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## **When organisations and ecosystems interact: toward a law of requisite fractality in firms**

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**Bill McKelvey\***

Euromed Management School,  
Rue Antoine Bourdelle,  
Domaine de Luminy BP 921,  
13288 Marseille Cedex 9, France  
E-mail: mckelvey@anderson.ucla.edu  
\*Corresponding author

**Benjamin B. Lichtenstein**

Management/Marketing Department,  
University of Massachusetts,  
100 Morrissey Blvd., M5/214,  
Boston, MA 02125, USA  
E-mail: benjamin.bml@gmail.com

**Pierpaolo Andriani**

Euromed Management School,  
Rue Antoine Bourdelle,  
Domaine de Luminy BP 921,  
13288 Marseille Cedex 9, France  
E-mail: pier2paolo@gmail.com

**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-organised adaptation as explained through computational simulations, and now to its most recent focus on power laws and their basis in scale-free causes. After briefly reviewing these three approaches to complex systems, we attempt to integrate them into a broad-based model of organisational design and performance. Our model develops the law of 'requisite fractality' – an updated version of Ashby's original law for organisations in dynamic environments. Implications for organisations and managers are discussed.

**Keywords:** complexity science; dissipative structures; self-organisation; power laws; scale-free causes; organisation design; requisite fractality; Ashby's law; dynamic environments; implications.

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**Biographical notes:** Bill McKelvey is an Emeritus Research Professor of Strategic Organising, Complexity Science, and Econophysics at the UCLA Anderson School of Management. His book, *Organizational Systematics* (1982) remains the definitive treatment of organisational taxonomy and evolution. He chaired the building committee that produced the \$110,000,000 Anderson Complex. He co-edited *Variations in Organization Science* (with J. Baum, 1999), a special issue of *Emergence* (with S. Maguire, 1999), and a special issue of *Int. J. Complexity in Leadership & Management* (2013). He is Co-Editor of *SAGE Handbook of Complexity and Management* (2011). He is the Editor of Routledge Major Work: *Complexity: Critical Concepts* (2012; five-volumes, 2000 pp.). He has 70+ papers on organisational complexity since 1997.

Benyamin B. Lichtenstein is an Associate Professor of Entrepreneurship and Management at the University of Massachusetts, Boston. His research explores emergence – the coming-into-being of organisations, projects, and social entities; he is currently writing a book on the topic for Oxford University Press. His three other books and 40+ papers have used the complexity sciences to explore new venture creation, organisational change and transformation, relationality, and sustainability. He has published in journals such as *Organization Science*, *Journal of Business Venturing*, *Entrepreneurship Theory and Practice*, and *Human Relations*.

Pierpaolo Andriani is an Associate Professor of Complexity and Innovation Management at Euromed Management in Marseille, France. He received his PhD from Durham University, UK. His research interests are focused on the impact of complexity theory on innovation, organisational theory and entrepreneurship. His research has been published in journals such as *Organization Science*, *Journal of International Business Studies* and *Long Range Planning*.

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‘I think the next century will be the century of complexity’, *Stephen Hawking*<sup>1</sup>

## 1 Introduction

Complexity science has been heralded as new paradigm in management – a powerful set of methods for explaining non-linear, emergent behaviour in organisations (Stacey, 1992; Brown and Eisenhardt, 1997; McKelvey, 1997; Anderson et al., 1999; Maguire et al., 2006). Many specific theoretical notions of complexity science have already been tested using computational experiments, including key aspects of learning (Carley and Svoboda, 1996), organisation design (Levinthal and Warglien, 1999), network structuring (Carley, 1999; Lenox et al., 2006), organisational evolution (Allen, 1975, 1988, 1994; Levinthal, 1997; Morel and Ramanujam, 1999; Levinthal and Posen, 2007), strategic human resource management (Colbert, 2004) and strategic adaptation (Gavetti and Levinthal, 2000; Rivkin, 2001; Siggelkow and Levinthal, 2005; Siggelkow and 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-organisation, 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 legitimisation for loose thinking about non-linearities, 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 organisations, and as a result, the community has not learned as much from complexity science as it should (Maguire and 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 and 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 et al., 1988; Arthur, 1988; Holland, 1988; Kauffman, 1993; Gell-Mann, 1994; Cowan et al., 1994), explores the *form* and inter-system *processes* associated with emergent order: agent heterogeneity, agent interactions, co-evolution, 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.<sup>2</sup>

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 digitised knowledge-based economy, globalisation, the sustainability imperative, and the increased importance of emerging organisations and emerging markets (Sanders and McCabe, 2003; Maguire et al., 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 and Taylor, 1999). *Complexity science is the study of order creation* – the only science dedicated to explaining how new order emerges through self-organisation 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 organisations is foundationally important.

