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Towards an econophysics view of intellectual capital dynamics: from self-organized criticality to the stochastic frontier

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Abstract

The paper begins with research studying the concept and nature of Intellectual Capital (IC), as well as how close IC firms are to the stochastic frontier. Then basic concepts of complexity theory – such as agents, self-organized criticality (SOC), connectivities, fractals, and power laws (PLs) – are used to distinguish between two kinds of IC firms' success: traditional SOC applications to how firms maintain their position in a changing industry *vs.* how an IC firm (such as Apple) creates a new stochastic frontier. The research sets up PLs as indicators of whether or not firms and industries are SOC-effective and includes propositions about: (1) How IC firms benefit from complexity dynamics and SOC; (2) How PL distributions are indicators of efficacious SOC and adaptivity; and (3) Why IC attributes serve to create more transient dynamics pertaining to the stochastic frontier and the rest of the industry's rank/frequency distribution.

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Introduction

Over the past 50 years or so, more and more of the value of companies has shifted from tangible capital assets – for example, land, natural resources, cheap labour, and financial capital – to intangible Intellectual Capital (IC) assets – for example, education, knowledge, technical skills, communication, learning, and social networking. From a methodological perspective, tangible assets fit the prevailing normal distribution assumptions of econometricians (Cameron & Trivedi, 2005; Greene, 2011). However, once intangibility and social networking effects are added, the growth and value of IC assets have a high probability of showing non-linear dynamics (Allee, 2003; Ehin, 2005).

Given non-linear dynamics, Pareto distributions become more likely (Strogatz, 2001; Barabási & Bonabeau, 2003; Caldarelli, 2007; Newman, 2010), whereas assumptions of *i.i.d.* (identical and independently distributed data) and normal distributions, and in general linear regression and related econometric methods become less appropriate. Consequently, information about 'average' firms is pretty much useless to practitioners for managing their firm's goal of reaching its stochastic frontier, defined as the maximum technically feasible output given inputs. Consequently, Dumay (2009) advocates using alternative methods or modes of investigating IC by utilizing other techniques, such as complexity theory, narratives, numerical, statistical, and visual techniques that outline the

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skills practitioners and researchers may need to acquire and develop in order to break free from the accounting-based frameworks dominating IC measurement today.

As the United States loses its production capacity to China and elsewhere because of cheap labour and construction costs, the importance of IC assets increases. A recent analysis by Shane (2008) shows that the 'professional, scientific, and technical service' industry had the largest share (14%) of all industries doing business in the United States. As the ratio of intangible-to-tangible assets increasingly favours IC, prevailing econometric methods and academic research findings increasingly offer less relevant knowledge to practitioners because the prevailing econometric assumptions ignore the reality of industries as rank/frequency (R/F) distributions: For example, in the US retail industry, Walmart is the world's largest retail firm out at the end of one long (high rank) Pareto tail, whereas there are 17 million Ma&Pa stores (officially defined as having no paid employees) out at the end of the other (high frequency) long tail. Since IC 'value networks' (Christensen, 1997; Normann & Ramirez, 1998; Allee, 2003; Ehin, 2005) are also a function of social networking, and we now know that such networks are scale-free (Strogatz, 2001; Albert & Barabási, 2002; Barabási & Bonabeau, 2003; Dorogovtsev & Mendes, 2003; Newman *et al*, 2006; Caldarelli, 2007; Newman, 2010), there is a high probability that IC networks and IC effects produce non-linear dynamics, that is, they are dynamical.

At the time Porter (1980) wrote his first book, industries tended to be dominated by the three or four firms that colluded at the low-cost end of Porter's 'efficiency curve' with the rest of the industry more or less clustered at the opposite – higher cost, more product differentiation – end of the curve. Nowadays, the group of colluders has mostly disappeared, being replaced by single giants such as Microsoft, Walmart, ExxonMobil, Siemens, and Apple at the Rank = 1 position. While, yes, Walmart has reached the stochastic frontier (Kumbhakar & Knox Lovell, 2000; Lieberman & Dhawan, 2005) by importing cheap Chinese-made products, Microsoft, ExxonMobil, Siemens, and Apple have done so primarily via IC.

Iansiti & Levien (2004) emphasize the need for dominant firms such as Microsoft to protect their own viability by also nurturing their ecosystem – comprising the rest of the smaller firms in their industry. Research by Ishikawa (2006), Zanini (2008), and Glaser (2013) shows that the adaptive viability of firms in industries and resultant growth and size is Pareto and power law (PL) distributed with various implicit elements of self-organized criticality (SOC)[1] in operation. Moving towards the IC-defined stochastic frontier becomes a function of how well the complexity dynamics of both the firm and industry are operating. We draw on aspects of econophysics (Mantegna & Stanley, 2000; Chakrabarti *et al*, 2006; Sinha *et al*, 2011) to create a twenty-first-century perspective about how to achieve the IC-based stochastic frontier.

Using linear regression and focusing on the findings about 'average' firms, even if they are well versed in existing thinking about how best to reach the stochastic frontier, does not offer much useful information for practitioners in IC-rich firms aiming for their stochastic frontier. While more or less economically atheoretical in their empirical analyses, econophysicists are now offering many useful findings about industries that hold relevance for IC firms. Their findings are best viewed as reflecting the outcomes of the adaptive, emergent self-organized behaviours highlighted by complexity scientists (Arthur, 1994; Cowan *et al*, 1994; Mainzer, 1994; Holland, 1988, 1995; Bak, 1996; Arthur *et al*, 1997; McKelvey, 1999, 2001a, b, 2003, 2004; Gell-Mann, 2002; Maguire *et al*, 2006; Andriani & McKelvey, 2008; Wycisk *et al*, 2008; McKelvey & Salmador, 2011; Boisot & McKelvey, 2011, 2013; McKelvey *et al*, 2012). Since emergent behaviour is a function of tiny initiating events (Holland, 1988, 1995), magnified by scale-free causes (Newman, 2005; Andriani & McKelvey, 2009) and networking (Albert & Barabási, 2002; Barabási, 2002, 2005; Caldarelli, 2007), the outcomes are the long-tailed Pareto and PL distributions studied by the econophysicists (Mantegna & Stanley, 2000; Chakrabarti *et al*, 2006; Sinha *et al*, 2011).

We begin by reviewing IC research and how it fits with stochastic frontier research. Then we review basic complexity theory, with special attention to Bak's (1996) SOC, fractals, and PLs. Next we distinguish between two kinds of IC-firm success: (1) traditional SOC applications to how species maintain their position in a changing niche or how firms maintain their position in a changing industry *vs* (2) how an IC firm (such as Apple) creates a new stochastic frontier. We discuss how to use PLs as indicators of whether or not firms and industries are SOC-effective. We also include various propositions calling for empirical tests of how complexity theory and SOC apply to the performance of IC industries and moves of firms towards the stochastic frontier. A conclusion follows.

Intellectual capital and the stochastic frontier: a brief review

Intellectual capital

It is now widely recognized in organizations that intangible elements are the main differentiators and drivers of competitive advantage. IC, understood as the knowledge and other intangibles that produce or create value in the present, as well as knowledge and other intangibles that will produce or create value in the firm in the future (Viedma & Enache, 2008; Amitava & Ghosh, 2012), becomes one of the main concerns related to wealth creation in the context of knowledge economies.

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[1] Bak (1996) uses 'self-organized criticality' to refer to how a system constantly adapts so as to maintain a continuing efficaciously adaptive functional state in changing circumstances.

Literature on knowledge management and IC accepts the idea that the concept of IC is a key element to explain the difference between market value and book value (Edvinsson & Malone, 1997; Sveiby, 1997; Roos *et al*, 1997). Traditional accounting does not provide information on firms' IC. In addition, traditional tools for business management are oriented towards tangible resources. Thus, this situation demands the development of new and appropriate tools to measure, report, and manage organizational resources based on knowledge (Petty & Guthrie, 2000; Mouritsen *et al*, 2001). Consequently, there is the endeavour to better manage, measure, and report these often elusive but critical success factors.

Since the beginning of the 1990s, there have been important efforts to develop managerial tools to measure and manage knowledge-based resources. As a result of these efforts, new models of IC measurement have emerged. Viedma (2003) notes the representative models and methodologies from what can be called the standard theory (or the 'prevailing paradigm') in IC. They are: the 'Intangible Assets Monitor' (Sveiby, 1997), the 'Balanced Scorecard' (Kaplan & Norton, 1996), and the 'Skandia Navigator' (Edvinsson & Malone, 1997). Despite the different terminologies that they each use, these models all break down IC into its distinct elements. These elements can be summarized as human capital (including the knowledge, skills, experiences, and abilities of employees), structural capital (comprising both organizational and technological capital, including, e.g., organizational routines, procedures, systems, cultures, databases), and relational capital (defined as all resources linked to the external relationships of the firm such as customers, suppliers, R&D partners, investors, creditors, etc.). Viedma (2003) also highlights other models and methodologies as alternatives to the standard theory. These include the 'Intellectual Capital Benchmarking System' (Viedma, 2001), representing an introductory methodology to the new theory of IC, which evaluates the core competencies as the only intangible assets to manage and breaks down core competencies into their constituent intangible assets.

