When Organizations and Ecosystems Interact:
Toward a Law of Requisite Fractality in Firms

Bill McKelvey

UCLAAnderson School of Management
110 Westwood Plaza, Los Angeles, CA 90095-1481
310/825-7796   310/206-2002 Fax   mckelvey@anderson.ucla.edu

Benyamin B. Lichtenstein

Management/Marketing Department, University of Massachusetts, Boston
100 Morrissey Blvd; M-5/214
Boston, MA 02135-3393
617/287-7887   617/287-7877 Fax   benyamin.bml@gmail.com

and

Pierpaolo Andriani
His university location is changing. Have to let you know in a month or so.

March 17, 2010

Chapter Accepted for edited book:

Chaos and Complexity in Organizations and Society.
Edited by Dr. Marcial J. Lopez Moreno; Published by UNESA.

When Organizations and Ecosystems Interact: Toward a Law of Requisite Fractality in Firms

Abstract

Complexity science has evolved greatly in the past 30 years, starting from its European roots in Prigogine's dissipative structures model of phase transitions, continuing through the Santa Fe School's focus on self-organized adaptation as explained through computational simulations, and now to it's most recent focus on power laws and their basis in Scale-free theory. After briefly reviewing these three approaches to complex systems, we attempt to integrate them into a broad-based model of organizational design and performance. Our model develops the law of 'requisite fractality' – an updated version of Ashby's original law for organizations in dynamic environments. Implications for organizations and managers are discussed.

'I think the next century will be the century of complexity'. *Stephen Hawking*[1]

Complexity science has been heralded as new paradigm in management – a powerful set of methods for explaining non-linear, emergent behaviour in organizations (Stacey, 1992; Brown & Eisenhardt, 1997; McKelvey, 1997; Anderson, Meyer, Eisenhardt, Carley & Pettigrew, 1999; Maguire, McKelvey, Mirabeau & Oztas, 2006). Many specific theoretical notions of complexity science have already been tested using computational experiments, including key aspects of learning (Carley & Svoboda, 1996), organization design (Levinthal & Warglien, 1999), network structuring (Carley, 1999; Lenox, Rockart & Lewin, 2006), organizational evolution (Allen, 1975, 1988, 1994; Levinthal, 1997; Morel & Ramanujam, 1999; Levinthal & Posen, 2007), strategic human resource management (Colbert, 2004) and strategic adaptation (Gavetti & Levinthal, 2000; Rivkin, 2001; Siggelkow & Levinthal, 2005; Siggelkow & Rivkin, 2006), to name just a few.

At least three problems block further progress toward applying complexity in management. **First**, even though the expressed focus of complexity science is the *emergence of order*, management applications of complexity rarely define what emergence is – there is no accepted definition for emergence in the field. More importantly, most non-computational applications do not reveal the underlying processes and dynamics of self-organization, which is said to be the driver of emergence (Holland, 1995).

Second, many writers convert core concepts from complexity science into simple metaphors that appear to offer managers 'hard' science legitimation for loose thinking about nonlinearities, and for their use of traditional employee empowerment theory, which in many of these 'O.D.' approaches is seen as an application of the 'emergence principle' (McKelvey, 1999). As such, many of the fundamental principles from complexity science are inappropriately applied to organizations, and as a result, the community has not learned as much from complexity science as it should (Maguire & McKelvey, 1999).

Third, this problem is compounded by a significant split between two schools of thought within the complexity field itself (McKelvey, 2004). The *European School*, originating from Prigogine's dissipative structures theory (Prigogine, 1955; Prigogine & Stengers, 1984), explores the *dynamics* that initiate and sustain order creation in far-from-equilibrium environments. In contrast, the *American School*, represented primarily by the coevolution-framed work coming out of the Santa Fe Institute (Anderson, Arrow & Pines, 1988; Arthur, 1988; Holland, 1988; Kauffman, 1993; Gell-Mann, 1994; Cowan, Pines & Meltzer, 1994), explores the *form* and inter-system *processes* associated with emergent order: co-evolution, 'power-laws', and the 'edge of chaos'. Not only have these two Schools generated seemingly contradictory approaches for explaining emergence, their epistemic and ontological turf-war has slowed the drive toward a single overarching complexity framework.[2]

This turf-war is particularly unfortunate due to the critical need to develop managerial practices that, unlike Industrial Age models, are relevant to 21st century issues, including the emergence of intangible assets, the rise of a digitized knowledge-based economy, globalization, the sustainability imperative, and the increased importance of emerging organizations and emerging markets (Sanders & McCabe, 2003; Maguire, Hardy & Lawrence, 2004). These dynamics are driven by *new order creation,* rather than by traditional notions of control, efficiency, economies of scale, equilibrium, and so on (Halal & Taylor, 1999). *Complexity science is the study of order creation* – the only science dedicated to explaining how new order emerges through self-organization in physical, biological, and social systems (Kauffman, 1993; Mainzer, 1994/2007; Chaisson, 2001, McKelvey, 2004). Given that complexity is unique in this respect, providing a complexity-science-based theory of emergent order creation that applies to organizations is foundationally important.

One place where the international community of complexity researchers *has* come together is on discoveries pertaining to Pareto distributions, power laws, and scale-free theory – best signified by the references in Andriani and McKelvey, 2007, 2009. Our goal here is to build on earlier research (McKelvey & Lichtenstein, 2007) in which we explain the 'bottom-up emergence' of organizations in terms of four stages or levels: Emergent Networks, Emergent Groups, Emergent Hierarchy, and Emergent Coordination Complexity. Each of these levels is well expressed in existing agent-based computational models of emergence in organizations. In this chapter we expand that idea by considering the fractal structures which emerge across these and further levels, as organizations adapt to their dynamic environments. We also build on McKelvey and Boisot's (2009) updating of Ross Ashby's (1956) *Law of Requisite Variety* to develop and our proposed *Law of Requisite Fractality* and apply it to organizations.

We start by drawing on the key insights of the European School to explain the driver that initiates self-organizing dynamics in economic and organizational contexts. Next, we combine the American School's early insights into the *form* of self-organized structures – and especially Per Bak's (1996) work on 'self-organized criticality' – with the more recent international research on power laws, fractals, and scale-free theory. Finally we cite 19 biological studies of interacting fractal eco-structures and draw as well on various scale-free theories from Andriani and McKelvey (2009) to substantiate our proposed *Law of Requisite Fractality*.

EMERGENCE: WHAT ARE WE LOOKING FOR?

An ever-proliferating range of meanings and operationalizations can be found for emergent order in management. For example, Winter (1984) looks at the emergence of economic order in a competitive yet growing industry; Axelrod and Bennett (1993) define order in terms of emergent outcomes of co-evolutionary games; Cheng and Van de Ven (1996) define order through the emergence of 'strange attractors' in two innovation projects; Brown and Eisenhardt (1997) define order as the emergence of dynamic yet balanced structuring; Levinthal (1991) defines order as the levels of strategic adaptiveness that emerge in competitive conditions; and MacIntosh and MacLean (1999) define order as the emergence of structure in far-from-equilibrium strategic situations. Ironically, only by putting some *order* into the definition of order can complexity science make a coherent contribution to organization studies (Cohen, 1999).

For over 100 years the question of what is emergence has intrigued and dogged scholars from many disciplines, including *philosophers* (Lewes, 1877; Popper, 1926; Stephen, 1992), *evolutionists* (Darwin, 1859; Morgan, 1923; Fisher, 1930; Eldredge & Gould, 1972; Kauffman, 1993; Salthe, 1993), *complexity scientists* (Prigogine, 1955; Allen, 1975; Holland, 1988; Nicolis & Prigogine, 1989; Crutchfield, 1994; Mainzer, 1994); and a wide range of *management scholars* (Selznick, 1943; Homans, 1950; Burns & Stalker, 1961; Weick, 1977; Goldstein, 1986; Stacey, 1992; McKelvey, 1997; Malnight, 2001; Chiles, Meyer & Hench, 2004).

An initial frame, taken by the evolutionary emergentists, was to develop a non-deductive explanation of the qualitative novelty expressed by successive levels of reality (Blitz, 1992). In Newman's (1996: 247) words, 'For an emergent evolutionist, a property of a system is emergent if its existence is novel at the level of evolutionary or physical complexity in which the system is found'. This leads to a modern definition of emergence as *a systemic process of order creation through which properties and or structures come into being that are unexpected and unpredictable, given the known attributes of component agents*[3] *and environmental forces*. Although this definition is not without merit, in some measure it has not progressed much further than the definition offered in 1938 by sociologist Herbert Mead:

> When things get together, there then arises something that was not there before, and that character is something that cannot be stated in terms of the elements which go to make up the combination. It remains to be seen in what sense we can now characterize that which has so emerged. *(Quoted in Mihata, 1997: 30).*

The goal of complexity science is to characterize that which has so emerged. A critical problem is that emergence is being explained in two very different ways by two contrasting schools of complexity. Like the blind people looking at the elephant, we believe that insights from each view are crucial but incomplete. Thus, we briefly introduce these different views, and explore why this difference makes a difference in complexity.

1. The European View: Emergence as Energy-induced Phase Transitions

The European perspective draws from Prigogine's (1955; Nicolis & Prigogine, 1989) research into phase transitions at what is called the '1st critical value', R_{C1} – the 'edge of order'. When imposed energy levels tip across R_{C1}, 'dissipative structures' form; these are emergent 'self-organized' structures that speed up the dissipation of imposed energy differentials, by creating new intra-system order. Essentially, environmentally imposed energy differentials generate an 'adaptive tension' in the system, giving it an inherent drive to be dissipated (Wicken, 1986; McKelvey, 2008).

This approach has been used to explain a broad range of organizational, sociological, and economic phenomena (e.g., Weick, 1977; Schieve & Allen, 1982; Ulrich & Probst, 1984; Adams, 1988; Smith & Gemmill, 1991; De Vany, 2004; Zohar & Borkman, 1997; Dosi & Fagiolo, 1998; Lesourne & Orlean, 1998; Saviotti & Mani, 1998; Lichtenstein, Carter, Dooley & Gartner, 2007). For example, a technical or process innovation (Schumpeter, 1934; Tushman & Anderson, 1986) can set up disequilibrium between the entrepreneur and the current market; these innovations drive the self-organized emergence of new firms and new industries (Binks & Vale, 1990; Foster, 2000). Slevin and Covin (1997: 56) describe this process by suggesting that 'successful entrepreneurial firms act as energy conversion systems'. In a broader managerial context Anderson (1999: 222) suggests that adaptive tension may be generated by organizational leaders:

> Those with influence and/or authority turn the heat up…on an organization by recruiting new sources of energy (e.g., members, suppliers, partners, and customers), by motivating stakeholders, by shaking up the organization, and by providing new sets of challenges that cannot be mastered by hewing to existing procedures.

By this theory, organizations and their internal structures emerge by importing locally accessible bundles of order, e.g., opportunities and resources (Schrödinger, 1944; Dyke, 1988; Frederick, 1998). In management terms, an entrepreneur imagines and identifies a 'bundle' of potential resources that s/he can transform into value for customers by organizing a new venture (Gartner, 1985). This projection of possibility generates an 'opportunity tension' inside the entrepreneur (Lichtenstein, 2010), who (a) gains an insight about a possible market or the capacity to do something 'better, cheaper, faster', and (b) gains the internal will and passion for making his idea a reality (Adler & Obstfeld, 200). In literal terms this process is literally opportunity from tension – which we describe as opportunity tension. Both aspects are required: An ability to identify/enact a business opportunity, and the internal passion and will to do what it takes to make it happen (Gartner, Bird & Starr, 1992).