One place where the international community of complexity researchers *has* come together is on discoveries pertaining to Pareto distributions, power laws (PLs), and scale-free theory – best signified by the references in Andriani and McKelvey (2007, 2009) and McKelvey and Salmador Sanchez (2011). Our goal here is to build on earlier research (McKelvey and Lichtenstein, 2007; Lichtenstein and McKelvey, 2012) in which we explain the ‘bottom-up emergence’ of organisations 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 organisations. In this article we expand this idea by considering the fractal structures which emerge across these and further levels, as organisations adapt to their dynamic environments. We also build on McKelvey and Boisot’s (2009) updating of Ashby’s (1956) *Law of Requisite Variety* to develop and our proposed *Law of Requisite Fractality* and apply it to organisations.

We start by drawing on the key insights of the European School to explain the driver that initiates self-organising dynamics in economic and organisational contexts. Next, we combine the American School's early insights into the *form* of self-organised structures – and especially Bak's (1996) work on 'self-organised criticality' – with the more recent international research on PLs, 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*.

## 2 Emergence: what are we looking for?

An ever-proliferating range of meanings and operationalisations 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 organisation 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; Pepper, 1926; Stephen, 1992), *evolutionists* (Darwin, 1859; Baldwin, 1896, 1902; Morgan, 1923; Fisher, 1930; Eldredge and Gould, 1972; Kauffman, 1993; Salthe, 1993), *complexity scientists* (Prigogine, 1955; Allen, 1975; Holland, 1988; Nicolis and Prigogine, 1989; Crutchfield, 1994; Mainzer, 1994); and a wide range of *management scholars* (Selznick, 1943; Homans, 1950; Burns and Stalker, 1961; Weick, 1977; Goldstein, 1986; Stacey, 1992; McKelvey, 1997; Malnight, 2001; Chiles et al., 2004).

An initial approach, 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, p.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<sup>3</sup> 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." [Mihata, (1997), p.30].

The goal of complexity science is to characterise 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.

### *2.1 The European view: emergence as energy-induced phase transitions*

The European perspective draws from Prigogine's (1955) and Nicolis and 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-organised' 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 organisational, sociological, and economic phenomena (e.g., Weick, 1977; Schieve and Allen, 1982; Ulrich and Probst, 1984; Adams, 1988; Smith and Gemmill, 1991; De Vany, 2004; Zohar and Borkman, 1997; Dosi and Fagiolo, 1998; Lesourne and Orlean, 1998; Saviotti and Mani, 1998; Lichtenstein et al., 2007). For example, a technical or process innovation (Schumpeter, 1934; Tushman and Anderson, 1986) can set up disequilibrium between the entrepreneur and the current market; these innovations drive the self-organised emergence of new firms and new industries (Binks and Vale, 1990; Foster, 2000). Slevin and Covin (1997, p.56) describe this process by suggesting that 'successful entrepreneurial firms act as energy conversion systems'. In a broader managerial context Anderson (1999, p.222) suggests that adaptive tension may be generated by organisational 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, organisations 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 organising 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'
- b is motivated by a 'creative tension' (Fritz, 1989) to make his/her idea a reality (Adler and Obstfeld, 2006).

In literal terms this process is opportunity intention – the identification/enactment of a business opportunity with the internal motivation/passion to do what it takes to make it happen (Gartner et al., 1992).

Assuming a substantive increase in resource flow driven by opportunity tension by an entrepreneurial leader, 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, i.e., as soon as* enough resources are available (Swenson 1989, 1992, 1997). That is, in the absence of other constraints, new order will self-organise instantaneously (Getling and Brausch, 2003) in order to dissipate new 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 (von Bertalanffy, 1956, 1968; Bateson, 1972; Miller, 1978), by describing organisations as a series of nested systems, each level increasingly complex as it is generated through the interactions of its lower-level components (Ashmos and 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 organising (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 organisations. 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 provide unique explanations for organisational identity (Drazin and Sandelands, 1992) and growth (Csanyi and Kampis, 1985), as well as shared cognition in social settings (Maturana and Varela, 1987).

