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## **Four types of emergence: a typology of complexity and its implications for a science of management**

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**Abstract:** Complexity science has the potential to explain emergence; unfortunately most management applications of complexity rarely define emergence. We develop a typology that defines four increasingly demanding definitions of emergence, and use this typology to organise a review of the complexity literature, focusing on computational models that have been utilised by management scholars. We generate propositions addressing the value of emergence and complexity for integrating theory and practise in the field. Self-organisation and emergence offer methods for integrating a variety of management frameworks, allowing researchers to draw together some of the disparate threads of management theory and practise. An expansion of 'emergence' processes in organisations fosters adaptive bottom-up innovations and change.

**Keywords:** complexity science; emergence; self-organisation; typology; organisation science; heterogeneous agents; agent-based computational modelling; epistemology; social science; social structure

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## 1 Complexity science in management

Many researchers suggest that complexity research can play an important role in organisation science and management (Brown and Eisenhardt, 1997; Anderson et al., 1999; Lichtenstein et al., 2006; Dooley and Lichtenstein, 2008; Allen and Boulton, 2011; Merali and Allen, 2011; McKelvey et al., 2011b; Thietart and Forgues, 2011). Complexity science aims to explain how heterogeneous agents 'self-organise' to create new structure in interactive systems, with the goal of understanding how such structures emerge and develop (Anderson et al., 1988; Colander, 2000; Dal Forno and Merlone, 2007; Epstein, 2007; Hazy et al., 2007; McKelvey and Lichtenstein, 2007; Miller and Page, 2007; Schreiber and Carley, 2007, 2008; Spada, 2007; Mitchell, 2009; Goldstein, 1999, 2007, 2011; Prietula, 2011; Tracy, 2011).

Complexity has been used in various management contexts to explain such phenomena as *leadership* (Uhl-Bien et al., 2007; Marion, 2008; McKelvey, 2008, 2010; Marion and Uhl-Bien, 2011), *organisation design* (Levinthal and Warglien, 1999; Azadegan and Dooley, 2011; Boisot and McKelvey, 2011a), *network structuring* (Carley, 1999b; Andriani and Passiante, 2001; Newman et al., 2006), *organisational evolution* (Dyke, 1988; Khalil and Boulding, 1996; Morel and Ramanujam, 1999; Mitleton-Kelly, 2003), *innovation and entrepreneurship* (Andriani, 2011; Lichtenstein, 2011a) and *strategic adaptation* (McKelvey, 1999a; Gavetti and Levinthal, 2000; Rivkin, 2000; Baumann and Siggelkow, 2011; Eisenhardt and Piezunka, 2011), to name just a few.

Understanding how and why new structural order emerges in social systems has been at the core of sociology and management studies for many decades, as evidenced by the following:

- Adam Smith's exploration into the development of industrialisation through division of labour.
- early studies of bureaucracy (Weber, 1924, 1947) and the evolution of professional management by Barnard (1938)
- research on the impact of internal structure on work group behaviour (Roethlisberger and Dixon, 1939)

- studies of the relationship between internal and external order (Lawrence and Lorsch, 1967; Thompson, 1967)
- analyses of strategic partnerships (Powell, 1990; Yoshino and Rangan, 1995)
- ongoing management studies into the emergence of order and structure within entrepreneurial executive teams and firms (Bygrave and Hofer, 1991; Lichtenstein, 2000)
- many studies of organisational network dynamics (Nohria and Eccles, 1992)
- studies of organisations experiencing rapid change (Brown and Eisenhardt, 1997).

These studies exemplify the enduring importance of emergence in the study of organisations. Complexity science embodies important, new research methods and an epistemology for understanding the nature of, and processes underlying, agent self-organisation and emergence.

Unfortunately, management applications of complexity rarely explain what ‘emergence’ is, nor do they reveal the underlying dynamics of self-organisation (Cohen, 1999). Reviewers have lamented that complexity writers often use these ideas merely as a figure of speech that makes vague references to emergent phenomena, without providing a scientifically grounded definition of emergence (Maguire and McKelvey, 1999). Moreover, very few authors have shown how complexity science explains organisational phenomena more completely or differently than existing management theories. Without some clear ‘value added’, complexity is simply another management fad (McKelvey, 1999b).

In order to expand the explanatory power of complexity science, and to further our understanding of emergence in general, two criteria must be met. First, a clear definition of emergence is necessary to guide the development of models and to focus attention on those studies that reveal the dynamics of emergence. Second, complexity science must provide a useful and testable understanding of emergent behaviour in organisational settings.

We attempt to satisfy both of these criteria in the present paper. To begin, we integrate two dimensions of prior research to develop a four-cell typology that defines four types of emergent structure. Next, we provide a complete review of computational complexity studies in the management literature, using our typology as an analytic framework. Specifically, we focus on agent-based computational models (ABMs), since these are particularly useful for theorising about emergent social structure. Finally, we draw out the implications of our analysis, which suggest that the methods and epistemology of complexity – when used appropriately – can bridge the longstanding gap between traditional science and postmodernist narrative-style research (McKelvey, 2003; Boisot and McKelvey, 2010, 2011a, 2011b; Byrne, 2011; Cilliers, 2011), eliminate the dichotomy between academic scholarship and management practise (Sussman and Evered, 1978; Whyte, 1989; Rynes et al., 2001; Bennis and O’Toole, 2005; Ghoshal, 2005; Benbya and McKelvey, 2006, 2011; Van de Ven and Johnson, 2006; Gulati, 2007; McGahan, 2007), and bring management into the leading edge of epistemologically legitimised social science research.

## 2 Emergence and complexity in organisation studies

Fundamental complexity research has existed for several decades. According to some complexity scholars (Mainzer, 1994) complexity science begins with Prigogine's (1955) research on far-from-equilibrium thermodynamics, which explains how regimes of order, as 'dissipative structures', come into being and retain their form amidst a constant dissipation of energy and resources.<sup>1</sup> At the same time researchers in many disciplines began to study non-linear processes inherent in dynamic systems. Several major schools of thought materialised, including cybernetics (Weiner, 1948/1961), system dynamics (Forrester, 1961), self-organisation (Ashby, 1947), genetic algorithms (GAs) (Holland, 1975), chaos theory (May, 1976), synergetics (Haken, 1977), catastrophe theory (Zeeman, 1977), autopoiesis (Maturana and Varela, 1980), fractals (Mandelbrot, 1983), and complex adaptive systems (CASs) (Holland, 1995, 1998). Each of these has contributed to a broadening interest in the phenomenon of emergence (Goldstein, 1999, 2000, 2011).

Following Gleick's (1987) best-selling book, some of these approaches became known as 'chaos' theory. Some years later, Lewin (1992) and Waldrop (1992) developed syntheses of these models using 'complexity' as an overarching framework. Complexity theory insights relevant to management have been featured in several special issues in top journals including the *Journal of Management Inquiry* (Bartunek, 1994) and *Organization Science* (Anderson et al., 1999), and this research has generated whole new journals dedicated to these ideas, including *Nonlinear Dynamics in Psychology and the Life Sciences*, *Emergence* (now *Emergence: Complexity & Organization*), and the *International Journal of Complexity in Leadership and Management*. In just the past 20 years, 4,222 articles using key themes of complexity have been published in management journals.<sup>2</sup>

With this florescence, however, has grown theoretical and empirical obfuscation, due to an ever-proliferating range of meanings and operationalisations for emergent order in management settings. 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 (1997) 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 this broad range of definitions can complexity science make a coherent contribution to management theory (Cohen, 1999).