Assuming a substantive increase in resource flow – driven by opportunity tension in entrepreneurial ventures – the theory then makes a very strong hypothesis: At a minimum threshold of bifurcation, new order will emerge *as rapidly as possible in the system – as soon as* enough resources are available (Swenson 1989; 1992; 1997). That is, in the absence of other constraints, new order will self-organize as optimally as possible (Getling & Brausch, 2003) in order to dissipate energy potentials at the maximal rate (Swenson, 1992; 1997; Lichtenstein, 2000; McKelvey, 2004). Since the most efficient way to dissipate these tensions is through endogenous order production (i.e. order creation), that's what will happen. Essentially, the biological and social world is in the 'order production' business.

Our approach runs deeper yet parallel to original versions of General Systems Theory (Bertalanffy, 1956, 1968; Bateson, 1972; Miller, 1978), by describing organizations as a series of nested systems, each level increasingly complex as it is generated through the interactions of its lower-level components (Ashmos & Huber, 1987; Chaisson, 2001). Assuming an initial condition of multiple, heterogeneous agents in an environment that is already imposing some form of adaptive tension, we would expect to see emergence appear as a progression of increasingly complex stages of organizing (Miller, 1978; Adams, 1988; Salthe, 1985), which of course is what we see in the social world (Boulding, 1988).

The European view thus shows how adaptive tension drives the emergence of intra-system order within organizations. Europeans have long explored this ordering process, seeking to explain how agents-that-emerge create clear boundaries and identities amidst interdependent interactions. For example, Maturana and Varela (1980) develop their theory of Autopoiesis to explain how biological entities understand the world around them in the presence of this constant order-creation process that defines who and what they are. Autopoiesis and autogenesis also provid unique explanations for organizational identity (Drazin & Sandelands, 1992) and growth (Csanyi & Kampis, 1985), as well as shared cognition in social settings (Maturana & Varela, 1987).

We now ask a broader question: Is there a *pattern* to these stages of emergence across multiple organizational levels? This question is a core focus of the American School of complexity.

2. The Santa Fe View: Emergence from Continuously Adapting Heterogeneous Agents

The *American School* consists largely of people associated with the Santa Fe Institute (Pines 1988; Anderson, Arrow & Pines, 1988; Cowan, Pines & Meltzer, 1994; Arthur, Durlauf & Lane, 1997). In contrast to the Europeans' focus on dramatic phase transitions at the 1st critical value, R_{C1}, that give rise to new levels of order dissipative structures within a system, American complexity scientists focus on the upper bound of criticality, R_{C2} – the 2nd critical value, originally known as the '*edge of chaos*' (Lewin, 1992/1999; Kauffman 1993). What happens at R_{C1} is better understood; what happens at R_{C2} is more obscure. As such, the American complexity literature focuses on the *intra-system processes* of emergent complexity, especially the ways that coevolution and seemingly insignificant triggering effects can generate self-organizing structures that have a consistent form or pattern.

One of the key insights from the American School is the critical role that *interdependence* plays in the emergence of order. Kauffman's work on *NK* landscapes shows how the order that emerges is dependent not on the number N of agents but on the degree of interdependence K of the agents in the system. Management scholars have gained wonderful insights from this work. For example, looking at the explorative process of invention, Fleming and Sorenson (2001: 1025) show that the value and quality of inventions are dependent on the degree of interaction between their components, not on the number of components that an innovator is hoping to combine.

Interdependence among agents creates a kind of 'basin of attraction' for emergent order in 'edge cities' (Krugman, 1996), and it is at the core of Marion's (1999) useful framework of 'complex attractors' in organizations. In a different way, Holland's (1995, 1998) innovations around genetic algorithms are based on the idea that agents become increasingly interdependent as they interact and exchange knowledge and resources with each other. Likewise, studies of interdependent interactions across industries show how the evolution of organizations and institutions is a kind of 'self-organizing' process (Malerba, Nelson, Orsenigo & Winter, 1999)

An advanced stream of this research shows how computational agents with heterogeneous levels of knowledge and other traits, will self-organize multiple nested-levels of order as they follow a small number of 'motivating' rules. For example, Carley's ORGAHEAD model (1990) consists of knowledge workers in emergent groups that create their own 'rules' of interaction derived from strategies that emerge from an executive team – which itself generates a culture that influences the workers, groups and organization as a whole. Other multi-level emergent models have been designed, including early ones by Epstein and Axtell (1996) and Paul, Butler, Pearlson & Whinston (1996).

3. The Econophysics View: Scale-free Theory

An important implication of the American approach is the idea that emergent organizing, when extended to multiple levels within a system, often takes on certain patterns that can be explained using a single rule or function. Researchers in this tradition use these simple functions – so-called 'scale-free' theories that are identified by power laws – to make scalable connections across multiple levels of dynamic systems. Making these connections is tantamount to developing a coherent theory of emergence that is scale-free – i.e., that utilizes the same simple explanatory functions across multiple levels of organizational behaviour. For example, Brock (2000: 29, 30) expresses the importance of scaling laws to a theory of emergence as follows:

> The study of complexity considers whether these patterns [of emergence] have a property of universality about them…. [Complexity] tries to understand the forces that underlie the patterns or scaling laws that develop [as newly ordered systems emerge].

Bak (1996) provides one of the first extended treatment of this insight in his discovery of '*self-organized criticality*' – a process represented by a simple power law – in which small initial events can lead to complexity cascades of avalanche proportions. Arthur (1988, 1990) also focuses on positive feedbacks stemming from initially small instigation events; as do Casti (1994) and Brock (2000). Europeans have also been at the vanguard of this project, starting with Mandelbrot (1982). His work on '*fractal geometry*' introduced the notion of '*scalability*' – in certain contexts like coastlines, clouds and cauliflowers, no matter what the scale of measurement, the phenomena appear the same.

For example, cut off a 'floret' of a cauliflower, then cut off a smaller branch, then an even smaller one. Each subcomponent (i.e. fractal) is smaller than the former yet each has the *same shape and structure.* They exhibit a '*power law effect*' because they shrink by a fixed ratio. Cauliflowers – and all examples of power laws – call for 'scale-free' explanations because the same 'theory' or causal dynamic applies to each of the different levels in turn.

Power-law effects are Pareto as opposed 'normally' (i.e., Gaussian) distributed. Pareto distributions are also known by the '80–20' rule: 80% of the outcome is expressed in only 20% of the sample, and the other 80% seem to have virtually no impact at all. For example, 80% of all phone calls are made by only 20% of all customers, and 80% of sales are made by the top 20% of salespeople. Statistically, Pareto distributions have very 'long tails', nearly infinite variance, unstable means, and unstable confidence intervals. Oppositely, Gaussian distributions have vanishing tails – allowing for limited variance and stable means – and confidence intervals that are clearly defined and narrow. The overall result is statistical significance that is very easy to demonstrate but has virtually no significance to managers – a point that reflects our overall belief in General Linear Reality (Abbott, 1988) to the exclusion (up to now) of an organization science of nonlinearity and disequilibrium (Meyer, Gaba & Colwell, 2005).

Power laws are ubiquitous in nature and society (Casti, 1994; Andriani & McKelvey, 2007, 2009). For example, cities follow a power law when ranked by population (Auerbach, 1913; Zipf, 1949; McKelvey, forthcoming). The structure of the Internet follows a power law (Albert *et al*., 1999), as does the internal structure of growing firms (Stanley *et al*., 1996). Axtell (2001) shows that U.S. firms are Pareto distributed.

Clearly, fractals – and the scale-free regularities they represent – are not idle mathematical curiosities. Power laws have been found at every level of reality (across 32 orders of magnitude): from the smallest atomic structures measured in nano-meters – 0.00000000001 meter, to the largest galactic structures we know of, measured in mega-parsecs: 1,000,000,000,000,000,000,000 meters (Baryshev & Teerikorpi, 2002). In biology, West and Brown (2004) demonstrate a power law relationship between the mass and metabolism of virtually any organism and its components – based on fractal geometry of distribution of resources – across 27 orders of magnitude (of mass). Andriani & McKelvey (2007, 2009) list ~140 kinds of power laws ranging from atoms to galaxies, DNA to species, and networks to wars. Table 1 presents a partial list from their work, focusing on social and organizational scale-free phenomena.

<<< Insert Tables 1a, 1b about here >>>

In a formal sense, a scale-free theory of management is based on the premise that a single process – a specific set of sequences, patterns, and behaviours (Lichtenstein & Plowman, 2009) – drives order creation at *every level* of specific phenomena (Kaye, 1993; Casti, 1994; West, Brown & Enquist, 1997). This new research program seeks to identify *which* organizational phenomena are scale-free, and find the simplest explanation for all the levels involved (Bak & Chen, 1991; Stanley *et al*., 1996)

As Table 1 shows, there is good reason to believe that power-law effects occur frequently in organizations and have far greater consequence than current users of statistics presume (Andriani & McKelvey, 2007). To the extent this is true, researchers ignoring power law effects risk drawing false conclusions in their articles and promulgating useless advice to managers. This because what is important to most managers are the extremes they face, not the averages.

To be fair, not all management phenomena display power law effects. In natural science, as a comparison, data points are frequently independent. Further, power laws may result from causes other than interdependence-caused fractals (Andriani & McKelvey, 2009). Interdependence, nevertheless, is a common cause of power law effects and Pareto distributions. As the world becomes increasingly interconnected because of globalization and digital technology (resulting in the Internet, email, mobile phones, etc.) the probability of Pareto distributions and fractal structures is significantly increased (Boisot & McKelvey, 2010).

4. A Synthetic Approach to Emergence

In summary, the European School of complexity explores the dynamic processes that give rise to emergent behaviour in far-from-equilibrium systems. Guided by Prigogine's theory of dissipative structures, this approach explains the order creation process within complex adaptive systems, a process that is initiated by environmentally imposed adaptive tensions on the system. In effect, this theory explains how imposing forces (i.e., adaptive tensions) drive the emergence of order creation across levels, including the creation of units, components, and structures.

In contrast, the American School of complexity explores the region within which self-organizing behaviour takes place, and the form that such behaviour takes when examined across multiple levels of organizing. Guided by research at the region of emergent complexity – at the so-called 'edge of chaos' – and self-similarity theory, it studies the pattern of order emerging across multiple levels of complex adaptive systems, a pattern that is initiated through internal system characteristics. In effect, this approach explains how intra-system characteristics and forces drive the emergence of order across systems.

The third view, from Econophysics, suggests power laws are at the core of self-organizing organization behavior. These dynamics result in fractal structures. They are explained by scale-free theories.

Drawn together, these three approaches provide a more complete and useful explanation for emergent order, particularly in its forms within and across organizations. With this new synthesis as context, we now review what complexity studies tell us about emergence in organizations.

TOWARD A FRACTAL THEORY OF ORGANIZATION

In this section we apply lessons from econophysics to organizations by updating Ashby's classic *Law of Requisite Variety* (1956). We draw out a few of the fifteen scale-free theories identified by Andriani and McKelvey (2009) to make our argument that a principal means by which organizations adapt to their external competitive environment is by understanding how various fractal dynamics associated with the emerging stages can both help and disrupt efficacious adaptation.

1. From Outside In: Building from Ashby's Law

In his classic work, *An Introduction to Cybernetics*, Ashby (1956: 131–134) says:

> When a constraint exists advantage can usually be taken of it… Every law of nature is a constraint… Science looks for laws… Constraints are exceedingly common in the world around us… A world without constraints would be totally chaotic… That something is predictable implies that there exists a constraint… Learning is worth while only when the environment shows constraint.