Therefore, the development of IC has advanced, thanks to the contributions of research in various fields, leading to a truly multi-disciplinary body of knowledge. Marr & Roos (2005) also offer a relevant review identifying different perspectives about the development of IC, including accounting, strategy, marketing, human resource management, operations management, information systems, and economics. They also offer interdisciplinary views on IC from the perspectives of public policy, knowledge management, and epistemology.

All previous efforts are relevant for answering the question 'What is IC?', but in order to keep advancing in this realm the next question in line should be 'How is IC measured?' (O'Donnell *et al*, 2006; Dumay, 2009). This question becomes very relevant because IC is concerned with intangibles based on knowledge as opposed to tangibles. In this light, a major concern of strategic management, raised by the Resource-Based View of the firm (i.e., Barney, 1991; Peteraf, 1993), as well as other derived frameworks such as the Intellectual Capital-Based View (Roos *et al*, 1997; Bontis, 1998) and the Knowledge-Based View (Grant, 1996; Spender, 1996), is the strategic role of different types of resources, and their influence on value creation and competitive advantage in organizations.

A firm's processes that use resources to match and even create market change are radically different for tangible and intangible resources, because their nature and dynamics are so different (Itami & Roehl, 1987; Nonaka & Takeuchi, 1995; De Geus, 1997; Kelly, 1997). For instance, while the former are depreciated when used, the latter are appreciated with utilization. As opposed to physical equipment, knowledge becomes refined with use. The more we practice a certain skill, the better we will become at it. Also, while the former can be managed through control, the latter requires alignment. Similarly, while the former are static because they can be stored, the latter are dynamic and if they are not used they become obsolete, especially in socio-economic environments characterized by marked change. While the former can be duplicated, the latter are difficult to copy. Along this same line of reasoning, while the dynamics of the former are basically linear and mechanical, close to a machine metaphor, the latter, as a living system, follows biological and/or complex systems logic. In addition, intangible resources have other primary qualities that make the attainment of synergies possible. They can be used in simultaneous ways, and they may be combined and recombined to obtain new knowledge.

Moreover, intangibles based on knowledge can be classified into tacit and explicit (Polanyi, 1966), and each type of knowledge needs its own kind of space or 'ba' (Nonaka & Konno, 1998) that allows different intangibles to be conceived, combined, and reshaped, since their nature and behaviour are basically different as well. Tacit knowledge is hard to formalize and extremely personal. Encompassing intuition, hunches, gut feelings, and subjective insights, tacit knowledge is knowing more than can be related in words. It is entrenched in values, ideals, customs, routines, and emotions. Hence, tacit knowledge relates to the 'right now', requiring the simultaneous processing that makes it difficult to communicate. Explicit knowledge, on the other hand, is knowledge that can be expressed in verbal and written language, and is therefore shared relatively easily. It can be formally presented in data, scientific equations, instruction manuals, and other documents. As such, explicit knowledge is easily transferred from individual to individual, group to group, spanning periods of time as well as context.

In sum, tangible resources, such as land or financial capital, have a radically different nature and behaviour compared with intangible resources. Furthermore, intangible resources based on explicit knowledge differ from intangible resources based on tacit knowledge. Knowledge assets embodied in people behave differently, because people meet, connect, learn from, force others to join groups, start herding behaviour and so on. Consequently, and because this different nature and behaviour affects knowledge development, knowledge flows, and knowledge evaluation, these kinds of intangibles based on tacit knowledge need to be studied via different methods than traditional math and accounting or econometric methods, which treat entities like billiard balls – they all respond the same way to imposed force, do not form groups, and only influence each other in predictable ways. Intangibles – sometimes further complicated by their tacit nature – offer myriad ways in which people (heterogeneous agents[2]) may differ from one another. This, coupled with possible connectivities among any given set of agents, creates an ontology, fundamentally different and vastly more complex than what is typically conceived to represent the billiard ball-like components of physical systems.

Stochastic frontier

Firms in a given industry, as comparable economic agents, can be assumed to operate according to a common technology. The stochastic production frontier for such firms is defined as the maximum technically feasible output given inputs. Accordingly, firms can be thought of as operating either on or within the stochastic frontier; and the distance from the frontier therefore reflects inefficiency (Aigner *et al*, 1977; Kumbhakar & Knox Lovell, 2000).

Over time, output growth can be defined with respect to three different components: (1) *Efficiency change*, meaning that a firm can potentially become less efficient and need to 'catch up' to the frontier; (2) *Technical change*, implying that the frontier itself can shift over time, implying technical progress; and (3) *Input change*, indicating that a firm can move towards the frontier by changing inputs (Koop *et al*, 1999). These definitions provide a framework for addressing a number of questions, including issues about which firms are making the most efficient use of their inputs, and whether an industry's growth is driven by changes in technology or input changes.

The identification of reliable and scientifically valid efficiency measurement strategies is what is typically focused on for stochastic frontier achievement (Hollingsworth & Street, 2006). In knowledge-intensive industries, however, IC and related intangible assets are the fundamentally essential factors by which firms can maintain their competitive position and future viability (Stewart, 1997; Bontis, 1998; Edvinsson & Sullivan, 1996). Furthermore, Abarnethy *et al* (2003), in their study of the measurement of intangible assets and associated reporting practices, conclude that investment in IC creates twice the benefit as compared with the same amount of investment in physical assets. Previous empirical research also shows this significance of IC at corporate level (i.e., Chen *et al*, 2005; Ghosh & Wu, 2007).

Nevertheless, most of the research related to stochastic frontier analyses focuses on measures of tangible elements in firms (Coelli *et al*, 2005). However, there is some previous work that mentions IC elements of firms in conjunction with stochastic frontier dynamics, though they do not show much in the way of measuring specific intangible elements. For instance, several studies comparing National Health Systems efficiency (e.g., Hollingsworth & Wildman, 2002; Gravelle *et al*, 2003, 2004) using the World Health Organization data (World Health Report, 2000) were based on two output measures, a composite measure of health care delivery and disability adjusted life expectancy; and two inputs, health care expenditure and education levels.

Zhi & Hu (2011) study the efficiency of life insurance companies. There are three input variables in the data envelopment analysis (DEA) model: The first input is the total number of employees since the life insurance industry is labour intensive. The second input is the debt equity, which reflects the scale of business. The third input is equity capital, which reflects the warranty to give benefit payments to the insured. There are two output variables in the DEA model: the first output is the insurance premium revenue, which is the result of a life insurance company's operations. The second output is investment revenue, which comes from the financial intermediacy function of a life insurance company.

Kuo & Yang (2012) use the Simar & Wilson (2007) procedure with a truncated regression to explore the impact of IC variables on performance and competitive advantage in Taiwan's integrated circuit design industry. Their study adopts Seiford & Zhu's (1999) two-staged profitability and marketability model. The profitability performance model measures three inputs (equity, liability, and employees) and two outputs (revenues and intangible assets). The marketability performance model evaluates two inputs (revenues and intangible assets) and two outputs (outstanding shares and market value). The data are collected from the database of the *Taiwan Economic Journal*.

Saengchan (2007) measures the impact of IC on efficiency in the banking industry by using the stochastic efficient frontier methodology as with previous research in the industry (Kwan & Eisenbeis, 1996). The Value Added Intellectual Coefficient proposed by Pulic (1998) was used as the efficiency measure of the capital used and IC. Capital used consists of equity, the accumulation of profit-adjusting entries, and liabilities with interest. IC consists of human and structural capital.

How and why IC systems behave as complex adaptive systems (CASs)

Most empirical studies of companies are based on tangible data consisting of economic 'countable' numerical quantities and counts of people and firms or other more tangible entities. However, is there any reason to

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[2] 'Agent' is a term in complexity science and agent-based computational modeling that can refer to entities such as cells, DNA molecules, organs, people, groups, departments, organizations, industries, cities, and societies.

believe that IC phenomena – which are mostly intangible – in any way relate to complexity theories and dynamics? To offer a positive answer, we connect various elements of IC concepts to key aspects of CASs in this section. We first define various aspects of CASs and then relate them to elements and processes in IC-dominated firms. By doing this, we show the degree to which IC systems are more prone to behave like CASs. As one may see, many key elements described in well-known works pertaining to IC can be seen as embodying various aspects of CASs.

