, new product ideas, new directions of knowledge accumulation; and
4. Networks that speed up metabolic (energy or adaptive tension conversion) rates of event occurrence.

The danger is that there could be many coevolutionary events at GE, or in any other firm, that are disconnected from adaptive tensions. There could also be many coevolution events that are essentially rebellions against managerially identified or imposed tensions. Thus, one of the things that Welch did at GE was to make sure all the key players were "with the program" by "…placing committed allies in charge of businesses that were resisting change" Tichy and Sherman 1994, p. 83). Absent the tension and employee motivation to respond to it, coevolutionary events are headless—like headless chickens running in circles.

Adaptive tension statements accomplish two objectives. First, they steer emergent coevolutions in efficaciously adaptive directions. Second, at the same time they damp down maladaptive coevolutions by demotivating agents to pursue these. Simultaneously, they (1) define appropriate efficaciously adaptive directions and (2) deal with what economists call "agency problems" by focusing agents' attention on relevant technologies, markets, products, etc.—where "relevance" is defined by what works to improve economic rents and shareholder value (Besanko, Dranove and Shanley 2000). Welch's phrase and all of its kindred decompositions mentioned above, act as both steering and damping mechanisms.

5.3.9 Corrupted Weak-Tie Fields

One of the differences between physical and biological, and especially, social order creation has to do with the corruption of weak tie fields McKelvey (2002) discusses this at some length. With traditional Bénard cells, if R is lowered below R_{c1} the agents return to their initial states, with their form of connectivity among each other remaining intact. With social systems, however, once through an order-creating event, with order and possibly strong cliques, boundaries, group cultures, and so forth, created, these phenomena do not just go away or return to the initial weak-tie fields from which the order first emerged. In short, path dependency emerges as well. And, as order-creation events progress, path dependencies get stronger. It may take a long time before organizational memories fade to the point of diminishing path dependence (see Argote 1999, for some pros and cons on the role of organizational memory). There is virtually no mention, in the complexity science literature that I have encountered, of the possibility of corrupted weak-tie fields (entanglement fields in quantum physics (Gell-Mann 1994)) undermining the subsequent ability of systems to self-organize toward efficacious adaptation.

Coevolution-caused emergence, whether from phase transitions or miniscule random instigating (butterfly) effects, thus, contains the seeds of its own eventual ineffectiveness. Even though phase transitions or butterfly effects continue, and adaptive tension continues, order creation eventually erodes the essential, basic, requirement(s) of heterogeneous, adaptive learning, interconnected, and mutually influencing agents. Managers have to constantly work to counteract the corrupting effect of order-creation events on the primordial pool, so to speak, of weak-tie connections. I have mentioned several of these already. The main point of this section is that rather than simply Salthe's senescence effect, or Kauffman's complexity catastrophe effect, there is an order-creation succession effect where multiple order-creation events build up path dependences and the tendency of the agents to replicate themselves or the current system's attributes.

Given a changing competitive context requiring constant reinvention, managers can't rely on just one order-creation event from the primordial weak-tie field. They need continual order-creation events. They need to try to balance the strength of the forces aimed at recurrent efficacious adaptation with the strength of forces aimed at constantly recreating the primordial weak-tie conditions. If strategic alliances work properly, they can be a wonderful source of weak-tie flooding (a good discussion of an "agent-level" perspective on how agents in allied firms may or may not promulgate weak-tie flooding appears in Yoshino and Rangan 1995). Merger and acquisition activities could also be a source of efficacious weak-tie flooding, but the record suggests that most of these actually fail to produce the expected synergies (???). One of the things Jack Welch accomplished in his first ten years at GE—which gave him the "neutron Jack" reputation, was to divest large number of GE divisions, businesses, and employees while at the same time replacing them with many others. Besides vastly altering GE's portfolio of operating "businesses," this move brought all sorts of weak-tie connections into the firm. This effect, coupled with the enforcing GE's simple-rules, acted to keep the GE system from totally locking down into rigid path dependences as a result of recurrent order-creation events.

5.3.10 Boiled Frog Effects

I have been talking about the boiled frog effect throughout this paper. It places emphasis on the threshold gates of agents. Are agents sensitive to what is going on around them? Are they sensitive and responsive to messages coming at them via their connection with other agents? Are their threshold gates so high that even "normal" phase transitions have no effect? Some time ago Mike Tushman conducted a study of some 80 minicomputer firms. He found that only six of them managed to start revitalization absent outright bankruptcy or a multi-year period of near failure. I happen to work in a "boiled frog business school"—we have been sliding in the b-school rankings for some ten years and yet, across four different Deans and several Department Chairs, no adaptive response has been forthcoming—the faculty members seem incapable of self-organizing to respond as well. It seems easy for everyone to keep the threshold gates up to the level where adaptive tensions simply don't register—faculty members just go off and work on their papers rather than worry about vague things like rankings. The problem could lie with the agents' requisite variety, their threshold gates and/or the problem could be in lack of agents' connectivity.