He also notes that order (organization) exists between two entities, *A* and *B*, only if the link is 'conditioned' by a third entity, *C* (Ashby, 1962: 255). If *C* symbolizes the 'environment', which is external to the relation between *A* and *B*, environmental constraints are what cause order (Ashby, 1956). This, then, gives rise to his famous Law of Requisite Variety: 'ONLY VARIETY CAN DESTROY VARIETY' (p. 207; his capitals). It holds that for a biological or social entity to be efficaciously adaptive, the variety of its internal order must match the variety of the environmental constraints. Since 'variety' equates to 'degrees of freedom' and the latter phrase is the signature definition of complexity (Gell-Mann, 1994), we can safely update Ashby's Law as follows:

- 'Only variety can destroy variety'.
- Only internal degrees of freedom can destroy external degrees of freedom
- Only internal complexity can destroy external complexity

- Only internal fractality can destroy external fractality.

In describing the Santa Fe Institute's Vision, Brock (2000: 29) says,

> The study of complexity…is the study of how a very complicated set of equations can generate some very simple patterns for certain parameter values. Complexity considers whether these patterns have a property of universality about them. Here we will call these patterns scaling laws.

In this view, as soon as phenomena are described as 'complex' then they also are seen as fractal, which justifies our last 'update' above, that ONLY REQUISITE INTERNAL FRACTALITY CAN DESTROY EXTERNAL FRACTALITY.

Ashby, thus identifies a key law of systemic complexity, namely that in order to remain viable, a system needs to generate the same degree of internal variety as the external variety it faces in the environment. Formally, '*R's* capacity as a regulator cannot exceed *R's* capacity as a channel of communication' (Ashby, 1956: 211). Essentially, external complexity – including 'disturbances' or uncertainty – can be managed or 'destroyed' by matching it with a similar degree of internal complexity.

The **first** lesson from Ashby is that for strategists to find emerging patterns in what appear to be chaotic environments, they need to uncover the contextual constraints. The **second** lesson is that degrees of freedom (complexity) within a firm need to match the degrees of freedom among environmental constraints. A **third**, related lesson comes from Allen (2001). Since it is impossible to know in advance which of a firm's degrees of freedom will actually be relevant to a particular environment, Allen proposes his '*Law of Excess Variety*'. A firm can't simply create internal variety to *match* the environment. It has to create *excess* variety. It follows that a pattern-finding social network within a firm has to be *more* complex than the complexity of its competitive environment.

The creation of internal variety has been described at multiple levels of management theory. The very study of cognitive schema is based on the simplified concept that in order to operate effectively in organizational or social settings our internal constructions of the world (mental models) must be representative of the complexity we experience (Boulding, 1956). When faced with phenomena that fall outside our schema we may expand our schema (increase our requisite variety) to account for those unaccountable experiences (Boulding, 1961) or restrict our perception of reality (mitigate external variety) to rationalize or simply deny the conflicting information (Staw, Sandelands & Dutton, 1981). Gell-Mann (2002) argues that one has to work toward '*effective complexity*' basis of schema formation. McKelvey and Boisot (2009) discuss ways of both reducing environmental complexity from possible to probable variety as well as, then, expanding internal complexity to cope with *probable* external complexity.

In entrepreneurial leadership settings, management scholars suggest that facing the challenges of more complex organizations requires the adoption of a more complex style of thinking, by developing for example a more 'complicated understanding' of organizational phenomena (Bartunek, Gordon & Weathersby, 1983). This view is supported by Weick & Robert's (1993) recognition that dealing with the extremely complex dynamics of landing planes on an aircraft carrier requires a mutually constructive and complicating process of 'heedful interrelating'. This approach is reflected in research that shows how complex organizational problems may sometimes be solved by greatly expanding the contextual information surrounding the problem (i.e. increasing requisite variety), through situated learning (Lave, 1991; Orlikowski, 1996) or through communities of practice (Brown & Duguid, 1991) which benefit from the accumulated knowledge of many agents.

2. Requisite Fractal Structure from Emergent Stage Dynamics

A Power-Law Explanation of Emergence Stages. Dissipative structures theory tells us when new order via phase transition will appear – such as the four 'levels' we find in the computational and narrative studies. However, that theory says virtually nothing about the form of these changes. Power law theory, in contrast, argues that each emergent level will occur much less often and is dependent on the appearance of a *prior* *stage*. Specifically, each stage will emerge an *order of magnitude* less frequently than the prior (and thus more likely) emergent stage. The key point is that each step in this hierarchy of order has a decreasing probability of occurrence; the probability of reaching early stages of emergence is always higher than the probability of reaching later stages, and so on (McKelvey & Lichtenstein, 2007).

Our synthetic view can be summarized as follows: By far the most frequent type of emergence appears as networks – McKelvey and Lichtenstein's Stage-1 emergence (2007). Some of these emergent network configurations lead to the emergence of groups and group norms – their Stage-2. In certain cases, groups differentiate to more advantageously draw in environmental resources. This results in the beginnings of hierarchy (Massie, 1965; Salthe, 1993). This Stage-3 emergence solidifies the definition of 'qualitative novelty' – an emergent property is defined as 'different in kind' from its components (Blitz, 1992; Newman, 1996). Finally, a few hierarchies grow to become larger, i.e., large enough that new kinds of more complex coordinating structures and regulation processes must emerge if adaptive capability and efficiency are to be maintained – their Stage-4 emergence.

Measuring Emergence in/of Organizations. The key question answered by a power-law based theory is, what is the relationship between emergent stages in given dynamic system? In a formal sense, what is the likelihood, for example, that a network structure will emerge out of an assemblage of agents? What is the likelihood that a group will emerge out of that set of emergent networks? And how are these two events related? We recast this question in terms of probabilities of emergence, and suggest that the probability of a specific structural level emerging is a function of the emergence of some number of precursor stages (levels).

Specifically, we hypothesize that the next stage of order emerges as a function of *its* probability times the joint probability of all prior stages emerging. For example, if the probability of each emergent level is 0.1, *the emergence of each successive level is one order of magnitude less likely than the one before.* Thus, if we assume 1,000,000 emergent networks, power law theory predicts the emergence of 100,000 groups, 10,000 hierarchies, and so on. Of course, the actual probabilities are an empirical question. Based on this logic:[4]

Proposition 1: *The likelihood that any subsequent stage will emerge is the joint probability of emergence of it times all prerequisite stages.*

A visual representation of this idea is presented in Figure 1.

<<< Insert Figure 1 about here >>>

3. Requisite Fractal Structure from Underlying Scale-free Theory

There are a number of scale-free theories we can draw upon to further solidify our notion that as further stages emerge, the organization increasingly moves toward an internal fractal structure. This requires that we apply scale-free theories (drawn from various sciences) to organizations. This analysis was recently achieved by Andriani and McKelvey (2009), who list fifteen scale-free theories can be applied to organizations. Here we mention only those that most clearly apply to the stages of emergence idea.

Hierarchical Modularity. In his classic paper on the 'architecture of complexity', Simon (1962) offers a variant to the square/cube and connection-cost laws. He focuses on '*nearly decomposable*' systems, wherein modules are designed so as to minimize the connection-cost problem. The scale-free principle causing fractal structure is the idea that at each level in an organization, agents attempt to minimize connection costs by designing toward nearly-autonomous modules. In this way the resulting structures are 'fractally' composed. Zimmerman and Hurst (1993: 336) explain this link between self-organization and fractal (self-similar) composition as follows:

> Fractal structures, then, can be thought of as the past tense or evidence of self-organizing systems. Fractals represent the discernible outcomes, or histories, that reveal the self-organizing propensities of dissipative structures.

Simon's canonical example compares two watchmakers making timepieces with 1000 parts. In the approach used by Tempus, any interruption in the process of assembling all 1000 pieces would cause the watch to fall to pieces, requiring him to reassemble it from scratch. In contrast, Hora designed the task into subassemblies of about ten elements each, each of which were put together in further sets of ten; all ten of the latter assemblies constituted the whole watch. We also have Adam Smith's 300 year old focus on division of labour. It was followed by contingency theory's discovery that differentiated subunits improved performance (Woodward, 1958; Burns & Stalker, 1961; Lawrence & Lorsch, 1967).

Following Simon's principle, and more recent research (Carneiro, 1987; Sanchez & Mahoney, 1996; Schilling, 2000; Shulman, 2004), we see that external competitors gain survival, growth, and competitive advantage by continually decomposing – i.e., self-organizing – into modular subunits. For example, the CEO has 4 division Presidents reporting; they each have four VPs; they each have 4 companies reporting, and so on. By this reasoning the most dangerous competitor firms surrounding a focal firm will be fractally structured. Many studies of competitive biological predator/prey ecosystems (we cite 19 here) show repeatedly that they have fractal structures (McMahon & Bonner, 1983; Schmidt-Nielsen, 1984; Aronson, 1992; Russell *et al*., 1992; Niklas, 1994; Tsuda, 1995; West, Brown & Enquist, 1997; Solé, Alonso, Bascompte & Manrubia. 2001; Cuddington & Yodzis, 2002; Haskell, Ritchie & Olff, 2002; Shinchi *et al.* 2002; Xiao, Cheng &Tang, 2002; Hoddle, 2003; Liu & Chen, 2003; Ferguson, 2004; Laidre *et al*., 2004; Phillips *et al*., 2004; Tremblay, Roberts & Costa, 2007; Sims *et al*., 2008).

Square/Cube Law. Dating back to Galileo (~1638), the square/cube law is the oldest scale-free theory. In organisms, surfaces absorbing energy grow by the square, but the organism grows by the cube, resulting in an imbalance. In cauliflowers, the fractal structure is very visible – the structure, function, and causal dynamics are the same for the whole and continuing down from the largest to smallest florets. The fractal structure emerges to bring surface/volume back into balance.

Haire (1959) first applied it successfully to four firms. Levy and Donhowe (1962) confirm his findings in 62 firms in eight industries. Stephan (1983) derives his application of the square-cube law to firms via 'time minimization' theory. He defines organizational effectiveness in terms of time-minimization. Employees dealing with people outside the firm are 'surface' employees – they bring in the resources from the environment. 'Volume' employees are those inside who produce and coordinate. The square-cube law reflects the most efficient ratio. In a different context, Carneiro (1987) applies the law to explain the upper bound on the size of villages. The law limits their size unless they develop what he terms 'structural complexity', where complexity grows at 2/3 power of a village's population. Only by doing this do villages avoid splitting in two. Whereas Stephan's theory is in terms of a specific variable, time-minimization, Carneiro's theory is more general, saying simply that social entities can increase in size only by building in structural complexity. In his data, for example, 100-person villages had 10 'complexity traits' where as 1000-person villages had four to five times as many.

Connection-Cost Law.[5] While the square/cube law responds to the problem of creating more subunits so as to keep the surface/volume ratio constant as the system grows, the connection-cost law operates in reverse. Supposing modularity grows by the square, connectivity could increase by $n(n-1)/2$, producing an imbalance between the gains from modularity vs. the cost of maintaining connectivity. Consequently organisms and organizations form fewer cells or modules so as to reduce the cost of connectivity. Here the fractal structure emerges so as to keep connection costs under control.

Organisms and organizations usually grow to copy with or take advantage of a demanding environment – resources, constraints, competitors; they gain economies of scale or even increasing returns to scale (Arthur, 1988). An entity can do this by growing in size, i.e., doubling, and then doubling again, and so on. While divisions increase by the square, however, their pair-wise connections, c, increase by the formula: $n(n-1)/2$, where n = # of units; thus if $n = 2, 4, 8, 16, 32, 64$ then $c = 1, 6, 28, 120, 496, 4032$. A module has to accomplish two things: (1) Use energy in coping with its environment – it has to move, find resources, process what it intakes, accomplish various survival tasks (Kauffman, 1993), etc.; and (2) Use energy in maintaining and using the pair-wise communications with other modules.