Associating complexity ingredients with IC elements

Complexity: Tension effects– Knowledge about how imposing tension (imposed from the environment or by internal changes) can cause major changes (phase transitions) began with the Bénard (1901) process – an energy differential is set up between warmer and cooler surfaces of a container (measured as temperature, ΔT). In between the first and second critical values (R_{c1}, R_{c2}), a *Region* is created where the system undergoes a marked shift in the nature of fluid flow. For example, increasing the heat *under* water molecules in a tea kettle, which are exposed to colder air *above* the upper surface of the water, leads to geometric patterns of hotter and colder water – the chef's 'rolling boil' emerges; new order appears (Prigogine & Stengers, 1984; Mainzer, 1994/2007). The two critical values define the *melting zone* (Kauffman, 1993), within which new structures spontaneously emerge; Prigogine (1955) termed these *dissipative structures* because they are pockets of order – governed by the first law of thermodynamics – that speed up the dissipation of the imposed energy towards randomness and entropy according to the second law of thermodynamics (Swenson, 1989).

IC: Tension– New knowledge giving rise to challenges stemming from changes in the market and/or consequent organizational discontinuities is one source of imposed tension (Bettis & Hitt, 1995; Prahalad, 1998). Tension in the form of 'creative chaos' – generated externally because of changes in technologies or market needs, or internally when managers propose (or impose) challenging goals – increases tension within the organization and leads to forming and solving new problems and triggers, which motivates knowledge creation in organizations (Nonaka, 1994).

IC: Edge of order– Changing IC intangible assets can impose tensions creating the need to make changes in how other assets of firms are managed. More specifically, IC (or other) tensions have to rise above the *first critical value* (i.e., the *edge of order*) before meaningful change occurs. With tension above the edge of order, we see organizational redesigns based on changes in mission, strategy, operations (including structural and technological changes), and changing attitudes and behaviours of personnel (Bradford & Burke, 2005), all of which call for various kinds of changing IC. The occurrence of periodic 'breakdowns' in human perceptions and behaviours present opportunities to reconsider fundamental thinking and perspectives (Winograd & Flores, 1986). Significant contradictions in the interactions between a subject (firm, departments, or employees) and imposed environmental tensions can lead to new perceptions and behaviours (Piaget, 1974a, b).

IC: Dissipative structures– Entrepreneurial firms and organizational subunits redesigned as a result of new knowledge so as to dissipate the tensions between supply and demand are obvious examples of tension dissipative structures (Barnard, 1938). Intangible dissipative structures emerge when individuals recreate their own systems of knowledge to take account of ambiguity, redundancy, noise, or randomness generated by adaptive tensions between an organization and its environment (Nonaka, 1994). In the context of evolutionary theory, most, if not all, newly evolved organizational systems appear as some sort of dissipative system – not necessarily to reduce uncertainty and complexity – but rather to increase the spectrum of adaptive response options. In IC-dominated firms, imagination comes into play (Jantsch, 1980, p. 267). Decision making as 'organized anarchy', emphasizing the strategic aspect of the trial-and-error approach, is a key element in the creation of IC-based dissipative structures (March & Olsen, 1976).

IC: Edge of chaos– Responding to too many different imposed tensions via too many new strategies calling for too many structure and process changes in too many different directions instigated more or less at the same time sends firms over the edge of chaos (Beinhocker, 1997). As Nonaka (1994, p. 28) puts it, the introduction of fluctuation tends to produce 'destructive' chaos.

IC: Enslaved: Haken's 'slaving principle' (Haken, 1983) holds that as a change (phase transition) occurs because a system enters the region of emergence between the 1st and 2nd critical values, the nature of the emergent change can often be enslaved (controlled) by an existing network among a few agents. As most of the other agents' influences become randomized because of their individual responses to various tension effects, the nature of the emergent new order becomes increasingly dominated by the wishes of the few well-networked agents. For example, as Egypt has become increasingly chaotic, the long existing network among members of the Muslim Brotherhood has come to dominate the Egyptian government.

Complexity: Bottom-up emergence emphasizes agents' self-organization absent outside direction and influence. Its advocates consist largely of scholars associated with the Santa Fe Institute (Anderson, 1972; Kauffman, 1984, 1993; Gell-Mann, 1988; Holland, 1988, 1995; Arthur, 1994); see also (Pines, 1988; Anderson *et al*, 1988; Cowan *et al*, 1994; and Arthur *et al*, 1997). While Phase 1 focused mostly on marked phase transitions at R_{c1}, – the *edge of order* – Phase 2 complexity scientists focus mostly on R_{c2} – the *edge of chaos* (Lewin, 1992; Kauffman, 1993). Focusing on living systems (Gell-Mann, 2002), Phase 2 emphasizes the spontaneous co-evolution of entities (i.e., the agents) in a CAS. Agents restructure themselves continuously, leading to new forms of emergent order consisting of patterns of evolved agent attributes and hierarchical structures displaying both upward and downward causal influences. The signature elements within the melting zone are self-organization, emergence, and non-linearity. Kauffman's *spontaneous order creation* begins when three elements are present: (1) heterogeneous agents; (2) connections among them; and (3) motives to connect – such as mating, improved fitness, performance, learning and so on. Remove any one element and nothing happens. According to Holland (2002), we recognize emergent phenomena as *multiple-level hierarchies*, *bottom-up and top-down causal effects*, and *non-linearities*. Non-linearity often stems from scalability reflected as PLs.

IC: Emergence via heterogeneous agents– By allowing people (agents) to act autonomously, an organization can increase its discovery of knowledge, unexpected ideas, and novel opportunities of the type that are sometimes associated with the so-called 'garbage can' metaphor (Cohen *et al*, 1972). Developing teams by bringing together heterogeneous team members improves the team's and a firm's ability to respond to changing 'requisite varieties' (i.e., constant imposing changes) in its environment (Morgan, 1986). Early on in social psychology, Lewin (1948, p. 184) emphasized the definition of a group as 'a dynamic whole based on interdependence rather than on similarity'. Heterogeneous agents come with what Granovetter (1973) calls 'weak ties' – meaning that they seldom contact each other – hence they are more apt to bring new ideas to other new teammates.

IC: Emergent ideas– New knowledge gives rise to new emergent strategies (Mintzberg & Waters, 1985). Organizational information created to deal with many known contingencies often generates various combinations of information relevant to unexpected situations (Nonaka, 1994). Strategy revolution stems from new knowledge (Hamel, 1998). Leveraging the power of external ideas by importing innovative ideas allows the exportation of IC through open innovation (Chesbrough, 2003).

IC: Emergent groups and networks– Communities of practice represent a key dimension to socialization and its input to the overall knowledge creation process (Lave & Wenger, 1991). Barry & Stewart (1997) identify self-managed teams resulting from needs to learn about, develop, and/or apply new knowledge. Cluster formation (Feldman & Francis, 2004) and alliance networks (Gay & Dousset, 2005) are instrumental for building new knowledge, especially if they bring heretofore 'weak-tied' agents; novelty and entrepreneurship are more likely (Granovetter, 1973).

IC: Emergent influence streams and hierarchies– Nonaka & Takeuchi (1995) create a 'Middle–Up–Down Management' model so as to promote a form of self-organization leading to the efficient creation of new knowledge in business organizations. Galbraith (1982) emphasizes organization design stemming from new knowledge applications. Lewin & Stephens (1993) emphasize the challenges to, and opportunities for, organizational design in the IC-intensive post-industrial society. New organizational forms based on the foregoing new knowledge applications for managing in hypercompetitive environments are highlighted by Illinitch *et al* (1996).

IC: Coevolution– The IC capabilities of an organization are shaped by the evolving complex pattern of factors within and outside the organization (Norman, 1988). The significance of links between individuals who span boundaries, both within and outside an organization, offers insights into the IC of 'evolving communities of practice' (Brown & Duguid, 1991). Organizational knowledge creation is a circular process not confined to the organization but including many interfaces with the environment. And, at the same time, the environment is a continual source of stimulation to knowledge creation within an organization (Nonaka, 1994, p. 27). Co-evolution between an organization and its competitive environment appears as a continual process of interacting new knowledge developments (Von Krogh *et al*, 1994).

Self-organized criticality and adaptive viability– In his now classic book, *How Nature Works* (1996), Per Bak explained PL distributions by looking at how sandpiles build up: falling grains of sand are allowed to slowly accumulate in a pile. Eventually, the sandpile becomes high enough and its slope steep enough to trigger sand avalanches of varying sizes. These restore stability to the slope. The steepness of the slope depends on two elements: (1) *gravity* and (2) the sharp *irregular* shape of the individual sand grains. Take away gravity and there is no force causing the grains to slide down past each other – call the influence of this force the *tension* effect. On the other hand, take away the irregular shape of the individual grains, and they become frictionless, unable to resist the downward force exerted by gravity – somewhat like smooth M&M peanuts, they will then scatter, unable to stick together enough to build up a pile. Call the influence of the friction the *connectivity* effect. Bak observed that sand grain movements varied from the frequent but barely perceptible movement of a few isolated grains to the rare but gigantic avalanches in which thousands of sand grains move in unison. The size and frequency of sand grain avalanches are PL distributed (Bak *et al*, 1987).