I have discussed boiled frog effects, agent attributes, threshold gates, and connectiveness throughout this paper. Based on this discussion, one can see that a number of damping mechanisms could be relevant to the boiled frog effect. Managers would have to damp down things that: (1) prevent requisite variety from developing—such as employee selection preferences, myopic training programs, over specialization, poor absorptive capacity, inappropriate incentive systems, inhibited individual and organizational learning, etc.; (2) cause threshold gates to rise—such as group culture, boundary effects, prejudice, not-invented here, etc.; (3) stop connectivity—strong cliques with strong-tie formation, no weak-tie flooding via bringing in new people, no organizational activities that keep mixing people from different departments, functions, product lines, together, none of the GE simple-rules (or parallels to them), etc. Programs can be started that train employees to be better tuned in to requisite variety, to constantly work to lower their threshold gates, to keep adding to their connectivity. Incentives can be factored in as well. Finally, making the adaptive tension drivers more pointed, directed, strong, obvious, and harder to ignore helps as well. Not burdening employees with too many disparate tension drivers also makes sense—one could just, by imposing a number of counteracting drivers, simply load up employees with too much tension while at the same time averaging out the "adaptive tension" directivity.

5.3.11 SELF-ORGANIZED MICRO DEFENSES AGAINST COEVOLUTION

One of the things we now know about the immune system is that the agents in our bodies, that are responsible for immunizing activities, self-organize an immunization approach based on a set of simple rules (????). The reason why the HIV virus is so successful is that it mutates into new forms faster than our bodies can self-organize to attack it. It fits into what Manfred Eigen calls a quasi-species (????). Now, if you think of viruses or bacteria as analogous to new ideas coming into a firm via the weak-tie network—the *C* effect in Kauffman's *NK*[*C*] model—you can see right away that coevolution dynamics inside the firm could arise to combat new, efficaciously adaptive ideas. There is no guarantee that coevolution dynamics are always for the better. In this case, immunizing self-organization defeats adaptive self-organization. In this way coevolution emerges to stop coevolution. Coevolution itself becomes a damping mechanism.

The fact of the matter is that organizations are full of all kinds of coevolutionary dynamics, some good, some bad. Managers don't want to shut them all down; nor do they want to let them all run loose. As McKelvey (2001a, forthcoming) points out, the best way for a manager to sort this out is to start with a full understanding of what the environmentally imposed adaptive tensions are that are hitting his/her firm. These can then be used as criterion variables to decide which coevolutions to encourage and which to stop. The latter need to have damping mechanisms applied. Rebellious appearing coevolutions could be going in either direction. The "rebel agents" could have a better understanding of the technological and market tensions imposing on the firm and then start self-organizing in the face of a correct interpretation of the adaptive tension and thereby lead efficacious adaptation against a recalcitrant bureaucracy. Or "management" could have the correct interpretation and the informal self-organizing group could be dysfunctional—perhaps like a union organizing to fight off a new cost-cutting technology that could keep the firm in business. My point here is that coevolutionary dynamics can be a two-edged sword needing careful treatment. Adaptive new organizational forms may be the result of efficacious coevolution, but not all coevolution leads to efficacious adaptation. One has to be careful about selecting on the dependent variable.

5.3.12 COEVOLUTION OF MACRO DRIVEN MICRO DEFENSES

Coevolutionary dynamics also occur between or among firms. The recent Enron/Anderson scandal is a good case in point. First, Enron coevolved a number of approaches to energy trading with other competing and/or colluding energy firms, and according to recent information, even with the Los Angeles Department of Water and Power—a public agency—to fraudulently increase income in a money-losing industry. Second, Anderson had multi-million dollar CPA and consulting contracts with Enron. In addition Anderson had a contract to do actual internal accounting for Enron. Enron had its various contracts with Anderson and had all of the off-balance sheet partnerships. The coevolution of these aspects led to the cover-up. In this case, unfortunately for hundreds of stock holders, the third coevolution of self-organizing damping mechanisms by the Securities and Exchange Commission and the Federal Energy Regulation Commission, or the various States, were woefully inadequate and late, besides.

The first set of coevolutionary dynamics developed to defend an industry where the firms were actually losing money. The second set of coevolutionary dynamics developed to defend by covering up the former fraudulent coevolutions. The third defensive set of coevolutions has yet to fully materialize. In this case the Red Queen race effect was working rather well for the first two coevolutions—since the firms were all aiming at making more money. The SEC and FERC coevolutions were very slow by comparison, so the situation got out of hand. Just another example where the *rate* of coevolution is the deciding factor. This rate depends on the rate of relevant micro damping mechanisms.

Williamson (1975) brought to our attention the idea that firms vertically integrate where there are not fair markets. A second reason why firms choose to vertically integrate is to bring interfirm coevolutionary dynamics in under one roof where they are easier to speed up or damp down, that is, manage, as necessary. This is definitely not to say that firms manage coevolutionary dynamics for the benefit of the larger society, or as in the Enron case, even for their shareholders.