Because of the $n|c$ ratio, however, at some point the amount of energy going into communication significantly detracts from the module's ability to cope successfully with its environment. At this point the system recombines modules and divides into two macro units specialized in different tasks, bringing the over-communication problem back under control. The underlying cause of the power law is the basic $n|c$ relationship and the need to keep dividing to better cope with the environment but keep communication costs under control. Note that our suggested growth of n is exponential, as is the growth of c. In real entities, the growth of the communication network could grow because of interactions, positive feedback, and contextually-caused bursts, leading to a power law signature rather than exponential or lognormal.

Self-organized Criticality (SOC). Under constant tension of some kind (gravity, ecological balance, delivery of oxygen), some systems reach a critical state where they maintain stasis by preservative behaviours – such as Bak's famous sandpile avalanches, as well as forest fires, changing heartbeat rates, growth rates of firms, etc. – which vary in size of effect according to a power law (Bak, Tang & Wiesenfeld, 1987; Drossel & Schwabl, 1992; Bak, 1996). Here the fractal is dynamic – actions to cause change – may be very small or of avalanche proportions.

Bak (1996) applies his SOC principle to economies, arguing that individual decisions are sticky like irregular sand grains, not like marbles. The result is that even though the tension between supply and demand builds, actions to reduce it are not of equal size and regularity. Consequently economies operate at or near the critical state. This shows up in the things like the price of cotton and many other economic realities described by Mandelbrot and Hudson (2004), consumer product sales (Moss, 2002; Sornette *et al*., 2004), entrepreneurial responses and results leading to different sized firms (Stanley *et al*. 1996), and stock-market price volatilities (Zhou & Sornette, 2002, 2003, Sornette & Zhou, 2006, Jondeau, Poon & Rockinger, 2007; Masakawa, 2007, Calvet & Fisher, 2008; Du & Ning, 2008, Eom *et al*., 2008, Kumar & Deo, 2009; Sornette & Woodard, 2009; Yan, Woodard & Sornette, 2010; McKelvey & Yalamova, forthcoming; Yalamova & McKelvey, forthcoming) – all of which show power-law signatures. The parallel to sand avalanches is clear: from gravity to supply/demand; from irregular sand grains to irregular consumer and managerial decision processes and outcomes, from biological SOC to firms' and stock market SOC. The results are similar: power law shaped avalanches vs. power law shaped economic events and changes. Embedded within the broader economic outcomes are individual human decision processes and consequent organizational dynamics.

Even more relevant here, is the idea that SOC also applies to actions aimed at optimizing the square/cube ratio, modularity vs. connection costs, or moves toward or away from Simon's nearly autonomous subunits. It is easy to see that either top-down managerial efforts or more self-organized, informal, autonomous, bottom-up efforts may resolve problems via many small, irregular steps or more rare major reorganizations, as shown by Thomas, Kaminska-Labbé, and McKelvey (2005). In this case we have one kind of scale-free theory governing the operation of three others, or in other words, fractal dynamics upon fractal dynamics.

Least Effort. Word frequency is a function of ease of usage by both speaker/writer and listener/reader; this gives rise to Zipf's (power) law (1949). While his least-effort scale-free explanation is second only to the square/cube law in date or origin, and was originally applied to cities and language, it has very recently taken on a new life. Recent studies put new light on where we are most likely to find fractal design responses to external complexity and fractality.

Zipf's least-effort theory is now shown to apply only under changing circumstances. Ishikawa (2006) shows that power laws show up in firms where there is higher rate of job growth and change, but does not apply to large firms where growth is slow. Dahui, Li & Zengru, (2006) show that the distribution of firms in growth markets is a power law but in markets without growth it is not. Finally, Podobnik *et al*. (2006) find empirically – and test further with a computational model – that transition economies (e.g., Hungary, Russia, Slovenia, etc.), show the power law signature whereas stable economies do not. McKelvey (forthcoming) uses power laws to show how broken is the UK economy. From these new discoveries we conclude that the *least effort* scale-free theory applies, especially, to organizations, industries, and economies that are growing or are in transition.

Preferential Attachment. Given newly arriving agents into a system, larger nodes with an enhanced propensity to attract agents will become disproportionately even larger, resulting in the power law signature (Yule, 1925; Barabási, 2002). This is otherwise known as the 'rich get richer' dynamic. If per chance the fractal structure of a system were seemingly to stabilize, preferential attachment is a scale-free dynamic that serves to disrupt all of the foregoing fractal structures.

This positive feedback process is most evident in the long demonstrated need for antitrust laws. The robber barons of the 19th century were notorious for using the resources they controlled so as to gain even more. It shows up in Arthur's (1994) focus on increasing returns – firms making profits can invest in things that make even more profits – Microsoft is the best modern example. It appears in the development of the biotech industry (Powell *et al*., 2005). It shows up in the growth of airport hubs – larger hubs attract even more flights (Barrat, Barthélemy & Vespignani, 2004; Guimerà & Amaral, 2004). Marketing and sales via the Internet is very much a positive feedback process (Anderson, 2006, pp. 15–17). As nodes change in relative size, the fractal balancing process begins, whether square-cube or modules vs. connection costs. A modern example here are the various dynamics associated with the growth of Wal-Mart, such as the merger of Target and Sears and all the dynamics stemming from that.

Adaptive Tension. As we described earlier, exogenous energy impositions tipping over the 1st critical value, R_{C1}, cause emergent dissipative structures (Prigogine, 1955; Stauffer, 1985; Nicolis & Prigogine, 1989; Kauffman 1993). These are new interaction groupings having some probability of showing a power law signature and fractal structure (Mantegna & Stanley, 2000; Sornette, 2006; Newman, 2005). Tension effects in general have the same SOC effect as gravity imposes on Bak's sandpiles.

Forcing adaptive tension above the 1st critical value instigates phase transitions. Jack Welch – *Fortune* magazine's 'Manager of the Century' – set the phase transition in motion at GE with his famous rule of 'Be #1 or #2 or [else]' (Tichy & Sherman, 1994: 108). Kotter does it by 'pushing up the urgency level' (1996: 42). Collins forces the phase transition with his chapter title: 'CONFRONT THE BRUTAL FACTS' (2001: 65). 3M does it by wanting 20% new products every five years. This adaptive tension imposed by CEOs, from *inside*, sets positive feedback in motion, resulting in our stages of emergence – networks, groups, hierarchy, and then causal complexity (Lichtenstein, 2010). Of course, similar levels of *externally imposed* tension occur when new technologies, new markets, new competitors, or new political regimes appear.

Contagion Bursts. Often, viruses are spread exponentially – each person coughs upon two others and the network expands geometrically by the square. But, changing *rates* of contagious flow of viruses, bacteria, stories, and metaphors, because of changing *settings* such as almost empty or very crowded rooms and airplanes, result in bursts of contagion or spreading via increased interactions; these bursts result in the power-law signature (Taylor, 1984; Agar, 2005)

Baskin (2005) talks about feedback loops that occasionally spiral. In his view, a story is a simplification of a complex reality that spreads more easily or quickly. If the story confirms peoples' experience it is reinforced and then spreads more rapidly. In an organization, if people tell their stories, ideas, etc. in meetings, as opposed to one-on-one conversations, and others also spread the story in groups, where story-telling-and-listening bursts can result that lead to the power law signature. A good story, thus, is like a virus that mutates from animal to human and becomes airborne and highly contagious. Given that contagious stories can be told to groups and even larger audiences, they can spread very rapidly. These, then, may become agents for reshaping the dynamics of an organization, changing the preferential attachment dynamics, size of modules, levels of connections, and so on, such that the SOC process starts up to rebalance the fractal structure.

We have taken some effort to present a variety of scale-free theories, all of which apply to organizations. They not only apply one by one, but also in combination. The SOC fractal dynamic emerges as other fractal imbalances need to be rebalanced. While some fractals are designed to foster efficacious adaptation, other fractals are disruptive, thereby keeping the SOC dynamic continually operative. Our stage fractals operate over time, showing emergence from agents to complex hierarchies. From this we see structural fractals as we work up from the bottom to top of organizations. From our *Law of Requisite Fractality* – based on our updating of Ashby's *Law of Requisite Variety* – we can formulate three Propositions calling for further research to confirm findings from econophysics (Stanley et al., 1996; Mantegna & Stanley, 2000; Axtell, 2001; Newman, 2005).

> ***Proposition 2:*** *The external complexity surrounding organizations is essentially fractal in both structure and dynamics.*
>
> ***Proposition 3:*** *The Law of Requisite Fractality thus applies, such that we expect to see requisite fractality inside organizations that have completed efficacious adaptive responses to their surrounding competitive context.*
>
> ***Proposition 4:*** *The number of emergent, fractal, internal structures surviving in each subsequent stage diminishes by a probability that appears as a power law, such that the internal structure and fractal dynamics mirror Stanley et al. and Axtell's population power-law findings across the population of U.S. manufacturing firms and presumed constituent industry fractals.*

By way of some preliminary evidence in support of Proposition 2, we did a power law analysis of recent data on the software ecosystem surrounding Microsoft – shown in Table 2. As one can see, it appears as a Pareto rank/frequency distribution.[6] That it really is a Pareto distribution is indicated in Figure 2 where we plot the numbers in a double-log graph, thereby showing a straight-line power law distribution. Except for the five largest firms, the Figure shows a perfect power law distribution. This indicates that the ecosystem surrounding Microsoft is indeed fractal.

<<< Insert Table 2 & Figure 2 about here >>>

One significant implication becomes apparent when we go beyond our initial, restrictive set of four stages, and focus more broadly on any set of hierarchically nested systems in a firm. For example, one might apply power-law theory to the emergence of a new corporate venture by proposing a series of progressive stages, each being contingent prior ones. A good example is provided by Brush, Green, and Hart (2001), who show how the viability of a corporate venture depends on a build-up of increasingly complex resource combinations, from generic resources to capabilities to core competencies to strategic assets to unique advantage. According to our theory, the more consistently (across levels) the 'resource combination' approach is applied, the more likely the venture will emerge successfully. Similar claims could be made and empirically tested for new product development, alliance formation, and industry emergence.[7]

CONCLUSION

In his introductory essay in the Santa Fe Institute's 'founding anthology' (Pines, 1988), Nobel Laureate Murray Gell-Mann (1988) set the stage for some 31 disciplines coming together to focus on '*emergence*' and '*deep simplicity*'. More recently (2002), he translates 'deep simplicity' into *scalability*, and then elevates scalability to a scientific status equal to the traditional scientific focus on conservation of energy, law-like equations, and explanation via reductionism. So, based on this we now have two 'regularities' – lawlike reductionist and scalable across levels – deserving the attention of scientific theorists and researchers.

Perhaps the three most far-reaching discoveries from the American School are: (1) the value of *computational agent-based experiments* for studying emergence; (2) the widespread existence of *power law effects* characterizing emergent structures; and (3) *scale-free theory* wherein seeming complexity reduces to simplicity (Casti, 1994; Brock, 2000; Gell-Mann, 2002). While the first of these discoveries has infused into organization and management research, the last two remain largely unexplored.[8]

With the goal of developing a power-law theory for management, (McKelvey & Lichtenstein, 2007) define emergence as a multi-dimensional construct, and search the computational modelling literature to see what types or levels of organizational emergence have been created through the technology of computational experiments. They also find that true bottom-up emergence generates a very large number of emergent networks, a much smaller number of emergent groups and hierarchies, and few increasingly intricate emergent causal structures. Using European dissipative structures theory, we explain, here, what gives rise to these ‘stages of emergence’. Using American complexity theory, we propose that these stages have a power-law relationship with each other. We then expand our analysis to consider the similarity of drivers *across* stages, and then present a new *Law of Requisite Fractality* applied to organizations. Finally we signify several organizational implications arising from our requisite fractality theory in the form of Propositions.