To organise these disparate notions of emergence, we classify them according to heuristics developed by philosophers studying the nature and properties of emergence more broadly. This analysis, in the following section, leads to our typology of emergence.

## 3 Degrees of emergence and a typology

Evolutionists and philosophers of science have observed the basic elemental qualities of emergence for over 100 years (Lewes, 1877; Morgan, 1923; Pepper, 1926; Zipf, 1929, 1949; Wheatley, 1992; Goldstein, 1999, 2011). Basically, emergence is a systemic

process through which properties and or structures come into being that are unexpected, given the known attributes of component agents and environmental forces. Sociologist Herbert Mead provided an intuitive definition in 1938:

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

Straightforward as Mead's statement appears to be, philosophers are still debating the challenges this early conception raised for defining the nature of emergence and its causal properties in complex multi-level systems (Kim, 1992; Bedau, 1997; Schröder, 1998). These challenges go beyond defining what it means when 'things get together', or how to identify 'something that was not there before', or how to understand the influence that the emergent combination has on the components that make it up.

A number of ways of measuring the impact of emergence have been developed by complexity researchers (e.g., Dooley and Van de Ven, 1999; Lichtenstein et al., 2007). However, virtually all of these can be integrated into a simple  $2 \times 2$  framework for explaining emergence in dynamic systems. We summarise these constructs as *agent heterogeneity* and *causal intricacy*. These constructs can be framed as dimensions that describe two fundamental elements of complexity science:

- 1 *Agent heterogeneity* refers to the degree of heterogeneity that agents, the basic units of complexity, are assumed to have. Traditionally sciences have assumed agents to be homogeneous – all atoms or molecules alike, for example (Suppe, 1977; Casti, 1997). In contrast, the social sciences have progressively emphasised the uniqueness of agents for purposes of analysis within a discipline (e.g., sociologists do not assume all social entities are homogeneous), instead focusing on the elemental properties of agents as increasingly heterogeneous, more clearly defined, and more distant from the properties of adjoining agents.

One key assumption that remains in all sciences except complexity, is that agents at a lower level must be assumed homogeneous for variance to be explained at a higher level (Rousseau, 1985). Instead of making this assumption, complexity scientists identify the degree of *agent heterogeneity* in a system. This has helped philosophers distinguish weak vs. strong forms of emergence (Newman, 1996; Bedau, 1997), and has also helped to explain the emergence of one versus multiple levels of order, particularly in complex social environments (Broad, 1929; Simon, 1962). Complexity science's emphasis on agent heterogeneity is reflected in the number of disciplines (languages) used to describe agents, including physics, biology, neurophysiology, psychology, social psychology, sociology, economics, etc.; together these identify the multiple layers of agents and their components (Coren, 1998).

- 2 *Causal intricacy* refers to the influences that coevolving agents have on adjacent higher and lower levels (groupings) of agents that emerge through agent interactions. Two types of *causal intricacy* are well described in science. *Traditional reductionism* assumes only upward causality; thus it defines emergence solely as a linear accumulation of properties, the outcome of which is broadly deducible assuming that agent behaviour and interaction rules are known (Kauffman, 1993;

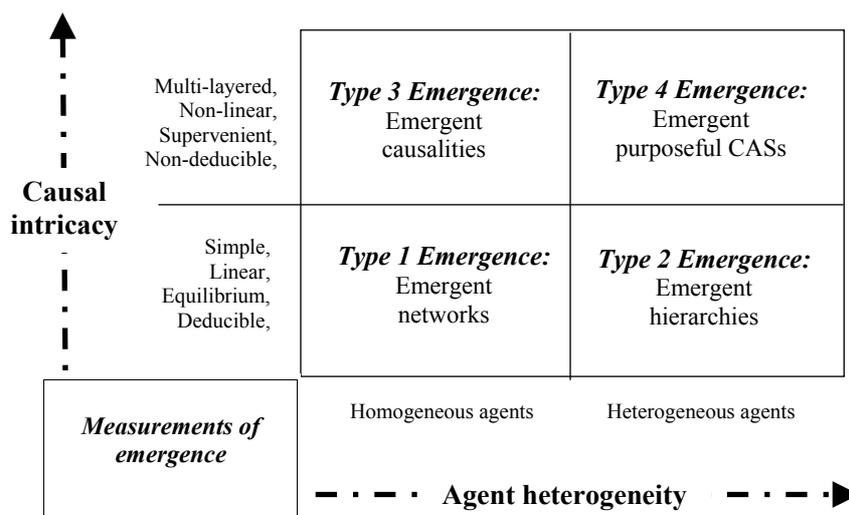
Crutchfield, 1994; Levinthal, 1997). At the other end of the *causal intricacy* spectrum are studies of *Emergence* that show how an emergent structure influences its components through downward causality or ‘supervenience’ (Klee, 1984; Sperry, 1986; Blitz, 1992). Such ‘top-down’ effects complicate causal connections and forces, making it much more difficult to pinpoint and predict the origin of specific effects. As McKelvey (2004) showed in his paper on complexity science in entrepreneurship, emergent systems – those with coevolutionary and supervenient properties – may demonstrate one of six distinct modes of causality,<sup>3</sup> including Aristotle’s final cause, i.e., purposefulness (Ackoff and Emory, 1972). Interacting, the six causes result in non-deducibility (Schröder, 1998) and potentially striking non-linearities (Maruyama, 1963).

For analytical simplicity we frame these constructs as two dimensions which we assume to be orthogonal; this leads to a two-by-two typology with four quadrants (see Figure 1):

- Type 1 emergent networks
- Type 2 emergent hierarchies
- Type 3 emergent causalities
- Type 4 emergent purposeful CAS.

The first two types of emergence comprise simple upward causality and homogeneous agents. The second two types comprise coevolving heterogeneous agents with increasing degrees of causal complexity. Each type of emergence is progressively more intricate and multifaceted than its predecessor. More importantly, each successive type defines emergence in a more stringent way, such that what is considered ‘emergence’ of the first type would not be defined so in types two through four, and so on. In the same way, the four types range along a continuum of analytic intricacy and arduousness, such that each successive type presents more challenges to researchers and modellers.

**Figure 1** Typology of emergence



Finally, our typology highlights two additional dynamics to be discussed later in the paper. The first dynamic represents the continuum of analytic complexity, from the minimal specifications of an agent as a two-level hierarchy of components and emergent properties (Type 2 emergence), to the analytic richness gained by three-level specifications (Type 3 emergence) in which agents are defined by their components, a focal level of action, and by their contexts (Koestler, 1979; Salthe, 1989, 1993). The second emergent dynamic foreshadows our argument that complexity science may be epistemologically more effective than traditional science at explaining the complex emergent phenomena most relevant to management scholars.

Next, we describe these four types, highlighting the definitional differences. After setting up our typology, we use the four types of emergence as a framework for understanding the agent-based computational-modelling-based complexity research in management. Finally, we discuss the implications of our typology for management science, by detailing the two additional dynamics referred to just above.

## **4 The four types of emergence**

In the next four subsections, we describe most of the properties within each of these four types of emergence. In addition to a useful integrating mechanism, each type can be linked to any of the publications on ‘complexity science’ – these four capture all current research in the field, and point a way forward to further possibilities. Note that each set of citations refers to a rather large literature; for example Schröder (1998) and Bechtel and Richardson (1992) reflect just two of about 100 articles in the philosophy of science asking: How exactly can we define ‘emergence’.