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

## 2.2 *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 et al., 1988; Cowan et al., 1994; Arthur et al., 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, US 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 US complexity literature focuses on the *intra-system processes* of emergent complexity, especially the ways that coevolution and seemingly insignificant triggering effects can generate self-organising 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 various insights from this work. For example, looking at the explorative process

of invention, Fleming and Sorenson (2001, p.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 organisations. In a different way, Holland’s (1995, 1998) innovations pertaining to 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 organisations and institutions is a kind of ‘self-organising’ process (Malerba et al., 1999).

An advanced stream of this research shows how computational agents with heterogeneous levels of knowledge and other traits, will self-organise multiple nested-levels of order as they follow a small number of ‘motivating’ rules. For example, Carley’s (1990) ‘ORGAHEAD’ model 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 organisation as a whole. Other multi-level emergent models have been designed, including early ones by Epstein and Axtell (1996) and Paul et al. (1996).

### 2.3 *The econophysics view: scale-free theory*

An important implication of the US approach is the idea that emergent organising, 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’ causes that are identified by PLs – to make scalable connections across multiple levels of dynamic systems. Making these connections is tantamount to developing theories of emergence that are scale-free – i.e., that utilise the same simple repeating explanatory functions across multiple levels of organisational behaviour. For example, Brock (2000, pp.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) provided one of the first extended treatments of this insight in his discovery of ‘*self-organized criticality*’ – a process represented by a simple PL – 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 (1975, 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 ‘florete’ 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 ‘*PL effect*’ because they shrink by a fixed ratio. Cauliflowers – and all examples of PLs – call for ‘scale-free’ explanations

because the same ‘theory’ or causal dynamic applies to each of the different levels in turn.

PL effects are Pareto distributed, as opposed ‘normally’ (i.e., Gaussian) distributed. Pareto distributions are also known by the ‘80–20’ rule: 80% of the outcome is generated by only 20% of the sample, whereas the other 80% have virtually no impact at all. For example, 80% of all phone calls are made by only 20% of all phone callers, 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 scholars’ overall belief in general linear reality (Abbott, 1988) to the exclusion (up to now) of an organisation science of non-linearity and disequilibrium (Meyer et al., 2005; Andriani and McKelvey, 2007, 2009, 2011).

PLs are ubiquitous in nature and society (Zipf, 1949; Casti, 1994; Newman, 2005; Andriani and McKelvey, 2007, 2009). For example, cities follow a PL when ranked by population (Auerbach, 1913; Zipf, 1949; McKelvey, forthcoming). The structure of the internet follows a PL (Albert et al., 2000), as does the internal structure of growing firms (Stanley et al., 1996). Axtell (2001) shows that US firms are PL distributed. Glaser (2009) shows that firms’ market capitalisation is PL distributed.

Clearly, fractals – and the scale-free regularities they represent – are not idle mathematical curiosities. PLs have been found at every level of reality (across 32 orders of magnitude): from the smallest atomic structures measured in nano-metres, i.e., 0.0000000001 metre, to the largest galactic structures we know of measured in mega-parsecs: 1,000,000,000,000,000,000 metres (Baryshev and Teerikorpi, 2002). In biology, West and Brown (2004) use fractal geometry of distribution of resources to demonstrate a PL relationship between the mass and metabolism of virtually every organism and its components across 27 orders of magnitude (of mass). Andriani and McKelvey (2007, 2009) list ~140 kinds of PLs 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 organisational scale-free phenomena. McKelvey and Salmador Sanchez (2011) list an additional 80+ in financial economics.

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 and Plowman, 2009) – drives order creation at *every level* of specific phenomena (Kaye, 1993; Casti, 1994; West et al., 1997). This new research program seeks to identify *which* organisational phenomena are scale-free, and find the simplest explanation for all the levels involved (Bak and Chen, 1991; Stanley et al., 1996).

As Table 1 shows, there is good reason to believe that PL effects occur frequently in organisations and have far greater consequence than current users of statistics presume (Andriani and McKelvey, 2007). To the extent this is true, researchers ignoring PL 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.