Though we cite 19 biological research articles/books showing evidence of fractal ecological systems and, thus, evidence of requisite fractality in biology, this is a largely un-researched subject in organization science. We show the software ecosystem to be fractal; Axtell (2001) shows all U.S. firms to be fractal; Ishikawa (2006) shows that some SIC 2-digit industry groupings are fractal; Stanley *et al*. (1996) offer some evidence that the internal structure and growth and decline of firms is fractal; Glaser (2009) shows that the market capitalization of firms in various industries from 1930 to 2008 is power-law distributed, and Chou and Keane (2009) show power-law distributions for four Internet industries; but on balance this is pretty sketchy evidence. Our propositions specifically, and requisite fractality in general, are surely in need of further research.

Overall, our greatest potential contribution is to provide a more explicit complexity theory of emergence. More than reviewing the science of complexity, we claim to have developed new theory through our explanation for *how* and *why* emergence happens, in conjunction with a description of *what* actually emerges within and across ontological levels of organizing (Whetten, 1989). The relevance of such a theory is clear, given the critical importance of understanding emergence in this age of intangible assets, a digitized knowledge-based economy, globalization, the sustainability imperative and the increasing impact of emerging ventures and emerging markets. In sum, our formulation of a requisite-fractality complexity theory of emergence can provide a new foundation for management scholars researching emergence across many levels, as well as a powerful set of conceptual tools for improving the quality of management in 21st century organizations.

END NOTES:

[1] Steven Hawking, January 2000; quoted in Sanders and McCabe, 2003: 5.

[2] These admittedly fuzzy sets make an important distinction – it is analytically useful to show how they are historically separate so as to better understand the importance of, then, integrating them, a process that is currently underway. Two exceptions are worth noting: One of Prigogine's colleagues, Allen (1975, 1988, 1993), writes more in the American coevolution and computational modeling tradition, while Santa Fe scholars Kelso, Ding & Schöner (1992) make the best statement of the European school's perspective (McKelvey 2004) – though we hasten to note that Kelso is a student of, and coauthor with, Haken.

[3] 'Agent' is a general term used to designate semi-autonomous entities (i.e. 'parts' of systems), such entities as atoms, molecules, biomolecules, organelles, organs, organisms, species, processes, people, groups, firms, industries, and so on. In organizations, agents may include structures, departments, sub-units, units, divisions, etc.

[4] Our logic here is the same as Kolmogorov's (1941) 'breakage theory', which Montroll and Badger (1974) built from for their theory of wealth creation (their eight criteria for becoming wealthy) – which are multiplicative and result in a power-law formation. This is to say that there is some probability that networks will interact so as to produce (with a 0.1 probability in this example) the next stage networks.

[5] The idea for this theory came from Val Bykoski's email message of 2003 titled 'Was Zipf's law – Now: Life is about hierarchies'. It originally appears on the necsi.org email list, but is no longer accessible.

[6] The single firms at the lower right of the Table are very large firms like Nokia and Motorola (though not as large as Microsoft). At the upper left we see over 7700 of the smallest firms. The Iansiti/Levien data don't show firm size (assets or # of employees, etc.), but we know that the single firms down at the lower right of Table 2 are firms like Nokia and Motorola and we assume that the 7700 companies at the upper left are small—since there are so many of them. Even so we get a pretty good straight-line power law distribution.

[7] See also the classic work on this by Carneiro (1987). He studies how added complexity traits allow villages to avoid fission because of the so-called 'square/cube power law'. In biological organisms, when the energy demands of an organism's efforts to adapt (measured as volume) surpass its energy absorption rate (measured as surface) it undergoes fission. This is a somewhat different explanation of Simon's near decomposability – and a more real-world one – than his watchmaker story. Carneiro shows that villages overcome this law by taking advantage of more complexity traits.

[8] Exceptions are Zimmerman & Hurst (1993), Stanley *et al*. (1996), Axtell (2001), Andriani & McKelvey (2007, 2009, 2010), Boisot & McKelvey (2010), and McKelvey (forthcoming).

REFERENCES

Abbott, A. (1988): Transcending general linear reality, *Sociological Theory*, 6, 169-186.

Adler, P.; Obstfeld, D. (2006): The role of affect in creative projects and exploratory search, *Industrial and Corporate Change*, 16, 19-50.

Adams, R. N. (1988): *The Eighth Day: Social Evolution as the Self-organization of Energy*, University of Texas, Austin, TX.

Agar, M. (2005): We have met the other and were all nonlinear: Ethnography as a nonlinear dynamic system, *Complexity*, 10, 16-24.

Albert, L.; Jeong, H.; Barabási, A. L. (2000): Attack and error tolerance of complex networks, *Nature*, 406, 378-382.

Allen, P. M. (1975): Darwinian evolution and a predator-prey ecology, *Bulletin of Mathematics and Biology*, 37, 389.

Allen, P. M. (1988): Evolution: Why the whole is greater than the sum of its parts, in Wolff, W.; Soeder, C.-J.; Drepper, F. R. (eds.): *Ecodynamics*, Springer-Verlag, Berlin, 2-30.

Allen, P. M. (1993): Evolution: Persistent ignorance from continual learning, in Day, R. H.; Chen, P. (eds.): *Nonlinear Dynamics & Evolutionary Economics*, Oxford University Press, Oxford, UK, 101-112.

Allen P. M. (1994): Evolutionary complex systems: Models of technology change, in Leydesdorff, L.; van den Besselaar, P. (eds.): *Chaos and Economic Theory*, Pinter, London.

Allen, P. M. (2001): A complex systems approach to learning, adaptive networks, *International Journal of Innovation Management*, 5, 149-180.

Anderson, C. (2006): *The Long Tail*, Random House Business Books, London.

Anderson, P. (1999): Complexity theory and organization science, *Organization Science*, 10, 216-232.

Anderson, P. W.; Arrow, K. J.; Pines, D. (eds.) (1988): *The Economy as an Evolving Complex System*, Proceedings of the Santa Fe Institute, Vol. V, Addison-Wesley, Reading, MA.

Anderson, P.; Meyer, A.; Eisenhardt, K.; Carley, K.; Pettigrew, A. (1999): Introduction to the special issue: Applications of complexity theory to organization science, *Organization Science*, 10, 233-236.

Andriani, P.; McKelvey, B. (2007): Beyond Gaussian averages: Redirecting organization science toward extreme events and power laws, *Journal of International Business Studies*, 38, 1212-1230.

Andriani, P.; McKelvey, B. (2009): From Gaussian to Paretian Thinking: Causes and Implications of Power Laws in Organizations. *Organization Science*, 20(6): 1053-1071.

Andriani, P.; McKelvey, B. (2010): Using scale-free theory from complexity science to better manage risk, *Risk Management, An International Journal*, 12(1), 54-82.

Aronson, R. B. (1992): Biology of a scale-independent predator–prey interaction, *Marine Ecology Progress Series*, 89, 1-13.

Arthur, W. B. (1988): Self-reinforcing mechanisms in economics, in Anderson, P.; Arrow, K. J.; Pines, D. (eds.): *The Economy as an Evolving Complex System*, Addison-Wesley, Reading, MA, 9-31.

Arthur, W. B. (1990): Positive feedback in the economy, *Scientific American*, 262, 92-99.

Arthur, W. B. (1994): *Increasing Returns and Path Dependence in the Economy*, University of Michigan Press, Ann Arbor, MI.

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

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

Ashby, W. R. (1962): Principles of the self-organizing system, in Foerster, H. von; Zopf, G. W. (eds.): *Principles of Self-Organization*, Pergamon, New York, 255-278.

Ashmos, D.; Huber, G. (1987): The system paradigm in organization theory: Correcting the record and suggesting the future, *Academy of Management Review*, 12, 607-621.

Auerbach, F. (1913): Das Gesetz der Bevolkerungskoncentration, *Petermanns Geographische Mitteilungen*, 59(1), 74-76.

Axelrod, R.; Bennett, D. S. (1993): A landscape theory of aggregation, *British Journal of Political Science*, 23, 211-233.

Axtell, R. L. (2001): Zipf distribution of U.S. firm sizes, *Science,* 293, 1818-1820.

Bak, P. (1996): *How Nature Works: The Science of Self-organized Criticality*, Copernicus, New York.

Bak, P.; Chen, K. (1991): Self-organized criticality, *Scientific American*, 264, 46-53.

Bak, P.; Tang, C.; Wiesenfeld, K. (1987): Self-organized criticality: An explanation of $1/f$ noise, *Physical Review Letters*, 59, 381-384.

Barabási, A.-L. (2002): *Linked: The New Science of Networks*, Perseus Publishing, Cambridge, MA.

Barrat, A.; Barthélemy, M.; Vespignani, A. (2004): Weighted evolving networks: Coupling topology and weight dynamics, *Physical Review Letters*, 92, 228701:1-4.

Bartunek, J., Gordon, J. and Weathersby, R. (1983): Developing 'complicated' understanding in administrators, *Academy of Management Review*, 8(2), 273-284.

Baryshev, Y.; Teerikorpi, P. (2002): *Discovery of Cosmic Fractals*, World Scientific, Hackensack, NJ.

Baskin, K. (2005): Complexity, stories and knowing, *Emergence: Complexity & Organisation*, 7, 32-40.

Bateson, G. (1972): *Steps to an Ecology of Mind*, Ballantine Books, New York.

Bertalanffy, L. von (1956): General system theory, *General Systems*, 1, 1-10.

Bertalanffy, L. von (1968): *General System Theory: Foundations, Development, Applications*, Braziller, New York.

Binks, M.; Vale, P. (1990): *Entrepreneurship and Economic Change*, McGraw-Hill, London.

Blitz, D. (1992): *Emergent Evolution: Qualitative Novelty and the Levels of Reality*, Kluwer Academic, Boston, MA.

Boisot, M.; McKelvey, B. (2010): Integrating modernist and postmodernist perspectives on organizations: A complexity science bridge. *Academy of Management Review*, 35(July).

Boulding, K. E. (1956): General systems theory – the skeleton of science, *Management Science*, 2, 197-208.

Boulding, K. E. (1988): *The World as a Total System*, Sage, Thousand Oaks, CA.

Boulding, K. E. (1961):*The Image*. Ann Arbor Paperbooks, Ann Arbor, MI.

Brock, W. A. (2000): Some Santa Fe scenery, in Colander, D. (ed.): *The Complexity Vision and the Teaching of Economics*, Edward Elgar, Cheltenham, UK, 29-49.

Brown, J. S.; Duguid, P. (1991): Organizational learning and communities-of-practice: Toward a unified view of working, learning, and innovation, *Organization Science*, 2(1), 40-57.

Brown, S. L.; Eisenhardt, K. M. (1997): The art of continuous change: Linking complexity theory and time-based evolution in relentlessly shifting organizations, *Administrative Science Quarterly*, 42, 1-34.

Brush, C.; Greene, P.; Hart, M. (2001): From initial idea to unique advantage: The entrepreneurial challenge of constructing a resource base, *Academy of Management Executive*, 15, 64-78.

Burns, T.; Stalker, G. M. (1961): *The Management of Innovation*, Tavistock, London.

Calvet, L. E.; Fisher, A. J. (2008): *Multifractal Volatility: Theory, Forecasting, and Pricing*. Academic Press: Burlington, MA.

Carley, K. M. (1990): Group stability: A socio-cognitive approach, in Lawler, B. M. E.; Ridgeway, C.; Walker, H. (eds.): *Advances in Group Processes*, Vol. 7, J.A.I Press, Stamford, CT, 1-44.

Carley, K. M. (1999): On the evolution of social and organizational networks, in Andrews, S. B.; Knoke, D. (eds.): *Research in the Sociology of Organizations*, Vol. 16, JAI Press, Stamford, CT, 3-30.