### *4.1 Type 1 – emergent networks*

The simplest type of emergence focuses on system-wide characteristics that can be distinguished from the components of which they are comprised. This type depicts basic reductionist science – the nature of the whole may be deduced from the nature of its parts. Unlike the other three types, these emergent characteristics are analytically deducible post-hoc: The systemic structures can be predicted from a linear analysis of the components and their relational properties. In Type 1 emergence the distinction between the agents and their collective properties is fuzzy at best; the term ‘network’ captures the indistinct interactions between components and structure.

The most common management applications of Type 1 emergence involve the explanation of collective action (Granovetter, 1978; Macy, 1991). Mathematical sociologists utilise network theories to explain the emergence of behavioural structures in social networks (Burt, 1992; Zeggelink et al., 1996). In these models, network structures at one systemic level are emergent phenomenon that can generate unexpected levels of social action (Gladwell, 2000). Yet, the actual emergence of these structures is fully explainable by the theory (So and Durfee, 1996). Equally important, mathematical algorithms have been developed for logically deducing how each individual’s place in the network explains the structural features of the network as a whole (Borgatti et al., 1992). In this sense, emergent network structures are deducible from an understanding of the network’s components (people) and a composition principle (their relationships) using traditional algebraic logic (Wasserman and Faust, 1994).

#### 4.2 *Type 2 – emergent hierarchies*

The second type of emergence evokes the more formal definition of ‘qualitative novelty’ – an emergent property or structure is defined as ‘different in kind’ from its components. One of the most effective ways to distinguish qualitative novelty is when the disciplinary ‘language’ needed to describe the emergent entity is different than the discipline that describes its components (Crutchfield, 1994; Goldstein, 1999). This type depicts the basic hierarchy of scientific disciplines as they develop new analytical languages to cope with the increasing variety and complexity of the agents they try to explain and/or predict – physics, chemistry, biology, and continuing to economic agents and terms. Bechtel and Richardson (1992, p.263) express this clearly, offering a basic, two-level (parts and wholes) definition of an agent:

Very often there will not only be different vocabularies for discussing the parts and the wholes, but also different disciplines that investigate them and different research tools employed in performing these investigations.

One of the strongest examples of a two-level description of an emergent phenomenon is the physical analysis of water. The language of biochemistry describes the systemic property of wetness, whereas the components of H<sub>2</sub>O – the configuration and interaction of the three atoms comprising a water molecule – may be described by the (very different) discipline of atomic physics (Schröder, 1998). Simon (1999, p.237) takes this one step further, remarking that each discipline, whether natural science or social science, varies by one or more magnitudes in the dynamics (frequency rate of substantive changes) at which it operates. In social science, thus, his ranking is: psychology, economics, political science, sociology, history, and archaeology.

A managerial example of a two-level hierarchical description may be found in the literature on emergent strategy formation (Mintzberg, 1994; Nonaka, 1994). Specifically, the components of an emergent strategy are generated through individual- and group-level interactions (human, social, and relational capital), whereas the accumulative (performance) impact of these strategic innovations can only be defined in terms of corporate strategy, competitive advantage, and dynamic environmental adaptiveness (Quinn, 1992; Brown and Duguid, 1998; Teece et al., 1997). The increasing complication of agents, as hierarchical relationships between parts and wholes becomes increasingly layered, distinguishes Type 1 from Type 2 emergence.

More specifically, Type 2 emergence generates rank/frequency distributions that are not normally distributed but rather have one large entity or event at the end of one long tail (e.g., Walmart or a #9 earthquake) and up to millions of entities or events at the end of the opposite long tail (e.g., millions of small stores or level-1 quakes). Barabási and Albert (2001) mention some early studies of rank/frequency Pareto-distributed networks (e.g., Lawrence and Giles, 1998; Watts and Strogatz, 1998); many other studies follow (e.g., Battiston and Catanzaro, 2004; Gay and Dousset, 2005; Souma et al., 2006; Chmiel et al., 2007; Song et al., 2009).

#### 4.3 *Type 3 – emergent causalities*

With the third type of emergence, causal complexity expands from the unilinear, upward effects that a system’s components have on its higher structures, to include the coevolving interaction of agents across levels, including the non-linear effects that an

emergent structure may have on its components. This type depicts the essential analytical elements of complexity science:

- 1 horizontal coevolutionary causal effects
- 2 the interacting upward (reductionist) and downward (supervenient<sup>4</sup>) strands of causality.

Due to these horizontal, supervenient, and other multi-causal effects, an emergent level may causally influence its components by changing the behaviour of its parts, while the parts simultaneously alter the nature of the larger whole (Thomas et al., 2005). Blitz (1992, p.102) says that higher-level emergent processes causally influence their lower level constituents in such a way that ‘...lower level processes proceed ‘differently’ – in a sense not further analysed – under the influence of the higher level emergents’.

The strongest form of downward causation is presented in Sperry’s (1986, p.267) definition of macro-determinism, which occurs when: ‘...the fate of the parts from that time onward, once a new whole is formed, are thereafter governed by entirely new macro-properties and laws that previously *did not exist*, because they are properties of the new configuration’. Although Sperry’s ideas are not widely held (Klee, 1984; Newman, 1996), supervenience remains for many the defining quality of emergence [see for example the concept of ‘radical openness’ in Chu et al. (2003)].

The possibility of supervenience expands to a view of agent effects essential to Type 3 emergence. In this third type of emergence an ‘agent analysis’ must necessarily involve three levels:

- 1 the agents comprising focal system itself
- 2 the components of these agents that give rise to their emergent properties
- 3 the environment from which the focal system gains its resources and to which it continuously adapts (Schrödinger, 1944/1992; Miller, 1978; Chu et al., 2003).

Salthe (1985) calls this the ‘basic structural triad’ of all biological and social analysis. It includes the upward influence of the components, the horizontal, coevolutionary causal actions of the agents within the focal system, and introduces the supervenience of the environment onto the system components themselves.

Early documentation of supervenient effects in management appeared in Homans’s (1950) analysis of emergent group norms, i.e., individuals’ interactions lead to group formation, while group-level pressures through member interactions significantly altered the behaviour of member agents. Entrepreneurship researchers observe that the emergence of a new venture can alter the decisions and behaviours of its (component) entrepreneurial team (Gartner et al., 1992; Hanks et al., 1994; Slevin and Covin, 1997). Institutional theorists show how industry-level archetypes – created after entrepreneurs coevolved to create the industry in the first place – can in turn constrain their decisions about core organisational systems (Baron et al., 1996). These investigations extend to studies of institutional emergence, where scholars examine how macro-level (institutional) structures supervene on micro-level (individual) behaviour (Contractor et al., 2000). ‘To the degree that institutions are encoded in actors’ stocks of practical knowledge, they...determine what behaviours to sanction and reward’ [Barley and Tolbert, (1997), p.98].<sup>5</sup>

#### 4.4 *Type 4 – emergent purposeful CAS*

Type 4 emergence integrates the greater agent and causal complexity found in Type 2 and Type 3 emergence. These added degrees of emergent complexity combine to introduce two fundamentally different features to Type 4 emergence. First, with the addition of Aristotle's *final* cause, Type 4 emergence includes a feature characteristic of advanced, cognitively-sophisticated human systems: i.e., *purposefulness* – defined in the general systems literature as the ability to change goals (Ackoff and Emory, 1972). To those of us who study organisations, this feature is well known and essential to recognise in any meaningful scientific analysis.