The non-linear tensions and connectivities that lead to extreme outcomes (the largest avalanches) are key elements of complexity science. Bak labelled the results of the non-linear interplay of tension and connectivity 'SOC' – when the force of gravity encounters the friction-induced resistance of irregularly shaped grains of sand, these will move so as to maintain the sandpile's slope in a precarious state of equilibrium. The rate and volume of sand moving at any given instant is: (1) non-linear, (2) unpredictable, and (3) occasionally productive of extreme events. In addition to the normally distributed phenomena characterizing much of physical science and described by Gaussian statistics (data points assumed to be independent and identically distributed; *i.i.d.*), researchers have discovered an ever-increasing number of phenomena – from physical to biological to social – that are best described by the attributes 1–3 just above. These attributes are associated with *tiny initiating events* (what Holland (2002, p. 29) terms 'small inexpensive inputs' or 'lever point phenomena') and result in R/F distributions of outcomes that are PL distributed and best explained by scale-free theories.

IC: Self-organization– Knowledge-creating activities by self-organizing teams work as a measure that serves to prevent the so-called 'reverse function of bureaucracy' (i.e., control) (Merton, 1957). New knowledge-driven self-organization in organizations is described by Thompson (1967). Morgan (1986) identifies self-organization in IC systems where the autonomy of individuals is assured, or where only 'minimum critical specification' is imposed by higher management. The top layer of the 'hypertext' organizational design relates to the area where multiple self-organizing project teams create knowledge (Nonaka & Takeuchi, 1995). Self-organizing teams trigger organizational knowledge creation (Nonaka, 1994). Technology as a self-organizing intellectual system is described by Sahal (1981).

IC: Connectivities– Technology communications (Kelly, 1997), alliance networks (Gay & Dousset, 2005), and degrees of connectivity (Santiago & Benito, 2008) indicate awareness in the literature of knowledge connectivities across various groups and boundaries within firms

IC: Motives to connect– Motivation stems from how individuals form their approach to the world and try to make sense of their environment (Husserl, 1968). Cognition is the activity of knowing and understanding as it occurs in the context of purposeful activity (Neisser, 1976). Human beings, as organic systems, derive knowledge from the environment, which is based on their ultimate pursuit of survival (Shimizu, 1995). Intention makes it possible to judge the value of the information or knowledge that is perceived or created (Searle, 1983). Oliver & Roos (2000) mention knowledge-based managerial intentionalities in strategy making.

IC: Motives to survive and grow– 'Commitment' underlies human knowledge creating activities (Polanyi, 1966). Evolution involves the process of acquiring environmental information for better adaptation (Eigen, 1971). Learning and application of new knowledge in organizations fosters survival and growth (Argyris & Schön, 1978; Senge, 1990). New knowledge-based dynamics of organizations aid adaptive and evolving systems (Morel & Ramanujam, 1999) and give rise to different kinds of knowledge that then fosters co-evolutionary pockets and new knowledge-based strategies for survival (McKelvey, 1999).

IC: Tiny initiating events– 'Strategy as Weeds' – small ideas based on new knowledge (Mintzberg & McHugh, 1985). The common feature of strategy making among the innovative companies in high-velocity environments is an emphasis on action, which means experimentation and the principle of trial and error (Salmador & Bueno, 2005).

Fractals. Consider the cauliflower. Cut off a 'floret', cut a smaller floret from the first floret, then an even smaller one; and then even another and so on. Despite increasingly small size, each lower-level component performs the same function and has roughly the same design as the floret above and below it in size. This feature defines it as fractal. Fractals can result from mathematical formulas – as shown in Mandelbrot's *Fractal Geometry* (1983). We are more interested in fractal structures that stem from adaptive processes – such as the cauliflower (McKelvey & Salmador, 2011) – in biological, social and even financial contexts (McKelvey & Salmador, 2011). In fractal structures, the same adaptation dynamics appear at multiple levels. McKelvey *et al* (2012) cite 19 studies showing fractal dynamics in predator/prey niche-adaptation behaviours. Zanini (2008) argues that the same effects hold for merger and acquisition (M&A) activities in business niches.

Fractal structures are often indicated by PLs. The econophysicist Barabási (2002) connects scalability, fractal structure, and PL findings to social networks. He shows how networks in the physical, biological, and social worlds are fractally structured such that there is an R/F effect – an underlying Pareto distribution showing many sparsely connected nodes at one end and one very well connected node at the other. For example, if plotted on a double-log graph, the Pareto-distributed progression of increasing numbers of connections from, say, small airports to giant ones such as Heathrow and Atlanta appears as a negatively sloping straight line.

PLs. A well-formed Pareto R/F distribution plotted in terms of double-log scales appears as a PL distribution – an inverse sloping straight line. We illustrate the difference in Figure 1. PLs often take the form of rank/size expressions such as $F \sim N^{-\beta}$, where F is frequency, N is rank (the variable), and β, the exponent, is constant. In a typical 'exponential' function, for example, $p(y) \sim e^{(ax)}$, the exponent is the variable and e is constant. The now famous PL 'signature' dates back to Auerbach (1913) and Zipf (1929, 1949). Andriani & McKelvey (2007, 2009) list ~140 kinds of PLs in physical, biological, social, and organizational phenomena. Stanley *et al* (1996) find that manufacturing firms in the United States show a fractal structure, as does Axtell (2001) (see also Newman (2005); Newman *et al* (2006); Clauset *et al* (2009); Glaser (2009); and Chou & Keane (2009). McKelvey & Salmador (2011) list another 60 or so specifically in financial economics, some of which we cite in this paper.

Since PLs mostly appear to be the result of self-organization, they often, if not always, signify active self-organization processes at work maintaining some kind of SOC. Thus, Ishikawa (2006) shows PLs in adaptive and changing industries (as opposed to static ones). Podobnik *et al* (2006) show PLs in the stock markets of transition economies. The Dow Jones market capitalizations of the 30 largest US publicly traded firms show a

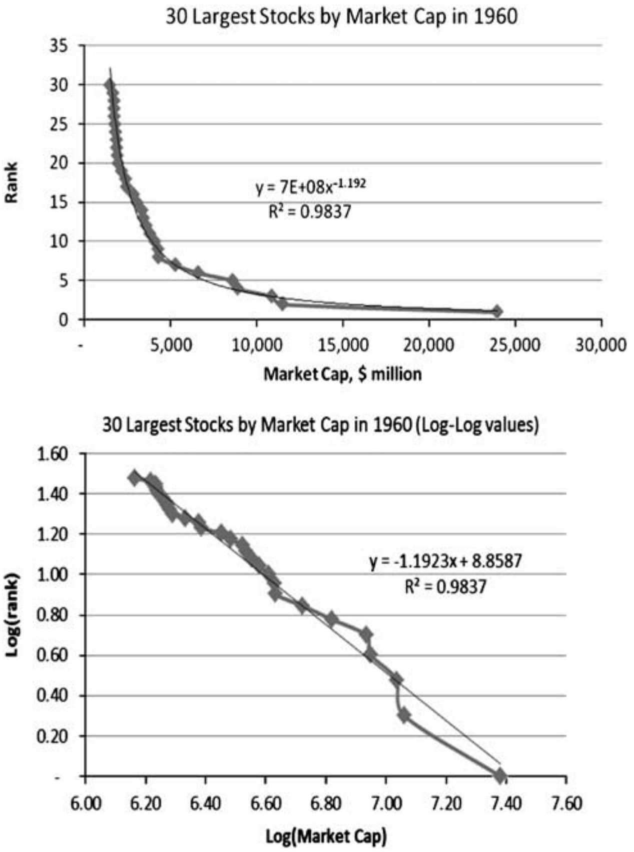

Figure 1 Pareto and PL distributions compared reproduced from Glaser (2013).

PL – again, evidence of fractals when traders are free to buy and sell as they wish (Glaser, 2013).[3] Iansiti & Levien (2004) show that the software industry is the most resilient across the 2002 dot.com bust. As compared with the machinery and chemical industries, Zanini (2008) shows the software industry to be much more Pareto distributed. Glaser (2009) shows that the software PL correlates with a straight line at 0.998.

Adaptive R/F distributions– Focus is on how order creation actually unfolds once the forces of emergent order creation by self-organizing agents are set in motion. New order often appears as R/F distributions; the latter date back to Pareto (1897). We present a stylized depiction of an R/F distribution in Figure 2. The *outcomes* of self-organization and emergent new order often appear as R/Fs. According to Holland (2002), we recognize emergent phenomena in multi-level hierarchies, in intra- and inter-level causal processes, and in non-linearities. Non-linearity incorporates two key ideas: *butterfly events* and *scalability*. Tiny butterfly events and scalability produce non-linearities that may extend across multiple levels within organisms or organizations or across multiple species or firms within an ecosystem. Extreme outcomes, long-tailed Pareto distributions, and PLs (Zipf, 1929, 1949; Casti, 1994 & Newman, 2005), scalability (Brock, 2000), and scale-free causes (Zipf, 1949; West & Deering, 1995; Andriani & McKelvey, 2007, 2009) often result.