Carley, K. M.; Svoboda, D. M. (1996): Modeling organizational adaptation as a simulated annealing process, *Sociological Methods and Research*, 25, 138-68.

Carneiro, R. L.(1987): The evolution of complexity in human societies and its mathematical expression, *International Journal of Comparative Sociology*, 28, 111-128.

Casti, J. L. (1994): *Complexification: Explaining a Paradoxical World through the Science of Surprise*, HarperPerennial, New York.

Chaisson, E. J. (2001): *Cosmic Evolution: The Rise of Complexity in Nature*, Harvard University Press, Cambridge, MA.

Cheng, Y.; Van de Ven, A. (1996): The innovation journey: Order out of chaos? *Organization Science*, 6, 593-614.

Chiles, T.; Meyer, A.; Hench, T. (2004): Organizational emergence: The origin and transformation of Branson, Missouri's musical theatres, *Organization Science*, 15, 499-520.

Chou, L.; Keane, C. (2009): How the Internet works: Inspired by Per Bak. Working paper, UCLAAnderson School of Management, Los Angeles, CA.

Cohen, M. (1999): Commentary on the organization science special issue on complexity, *Organization Science*, 10, 373-376.

Colbert, B. (2004): The complex resource-based view: Implications for theory and practice in strategic human resource management, *Academy of Management Review*, 29, 341-358.

Collins, J. (2001): *Good to Great: Why Some Companies Make the Leap…and Others Don't*, HarperBusiness, New York.

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

Crutchfield, J. (1994): Is anything ever new? Considering emergence, in Cowan, G.; Pines, D.; Meltzer, D. (eds.): *Complexity: Metaphors, Models, and Realty*, Addison-Wesley, Reading, MA, 515-537.

Csanyi, V.; Kampis, G. (1985): Autogenesis: Evolution of replicative systems, *Journal of Theoretical Biology*, 114, 303-321.

Cuddington, K.; Yodzis, P. (2002): Predator-prey dynamics and movement in fractal environments, *American Naturalist*, 160(1), 119-134.

Dahui, W.; Li, Z.; Zengru, D. (2006): Bipartite produce-consumer networks and the size distribution of firms, *Physica A*, 363, 359-366.

Darwin, C. (1859/1964): *On the Origin of Species by Means of Natural Selection*, Murray, London, [a Facsimile of the 1st ed. with an Introduction by E. Mayr (Harvard University Press, Cambridge, MA)].

De Vany, A. (2004): *Hollywood economics: How extreme uncertainty shapes the film industry*, Routledge, New York.

Dosi, G.; Fagiolo, G. (1998): Exploring the unknown. On entrepreneurship, coordination and innovation-driven growth. Lesourne, J.; Orléan, A. (eds.): *Advances in self-organization and evolutionary economics*, Economica, London, 308-352.

Drazin, R.; Sandelands, L. (1992): Autogenesis: A perspective on the process of organizing, *Organizational Science*, 3, 230-249.

Du, G.; Ning, X. (2008): Multifractal Properties of Chinese Stock Market in Shanghai. *Physica A*, 387, 261-260.

Dyke, C. (1988): Cities as dissipative structures, in Weber, B. H.; Depew, D. J.; Smith, J. D. (eds.): *Entropy, Information and Evolution: New Perspectives on Physical and Biological Evolution*, M.I.T. Press, Cambridge, MA, 355-367.

Eldredge, N.; Gould, S. J. (1972): Punctuated equilibrium: An alternative to phyletic gradualism, in Schopf, T. J. M. (ed.): *Models in Paleobiology*, Freeman, Cooper, San Francisco, 82-115.

Eom, C., Choi, S., Oh, G. & Jung, W.-S. (2008): Hurst exponent and prediction based on weak-form efficient market hypothesis of stock markets. *Physica A*, 387, 4630-4636.

Epstein, J. M.; Axtell, R. (1996): *Growing Artificial Societies: Social Science from the Bottom Up*, MIT Press, Cambridge, MA.

Ferguson, S. H. (2004): Influence of edge on predator-prey distribution and abundance, *Acta Oecologica*, 25, 111-117.

Fisher, R. A. (1930): *The Genetical Theory of Natural Selection*, Clarendon, Oxford, UK.

Fleming, L.; Sorenson, O. (2001): Technology as a complex adaptive system, *Research Policy*, 30, 1019-1039.

Foster, J. (2000): Competitive selection, self-organization and Joseph A. Schumpeter, *Journal of Evolutionary Economics*, 10, 311-328.

Frederick, W. (1998): Creatures, corporations, communities, chaos and complexity, *Business and Society*, 37, 358-389.

Gartner, W.; (1985): A conceptual framework for describing the phenomonon of new venture creation, *Academy of Management Review*, 10, 696-706.

Gartner, W.; Bird, B.; Starr, J. (1992): Acting as if: Differentiating entrepreneurial from organizational behavior, *Entrepreneurship Theory and Practice*, 16 (3), 13-30.

Gavetti, G.; Levinthal, D. A. (2000): Looking forward and looking backward: Cognitive and experiential search, *Administrative Science Quarterly*, 45, 113-137.

Gell-Mann, M. (1988): The concept of the institute, in Pines, D. (ed.): *Emerging Syntheses in Science*, Proceedings of the Founding Workshops of the Santa Fe Institute, Vol. I, Addison-Wesley, Redwood City, CA, 1-15.

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

Gell-Mann, M. (2002): What is complexity? In Curzio, A. Q.; Fortis, M. (eds.): *Complexity and Industrial Clusters,* Physica-Verlag, Heidelberg, Germany, 13-24.

Gettling, A. and Brausch, O. (2003): Cellular flow patterns and their evolution scenarios in three-dimensional Rayleigh-Benard convection, *Physical Review E*, 67, 046313-046317.

Glaser, P. (2009): Fitness and inequality in an increasing returns world: Applying the tools of complexity economics to study the changing distribution of US stock market capitalizations from 1930 to 2008. Working paper, UCLAAnderson School of Management, Los Angeles, CA.

Goldstein, J. (1986): A far-from-equilibrium systems approach to resistance to change, *Organizational Dynamics*, 15, 5-20.

Guimerà, R.; Amaral, L. A. N. (2004): Modeling the world-wide airport network, *European Physical Journal B*, 38, 381-385.

Haire, M. (1959): Biological models and empirical histories of the growth of organizations, in Haire, M. (ed.): *Modern Organization Theory*, Wiley, New York, 272-306.

Halal, W. E.; Taylor, K. B. (1999): *21st Century Economics: Perspectives of Socioeconomics for a Changing World*, Macmillan, New York.

Haskell, J. H.; Ritchie, M. E.; Olff, H. (2002): Fractal geometry predicts varying body size scaling relationships for mammal and bird home ranges, *Nature* (letters), 418, 527-530.

Hoddle, M. S. (2003): The effect of prey species and environmental complexity on the functional response of *Franklinothrips orizabensis*: A test of the fractal foraging model, *Ecological Entomology*, 28(3), 309-318.

Holland, J. H. (1988): The global economy as an adaptive system, in Anderson, P. W.; Arrow, K. J.; Pines, D. (eds.): *The Economy as an Evolving Complex System*, Addison-Wesley, Reading, MA, 117-124.

Holland, J. H. (1995): *Hidden Order*, Addison-Wesley, Reading, MA.

Holland, J. H. (1998): *Emergence: From Chaos to Order*, Perseus, Cambridge, MA.

Homans, G. C. (1950): *The Human Group*, Harcourt, New York.

Iansiti, M.; Levien, R. (2004): Strategy as Ecology, *Harvard Business Review*, 84(3), 68-78.

Ishikawa, A. (2006): Pareto index induced from the scale of companies, *Physica A*, 363, 367-376.

Jondeau, E., Poon, S.-H.; Rockinger, M. (2007): *Financial Modeling Under Non-Gaussian Distributions*. Springer-Verlag: London.

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

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

Kelso, J. A. S.; Ding, M.; Schöner, G. (1992): Dynamic pattern formation: A primer, in Mittenthal, J. E.; Baskin, A. B. (eds.): *Principles of Organization in Organisms*, Proceedings of the Santa Fe Institute, Vol. XIII, Addison-Wesley, Reading, MA, 397-439.

Kolmogorov, Á. N. (1941): Uher das logarithmisch Normale Verteilungsgesetz der Dimensionen der Teilchen hei Zerstuckelung, *Commits Rendus (DoLlady) de L'Academie des Sciences de l'URSS*. 31, 99-101, [cited in West, B. J.; Deering, B. (1995). *The Lure of Modern Science: Fractal Thinking*, World Scientific, Singapore].

Kotter, J. P. (1996): *Leading Change,* Harvard Business School Press, Boston, MA.

Krugman, P. (1996): *The Self-Organizing Economy*, Bradford Press, Cambridge, MA.

Kumar, S. & Deo, N. (2009): Multifractal Properties of the Indian Financial Market. *Physica A*, 388, 1593-1602.

Laidre, K. L.; Heide-Jorgensen, M. P.; Logsdon, M. L.; Hobbs, R. C.; Dietz, R.; Van Blaricom, G. R. (2004): Fractal analysis of Narwhal space use patterns, *Zoology*, 107(1), 3-11.

Lave, J.; Wenger, E. (1991): *Situated Learning: Legitimate Peripheral Participation*. Cambridge University Press, Cambridge, UK.

Lawrence, P. R.; Lorsch, J. W. (1967): *Organization and Environment*, Harvard Business School Press: Boston, MA.

Lenox, M.; Rockart, S.; Lewin, A. Y. (2006): Interdependency, competition and the distribution of firm and industry profits, *Management Science*, 52, 757-772.

Lesourne, J.; Orléan, A. (eds.). (1998): *Advances in Self-organization and Evolutionary Economics*, Economica, London.

Levinthal, D. A. (1991): Organizational adaptation and environmental selection-interrelated processes of change, *Organization Science*, 2, 140-144.

Levinthal, D. A. (1997): Adaptation on rugged landscapes, *Management Science*, 43, 934-950.

Levinthal, D.; Posen, H. E. (2007): Myopia of selection: Does organizational adaptation limit the efficacy of population selection? *Administrative Science Quarterly*, 52, 586-620.

Levinthal, D. A.; Warglien, M. (1999): Landscape design: Designing for local action in complex worlds, *Organization Science*, 10, 342-357.

Levy, S.; Donhowe, G. (1962): Explanations of a biological model of industrial organization, *Journal of Business*, 35, 335-342.

Lewes, G. H. (1877): *The Physical Basis of Mind: Being the Second Series of Problems of Life and Mind*, J. R. Osgood, Boston.

Lewin, R. (1992): *Complexity: Life at the Edge of Chaos*, University of Chicago Press, Chicago, IL, [2nd ed. published in 1999].

Lichtenstein, B. (2010): Moving far from far-from-equilibrium: Opportunity tension as the driver of emergence. *Emergence: Complexity and Organization,* 11 (4), 15-25.

Lichtenstein, B. (2000): Emergence as a process of self-organizing: New assumptions and insights from the study of nonlinear dynamic systems, *Journal of Organizational Change Management*, 13, 526-544.

Lichtenstein, B., Carter, N., Dooley, K.; Gartner, W. (2007): Complexity dynamics of nascent entrepreneurship, *Journal of Business Venturing*, 22, 236-261.

Lichtenstein, B.; Plowman, D. (2009). A complex systems leadership theory of emergence at successive organizational levels, *The Leadership Quarterly*, 20, 617-630.

Liu, X.; Chen, L. (2003): Complex dynamics of Holling type II Lotka-Volterra predator-prey system with impulsive perturbations on the predator, *Chaos, Solitons and Fractals*, 16, 311-320.