Second, in addition to complex causality and purposefulness, the emergence of a fourth vertical layer (or more) to Salthe's basic analytical triad sets up the possibility of multiple, potentially interacting, causal cycles of upward and downward causality. For example, there could be a focal system of agents with two emergent layers above it, each with upward and downward causal connections; further, there could be causal cycles among all three layers. The result is coevolving causalities where Aristotle's material, final, formal, and efficient causes all coevolve (McKelvey, 2004; Kaminska-Labbé et al., 2011). Like the three-body problem in physics, this could produce uncertainties working up and down among the three layers, making it impossible to identify where a particular causal force originates in the system and where it has its most pronounced effects (Chaisson, 2001). As such, Type 4 emergence may never really settle down or stabilise, making it impossible to derive a single solution or a stable resolution applying to any given level (Tsoukas and Chia, 2002).

Needless to say, because of these two effects – purposefulness and three or more causal cycles – Type 4 emergence may exhibit striking non-linearities. On the one hand, these may set the stage for unprecedented adaptability (Brown and Eisenhardt, 1997), allowing a system to operate at a high degree of effectiveness (Smith and Comer, 1994). On the other hand, they may lead to chaotic effects (Dooley and Van de Ven, 1999), or out-of-control coevolution (McKelvey, 2002).

Recent studies of co-evolution have shown how the emergence of an institution, along with its constituent purposeful agents – routines, networks, groups, entrepreneurs, firms, etc. – can be explained as the emergence of a new multi-level, coevolving ecology that selects the constituent agents on emergent criteria even as the agents enable and constraint the selectionist context (Garud and Karnøe, 2001). For example, Jones (2001) reveals how the emergence of the film industry was enabled and constrained by changing goals, new technologies, and existing networks, as well as by an influx of immigrants from Eastern Europe. These new Americans brought with them a unique background and culture taste, which created a purposeful context that selected a new form of movie-making over its precursors, while at the same time creating constraints on the format, content, and delivery of that new form.

These works illustrate purposeful CASs and multiple levels of emergence, including the emergence of knowledge, technology, networks, organisations, alliances, industry regulations, nation-wide demographic changes, and coevolving causalities. It also highlights the differential effects of supervenience and selection that stream from higher-level contexts onto purposeful agent components, resulting in a highly unpredictable CAS (the film industry) that generates wholly unexpected results, even today. The complex causality resulting from these purposeful, emergent selectionist contexts has also been described in the emergence of Starbucks (Koehn, 2001), and in

Siggelkow's (2002) evolutionary study of 'The Vanguard Group'. It is these coevolving causalities – material, final, formal and efficient – which create non-linear interactions across multiple levels, leading to emergent selectionist contexts; all of which distinguish Type 4 from the other three types of emergence. Due to the richness of data needed to capture Type 4 emergence, much of the rigorous empirical work in this quadrant is more mixed method and qualitative (e.g., Lichtenstein et al., 2007; McKelvey and Lichtenstein, 2007). At the same time, because of the way we define our two dimensions, many of the exemplar organisation science papers in complexity are described as 'metaphors of emergence'. Although other analyses have drawn these boundaries differently (e.g., Lichtenstein, 2011b), the value of making this distinction sharp is that it presents a clear direction for most of the complexity modellers at work today, who are steeped in agent-based models. Thus, the bulk of this paper will focus on agent-based models of emergence, without missing the value and importance of qualitative work in the field.

In summary we frame two core aspects of complexity – agent heterogeneity and causal intricacy – as two dimensions; together they generate a typology of emergence. The four types are increasingly elaborate in their definitions of emergence, each successive type expanding the conditions and standards for what counts as emergence. Our implicit argument is that the higher the degree (type) of emergence, the more complete will be its explanation of the underlying dynamics of self-organisation leading to emergent structuring. In the next section, our argument unfolds with our placement of 15 management-based streams of CAS modelling research into one of the five categories, depending on the degree of emergence each stream analytically reveals.

## **5 A review of complexity modelling research**

Agent-based modelling is relatively new to organisation science, even though computer simulations appear in several management classics (Cohen et al., 1972; Cohen and Levinthal, 1990; March, 1991). Narrative-style descriptions of emergence date back to the 1930s, particularly in classic works by Roethlisberger and Dixon (1939), Homans (1950), and Gouldner (1954). Complexity research in the past 15 years includes a wide range of studies, including qualitative narratives, case studies, surveys, and agent modelling.

Many of the most interesting findings from complexity science – drawn from research by e.g., Brown and Eisenhardt (1998), Lichtenstein (2000), Chiles et al. (2004), Plowman et al. (2007) are exemplary qualitative analyses which allow us to focus in on the real human dynamics that generate emergent structures. Due to the richness of such studies (McKelvey, 2001), their ability to explain social emergent dynamics is stronger, in part because they mainly demonstrate Type 4 emergence.

In order to fill out the entire spectrum of work in complexity science, we thus focus more space in our review to complexity modelling research. This is in part because of how we define the four types; for example in this typology we separate out 'metaphors for complexity' which in other frameworks becomes one of the important way to describe emergence (Lichtenstein, 2011a). More importantly, however, this literature is far larger and growing faster than the qualitative work, and it has not been reviewed in this way up to now. Thus, each of the four quadrants will receive the same amount of space, but since agent based models are doing virtually all the work in Type 1, Type 2, and Type 3

emergence, we do spend more space in the paper describing that work. We organise our review as follows:

- *Measurements of emergence*: ‘Chaos’ and other approaches which can only measure the results of emergence.
- *Type 1 emergence*: Models of emergent networks with deducible properties.
- *Type 2 emergence*: Models of emergent hierarchies showing minimal hierarchical complexity.
- *Type 3 emergence*: Models of structural triads showing minimal causal complication.
- *Type 4 emergence*: Causally intricate models of purposeful CASs.

### *5.1 Measuring emergence: complexity streams providing measures of complex systems*

#### *5.1.1 System dynamics*

A critical part of explaining interactions between and across levels depends on the degree to which negative and positive feedback loops are modelled and accounted for within a system of stocks and flows (Forrester, 1961; Sastry, 1997; Sterman, 2000). In system dynamics these stocks and flows are represented as simple differential equations, and their linkages can induce the system as a whole to work toward equilibrium or move toward calamitous outcomes (Hall, 1976). Because of its inclusion of positive feedback and its ability to explain highly complex system outcomes, systems dynamics has been identified as a complexity science (Sterman and Wittenberg, 1999; Lichtenstein, 2011a). However, while system dynamics does model agent interactions over time, these agents do not have objectives per se. More importantly system dynamics does not allow for the emergence of new order, nor can it describe agent self-organisation.<sup>6</sup> For these reasons we leave system dynamics outside our continuum of complexity-based models of emergence.

#### *5.1.2 Deterministic chaos theory*

At least from the time of Prigogine and Stengers’ (1984) book, *Order Out of Chaos*, deterministic chaos theory, complexity science, and self-organisation have been linked, especially in the early use of chaos theory by management scholars such as Begun (1994), Kiel (1994), Thietart and Forgues (1995). These links continue to be made (e.g., Eve et al., 1997; Frederick, 1998; Schweitzer, 1997; Marion, 1999). And yet, Brock (2000, p.29) says: ‘The study of complexity is the opposite of the study of chaos’. Why so?