**Table 1a** Power laws in the social world

Language word usage	Distribution of wealth	Casualties in war	Global terrorism events
Social networks	Publications and citations	Deaths of languages	Changing language
Structure of the WWW	Co-authorships	Delinquency rates	Sexual networks
Size of villages	Actor networks	Aggressive behaviour 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 organisational world

Firm sizes	Director interlock structure	Sales of consumer products	Internal structure of firms
Job vacancies	Supply chains	Cotton prices	Fordist hierarchic 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		Board of Director and other business networks	

*Source:* Drawn from Andriani and McKelvey (2007)

**Table 1c** Power laws in financial economics

Volatility of GDP growth	Macroeconomic disasters	Price movements in stocks	Mimetic trader behaviour
Growth rates of firms	Wealth and income	Trading strategy dynamics	Hurst exponent US mkts.
Economic fluctuations	Econophysics of wealth	Market indices	Hurst exponent and crashes
Financial crashes	World income	Multifractal price returns	Predicting stock markets
Firms' bankruptcies	Saving effects on wealth	Cascades in stock markets	
Size and duration of recessions	Macroeconomic phases in DJI	Detrended fluctuation analysis	
World-wide investment networks		Predicting tipping points in financial markets	

*Source:* Drawn from McKelvey and Salmador Sanchez (2011)

To be fair, not all management phenomena display PL effects. In natural science, as a comparison, data points are frequently independent. Further, PLs may result from causes other than interdependence-caused fractals (Andriani and McKelvey, 2009). Interdependence, nevertheless, is a common cause of PL effects and Pareto distributions. As the world becomes increasingly interconnected because of globalisation and digital

technology (resulting in the internet, email, mobile phones, etc.) the probability of Pareto distributions and fractal structures is significantly increased (Boisot and McKelvey, 2010, 2012; Battison et al., 2012).

#### *2.4 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-organising behaviour takes place, and the form that such behaviour takes when examined across multiple levels of organising. 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 PLs describe the outcomes of unfettered self-organising behaviour in organisations and industries. 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 organisations. With this new synthesis as context, we now review what complexity studies tell us about emergence in organisations.

### **3 Toward a fractal theory of organisation**

In this section, we apply lessons from econophysics to organisations by updating Ashby's (1956) classic *Law of Requisite Variety*. We draw on a few of the 15 scale-free theories identified by Andriani and McKelvey (2009) to make our argument that a principal means by which organisations 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.

#### *3.1 From outside in: building from Ashby's law*

In his classic work, *An Introduction to Cybernetics*, Ashby (1956, pp.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 (organisation) exists between two entities, *A* and *B*, only if the link is ‘conditioned’ by a third entity, *C* [Ashby, (1962), p.255]. If *C* symbolises 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). 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 internal variety can destroy external 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, p.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) p.211]. Essentially, external complexity – including ‘disturbances’ or uncertainty – can only 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 organisational or social settings our internal constructions of the world (mental models) must be representative of the complexity we experience (Boulding, 1956a). When faced with phenomena that fall outside our schema we may expand our schema (increase our requisite variety) to account for these unaccountable experiences (Boulding, 1956b) or restrict our perception of reality (mitigate external variety) to rationalise or simply deny the conflicting information (Staw et al., 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 organisations requires the adoption of a more complex style of thinking, by developing for example a more ‘complicated understanding’ of organisational phenomena (Bartunek et al., 1983). This view is supported by Weick and 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 organisational problems may sometimes be solved by greatly expanding the contextual information surrounding the problem (i.e., increasing requisite variety), through situated learning (Lave and Wenger, 1991; Orlikowski, 1996) or through communities of practice (Brown and Duguid, 1991) which benefit from the accumulated knowledge of many agents.

### 3.2 *Requisite fractal structure from emergent stage dynamics*

*A PL 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, this theory says virtually nothing about the form of these changes. PL 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 and Lichtenstein, 2007; Lichtenstein and McKelvey, 2012).

Our synthetic view can be summarised as follows: by far the most frequent type of emergence appears as networks – McKelvey and Lichtenstein’s (2007) Stage-1 emergence. 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.