MacIntosh, R.; MacLean, D. (1999): Conditioned emergence: A dissipative structures approach to transformation, *Strategic Management Journal*, 20, 297-316.

Maguire, S.; Hardy, C.; Lawrence, T. (2004): Institutional entrepreneurship in emerging fields: HIV/AIDS treatment advocacy in Canada, *Academy of Management Journal*, 47, 657-680.

Maguire, S.; McKelvey, B. (1999): Complexity and management: Moving from fad to firm foundations, *Emergence,* 1(2), 19-61.

Maguire, S.; McKelvey, B.; Mirabeau, L.; Oztas, N. (2006): Organizational complexity science, in Clegg, S.; Hardy, C.; Lawrence, T.; Nord, W. T. (eds.): *Handbook of Organizational Studies*, Sage, Thousand Oaks, CA.

Mainzer, K. (1994): *Thinking in Complexity: The Complex Dynamics of Matter, Mind, and Mankind*, New York: Springer-Verlag, [5th ed. published in 2007].

Malerba, F., Nelson, R., Orsenigo, L.; Winter, S. (1999). 'History-friendly' models of industry evolution: The computer industry, *Industrial and Corporate Change*, 8, 3-40.

Malnight, T. (2001): Emerging structural patterns within multinational corporations: Toward process-based structures, *Academy of Management Journal*, 44, 1187-1210.

Mandelbrot, B. B. (1982): *The Fractal Geometry of Nature*, Freeman, New York.

Mandelbrot, B. B.; Hudson, R. L. (2004): *The (Mis)Behavior of Markets: A Fractal View of Risk, Ruin, and Reward*, Basic Books, New York.

Mantegna, R. N.; Stanley, H. E. (2000): *An Introduction to Econophysics: Correlations and Complexity in Finance,* Cambridge University Press, Cambridge, UK.

Marion, R. (1999): *The Edge of Organization: Chaos and Complexity Theories of Formal Social Organization,* Sage, Thousand Oaks, CA.

Maskawa, J. (2007): Stock Price Fluctuations and the Mimetic Behaviors of Traders, *Physica A*, 382, 172-178.

Massie, J. L. (1965): Management theory, in March, J. G. (ed.): *Handbook of Organizations*, Rand McNally, Chicago, Il, 387-422.

Maturana, H. R.; Varela, F. J. (1980): *Autopoiesis and Cognition*, Reidel, Dordrecht, The Netherlands.

Maturana, H. R.; Varela, F. J. (1987). *The Tree of Knowledge.* Boston, MA, Shambhala Publications.

McKelvey, B. (1997): Quasi-natural organization science, *Organization Science*, 8, 351-381.

McKelvey, B. (1999): Complexity theory in organization science: Seizing the promise or becoming a fad? *Emergence*, 1(1), 5-32.

McKelvey, B. (2004): Toward a 0th law of thermodynamics: Order-creation complexity dynamics from physics & biology to bioeconomics, *Journal of Bioeconomics*, 6, 65-96.

McKelvey, B. (2008): Emergent strategy via complexity leadership: Using complexity science & adaptive tension to build distributed intelligence, in Uhl-Bien, M.; Marion, R. (eds.): *Complexity and Leadership: Part I: Conceptual Foundations*, Information Age Publishing, Charlotte, NC, 225-268.

McKelvey, B. (forthcoming): Fixing the UK's Economy, in McGlade, J.; Strathern, M.; Richardson, K. (eds.): *Complexity in Human and Natural Systems*, Litchfield Park, AZ: ISCE Publishing.

McKelvey, B.; Boisot, M. (2009): Redefining strategic foresight: 'Fast' and 'Far' sight via complexity science, in Costanzo, L.; MacKay, B. (eds.): *Handbook of Research on Strategy and Foresight*, Edward Elgar, Cheltenham, UK, 15-47.

McKelvey, B.; Lichtenstein, B. B. (2007): Leadership in four stages of emergence, in Hazy, J. K.; Goldstein, J.; Lichtenstein, B. B. (eds.): *Complex Systems Leadership Theory*, ISCE Publishing Company, Boston, MA, 93-107.

McKelvey, B.; Yalamova, R. (forthcoming): Introduction to econophysics: Correlated trader behaviours, bubbles & crashes, scalability dynamics, power laws & scale-free theories, in Sundström, G.; Hollnagel, E. (eds.): *Governance and Control of Financial Systems: A Resilience Engineering Perspective*.

McMahon, T. A.; Bonner, J. T. (1983): *On Size and Life*, Scientific American Library, New York.

Meyer, A. D.; Gaba, V.; Colwell, K.A. (2005): Organizing far from equilibrium: Non-linear change in organizational fields, *Organization Science* 16, 456-473.

Mihata, K. (1997): The persistence of emergence, in Eve, R. A.; Horsfall, S.; Lee, M. E. (eds.): *Chaos, Complexity, and Sociology*, Sage, Thousand Oaks, CA, 30-38.

Miller, J. G. (1978): *Living Systems*, McGraw-Hill, New York.

Montroll, E. W.; Badger, W. W. (1974): *Introduction to Quantitative Aspects of Social Phenomena*. Gordon and Breach, New York.

Morel, B.; Ramanujam, R. (1999): Through the looking glass of complexity: The dynamics of organizations as adaptive and evolving systems, *Organization Science*, 10, 278-293.

Morgan, C. L. (1923): *Emergent Evolution*, Williams & Norgate, London.

Moss, S. (2002): Policy analysis from first principles, *Proceedings of the National Academy of Sciences*, 99(Suppl. 3), 7267-7274.

Newman, D. (1996): Emergence and strange attractors, *Philosophy of Science*, 63, 245-261.

Newman, M. E. J. (2005): Power laws, Pareto distributions and Zipf's law, *Contemporary Physics*, 46, 323-351.

Nicolis, G.; Prigogine, I. (1989): *Exploring Complexity*. San Francisco, CA: Freeman.

Niklas, K. J. (1994): *Plant Allometry: The Scaling of Form and Process*, University of Chicago Press, Chicago, IL.

Orlikowski, W. (1996).Improvising organizational transformation over time: A situated change perspective, *Information Systems Research*, 7, 63-92.

Paul, D. L.; Butler, J. C.; Pearlson, K. E.; Whinston, A. B. (1996): Computationally modeling organizational learning and adaptability as resource allocation: An artificial adaptive systems approach, *Computational and Mathematical Organization Theory*, 2, 301-324.

Phillips, M. L.; Clark, W. R.; Nusser, S. M.; Sovada, M. A.; Greenwood, R. J. (2004): Analysis of predator movement in prairie landscapes with contrasting grassland composition, *Journal of Mammalogy*, 85(2), 187-195.

Pines, D. (ed.). (1988): *Emerging Syntheses in Science*, Proceedings of the Santa Fe Institute, Vol. I, Addison-Wesley, Reading, MA.

Podobnik, B.; Fu, D.; Jagric, T.; Grosse, I.; Stanley, H. E. (2006): Fractionally integrated process for transition economics, *Physica A*, 362, 465-470.

Popper, S. (1926): Emergence, *Journal of Philosophy*, 23, 241-245.

Powell, W. W.; White, D. R.; Koput, K. W.; Owen-Smith, J. (2005): Network dynamics and field evolution, *American Journal of Sociology,* 110, 1132-1205

Prigogine, I. (1955): *An Introduction to Thermodynamics of Irreversible Processes*, Thomas, Springfield, IL.

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

Rivkin, J. W. (2001): Reproducing knowledge: Replication without imitation at moderate complexity, *Organization Science*, 12, 274-293.

Russell, R. W.; Hunt, G. L., Jr.; Coyle, K. O.; Cooney, R. T. (1992): Foraging in a fractal environment: Spatial patterns in a marine predator-prey system, *Landscape Ecology*, 7(3), 195-209.

Salthe, S. N. (1985): *Evolving Hierarchical System: Their Structure and Representation*, Columbia University Press, New York.

Salthe, S. N. (1993): *Development and Evolution: Complexity and Change in Biology*, Bradford/MIT Press, Cambridge, MA.

Sanchez, R.; Mahoney, J. T. (1996): Modularity, flexibility, and knowledge management in product and organization design, *Strategic Management Journal*, 17, 63-76.

Sanders, T. I.; McCabe, J. A. (2003): *The Use of Complexity Science: A Survey of Federal Departments and Agencies, Private Foundations, Universities, and Independent Education and Research Centers*, a Report of the US Department of Education. Washington Center for Complexity & Public Policy, Washington, DC.

Saviotti, P. P.; Mani, G. S. (1998): Technological evolution, self-organization, and knowledge, *Journal of High Technology Management Research*, 9, 255-270.

Schieve, W.; Allen, P. (eds.) (1982): *Self-organization and Dissipative Structures: Applications in the Physical and Social Sciences*, University of Texas Press, Austin, TX.

Schilling, M. A. (2000): Toward a general modular systems theory and its application to interfirm product modularity, *Academy of Management Review*, 25, 312-334.

Schmidt-Nielsen, K. (1984): *Scaling: Why is Animal Size so Important?* Cambridge University Press, Cambridge, UK.

Schrödinger, E. (1944): *What is Life?* Cambridge University Press, Cambridge, UK, [2nd ed. published in 1992].

Schumpeter, J. (1934): *The Theory of Economic Development*, Harvard University Press, Boston, MA.

Selznick, P. (1943): An approach to a theory of bureaucracy, *American Sociological Review*, 8, 47-48.

Shinchi, T.; Kitazoe, T.; Nishimura, H.; Tabuse, M.; Azuma, N.; Aoki, I. (2002): Fractal evaluations of fish school movements in simulations and real observations, *Artificial Life Robotics*, 6, 36-43.

Shulman, J. M. (with Stalkamp, T.T.) (2004): *Getting Bigger by Growing Smaller,* Financial Times Prentice Hall, New York.

Siggelkow, N.; Levinthal, D. A. (2005): Escaping real (non-benign) competency traps: Linking the dynamics of organizational structure to the dynamics of search, *Strategic Organization*, 3, 85-115.

Siggelkow, N; Rivkin, J. W. (2006): When exploration backfires: Unintended consequences of multi-level organizational search, *Academy of Management Journal*, 49, 779-795.

Simon, H. A. (1962): The architecture of complexity, *Proceedings of the American Philosophical Society*, 106, 467-482.

Sims, D. W. *et al*. (2008): Scaling laws of marine predator search behaviour, *Nature*, 451, 1098-1103.

Slevin, D.; Covin, J. (1997): Time, growth, complexity, and transitions: Entrepreneurial challenges for the future, *Entrepreneurship Theory and Practice,* 22(Winter), 53-68.

Smith, C.; Gemmill, G. (1991): Self-organization in small groups: A study of group effectiveness within non-equilibrium conditions, *Human Relations*, 44, 697-716.

Solé, R. V.; Alonso, D.; Bascompte, J.; Manrubia, S. C. (2001): On the fractal nature of ecological and macroevolutionary dynamics, *Fractals,* 9, 1-16.

Sornette, D. (2006): *Critical Phenomena in Natural Sciences: Chaos, Fractals, Selforganization and Disorder: Concepts and Tools* (2nd ed.). Springer-Verlag, Heidelberg, Germany.

Sornette, D.; Deschâtres, F.; Gilbert, T.; Ageon, Y. (2004): Endogenous versus exogenous shocks in complex networks, *Physics Review Letters,* 93, 228701-1-4.

Sornette, D.; Woodard, R. (2009): Financial bubbles, real estate bubbles, derivative bubbles, and the financial and economic crisis. Submitted to *Quantitative Finance*. http://arXiv.org/abs/0905.0220 (accessed Mar. 15, 2010).

Sornette, D.; Zhou, W.-X. (2006): Predictability of large future changes in major financial indices, *International Journal of Forecasting*, 22, 153-168.