Reproduced from Glaser (2013)

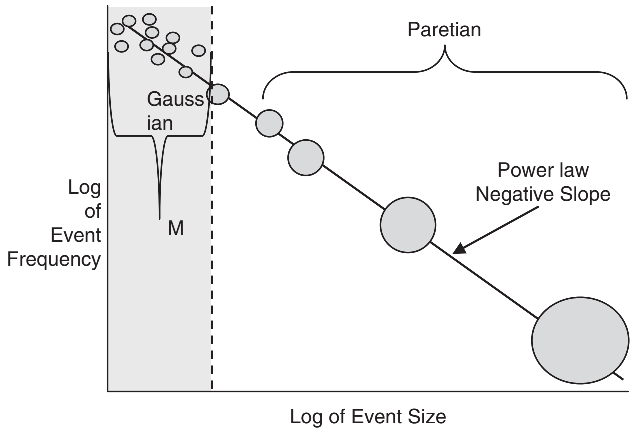

Figure 2 Stylized R/F distribution.

In his opening remarks at the founding of the Santa Fe Institute, Gell-Mann (1988) emphasized the search for scale-free theories – simple ideas that explain complex, multi-level phenomena. Brock (2000) goes so far as to say that *scalability* is the core of the Santa Fe vision – irrespective of the scale of measurement, the phenomena appear the same and result form the same causal dynamics. Gell-Mann (2002) concludes his chapter, *What is Complexity?*, with a focus on scalability in living systems. Key parts of scalability are *fractal structures*, *PLs*, and *scale-free theory*.

Mandelbrot applied fractal geometry and later PLs to economic R/F distributions (e.g., cotton prices in 1963) and later to financial markets (Mandelbrot, 1997; Mandelbrot & Hudson, 2004).[4] Econophysicists start with early foci on R/F distributions of: *returns in financial markets, income and wealth, economic shocks and growth-rate variations, firm sizes and growth rates*, and *scientific discoveries* (Rosser, 2008). McKelvey & Salmador (2011) list a 103-item sample of relevant studies in Table 1. Econophysicists often begin with a focus on Lévy skew distributions and applications of statistical physics methods to economic phenomena (Mantegna & Stanley, 1995, 2000). Rosser (2008) notes that econophysicists find that standard economic theory is inadequate or insufficient, or generally assumes away, the non-Gaussian distributions empirically observed in the many kinds of financial–economic phenomena that exhibit excessive skewness and leptokurtotic long-tailed distributions.

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[3] Correlation between PL and straight line is 0.984. Data are Dow Jones stock market prices in 1960. Firms include AT&T, GM, IBM, Standard Oil, Du Pont, and GE.

[4] The label 'butterfly event' comes from the title of a famous paper by Edward Lorenz (1972): 'Predictability: Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?' Paper presented at the 1972 meeting of the American Association for the Advancement of Science, Washington, DC.

Table 1 IC elements matched with complexity ingredients

	IC elements	*Main IC-related blocks*	*Complexity ingredients*
1	Organizational and environmental discontinuities (Bettis & Hitt, 1995; Prahalad, 1998); Creative chaos (Nonaka, 1994)	Structural capital; Relational capital	*Tension* (force causing adaptation)
2	Periodic 'breakdowns' in human perception (Winograd & Flores, 1986); The role of contradiction (Piaget, 1974a, b); Organizational redesign (Bradford & Burke, 2005)	Human capital; Structural capital; Relational capital	*First critical value* (edge of order)
3	Organization redesign (Barnard, 1938); Fluctuation (Nonaka, 1994); Planning and imagination (Jantsch, 1980, p. 267); Decision making as 'organized anarchy' (March & Olsen, 1976)	Structural capital; Relational capital	*Dissipative structures* (phase transitions)
4	Edge of chaos in strategy making (Beinhocker, 1997); Fluctuation (Nonaka, 1994, p. 28)	Structural capital	*Second critical value* (edge of chaos)
5	'Garbage can' metaphor (Cohen *et al*, 1972); Emergent strategies (Mintzberg & Waters, 1985)	Human capital; Relational capital	*Region of emergence* (melting zone)
6	'Requisite variety' (Morgan, 1986); Interdependence (Lewin, 1951); Open innovation (Chesbrough, 2003)	Human capital; Relational capital	*Heterogeneous agents*
7	Self-organization in organizations (Thompson, 1967; Anderson, 1999; Axelrod & Cohen, 1999; Pastor & García, 2007; Bueno *et al*, 2008); 'Minimum critical specification' (Morgan, 1986); Self-organizing teams (Nonaka, 1994); Hypertext organizational design (Nonaka & Takeuchi, 1995); 'Reverse function of bureaucracy' (Merton, 1957); Self-organizing intellectual systems (Sahal, 1981)	Structural capital	*Self-organization*
8	Strategy as weeds (Mintzberg & McHugh, 1985); Experimentation and trial and error in strategy making in high-velocity environments (Salmador & Bueno, 2005)	Structural capital	*Tiny initiating events* (butterfly events)
9	Technology communications (Kelly, 1997); Alliance networks (Gay & Dousset, 2005); Degrees of connectivity (Santiago & Benito, 2008)	Structural capital; Relational capital	*Connections*; *Connectivities*
10	Intentionality (Oliver & Roos, 2000; Searle, 1983); Purposeful activity (Neisser, 1976); Pursuit of survival (Shimizu, 1995); Sense making (Husserl, 1968)	Human capital; Structural capital	*Motives to connect*
11	Learning (Argyris & Schön, 1978; Senge, 1990); 'Commitment' (Polanyi, 1966); Organizations as adaptive and evolving systems (Morel & Ramanujam, 1999); Co-evolutionary pockets and rugged landscapes (McKelvey, 1999); Evolution (Eigen, 1971)	Human capital; Structural capital; Relational capital	*Motives to survive and grow* (learn, change, adapt etc.)
12			*Bottom-up emergence*
	Strategy revolution (Hamel, 1998); Organizational redundancy (Nonaka, 1994)	Structural capital	a. *Emergent ideas*
	Cluster formation (Feldman & Francis, 2004); Alliance networks (Gay & Dousset, 2005)	Relational capital	b. *Emergent networks*
	Self-managed teams (Barry & Stewart, 1997); Communities of practice (Lave & Wenger, 1991)	Structural capital	c. *Emergent groups*
	New organizational forms (Illinitch *et al*, 1996)	Structural capital	d. *Emergent hierarchies*
13	Middle–Up–Down Management (Nonaka, 1994); Organization design (Galbraith, 1982; Daft, 1992; Lewin & Stephens, 1993)	Structural capital	*Upward and downward influence*
14	Organization culture as a complex system (Hofstede, 1997; Frank & Fahrbach, 1999; Hampden-Turner & Trompenaars, 2000; Chevrier, 2003; Earley & Peterson, 2004; Cameron & Quinn, 2006)	Structural capital	*Haken's enslaving principle*
15	Co-evolution between organization and environment (Norman, 1988; Von Krogh *et al*, 1994; Dooley & Van de Ven, 1999); 'Evolving communities of practice' (Brown & Duguid, 1991); Organizational knowledge creation (Nonaka, 1994, p. 27)	Structural capital; Relational capital	*Co-evolution*
16	Environmental and organizational changes (Brown & Eisenhardt, 1997; Hock, 1999; MacIntosh & MacLean, 2001; Fitzgerald, 2002; Stacey *et al*, 2002; Houchin & Maclean, 2005; McKelvey & Yalamova, 2011)	Structural capital; Relational capital	*Non-linearities*
17	Increasing returns (Arthur, 1994)	Human capital; Structural capital; Relational capital	*Equivalents to the sandpile's slope*

Table 1 (*continued*)

	IC elements	*Main IC-related blocks*	*Complexity ingredients*
18	Emergent innovation (Oster, 2009)	Human capital; Structural capital; Relational capital	*Self-organized criticality*
19	Information systems (Benbya & McKelvey, 2006); Scale-free business networks (Souma *et al*, 2006); Scale-free networks (Barabási & Bonabeau, 2003)	Structural capital; Relational capital	*Multi-level scale-free phenomena*
20	Ontological dimension of knowledge (Nonaka & Takeuchi, 1995)	Human capital; Structural capital	*Fractals*
21	PL distributions of productivity of innovation (Jones, 2005), PL networks (Barabási, 2002); Board of director networks (Battiston & Catanzaro, 2004); Hierarchal network organization (Ravasz & Barabási, 2003); Alliance networks (Gay & Dousset, 2005); Company networks in Poland (Chmiel *et al*, 2007); Worldwide investment networks (Song *et al*, 2009)	Structural capital; Relational capital	*R/F distributions* *PL phenomena* *PL indicators*

Given the association of many IC concepts with complexity elements shown in Table 1, we conclude with the following set of intermixed IC concepts and complexity elements.

a: IC systems include heterogeneous agents.
b: IC agents show connectivities and PL distributed networks.
c: IC agents show motivations to adapt, learn, change, innovate, evolve and so on.
d: IC systems show self-organization, emergence, and SOC.
e: IC systems with SOC extending over time show a unique endemic supportive culture.