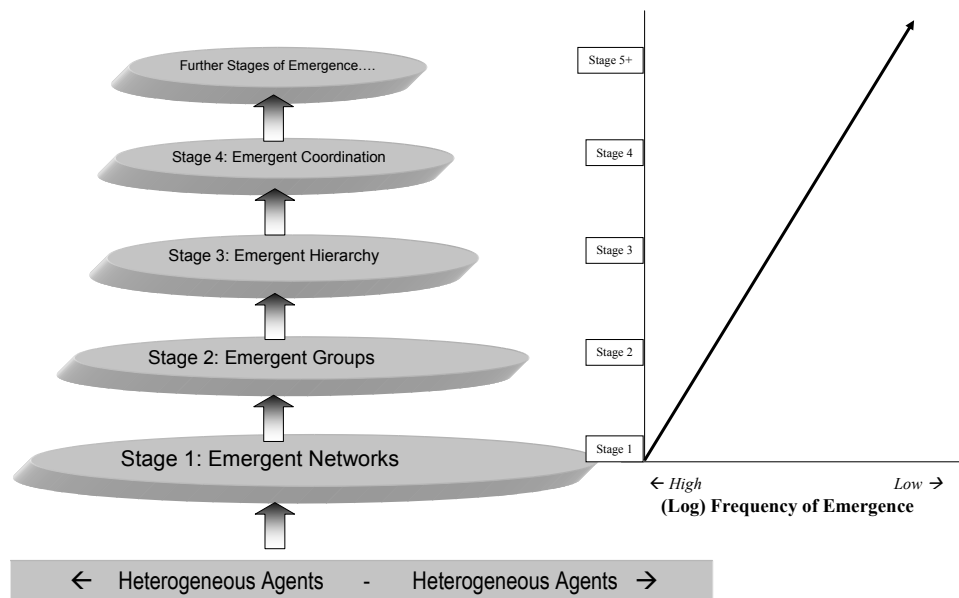
*Measuring emergence in/of organisations.* The key question answered by a PL based theory is, what is the relationship between emergent stages in a given dynamic system? In a formal sense, what is the likelihood, for example, that a network structure will emerge out of an assemblage of agents? What is 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 hypothesise 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, PL 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:<sup>4</sup>

*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.

**Figure 1** Emergence levels in/of organisations, and power law predictions of their frequency



### 3.3 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 organisation increasingly moves toward an internal fractal structure. This requires that we apply scale-free theories (drawn from various sciences) to organisations. This analysis was recently achieved by Andriani and McKelvey (2009), who list 15 scale-free theories can be applied to organisations. 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) offered a variant to the square/cube and connection-cost laws. He focused on ‘nearly decomposable’ systems, wherein modules are designed so as to minimise the connection-cost problem. The scale-free principle causing fractal structure is the idea that at each level in an organisation, agents attempt to minimise connection costs by designing toward nearly-autonomous modules. In this way the resulting structures are ‘fractally’

composed. Zimmerman and Hurst (1993, p.336) explain this link between self-organisation 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 compared two watchmakers making timepieces with 1,000 parts. In the approach used by Tempus, any interruption in the process of assembling all 1,000 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 and Stalker, 1961; Lawrence and Lorsch, 1967).

Following Simon’s principle, and more recent research (Carneiro, 1987; Sanchez and Mahoney, 1996; Schilling, 2000; Shulman, 2004), we see that external competitors gain survival, growth, and competitive advantage by continually decomposing – i.e., self-organising – into modular subunits. For example, the CEO has four division presidents reporting; they each have four VPs; they each have four 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 and Bonner, 1983; Schmidt-Nielsen, 1984; Aronson, 1992; Russell et al., 1992; Niklas, 1994; Tsuda, 1995; West et al., 1997; Solé et al., 2001; Cuddington and Yodzis, 2002; Haskell et al., 2002; Shinci et al., 2002; Xiao et al., 2002; Hoddle, 2003; Liu and Chen, 2003; Ferguson, 2004; Laidre et al., 2004; Phillips et al., 2004; Tremblay et al., 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) confirmed his findings in 62 firms in eight industries. Stephan (1983) derives his application of the square-cube law to firms via ‘time minimisation’ theory. He defines organisational effectiveness in terms of time-minimisation. 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-minimisation, 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 ten ‘complexity traits’ where as 1,000-person villages had four to five times as many.

*Connection-cost law.*<sup>5</sup> 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 organisations 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 organisations 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  $c = 1, 6, 28, 120, 496, 4,032$ . 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.
- 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 intra-module 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 specialised in different tasks, bringing the over-communication problem back under control. The underlying cause of the PL 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 PL signature rather than other kinds of skew distributions.

*Self-organised 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 PL (Bak et al., 1987; Drossel and Schwabl, 1992; Bak, 1996). Here the fractal is dynamic, whereby actions to cause change may be very small or of avalanche proportions.