Stacey, R. D. (1992): *Managing the Unknowable: Strategic Boundaries Between Order and Chaos in Organizations*, Jossey-Bass, San Francisco, CA.

Stanley, M. H. R.; Amaral, L. A. N.; Buldyrev, S. V.; Havlin, S.; Leschhorn, H.; Maass, P.; Salinger, M. A.; Stanley, H. E. (1996): Scaling behaviour in the growth of companies, *Nature* (letters), 379, 804-806.

Stauffer, D. (1985): *Introduction to Percolation Theory*, Taylor and Francis, London.

Staw, B. M.; Sandelands, L. E.; Dutton, J. E. (1981): Threat-rigidity effects in organizational behavior: A multi-level analysis, *Administrative Science Quarterly*, 26, 501-524.

Stephan, G. E. (1983): A research note on deriving the square-cube law of formal organizations from the theory of time-minimization, *Social Forces*, 61, 847-854.

Stephen, A. (1992): Emergence – A systematic view on its historical facets, in Beckermann, A.; Flohr, H.; Kim, J. (eds.): *Emergence or Reduction? Essays on the Prospects of Nonreductive Physicalism*, Walter de Gruyter, Berlin, 25-48.

Swenson, R. (1989): Emergent attractor and the law of maximum entropy production: Foundations to a theory of general evolution, *Systems Research*, 6, 187-197.

Swenson, R. (1992): Autocatakinetics, yes-autopoiesis, no: Steps toward a unified theory of evolutionary ordering, *International Journal of General Systems*, 21, 207-228.

Swenson, R. (1997): Thermodynamics and evolution, in Greenberg, G.; Haraway, M. (eds.): *Encyclopedia of Comparative Psychology*, Garland Publishers, New York, 217-218.

Taylor, L. R. (1984): Assessing and interpreting the spatial distributions of insect populations. *Annual Review of Entomology,* 29: 321-357.

Thomas, C.; Kaminska-Labbé, R.; McKelvey, B. (2005): Managing the MNC and exploitation/exploration dilemma: From static balance to irregular oscillation, in Szulanski, G.; Doz, Y.; Porac, J. (eds.): *Advances in Strategic Management: Expanding Perspectives on the Strategy Process*, Vol. 22, Elsevier, The Netherlands, 213-247.

Tichy, N. M.; Sherman, S. (1994): *Control your Destiny or Someone else Will*, HarperCollins, New York.

Tremblay, Y.; Roberts, A. J.; Costa, D. P. (2007): Fractal landscape method: An alternative approach to measuring area-restricted searching behavior, *Journal of Experimental Biology*, 210, 935-945.

Tsuda, A. (1995): Fractal distribution of an oceanic Copepod *Neocalanus cristatus* in the Subarctic Pacific, *Journal of Oceanography*, 51, 261-266.

Tushman, M. L.; Anderson, P. (1986): Technological discontinuities and organizational environments, *Administrative Science Quarterly*, 31, 439-465.

Ulrich, H.; Probst, J. B. (eds.) (1984): *Self-Organization and Management of Social Systems*, Springer-Verlag, Berlin.

Weick, K. E. (1977): Organization design: Organizations as self-designing systems, *Organizational Dynamics*, 6, 30-46.

Weick, K.; Roberts, K. (1993): Collective mind in organizations: Heedful interrelating on flight decks, *Administrative Science Quarterly*, 38, 357-381

West, G. B.; Brown, J. H. (2004): Life's universal scaling laws, *Physics Today*, 57(9), 36-42.

West, G. B.; Brown, J. H.; Enquist, B. J. (1997): A general model for the origin of allometric scaling laws in biology, *Science*, 276, 122-126.

Whetten, D. A.; (1989): What constitutes a theoretical contribution? *Academy of Management Review*, 14, 490-495.

Wicken, J. (1986): Evolutionary self-organization and entropic dissipation in biological and socioeconomic systems, *Journal of Social and Biological Structures*, 9, 261-273.

Winter, S. (1984): Schumpeterian competition in alternative technological regimes, *Journal of Economic Behavior and Organization*, 5, 287-320.

Woodward, J. (1958): *Management and Technology*, H.M.S.O., London.

Xiao, Y.; Cheng, D.; Tang, S. (2002): Dynamic complexities in predator-prey ecosystem models with age-structure for predator, *Chaos, Solitons and Fractals*, 14, 1403-1411.

Yalamova, R.; McKelvey, B. (forthcoming): Using Power Laws and the Hurst Coefficient to Identify Stock Market Trading Bubbles, in Sundström, G. Hollnagel, E. (eds.): *Governance and Control of Financial Systems: A Resilience Engineering Perspective*.

Yan, W.; Woodard, R.; Sornette, D. (2010): Diagnosis and Prediction of Tipping Points in Financial Markets: Crashes and Rebounds, *Physics Procedia*, 00, 1-17.

Yule, G. U. (1925): A mathematical theory of evolution based on the conclusions of Dr. J. C. Willis, *Philosophical Transactions of the Royal Society of London* B, 213, 21-87.

Zhou, W.-X.; Sornette, D. (2002): Generalized q-analysis of Log-periodicity: Application to Critical Ruptures, *Physical Review E*, 66(4), 129-136.

Zhou, W.-X.; Sornette, D. (2003): Non-parametric Analysis of Log-periodic Precursors to Financial Crashes, *International Journal of Modern Physics C*, 14, 1107-1126.

Zimmerman, B.; Hurst, D. (1993): Breaking the boundaries: The fractal organization, *Journal of Management Inquiry*, 2, 334-355.

Zipf, G. K. (1949): *Human Behavior and the Principle of Least Effort*, Addison-Wesley, Cambridge, MA.

Zohar, A.; Borkman, T. (1997): Emergent order and self-organization: A case study of alcoholics anonymous, *Nonprofit and Voluntary Sector Quarterly*, 26, 527-552.

Table 1a: Power Laws in the social World*

Language word usage	Distribution of wealth	Casualties in war	Global terrorism events
Social networks	Publications & citations	Deaths of languages	Changing language
Structure of the WWW	Co-authorships	Delinquency rates	Sexual networks
Size of villages	Actor networks	Aggressive behavior among boys during recess	
News website visitation decay patterns		Macroeconomics effects of zero rational agents	
Structure of Internet hardware		Number of hits received from website per day	

Table 1b: Power Laws in the Organizational World*

Firm sizes	Director interlock structure	Sales of consumer products	Internal structure of firms
Job vacancies	Supply chains	Cotton prices	Fordist hierarchical power
Salaries	Intra-firm decision events	Blockbuster drugs	Economic fluctuations
Growth rates of firms	Italian Industrial clusters	Movie profits	Entrepreneurial firms
Biotech networks	Firms in growing markets	Transition economies	Sales declines
Price movements on exchanges	Growth rate of country GDPs	Decision-making and queuing	
World trade relationships among countries			

* Drawn from Andriani and McKelvey (2007).

Table 2: Microsoft's Ecosystem

Systems Integrators	7,752	Unsegmented resellers	290
Development services companies	5,747	Media stores	238
Campus resellers	4,743	Mass merchants	220
Independent software vendors	3,817	Outbound software firms	160
Trainers	2,717	Computer superstores	51
Breadth value-added resellers	2,580	Application service provider aggregators	50
Small specialty firms	2,252	E-tailers	46
Top value-added resellers	2,156	Office superstores	13
Hosting service providers	1,379	General aggregators; Warehouse club stores	7, 7
Internet service providers	1,253	Niche specialty stores; Sub-distributors	6, 6
Business consultants	938	Applications integrators	5
Software support companies	675	Microsoft direct resellers	2
Outbound hardware firms	653	Microsoft direct outlets	1
Consumer electronics companies	467	Network equip. & service providers	1,1

From: M. Iansiti & R. Levien (2004: 71).

Figure 1: Emergence Levels in/of Organizations, and Power Law Predictions of their Frequency

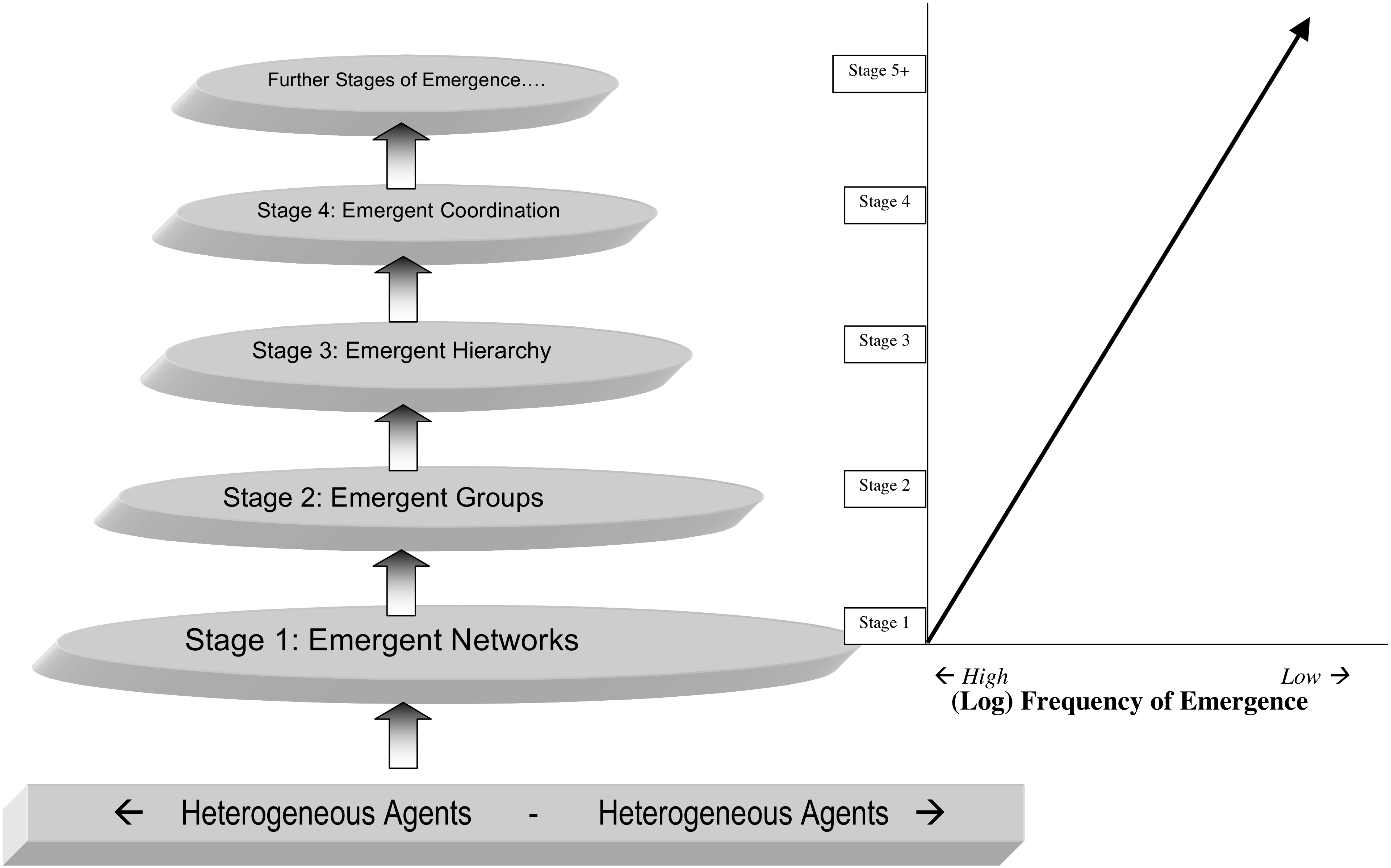

Figure 2: Ecosystem Shown as a Power Law Distribution