Deterministic chaos theory does not model emergence for several important reasons. First, whereas complexity reveals emergence through agent interactions, there are no agents in chaos theory, which is instead an analytic method for identifying types of order in random time-series data (Guastello, 1995, 2001; Dooley and Van de Ven, 1999). Second, the order that can be identified – termed an ‘attractor’ – is not caused by system (agent) behaviour per se; instead it is only the result of an external analysis, i.e., through a contextual effect outside the system (Kim, 1992). Thus according to recent philosophical analysis, the presence of a chaotic attractor does not in and of itself represent emergence

(Bedau, 1997; Goldstein, 1999). Third, the ‘surprise’ in chaos theory was that simple linear differential equations could generate non-linear, aperiodic behaviour (Casti, 1995), a claim far short of Type 1 emergence, which instead explores how interacting agents generate emergent network structures. Bak (1996, p.31) sums it up: ‘In short, chaos theory cannot explain complexity’; nor does it explain the process of emergence. At the same time, the paper by Cheng and Van de Ven (1996) provides a useful measure of emergence, and was one of the catalysts for the application of complexity science to management.

### 5.1.3 Catastrophe theory

Catastrophe theorists have shown that many types of *discontinuous* change can be explained in terms of seven mathematical models (Thom, 1975; Guastello, 1995). Management scholars have applied the basic ‘fold and cusp’ model to explain organisation-wide transformation (Bigelow, 1982; Gresov et al., 1993) and group-level dynamics such as leadership emergence, motivation, and personnel turnover (Guastello, 2001). Guastello (2001), for example, finds that a non-linear catastrophe analysis shows a “10-fold improvement in predictive accuracy compared to the conventional method” (p.142). Thus, the measurement capabilities of catastrophe theory are unique.

Yet, here again the fitting of a catastrophe model to change processes does not explain the spontaneous self-organising of these macro structures (i.e., the outcomes of change). However, like attractors in chaos theory, the measuring capabilities of catastrophe theory cannot reflect the actual self-organising activities that are generated through heterogeneous agent interactions.

### 5.1.4 Math fractals

Fractals are a central feature in popularisations of ‘new science’; the colourful images of fractals are prominent in the introductions by Gleick (1987) and Wheatley (1992), and an intriguing management application of fractal geometry is presented in Zimmerman and Hurst (1993). Fractals are a mathematical discovery originally developed by Mandelbrot (1983) to measure the density of a non-linear set of data, e.g., stock market behaviour or the shape of a coastline (Casti, 1995). When such measurements are taken at increasing orders of magnitude, each fractal dimension is self-similar to the ones before and after – a relationship governed by a power law<sup>7</sup> (Cramer, 1993). Although the notion of self-similarity is at the core of complexity science (Bak, 1996; Krugman, 1996), there are no interacting agents in math-based fractal geometry, and little (except beautiful graphics) actually emerges from the math (Favre et al., 1995; Iannaccone and Khokha, 1996; Peitgen et al., 2004).

### 5.1.5 Living-systems fractals

We note above that traditional math-created fractals – appearing as a common element in both chaos and complexity theories – emerge from equations. But in his 1983 book, Mandelbrot noted the connection between his fractal geometry, Zipf’s law, Pareto-distributed cotton prices and more generally the realisation that rank/frequency distributions very often appear as power-law distributions. This comes as no surprise since fractal equations and power-laws are both log-based.

Fractals are obviously present in living systems: biological, economic, social, and more specifically organisations and companies – just for starters Andriani and McKelvey (2007, 2009), McKelvey et al. (2011b) and McKelvey and Salmador Sanchez (2011) list some 180 power-law findings in living systems (with many more not listed). Power laws emerge from the combination of *tension* and *agent connectivity*. We see the effects of Bak's (1996) SOC in all four types of emergence. We specifically see Bak's SOC and power laws, and the mention of tension effects in causing phase transitions, in Type 1 emergence.

We also put power laws into Type 2 emergence, as reflected by Krugman's (1996) and Batty's (2005) studies of the city-size rank/frequency distributions. Although power laws are not reflected in Type 3 or Type 4 emergence, the increased connectivities described in these Types are well documented by the power-law distribution of most social networks – whether among people or firms (Andriani and McKelvey, 2007, 2009; McKelvey and Salmador Sanchez, 2011). Similarly, McKelvey et al. (2011b) suggest an updated *Law of Requisite Fractality* [building from Ashby (1956)], which argues that firms need internal fractal structures (rank/frequency fractals) to effectively cope with and/or adapt to the fractal structure of the industries in which they are embedded.

## 5.2 *Type 1 emergence: complexity streams that model emergent networks*

### 5.2.1 *Self-organised criticality*

This early complexity concept stems from an experiment in which individual unpolished grains of sand (slightly heterogeneous agents) are dropped onto a sand pile (Bak and Chen, 1991). Once the slope of the sand pile reaches a specific angle [a function of gravity and the irregularity ('stickiness') of the sand grains] one begins to see a series of sand movements ranging from the movement of single particles of sand, to the movement of a small number of sand particles, to an occasional very large avalanche. A power-law distribution governs the size of the movements and their frequency – the larger the bunch of sand grains moving, the lower its frequency. The power law describes the distribution of small movements to large avalanches (a rank/frequency distribution); the implication is that very large system changes are rare but normal (Bak and Chen, 1991).

This SOC state (defined as the angle of the sand pile's slope) is *self-organised* because the system (i.e., the sand grains) keeps adjusting so as to maintain a specific angle (given gravity and the amount of sand-grain stickiness) spontaneously; that is, without intervention by any higher-level agents. Further experimentation finds that this phenomenon of self-organised criticality (SOC) explains the dynamics behind earthquakes, species extinctions, and some stock-market behaviour (Casti, 1995; Bak, 1996; Krugman, 1996; Sornette, 2003; Chatterjee et al., 2005; Newman, 2005; Chakrabarti et al., 2006; Mandelbrot, 2010). McKelvey et al. (2011b) cite 19 biological examples of SOC in how species adapt to the predator/prey context of their niche. Zipf (1949), Krugman (1996), Dahui et al. (2005), Ishikawa (2006), Podobnik et al. (2006), Batty (2005), Park et al. (2011), Glaser (2009), and McKelvey (2011) all apply SOC and power laws to social, organisational, industry, and economic phenomena.

Management scholars have just begun to utilise the SOC approach. Gunz et al. (2001) find that vacancy chains in one industry follow a power law: most job changes generate very small vacancy chains, but occasionally one job change can cause a large cascade of

subsequent changes within the organisation. Andriani and McKelvey (2007, 2009) list 140+ examples of physical, social, organisational, and managerial studies involving SOC, power-laws, and scale-free dynamics. McKelvey and Salmador Sanchez (2011) list over 100 findings of power-laws in economic and financial markets. By examining how complexity reduces to order, Bak's work on SOC is an important element of complexity science (Brock, 2000). However, since there is neither hierarchy nor other properties associated with the state of SOC, his model is the most basic in Type 1 emergence.

At the same time, early use of 'self-organisation' by organisational development consultants very quickly turned complexity science into a fad, exactly as predicted by Maguire and McKelvey (1999). Only more recently have scholars learned how to operationalise 'self-organisation' in social systems, leading to some intriguing propositions about the leadership of emergence (Lichtenstein and Plowman, 2009).

### 5.2.2 *Edge of chaos: defining a region of emergence*

The next two approaches are based on cellular automata (CA) models, which examine the interactions of mildly heterogeneous agents on a two-dimensional grid. Each agent is initially assigned a random value between 0 and 1, representing the presence or amount of an attribute; these are often referred to as 'simple rules' (Epstein and Axtell, 1996). At each time period in the ensuing simulation, each of these agents evaluates itself with respect to its immediate neighbours, and the agent changes its own fitness or trait depending on the value states of its immediate neighbours. This computational model – best explained by Epstein and Axtell (1996) – simple though it is, reveals the self-organisation of cellular agents into emergent yet stable patterns of order that are not programmed into the simulation. The CA models in Type 1 emergence have only two levels: Agents in an ecology self-organise to produce some macro effect, such as improved fitness relative to the imposed selection context.