Bak (1996) applied 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 and Sornette, 2002, 2003, Sornette and Zhou, 2006, Jondeau et al., 2007; Maskawa, 2007; Calvet and Fisher, 2008; Du and Ning, 2008; Eom et al., 2008; Kumar and Deo, 2009; Sornette and Woodard, 2009; Yan et al., 2010; McKelvey and Salmador Sanchez, 2011; McKelvey and Yalamova, 2011a,

2011b; Yalamova and McKelvey, 2011) – all of which show PL 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: PL shaped avalanches vs. PL shaped economic events and changes. Embedded within the broader economic outcomes are individual human decision processes and consequent organisational dynamics.

Even more relevant here is the idea that SOC also applies to actions aimed at optimising 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-organised, informal, autonomous, bottom-up efforts may resolve problems via many small, irregular steps or more rare major reorganisations, as shown by Thomas et al. (2005, 2012). 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 (1949) (power) law. 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 PLs 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 et al. (2006) show that the distribution of firms in growth markets is a PL 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 PL signature whereas stable economies do not. McKelvey (forthcoming) uses PLs to show how broken is the UK economy. From these new discoveries we conclude that the *least effort* scale-free theory applies, especially, to organisations, 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 PL 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 stabilise, 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 – Google is a good modern example. Preferential attraction 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 et al., 2004; Guimerà and 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 follow-on 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 and Prigogine, 1989; Kauffman, 1993). These are new interaction groupings having some probability of showing a PL signature and fractal structure (Mantegna and Stanley, 2000; Sornette, 2006; Newman, 2005). Tension effects in general have the same SOC effect that 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 and Sherman, (1994), p.108]. Kotter (1996, pp.42) does it by 'pushing up the urgency level'. Collins (2001, p.65) forces the phase transition with his chapter title: 'confront the brutal facts'. 3M does it by insisting that 20% of annual revenues in each division be generated by new products developed over the past five years. This adaptive tension imposed by CEOs from the *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. We all now see the tension imposed on firms trying to (or failing to) compete against Apple's iPhone and iPad.

*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 PL 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 organisation, 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 PL signature. A good story, thus, is like a virus that mutates from animal to human and becomes airborne and highly contagious. When the spread of a comment, story, or video spreads quickly on the Internet it is now described as 'going viral'. 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 organisation, 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.

*Interacting fractals.* Many systems that are subjected to opposing regulatory pressures show PL-distributed variability. In physiology, for instance, heart rate and breathing are both subjected to the control of the sympathetic and parasympathetic nervous systems. The first tends to slow down heart beating, the second to accelerate it – each has a different fractal dimension. This makes heartbeats multifractal (West, 2006). The fractal structures of species are based on their food web [S. Pimm quoted in Lewin, (1992), p.121], which is a function of the fractal structure of predators and niche resources (Preston, 1948; Pimm, 1982; Solé et al., 2001; West, 2006).

In the business world, if predators (competitors) and niche resources (customers, suppliers, banks, etc.) and habitats (economic environments) are fractal, then large firms and/or industries that are subject to both sources of competitive pressure are likely multifractal. Stanley et al.'s (1996) study of '...all publicly traded manufacturing firms between 1975 and 1991' evidences this. They show firm size as a power law. It follows that most industry structures – competitors, firms in a 'target' industry, and resources – also have to be fractally structured; if the parts aren't mostly fractal, the whole can't be.

*Combination theory.* Sometimes no single skew distribution – such as those mentioned above – is sufficient to set off a dramatic extreme event. For example, McKelvey and Yalamova (2011b) offer a history of the build-up to the financial crisis of 2007 and the follow-on Great Recession. They connect various scale-free theories to key historical developments, none of which by itself set off an equivalent to the Great Recession:

- 1 Phase transitions: the invention of derivatives in 1972, along with financial engineering, gave rise to dramatic new trading methods
- 2 Contagion bursts: as more and more traders started working for global banks, had international email and phone connections, and world economies became more and more connected, skew distributions in risk-taking became more frequent as traders quickly learned from each other
- 3 Preferential attachment: needless to say, in banking the 'rich get richer' effect came to dominate; successful traders and banks had growing influence in global financial trading; the networked influence of the rich dominated; bigger banks could buy up smaller banks (see also Battiston et al., 2012)
- 4 Spontaneous order creation: the Clinton and Bush presidential policies of making it easier for people to buy houses – by reducing the importance of credit scores and personal income statements – coupled with the prior invention of mortgage-backed securities both lowered the risk of buying a house while at the same time allowed banks to treat home values like monetary reserves against risk. As long as the housing bubble kept increasing, risk was minimised so loans based on mortgage-backed securities rapidly grew in volume
- 5 Combination theory: the collective interaction of non-normal, somewhat skewed distributions can create a more dramatically skewed distribution that ends up as a PL distribution with an extreme outcome at the end of one tail – such as the Great Recession.