6 CONCLUSION

To talk about coevolutionary processes without also talking about damping mechanisms doesn't make sense. Coevolutionary processes are the engines that create the nonlinear dynamics central to complexity science. But since most nonlinear dynamics to not expand to the point where they totally dominate the physical, biological, or social worlds, there must be damping mechanisms controlling them. Usually damping mechanisms coevolve right along with the initial coevolutionary processes. In the biological world it may be ok, even preferable, to have damping mechanisms keeping bacteria, disease, rabbits, and foxes under control. We now understand that underlying firms' abilities to stay in the Red Queen race for competitive advantage are all the microcoevolutionary processes also need to be speeded up so that macrocoevolution is successful. We also know that coevolutionary processes are always responses to tensions of some kind imposing on the agents. Many tensions are imposed from the external environment—the external competitive context—and can stimulate efficaciously adaptive coevolutions. But there are lots of other tensions in and around firms that also serve to motivate coevolutions. These coevolutions may be irrelevant, negative in effect, or actually aimed at tensions created by efficaciously adaptive coevolutions. Coevolutions feed on each other—some are constructive; some destructive.

In principle, managers need to figure out how to increase the rate of efficaciously adaptive coevolutions in their firms. The Red Queen race can only be won by speeding up coevolutionary processes: (1) Managers can begin this process by focusing on the adaptive tension drivers—tensions starting with Jack Welch's famous phrase, "Be #1 or 2 in market share in your industry or you will be fixed, sold, or closed," and then decomposing it so that its effect extends down and through out a firm; (2) Managers need to focus on creating the agent-level conditions that foster emergent self-organizing behaviors—the basic elements of coevolution events; (3) Managers need to realize that they can originate, focus on, emphasize, select, and control only some of the tensions apt to set off coevolution events—once conditions are created to foster the nonlinear results of coevolution, the second part of the problem begins, to wit, the need for managing damping mechanisms. Since coevolutions pop up like weeds, this is a never ending process!

I have identified twelve kinds of damping mechanisms:

1. Loss of Agent Heterogeneity
2. Loss of Weak-tie Fields
3. Failing Human Capital (Nodes)
4. Senescence Due to Longevity
5. Growing Complexity Catastrophe
6. Loss of Coupled Dancing
7. Separation from Contextual Drivers
8. Disconnection from Adaptive Tension and Critical Values
9. Corrupted Weak-tie Fields
10. Boiled Frog Effects
11. Self-organized Micro Defenses Against Coevolution
12. Coevolution of Macro Driven Micro Defenses

The behaviors underlying some of these damping mechanisms have been well known since the early days of management and sociological research. Others have been more recently highlighted by complexity scientists. In most organizations, damping mechanisms must be dominating otherwise there would be lots of evidence of nonlinear dynamics gone wild. Since most of these damping mechanisms are already well entrenched in most firms, any attempt to initiate coevolutionary, nonlinear dynamics will immediately run up against the damping mechanisms. So, any attempt to manage by becoming more aware of coevolutionary processes requires an immediate attention to what kinds of damping mechanisms are prevalent, what kinds of tensions are energizing them, and what coevolutionary processes they are aimed at inhibiting.

Elsewhere (McKelvey 2001a, forthcoming) I argue that by focusing on adaptive tensions, and developing a limited portfolio of tensions relevant to each manager/employee—essentially expanding on Welch's famous phrase—managers can steer firms toward speedier efficacious adaptation. Constant focus on adaptive tensions also help deal with the agency problem. Having done this, however, managers also have to constantly work down through the list of damping mechanisms to thwart those that are damping efficacious self-organized adaptation events and encourage those that are damping down less desirable coevolutionary dynamics.

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

Below the 1st critical value '***Newtonian complexity***' exists where the amount of information necessary to describe the system is less complex than the system itself. Thus a rule, such as $F = ma = md^2s/dt^2$ 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 [Newtonian] complexity are strictly deterministic and allow for exact prediction" (1993, p. 213) They are also "reversible" (allowing retrodiction as well as prediction thus making the 'arrow of time' irrelevant (Eddington 1930, Prigogine and Stengers 1984).

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

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

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

Figure 1. The Lorenz "Strange Attractor" †

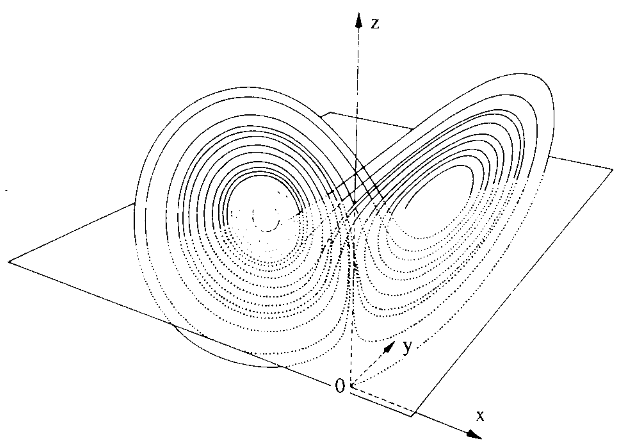

Fig. 2.21. Lorenz attractor

† Reproduced from Mainzer (1994, p. 59)