Prigogine (1955), Haken (1977) and Favre et al. (1995) among others, discovered that when temperature rises above the '*edge of order*' defined by the Rayleigh number – the 1st critical value – a phase transition occurs such as the rolling boil in a teakettle or a laser beam. A separate discovery – an early contribution of complexity theorists at the Santa Fe Institute – is the presence of the '*edge of chaos*' at a 2nd critical value. In the region between the two 'edges' we find a specific class of dynamic order in CA models that leads to self-organisation and order creation. Langton (1985) describes this class of order as (almost) at '*the edge of chaos*', and shows that it exists in the region between statistical randomness (entropy) and static order (attractors). This 'edge' notion underlies Kauffman's approach and that of others studying what causes the emergence region to exist in the physio-, bio-, and econospheres (Lewin, 1992; Waldrop, 1992; McKelvey, 2004; Epstein, 2007; Miller and Page, 2007; Rosser, 2009).

In management, the edge of chaos idea underlies Brown and Eisenhardt's (1997, 1998) and Pascale's et al. (2000) analyses of various qualities of dynamic adaptations in innovation projects and adaptive firms. McKelvey (2001, 2008, 2010) discusses ways in which managers may enlarge the region of emergence and improve the probability that self-organising behaviour will occur under appropriate conditions. According to Lewin et al. (1999, p.541) – who draw on March's (1991) concepts of 'exploitation' (efficiency) and 'exploration' (innovation) – as organisations or populations adapt in highly dynamic environments, successful ones evolve to a critical point, that is, a

balance between order (the pull of exploitation) and disorder (the pull of exploration) that is often called ‘the ‘edge of chaos’. At this point of dynamic tension, truly novel emergent behaviour can occur.

The ‘edge of chaos’ metaphor also appears in various other business applications (Dubinskas, 1994; Brown and Eisenhardt, 1997; Anderson, 1999; Marion, 1999; Pascale, 1999). Many complexity scholars equate this type of organising with metaphors of Kauffman’s *NK* landscape theory. In these analogies, the dynamic tension in the system is reflected by the behaviours and emotions of agents in the system, and the interdependence is reflected by their social interdependence. This leads to some intriguing hypotheses about organising and, as Ganco and Agarwal (2009) show, about entrepreneurship.

On the other hand, many have argued that the ‘edge of chaos’ is a misnomer, (Mitchell et al., 1993), and most Santa Fe researchers now disavow it [Horgan, (1996), p.197]. The ‘edge of chaos’ literature forms one foundation of complexity science, for even though it lacks the ability to distinguish different types of emergent structure, it does focus on the conditions that create the *region* of self-organisation. Without this region, however, complexity science is not possible. Therefore, we place this literature in Type 1 emergence.

### 5.2.3 *Tunable NK landscapes – emergent fitness*

Kauffman’s (1993) *NK* Fitness Landscape, is a well-known application of CA models, simulates a co-evolutionary process in which both the individual agents and the level of interdependency between them are modelled over time. *N* refers to the number of agents in the model, and *K* refers to the density of agent interactions. According to the model, an agent’s adaptive fitness depends on its ability to identify and ‘climb to’ the highest level of fitness of its neighbours. However, due to the nearest-neighbour search limitation, an agent surrounded by neighbours all having lower fitness levels gets trapped on a local optimum that may be well below the highest system-wide optimum.

As individual agents change, they affect all other agents, thus altering some aspects of the nearest-neighbour landscape itself. In this way, the level of complexity ‘tunes’ the agents’ search landscape by altering the number and height of peaks and depths of valleys they encounter. It turns out that the degree of order in the overall landscape crucially depends on the level of *K*, the degree of system-wide interdependence, that is, complexity (Kauffman, 1993). According to Kauffman, as complexity increases the number of peaks vastly increases in the landscape, while the difference between peaks and valleys diminishes, such that even though the pressure of Darwinian selection persists, emergent order cannot be explained by selection effects. He terms it ‘*complexity catastrophe*’. Instead, a moderate amount of complexity creates optimal ‘*rugged landscapes*’, which lead to the highest system-wide fitness levels.

Several researchers have applied the *NK* model to business settings by exploring what level of connectedness will bring an entire system to a higher level of fitness without locking it into a ‘complexity catastrophe’ of tight interdependence (Levinthal, 1997; Rivkin, 2000; Yuan and McKelvey, 2004; Ethiraj and Levinthal, 2004a, 2004b; Sommer and Loch, 2004; Siggelkow and Levinthal, 2005). Moderate levels of interconnection can be achieved through modularisation of the production process (Levinthal and Warglien, 1999), or through adopting strategies based on the industry-wide level of firm

interdependence (Baum, 1999). More recently the *NK* model has been used to study profits (Lenox et al., 2006), exploration (Siggelkow and Rivkin, 2006), myopia (Levinthal and Posen, 2007), competitive advantage (Porter and Siggelkow, 2008), and entrepreneurial start-ups (Ganco and Agarwal, 2009). In a rare empirical test of the *NK* application to innovation, Fleming and Sorenson (2001, p.1025) show ‘invention can be maximised by working with a large number of components that interact to an intermediate degree’.

In a recent study, McKelvey et al. (2011a) first argue that all of the *NK* model results are an artefact of the basic formula Kauffman uses:

$$W_t = \frac{1}{N} \sum_{i=1}^N W_{i,t}$$

Since  $N$  is the divisor, needless to say, as  $N$  gets larger the average of all of the summed  $W_{i,t}$  fitnesses inevitably trends toward the mean, which is what signifies complexity catastrophe. His formula works for studying epistasis among genes but does not transfer very well over to studying people in firms. There is a plus side to their research, however. Since all agents are connected with each other when complexity catastrophe prevails, this is equivalent to Janis’s (1972) ‘*groupthink*’, which is a strong-tie effect. McKelvey et al. then use the *NK* computational model to study the tipping point between weak- and strong-tie effects: How often over the course of a year can a person connect with another person before the weak tie turns into a strong tie?

There is not actually very much emergence, per se, in the *NK* model. For the most part, self-organisation is limited to agent connections (networks) with nearest neighbours. For example, when Kauffman studies the effects of species of varying size,  $S$ , he does so by changing  $S$  as a control parameter, not by allowing the size of  $S$  (groups) to emerge from agent interactions. In this respect most *NK* models represent a sophisticated example of Type 1 emergence, with the capability of advancing into Type 2 or Type 3 Emergence.<sup>8</sup>

### 5.3 Type 2 emergence: emergent hierarchies via elaborated CA models

#### 5.3.1 Schelling’s micro-sociology – emergent racial groupings

The classic model using mildly heterogeneous self-organising agents was developed by Schelling (1978) to answer questions about segregation in cities. His original checkerboard model is now available for free on the NetLogo website. Using a simple CA spatial model, he studies how agents with similar attributes become grouped together in a physical space. Simply by giving agents one basic rule to follow – ‘choose to live nearby agents who are moderately similar to you’ – he demonstrates the relatively rapid emergence of distinct segregations of agents that remain stable for long periods of time. Schelling gets this result giving agents only a single slight individual preference to live near a person like themselves, without recourse to any sociological principles. Though simple, it is the classic modelling of emergence resulting in the formation of hierarchy, i.e., groups of self-organising agents. Note that they are just groups; there is no evidence of the supervening effects of group norms on agent behaviours.