Proposition 1: *IC-dominated firms will benefit more from complexity dynamics (i.e., self-organization, emergence, and SOC) than will firms dominated by tangible assets.*

Proposition 2: *IC dynamics, outcomes, and adaptability behaviours will appear non-linear, whether towards negative or positive outcomes. This is because we relate key IC elements to complexity ingredients and complexity dynamics, which cause non-linear outcomes.*

IC success? SOC *vs* the stochastic frontier

As originally conceived, SOC is a niche dynamic that maintains adaptive stability but offers no movement up or down the R/F distribution of a species' ecosystem. First, the sandpile shows PL-distributed sand grain movements as the sandpile copes with the sand grains dropping down on top of it. SOC means that the *slope* of the sandpile is maintained at a constant angle, given the amount of gravity and the irregularity (connectedness) of the sand grains. Second, in a niche comprising grass, rabbits, and foxes, each species adapts to the others – for example, foxes evolve to run faster; the rabbits evolve to dart here and there more quickly and hide better; the grass becomes more resilient. In a niche, species' *balance* substitutes for a sandpile's slope. Third, in what Iansiti & Levien (2004) call a firm's ecosystem, as one firm avoids being acquired, competes effectively with its direct competitors, keeps up with relevant technology, and customer tastes, we see the sandpile's 'slope' appearing as *stability* in the context of niche competition. Their example is Microsoft's ecosystem; it consists of some 38,000 firms ranging from very large ones, such as Motorola, to thousands of small companies. Most firms maintain SOC to remain in their particular sector of the ecosystem, of which Iansiti & Levien list 27 different ranks. However, some firms change rank.

Over millions of years, the *T Rex* finally emerged on top as the most vicious dinosaur; the killer whale emerged at its stochastic frontier – the apex of predators; small cats finally evolved into the tiger species – another stochastic frontier; the elephant ends up at the #1 rank of land mammals by size. Some firms also move up in rank, getting larger and larger. Microsoft kept learning, changing, and growing such that it moved up to the top of the software industry and then stayed on top. Apple was left far behind until Steve Jobs returned as CEO and then led Apple through a number of changes that revolutionized the laptop computer and then created the iPhone, iPad, and related products to now being the most valuable firm in the computer industry (and the most valuable firm in the world in 2011). Apple has clearly reached its stochastic frontier. Walmart has done the same in the retail business; ExxonMobil has done so in petroleum. For the past century, the United States moved up and then stayed at the 'countries' stochastic frontier, but many observers now put China in this position by 2050 or sooner.

Firms achieving the stochastic frontier clearly do not stay within the bounds of the sandpile-depicted SOC – although via plate tectonics some might conclude that

Mt. Everest has been pushed up to the stochastic frontier of sandpiles. Mostly, we think of the sandpile as just that, a sandpile, not a mountain. We now think of tigers staying as tigers; we do not really expect them to further evolve – say by somehow getting mixed up with elephant genes – though in another 70 million years, who knows? But with firms within our lifetimes, we can see Microsofts, Apples, Walmarts, ExxonMobils, Carrefours, Siemenses, and other giant firms grow to become the #1 ranked firm in their R/F distributed industry. Interestingly, research by Ishikawa (2006) indicates that industries that, as a whole, appear to be maintaining SOC – meaning that there is lots of M&A, shrinking and growing, disappearing and so on within an industry – are the ones in which we see firms changing rank, whether by growing or shrinking or disappearing.

Using scale-free causes to reach the stochastic frontier

Pareto and PL distributions do not just happen by chance. We now are aware of various causes identified over the years in physics, biology, and to a much lesser extent in the social sciences that give rise to scale-free dynamics and consequently R/F distributions. What are scale-free (SF) causes?

Suppose that the same causal dynamic applies at multiple levels in some kind of R/F distribution, explanations of these are termed ‘scale-free theories’. Gell-Mann (2002) now refers to these as the second regularity in science, reductionism being the first and scalability being the second. Since well-formed long-tailed Pareto distributions are now equated with PL distributions, and since PL distributions are straight lines appearing when the data are plotted on double-log scales, it follows that the same causal dynamic repeats across the various sections of a log scale, that is, 1–10, 10–100, 100–1000, or 5–25, 25–250, 250–2500 and so on, as it does in hierarchies based on R/F distributions – as in the retail industry Walmart #1 at end of the hi-rank tail and the 17 million Mom & Pop stores at the end of the opposite long tail of the Pareto distribution. Andriani & McKelvey (2009) list 15 scale-free theories applying more obviously to organizations. We present several of these in Table 2. For further discussion of managerial implications, see Andriani & McKelvey (2011b) and McKelvey & Andriani (2010).

The *square–cube* law explains the growth of car manufacturers and dealerships; the bigger and more efficient the car manufacturing factory, the more dealerships are needed to show and sell cars to customers; the more dealerships, the larger the factory can become; the factory is the cost centre with ‘volume’ employees; the people working at dealerships are the ‘surface’ employees. As with the cauliflower, it takes the growth of many relatively small dealerships to attract customers in small towns and various neighbourhoods of larger cities to sell enough cars to pay for the cost of the factory. Making a great car is not enough; it also takes the square–cube ratio of factory and dealership growth.

Preferential attachment theory explains Amazon’s growth via the Internet as more people used Amazon to buy books. Amazon added other product lines, as each new line was added more people were attracted. Once people got used to using Amazon to buy one kind of product, it was efficient for them to use Amazon to buy other products. Shopping malls are also good examples of preferential attachment. The larger the mall, the more stores, brands, and products customers have access to on one shopping trip. The more the customers are attracted to the mall, the more incentive they have to add more stores and products. Or, as Southwest Airlines and Easy Jet lowered costs by buying only one kind of plane, lowering fares, making union jurisdictions more flexible, and shortening turn-around time at airports, they attracted more customers. Because they attracted more customers, they filled up more planes, became more efficient per flight, and then could lower costs and fares even more. Nowadays, they may not be at the stochastic frontier by size, but they have been fierce competitors against the other airlines.

Least effort in communicating accurately allows multinational companies to grow much faster, more efficiently, and with fewer mistakes if their employees have to use different languages accurately: each person learns just enough company-relevant words and grammar in the relevant foreign languages to understand presentations, relevant documents, and to communicate person-to-person well enough in the different languages to avoid damaging mistakes. Efficiency dominates because each employee only uses words that people from other countries understand, the latter only have to learn words other employees use. Boeing’s ability to sell planes in foreign countries – that is, continue dominating the global supply chain – means responding to each country’s requirement to build some parts locally. This requires managing quality control in multiple languages. The megastores that Walmart and Carrefour operate are also examples of least effort. They are least effort for customers since they get access to many more products on one shopping trip. They are least for the retailers since they need fewer employees per product to operate the giant stores.

The three SFs listed above apply to all kinds of firms, whether or not IC-dominated. The following four SFs are more apt to occur in IC firms because they are more idea-driven. Furthermore, ideas are more likely to be susceptible to the events that set off SF processes.

Spontaneous order creation stems from the random mixing of heterogeneous agents (employees). A classic example of this is when a new CEO at Monsanto created a circumstance in which five or six previously isolated employees (engineers, scientists, finance experts) came together to generate bioengineering at Monsanto, which in turn generated all sorts of new kinds of products, more advanced science and engineering, and more positive returns to scale (Day & Colwell, 2006). Monsanto is now at the global stochastic frontier of the agricultural chemicals industry.