While none of the first four scale-free dynamics in the foregoing list can be pointed to as *the* cause of the liquidity crisis, in combination they collectively gave rise to the Great Recession.

We have taken some effort to present a variety of scale-free theories, all of which apply to organisations. 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 organisations. From our *Law of Requisite Fractality* – based on our updating of Ashby's *Law of Requisite Variety* – we

can formulate an additional three propositions calling for further research to confirm findings from econophysics (Stanley et al., 1996; Mantegna and Stanley, 2000; Axtell, 2001; Newman, 2005).

*Proposition 2:* The external industry complexity surrounding organisations is essentially fractal in both structure and dynamics.

*Proposition 3:* The law of requisite fractality therefore applies; firms that have completed efficacious internal adaptive fractal responses to their surrounding fractal competitive context will show improved performance.

By way of some preliminary evidence in support of Proposition 2, we did a PL analysis of recent data (shown in Table 2) on the software ecosystem surrounding Microsoft. As one can see, it appears as straight-line PL distribution in Figure 2 where we plot the numbers in a double-log graph.<sup>6</sup> Except for the three largest firms down on the Y-axis, the figure shows a well-formed PL distribution. This indicates that the ecosystem surrounding Microsoft is well performing in part because, as Iansiti and Levien (2004) claim, it is fractal.

**Table 2** Microsoft's ecosystem

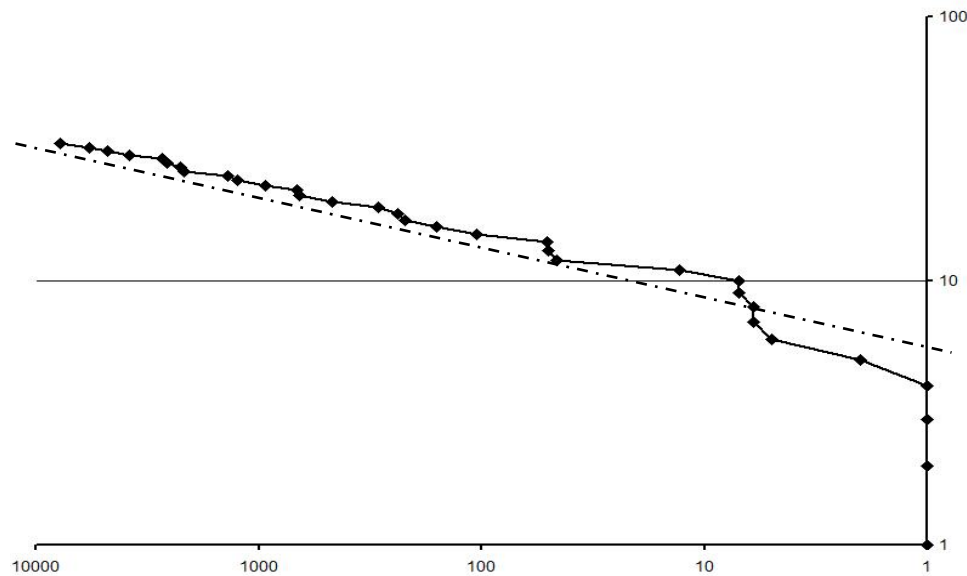
Systems integrators	7,752	Unsegmented resellers	290
Development services companies	5,747	Media stores	238
Campus resellers	4,743	Mass merchants	220
Independent software vendors	3,817	Outbound software firms	160
Trainers	2,717	Computer superstores	51
Breadth value-added resellers	2,580	Application service 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. and service providers	1, 1

*Source:* From Iansiti and Levien (2004, p.71)

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 PL theory to the emergence of a new corporate venture by proposing a series of progressive stages, each being contingent to prior ones. A good example is provided by Brush et al. (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.<sup>7</sup>