### 5.3.2 *Axelrod's coevolutionary games – emergent alliances*

Axelrod and Bennett (1993) use agent-based CA landscape models to study alliances and other social group formations. In contrast to Kauffman's approach, the goal of Axelrod's alliances is to achieve a *minimum* energy level, where the energy of an alliance is the weighted sum of 'frustration levels' across all agents. The result is an energy landscape in which members search for groupings that lower their frustration with other members – not unlike spin glass models (Fischer and Hertz, 1993). Applying this model, they use 1939 data to accurately predict the political alliance formation of all but one nation during WWII. They conclude, 'It is remarkable that such a simple theory and such a parsimonious operationalisation of its concepts can come up with a prediction that is very close to what actually happened' [Axelrod, (1997), p.88]. In another complexity extension of his previous work in game theory, Axelrod et al. (1995) study group formation as a result of extortion behaviour. In this game, agents make pay-tributes or fight-demands on their neighbours through emergent collaborations. Here again, a very few simple agent rules lead to self-organising behaviours that produce groups.

### 5.3.3 *Krugman's model of cities – emergent global system properties*

Using a simple CA application of spatial modelling, economist Krugman (1996) analyses two strange economic irregularities of urban centres. First, given Garreau's (1992) empirical finding that peripheral, smaller 'cities' appear on the outskirts of a metropolitan region, Krugman asks why these 'edge cities' form. Second, Krugman asks why the distribution of businesses (or any similar set of social agents) can be explained by Zipf's (1949) Law, the mathematical finding that the relationship between city ranks and city sizes is a virtually perfect linear power-law relationship – this power-law finding dates back to Auerbach (1913) and Zipf (1929).

In Krugman's edge-city simulations, agents are businesses that enjoy a certain percentage of business activity within the city's (connected) neighbourhoods. He presents a spatial simulation model in which business activities, initially randomly dispersed, always evolve into a highly ordered distribution of 'edge cities' around a central business district. He uses his model to support Simon's 'lumping/clumping' theory explaining the power-law distribution of city sizes in the USA.

Krugman describes it as 'spooky' that towns and cities in some countries with effective 'hot' SOC-characterised economies (like Japan, USA, China, and India) form a rank/frequency distribution from the single largest city (New York or Tokyo) down to thousands of small towns, the rank/frequency distributions are near perfect power laws (McKelvey, forthcoming). More recently, Batty (2005, p.514) describes a large number of models used to test various theories of urban power-law distributions. He concludes that the models are all quite impressive in showing the power-law distribution but he then says they are 'suggestive rather than definitive'.

Although few management researchers have taken up Krugman's model of self-organisation, it does exhibit hierarchical emergence: A few simple rules generate an emerging order – edge city groupings; these are ontologically distinct from their component businesses. Thus, his model falls under Type 2 emergence.

#### 5.4 *Type 3 emergence: emergent structural triads and causal complexity*

##### 5.4.1 *Holland's GAs – rule changing*

An important advance in modelling emergence occurs through the use of GAs, invented by Holland (1975, 1995). GAs allow agents to learn and change over time by changing the rules governing their behaviour: 'Agents adapt by changing their rules as experience accumulates' [Holland, (1995), p.10]. Axelrod and Cohen (1999, p.8) broaden the implications of GAs by asserting that:

...each change of strategy by a worker alters the context in which the next change will be tried and evaluated. When multiple populations of agents are adapting to each other, the result is a coevolutionary process.

In biological GAs, agents appear to 'mate' and produce 'offspring' that have different rule 'strings' (genetic codes, blueprints, routines, competencies) as compared with their parents (Biethahn and Nissen, 1995; Mitchell, 1996, 2009). But actually, in biological and organisational applications, agents' rule strings change over time without or without agent replacement and without having 'children' – agents just computationally reach out and copy the fitness level of a neighbouring agent. The upward causal effects of agents' components materialise as these rules. Whereas CA models typically are limited to a relatively few rules – because the landscape grows geometrically each time a rule or agent is added – GAs allow agents to have many rules (Macy and Skvoretz, 1998). New agent formations can have varying numbers of rules from each prior agent form, thus allowing the increased evolutionary fitness of complex processes such as decision-making and learning, along with recombinations of diverse skills. Two of the most detailed organisational GA applications are described next.

##### 5.4.2 *Simulated coordination models*

Paul et al. (1996) model adaptations to organisational structure by examining the adaptation of financial trading firms. Their firms survive in a financial market environment; each may have from 1 to 9 constituent agents, and each agent has a different rule set for buying and selling financial instruments or doing nothing. Firms may activate or deactivate their agents, or form combinations of seemingly better performing agents from prior periods. In an efficient market performance climate with a 50% probability of success, their model firms beat the market 60% of the time. Salthe's (1985) triad is present in this model: the behaviour of agents (components) can be altered by firm-level goals, thus allowing firms to better perform in the market environment. Further, due to the coevolution of up- and downward causality, results are not deducible from the initial agent configurations and rules. As such, it minimally exemplifies Type 3 emergence.

Another Type 3 model examines the classic organisation theory proposition that coordination, while necessary to accomplish interdependent tasks, is costly in terms of time. Crowston's (1996) GA model tests this hypothesis by simulating organisations consisting of agents, in sub-groups, in a market, with variable task interdependency – the basic triad with coevolving agents along with upward and downward causalities. Bottom-level agents have to perform their tasks in a specific length of time; agents who coordinate may expedite their tasks, but the cost of coordination means a lessening of

their time allotment according to the following rule: if an agent ‘talks’ to all the other agents all the time there would be no time left to accomplish any tasks. Results show that organisations and/or their employee agents do in fact minimise coordination costs through organising in particular ways. Crowston’s study is an example of a GA model being used to test a classic normative statement by setting up a computational experiment that allows groups to emerge as appropriate, given the conditions. It also incorporates Salthe’s triad and also has coevolution and upward and downward causalities. Modelling the minimisation of coordination costs connects the research to Simon’s (1962) classic focus on the desirability of creating ‘*nearly decomposable systems*’.

#### 5.4.3 *Carley’s multi-agent learning models*

Carley and her colleagues have produced some of the more sophisticated models to date in computational modelling. They have been validated against experimental lab studies (Carley, 1996), and archival data on actual organisations (Carley and Lin, 1995). The most unique feature of the Carley models is that agents have cognitive processing ability – individual agents and the organisation as a whole can remember past choices, learn from them, and anticipate and project plans into the future. These models combine elements of CA, GA, and neural networks.<sup>9</sup>

In Carley’s (1991) CONSTRUCT and CONSTRUCT-O models (Carley and Hill, 2001), simulated agents have a position or role in a social network and a mental model consisting of knowledge about other agents. Agents communicate and learn from others with similar types of knowledge. CONSTRUCT-O allows for the rapid formation of subgroups and the emergence of culture, which, when it crystallises, supervenes to alter agent coevolution and search for improved performance. These models show the emergence of communication networks (Type 1), the formation of stable hierarchical groups (Type 2), and the supervenience of higher levels that complexifies agent behaviours (Type 3).