Table 2 Empirical basis of scale-free causes of PL[a]

Theory	*Explanation*
Square/cube law	*Cauliflowers*: In organisms, surfaces absorbing energy grow by the square but the organism grows by the cube; results in an imbalance; surface subunits increase to bring in more energy to support the internal volume entities and re-establish balance. In firms, 'internal' employees are costs; 'surface' employees – those who connect with people buying the product – are sources of energy, that is, income
Least effort	*Efficiency*: Word frequency is a function of efficient learning of and ease of usage by both speaker and listener; they converge in their use of similar words; they do not spend energy learning words not used. This law applies to firms, cities, and economies in transition
Spontaneous order creation	*Heterogeneous agents* seeking out other agents to learn from so as to improve fitness generate networks; some networks become groups, some groups form larger groups and hierarchies
Phase transitions	*Turbulent flows*: Exogenous energy impositions cause autocatalytic interaction effects at a specific energy level – the first critical value or tipping point – such that new interaction groupings form. These appear as abrupt phase transitions, that is, dramatic innovations that are needed to deal with new problems. Apple's invention of the iPhone caused a phase transition
Preferential attachment	*Nodes*: Given newly arriving agents into a system, larger nodes with an enhanced propensity to attract agents will become disproportionately even larger. The rich gets richer. This explains the hub and spoke design of airports and why banks get bigger and bigger
Irregularity-generated gradients	*Unexpected groupings*: A crisis, significant change, or M&A activity brings strangers together. Seemingly insignificant random ideas, coupled with positive feedback, start an autocatalytic process feeding on emergent creativity, which produces even more creativity, which spirals into the growth of innovation systems and new product ideas
Contagion bursts	*Idea contagion*: Often, viruses are spread exponentially – each person coughs upon two others and the network expands geometrically. But changing *rates* of contagious flow of viruses, 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 avalanches result in the PL signature due to the small-world structures of the transient underlying networks
Self-organized criticality	*Adaptation to maintain stability*: Under constant adaptive tensions of various kinds (coping with changing competitors, products, and industry dynamics), firms reach a critical state where they are able to constantly maintain profitable stasis by preservative behaviours – such as new hires, organization and strategy changes, new products, M&A activities and so on – which vary in size of effect according to a PL

[a]Paraphrased from Andriani & McKelvey (2009); they list a total of 15.

Irregularity generated gradients are random tiny initiating events that have marked outcomes. Apple's translation of the traditional mobile (cell) phone into the iPhone markedly changed the world we live in and Apple's asset value. The iPhone combined several key elements of current computer design into a small hand-held device, including touchscreens, immediately available Apps (~650,000 applications now available), computing ability, cloud computing to add storage, state-of-the-art Internet connections and so on. It was followed by iTunes, iPod, iPad, and now the mini iPad. These immediately led to competing products from other companies. While the iPhone invention shot Apple out to the stochastic frontier, this position is now in contention from the likes of Samsung and Google, and perhaps even Microsoft and Nokia.

Contagion bursts are exemplified by the recent non-business examples in the Arab Spring uprisings in North Africa set off by some incident (like the man setting himself on fire) and then going 'viral' via mobile phone calls and associated networks. Networks can act as substitutes for crowded rooms or airplane cabins (the latter speed up the spreading of the flu-virus infection because a person's coughing is in a confined space). Or, one person learned what iPhones could do, happened to contact the social star of her/his network, and then this 'star' spread the idea to everyone else in the network. People already networking via mobile phones quickly lined up to buy iPhones and then iPads and so on. Until recently (late 2012), Apple had the highest market capitalization value of all companies worldwide. Yes, we have used the Apple example for two SFs; but then Apple has gone from an average to the stochastic frontier faster than most other companies.

Phase transitions usually stem from imposed tension, the classic example in the business world being Jack Welch's famous phrase, '*Be #1 or 2 … or else …*' (Tichy & Sherman, 1994, p. 114, somewhat paraphrased). Welch imposed the tension on the manager (and his/her superiors) of one of General Electric's 350 businesses (at the time), but left it up to the manager(s) as to how to change things in his/her business to get going on the needed improvements necessary to move up the

R/F distribution of his/her industry. Tension-induced phase transitions are marked changes initiated by unexpected employee interactions and idea exchanges stemming from combining departments or from M&A activities that bring in new people and ideas while getting rid of inefficient or intellectually dead departments.

Why aren't all firms equally likely, or equally susceptible, to the kinds of unusual SF-caused growth that can send a firm out to the stochastic frontier? First, many firms gain their competitive advantage via pursuing efficiency-dominated economies of scale (Miller, 1990; Arthur, 1994). Miller's book is about efficiency-dominated firms that put achieving efficiency above keeping up with a changing environment (i.e., maintaining SOC) – so much so that they are eventually driven out of existence. Second, as Arthur (1994) observes, 'positive returns to scale' not only provide above-average profits – as does the successful pursuit of efficiency – but they also do not face the ultimate limitations of efficiency. While there is a demonstrable limit as to how efficiently any given part of, say, an automobile can be made, there is – in principle – a much less-defined limit to positive returns to scale. IC, and specifically the association, fostering, mixing, creating, or discovering, and changing of ideas and intangible assets, in principle, face no limit to the potential positive returns to scale that may be forthcoming from new idea-generated new products. Therefore:

Proposition 3: *SF causes and dynamics underlie the positioning of firms out toward their industry's stochastic frontier.*

Proposition 4: *SF causes more readily apply to movements toward the stochastic frontier by IC-dominated firms.*

Since IC-dominated firms are especially susceptible to SF causes:

Proposition 5: *Attributes of IC-dominated industries also will be especially well characterized by PL distributions.*

When PLs may indicate effective IC complexity dynamics

Interestingly, we now have increasing evidence about what PLs describe as the changing dynamics that allow species and firms to maintain their position at a given rank of a species or industry R/F distribution, as illustrated in the 19 studies showing PL distributions of predator/prey dynamics cited by McKelvey *et al* (2012) – equivalent to M&A activities in industries. Reality shows that PL distributions characterize free-market dynamics, resilience of firms, resilience of ecosystems, evolutionary growth dynamics, and the ability of some species, some industries, and a few firms within a given industry to reach the stochastic frontier. What we see increasing evidence of is that PLs may be used as indicators of (1) SOC and also (2) industries open to free firms' movements up and down R/F distributed industries. Moving up an R/F distribution – that is, towards the rank = 1 end of the 'rank' long tail – could mean moving towards the stochastic frontier. We discuss PLs as indicators next.

PLs as indicators

What would it take for the Italian income data plot to become fully represented by a PL straight line? At the lower right of Figure 3, we see the PL line. This represents people having the highest incomes. Coelho *et al* (2008) actually find a 'double power law' for the rich and the very rich. Consider the 'theory of wealth' presented by Montroll & Badger (1974). They argue that 'wealth' requires minimum amounts of appropriate social background, education, personality type, technical ability, communication skills, motivation, being in the right place at the right time, willingness to take risks. When the young Billy Gates dropped out of Harvard University to buy the computer file management company just as IBM was creating its first portable computer, he had all of the 'wealth amounts' working for him (including his mother's connections with IBM's Board of Directors); the rest is history. Connectivities are a key part of the upper income class: they know the right financial and legal advisors, they know a board member, they play golf with other rich people, they readily meet and can connect with other rich people and so on. Alternatively, who is at the upper left low-income portion of the graph? These are the blue-collar workers and secretaries. What they get paid for is a function of what they do and how many hours they work, not on whom they know and not on their connections.

How straight is the PL line?

Physicists tend to think of good empirical research as finding 'universal' truths, like the earth goes around the sun. Thus, they take interest in the findings by Nitsch

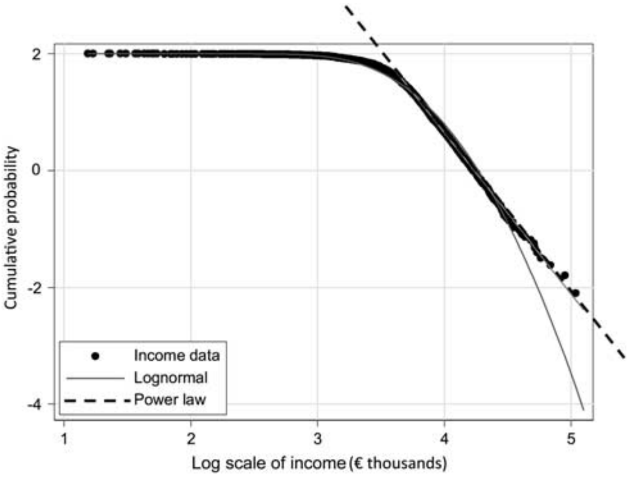

Figure 3 Italian income data.

(2005) and Soo (2005) that 'Zipf's Law' (Zipf, 1949) – which holds that the inverse-sloping PL line should show an $\alpha = -1$ slope of the ordinary least squares (OLS) line – is false, since it is not universally true. Nitsch and Soo both find that the PL alpha of the R/F of cities (from the one largest city to the thousands of small towns) in various countries shows considerable variance. For example, Nitsch finds that while the Zipf's Law alpha is pretty much normally distributed its range goes from 0.5 to 2.0 (they both ignore the minus sign). Hence, Zipf's Law in which $\alpha = 1$ is not a universal truth. Soo's study finds that the alphas of 73 countries range from 0.73 to 1.72. He finds that variables such as 'transport cost' and 'total government expenditure' have more effect on alpha than other economic geography variables. Thus, the more scale economies, the higher is alpha; the lower are transport costs, the higher is alpha; the more government expenditure, the higher is alpha. These factors combine to create weaker to stronger PL distributions of city sizes. There is no universal truth about how well each and every city works in any given economy, nor how or why it contributes to the value of alpha. But we do see, however, that countries with higher GDP have higher alphas; countries with lower GDP have lower alphas. Some high and low alpha examples are shown in Table 3.