**Figure 2** Ecosystem shown as a power law distribution



Note: Frequency of firms in each size of domain, from 7,752 down to 1

Building from the works of Iansiti and Levien (2004), Ishikawa (2006), Dahui et al. (2006), Podobnik et al. (2006), Glaser (2009) and McKelvey (forthcoming), it appears that positive working conditions of self-organised criticality (SOC) (Bak, 1996) at the ecosystem/industry level of analysis are indicated by PLs and fractal structures. Another recent indication of well working SOC is evidence that M&A activity – which is the industry indicator of predator/prey activities – is also power-law distributed, i.e., fractal (Park et al., 2011). External requisite fractality calls for requisite fractality inside firms. But to get fractality inside a firm, it needs to have well-functioning SOC inside.

Given intra-firm SOC and consequent intra-firm fractals, firms require very little information to build up into complex multifractal structures. First, as noted above, fractal systems build via the recursive action of scale-free generative causes (several of which we have described), which become activated any time the required internal or environmental conditions prevail. If one considers that the complexity of the cardiovascular system, for example, defines all the information that can be captured in the DNA, then it becomes clear that a highly fractal entity such as the cardiovascular system can only be built via a co-construction process in which generative rules interact with imposing internal and environmental pressures and coevolutionary responses. One of the reasons why fractal systems are so pervasive is the fact that their construction requires little pre-existing information acting like a blueprint. They are emergent!

Our second reason goes directly to the '*it takes internal fractality to thwart external fractality*' argument. West (2006) in *Where Medicine Went Wrong*, makes the point that a multifractal system is more robust than other systems because it can respond to a

disturbance within the appropriate time scale. Suppose the disturbance is a dramatic complex shock to a complex firm; a multifractal system can react within the required time scale since it has multi-scale levels of response capability. Since the disturbance stems from the nested fractal structure of competitors within the firm's competitive environment – e.g., its industry or larger socio-economic and/or political context – the various parts of the firm's internal fractal system need to become efficaciously SOC so that the required or requisite internal levels (parts) of its multifractal structure get involved in reacting in parallel to the various external fractal layers giving rise to the complex disturbance. One of the features of mature systems in both organisms and organisations – especially 'bureaucratic' organisations – is the loss of this multiscale response capability. This suggests:

*Proposition 4:* Firms need well-functioning SOC inside to perform well and grow in an external competitive industry environment that is characterised by a fractal (and possibly multifractal) structure.

#### 4 Conclusions

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' – law-like reductionism and scalability dynamics 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 PL effects characterising emergent structures
- 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 organisation and management research, the last two remain largely unexplored.<sup>8</sup>

With the goal of developing a PL theory for management, McKelvey and Lichtenstein (2007) define emergence as a multi-dimensional construct and search the computational modelling literature to see what types or levels of organisational 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 hierarchical structures. European dissipative structures theory explains what gives rise to these 'stages of emergence'. Using US complexity theory, we propose that these stages have a PL 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 organisations. Finally we signify

several organisational 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 organisation science. We show the software ecosystem to be fractal; Axtell (2001) shows all US firms to be fractal; Ishikawa (2006) shows that some SIC two-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 capitalisations of firms in various industries from 1930 to 2008 are PL distributed, and Chou and Keane (2009) show PL 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 organising (Whetten, 1989). The relevance of such a theory is clear, given the critical importance of understanding emergence in this age of intangible assets, a digitised knowledge-based economy, globalisation, 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 organisations.

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## Notes

- 1 Steven Hawking, January 2000, quoted in Sanders and McCabe, (2003, p.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 US coevolution and computational modelling tradition, while Santa Fe scholars Kelso et al. (1992) make the best statement of the European school's perspective (McKelvey, 2004) – though we hasten to note that Kelso was 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 organisations, 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 PL 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 appeared 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 7,700 of the smallest firms. The Iansiti/Levien data do not show firm size (assets or # of employees, etc.), but we know that the single firms down at the lower right of Table 2 are very large firms like Nokia and Motorola and that the 7,700 companies at the upper left are the smallest. 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 more real-world explanation of Simon's near decomposability than his watchmaker story. Carneiro shows that villages overcome this law by taking advantage of more complexity traits.
- 8 Exceptions are Zimmerman and Hurst (1993), Stanley et al. (1996), Axtell (2001), Andriani and McKelvey (2007, 2009), Boisot and McKelvey (2010, 2012), McKelvey and Andriani (2010) and McKelvey (forthcoming).