As we demonstrate with Italian income in Figure 3, a country's income distribution really consists of sub-distributions. Comparably, in most economies, part of the city's R/F is PL distributed but other parts may not be; weaker-performing cities do not plot out so as to closely fit the alpha slope. Generally, whether in city growth (Andriani & McKelvey, 2011a; McKelvey, forthcoming) or in corporate market capitalization (Glaser, 2013), faster growing economies, cities, and firms show an $\alpha < 1$ slope because they are moving up in the size rank (i.e., out to the right on the X-axis in Figures 1 & 2), whereas slower growing countries, cities, and firms show an $\alpha < 1$ slope because they are sliding down the R/F distribution.

While well-working 'hot' economies and firms show a higher truncated OLS (ordinary least squares) fit to a PL inverse-sloping line, they also show that cities in other regions of the country (or firms at a different position in their industry R/F distribution) are below the OLS line. While molecules and planets may show universally consistent behaviour, human beings, firms, cities, and the countries they are in usually do not. Consequently, it does not make sense to calculate the OLS estimate of alpha across entire country or industry R/F distributions, as Clauset *et al* (2009) suggest. Focusing on the truncated sections is more useful – we follow Goldstein *et al* (2004) in this approach. Comparing the straightness of the double-log data plot relative to an inverse straight line is useful, however, because one can see the cities or firms that are above or below the line and hence this shows whether or not segments of a country or industry are doing well. Alphas are not −1 sloped 'universal' features, as Zipf initially proposed and as recently empirically shown by Nitsch (2005) and Soo (2005) (see Table 3). Whether or not SOC dynamics are working well in various countries or industries, it is important to find this out and respond accordingly. There is, then, a fundamental conflict between using alpha to indicate whether the PL line fits across an *entire* R/F distribution *vs* using PLs to find out the *segment* of an R/F that is strong or weak.

Table 3 Zipf's law: strong and weak economies[a]

High-alpha countries	*Alpha*	*Low-alpha countries*	*Alpha*
Australia	1.23	Belarus	0.84
France	1.45	Chile	0.87
Germany	1.24	Ecuador	0.81
Japan	1.32	Guatemala	0.74
Sweden	1.44	Jordan	0.89
United Kingdom	1.40	Kenya	0.82
United States	1.37	Syria	0.74

[a] From Soo (2005, p. 246) Table 1; city-size data dates back to 1989–2000.

PLs offer indications that city PL distributions are associated with stronger economies (Table 3) and they also characterize firms' market capitalization distributions (Figure 1) – both of which show a city or firm out towards the end of the X-axis and thus at the top (stochastic frontier) of its R/F distribution. Given these findings, we follow Andriani & McKelvey (2011a) and McKelvey (forthcoming) in arguing that PLs may be treated as indicators of SF dynamics accompanied with other complexity dynamics, such as agent interactions, self-organization, emergence, well-working SOC. Therefore:

Proposition 6: *The greater the economic viability (i.e., adaptive capability and growth) of an IC-dominated industry, the more it will be characterized by a PL distribution and the more likely that individual firms within the industry will also have various PL distributed internal characterizations.*

IC, PLs, and the stochastic frontier

As noted earlier, much of the existing research pertaining to stochastic frontier analyses focuses on measures of tangible elements in firms. Although we cite a few articles that mention IC elements of firms in conjunction with stochastic frontier dynamics, it is important to note, however, that existing empirical studies do not show much in the way of measuring specific intangible elements. Mostly, they subtract tangible measures from overall market value to get a *proxy measure* of a firm's intangible value.

There is always the chance that a firm will be 'SOC' like a sandpile, that is, it will depend on self-organization, emergent behaviour, and SOC to maintain its particular competitive skills and adaptive capabilities – and hence its relative competitiveness and niche location – in the R/F distribution of its industry. But this is not a movement towards its stochastic frontier. There is always the chance (if not likelihood), however, that one or more firms, and especially one in particular, will find or develop a set of IC capabilities markedly better than the IC abilities of the other firms in its industry.

In fact, for Propositions 4 and 5 to hold, there has to be movement by various firms out towards the stochastic frontier (with one dominating out at the end of the long-tailed Pareto distribution) for the PL distribution to actually emerge. Presuming that one or more scale-free causes apply in a given IC-dominated industry, it follows that a few firms – and especially one – will be able to capitalize on several scale-free causes in combination so as to move out farthest towards the stochastic frontier, and in fact actually define it. Most likely, it is one particular firm – like Apple with its iPhone and iPad these days – that creates an IC stochastic frontier that no other firm even imagined, let alone accomplished. Needless to say, however, once Apple defines the new stochastic frontier, other IC firms (e.g., Samsung, Google, Microsoft, Nokia etc.) start competing movements towards the *new* frontier. In dynamic, novelty producing industries, there always seems to be one firm that defines a marked new efficiency-based stochastic frontier: for example, Ford Motor Co. nearly a century ago, Cunard Line with its Queen Mary, and more recently the Tata Group, Kraft Foods, and Walmart. In the IC arena, we had IBM, HP, Microsoft, Siemens, and now Apple.

Proposition 7: *Given complexity dynamics multiplied by intangibles and their enhanced connectivities, the rise of IC firms to the #1 rank at the stochastic frontier should appear more marked and happen more quickly, but their stay at the top is likely more transient.*

Conclusion

We begin by reviewing IC research and the few attempts to study how close IC firms are to the stochastic frontier. Then we review basic complexity theory, with special attention to Bak's (1996) SOC, fractals, and PLs. Next we distinguish between two kinds of IC firm success: (1) Traditional SOC applications as to how species maintain their position in a changing niche or how firms maintain their position in a changing industry *vs* (2) How an IC firm (such as Apple) creates a new stochastic frontier. We discuss how to use PLs as indicators of whether or not firms and industries are SOC-effective. We include seven propositions pertaining to: (1) How IC firms benefit from complexity dynamics and SOC; (2) Why they may be characterized by PL distributions; (3) How PL distributions are indicators of efficacious SOC and adaptivity; and (4) Why IC attributes (especially intangible components and connectivities) serve to create more transient dynamics pertaining to the stochastic frontier and the rest of the industry's R/F distribution (i.e., one large firm, e.g., Apple at the frontier and thousands of smaller firms fleshing out the rest of the industry's ecosystem) (Iansiti & Levien, 2004).

Judging from recent empirical research (Kwan & Eisenbeis, 1996; Jacobs, 2001; Simar & Wilson, 2007; Rosko & Mutter, 2008; Kuo & Yang, 2012), the empirical details of measuring how or why IC firms do or do not reach the stochastic frontier are mostly unmeasured or researchers rely on proxy measures. To develop a better and more relevant set of IC-rooted measurable intangible variables, we propose focusing on complexity theory-related intangibles like self-organization, emergent structures, SOC, and PLs, for the purpose of evaluating why some IC firms are more productive and innovative than others.

Our primary contribution is to focus on how and why the complexity concept, SOC, is especially useful in studying and explaining why some IC firms move out more quickly towards the stochastic frontier, or create a new frontier as Apple did, whereas others do not. What is especially interesting is that while SOC can help a firm stay in its competitive position in its industry R/F distribution, which is good for many firms, it is also good for a firm to leave its current position in its industry and move out towards, or even to, #1 rank at the stochastic frontier. The latter sets up a totally different application of SOC in industry dynamics. For an *industry* to survive or grow relative to competing industries (e.g., coal *vs* green; fast food *vs* healthy food; laptops *vs* iPhones and cloud computing), it needs new definitions of its stochastic frontier now and then. But in addition, a well-working competitive and appropriately changing industry needs SOC dynamics working all across the rest of the industry as firms change, grow, or fail given the new concept of the frontier firm – Apple being a good example of a new frontier firm and all the consequent survival tension imposed on the lower ranked competing firms. Microsoft's ecosystem is a good example of SOC working well across an entire industry (Iansiti & Levien, 2004), which is PL distributed (McKelvey *et al*, 2012). Given that well-working SOC dynamics are required for industry change, growth, and survival, the PLs become good indicators of whether or not an industry is well endowed with SOC dynamics.

We include a set of propositions that summarize the main contributions of our paper and set up our theoretical development for subsequent empirical tests. Our propositions mostly focus on SOC, connectivities among ideas and employees, and PL thinking, all of which fit IC dynamics and dominate the world of IC management practitioners. Current management research focuses almost entirely on the presumption of normal distributions and empirically measured tangible assets, especially obvious in the articles connecting IC firms to stochastic frontier research. Complexity theory and econophysics research offer many new theories, concepts, and methods that are especially relevant to IC theory and its application to firms. Consequently, the key elements in our summary propositions are especially relevant to IC practitioners. The more the current IC theorists apply complexity thinking to IC phenomena, the more practitioners will benefit.

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