### 5.5 *Type 4 emergence: emergent purposeful CASs*

#### 5.5.1 *Epstein and Axtell’s ‘sugarscape’ – emergent societies*

Quite possibly the most famous example of ‘bottom-up’ or ‘rule-based’ science is Epstein and Axtell’s ABM in Epstein and Axtell (1996). They boil their agent behaviour down to a single rule: ‘*Look around as far as your vision permits, find the spot with the most sugar, go there and eat the sugar*’ (p.6). Agents search for sugar on a CA landscape; additionally they can have sex, reproduce offspring, and begin to hold genetic/identity/culture identification tags according to a genetic algorithm. This model builds social networks (Type 1); as well, higher-level groups emerge (Type 2). Furthermore groups develop cultural properties; once these cultures form they can supervene and alter the behaviour and groupings of agents (Type 3). Epstein and Axtell’s simulation includes four distinct levels – agents, groupings, cultures, and the overall Sugarscape environment – making it a minimal example of Type 4 emergence.

#### 5.5.2 *Carley’s ‘ORGAHEAD’ model*

Her four-level simulation (Carley and Lee, 1998; Carley, 1999a) consists of small groups of interacting workers (agents) led by an executive team that develops firm-level strategy

based on environmental inputs, including decisions about design, workload, and personnel. This model allows for both the interaction of managerial downward ‘purposeful’ influence, along with supervenience from emergent ‘informal’ norms and culture onto agents. In addition, supervenience results from both structural and cultural effects: Once strong networks emerge these networks control ‘whom’ agents can interact with, learn from, and so on, thereby altering subsequent coevolutionary emergence by agents. Once there is collective agreement on what is appropriate to be known, the emergent learning culture then supervenes to alter the subsequent knowledge-creation strategies of agents. In these ways Carley’s model fits into Type 4 emergence.

Our earlier definition of Type 4 emergence specifies a minimal causal-influence form based on at least four hierarchical levels, the coevolution of agents, and a combination of upward and downward causal complexity. The *Sugarscape* model partially satisfies these minimal requirements – four levels emerge, although the upper levels show no evidence of managerial purposefulness. Similarly, *ORGAHEAD* has hierarchical and causal complexities that are just above the minimum thresholds – one layer more than the basic triad and with just the beginning of purposefulness. Neither model achieves the strong form mentioned earlier. We have not seen an agent-based complexity model that simulates purposefulness at multiple levels, nor that recreates multi-level causal cycles that could lead to indeterminacy in simulated organisational action. Most of the space in the Type 4 cell is blank, waiting for models well beyond current practise. The rest of the quadrant includes a good many rigorous qualitative studies of emergent order, a group we review next.

## 6 Narrative research in complexity science

The most recent complete reviews of qualitative studies in complexity science are in the new *SAGE Handbook of Complexity and Management* (Allen et al., 2011). Rather than repeating these reviews, we present six insights that management scholars have gained from studying self-organisation and evolutionary emergence within and across organisations.

*First*, narrative studies show that each level of agent behaviour incorporates at least two distinct and interdependent modes of interaction – rules and actions (Drazin and Sandelands, 1992; Katz, 1993). These two modes are complemented by a third – cognitive schema, which operates more actively at the individual and institutional levels of order. In this view, each agent level is composed of static traits (rules), general frameworks (schema), and dynamic conditions (actions); this dramatically complexifies agent heterogeneity. It is this combination of traits and conditions that some argue is the origin of emergent levels of organisation (Meyer, 1982; Barley, 1986).

*Second*, in addition to extending the meaning of ‘agent heterogeneity’, narrative longitudinal studies also expand our understanding of ‘causal intricacy’ by illustrating how complex causal loops interact at multiple levels of order. One example, described earlier, is Jones’s (2001) research on coevolution, which shows how the emergence of the modern film industry involved an intricate interplay between at least four different contexts: the ‘architectural innovation’ of cinematic technology, the competitive alliances

that emerged to differentially deal with that technological transformation, the bottom-up evolution of cultural preferences expressed by the influx of Eastern European immigrants, their movement to Hollywood to escape the attempts by Thomas Edison to form a his 'Motion Picture Patents Company' (otherwise known as the Edison Trust) so as to control film production in the USA, and the unexpected innovations in entertainment venues developed by those same Eastern European entrepreneurs once in Hollywood. Beyond 'bottom-up' causality and supervenient effects, her analysis reveals a rich and non-deterministic interplay of causes that include Aristotle's *material*, *formal*, and *formal* causes (see note #4). Similar claims apply to Koehn's (2001) insights into the emergence of Starbucks and the gourmet coffee industry, and Siggelkow's (2002) evolutionary analysis of the Vanguard Group (McKelvey, 2003; Kaminska-Labbé et al., 2011).

*Third*, besides complexifying the two dimensions of emergence, thick-description narrative research has shown that neither rules nor schema operate uniformly over time. Changes in system conditions can alter the way rules are applied (Drazin and Sandelands, 1992), and the way the system is perceived (Garud and Karnøe, 2001). Such shifts can become the catalysts for second-order transformative change, and generate unexpected degrees of emergent order (Lichtenstein, 2000; Lichtenstein et al., 2007). Mintzberg and McHugh (1985) showed that strategy appears as 'weeds' early on. With the passage of time, some 'weeds' emerge and scale up into competitive strategies.

*Fourth*, narrative research also demonstrates that the process of emergence is non-unitary. Researchers using the dissipative structures theory of change have shown that self-organisation is a punctuated yet non-unitary process involving three or more well defined 'phases' whose aggregation is not necessarily an incremental development (MacIntosh and MacLean, 1999; Smith and Gemmill, 1991). Moreover, far from there being a single generative mechanism for emergence, Siggelkow (2002) illustrates four evolutionary routes to organisational emergence including patching, thickening, trimming, and replacement. This stream of research has also shown that emergence is not an end-point nor a final outcome of dynamic interactions, but merely one step in a broader process of organisational development and evolution (Aldrich, 1999; Greiner, 1972).

*Fifth*, whereas virtually all computational models of emergence use algorithms that randomise traits of agents in progressive time periods, narrative studies have shown that emergent order is not based on random draws, but may also emerge from intentional, path dependent qualities in the system. For example, Brown and Eisenhardt (1997) show how emergent processes within continuously changing firms are enhanced when existing competencies are linked to emergent strategies, and when present projects are connected to emerging opportunities. Similarly, Lichtenstein (2000) finds that major transitions in entrepreneurial firms are more successful when the emergent order leveraged existing competencies and is 'self-referenced' to the accumulated learning in the organisation.

A *sixth* insight gleaned from thick-description narrative studies is that self-organised structures in the real world include at least one quality that cannot be traced post-hoc to already existing components (Boulding, 1978; Garud and Karnøe, 2001). For this reason, a pre-existing set of rules and algorithms is not likely to generate all of the forms of emergence that have been illustrated in non-computational studies. In summary, finding ways to incorporate these and other non-deterministic qualities into complexity models is crucial for balancing the power of analytic adequacy with the insights of ontological adequacy when examining emergence.

## 7 Emergence in management research: some propositions

We conclude our paper with several propositions that follow from our typology of emergence and its implications. One of these implications, shown in Figure 1, is based on the diagonal leading from cell 1 to cell 4 in our typology. This diagonal highlights the differences in explanatory power between traditional deterministic approaches and non-linear accounts of emergence in purposeful social systems. These advances have been expressed in accounts distinguishing ‘old’ versus ‘new’ science (Wheatley, 1992; Mainzer, 1994; Colander, 2000; Rosser, 2009), and in rigorous operationalisations of complexity to organisational phenomena (Lichtenstein, 2000; Curzio and Fortis, 2002; Lissack, 2002; Mitleton-Kelly, 2003; North and Macal, 2007; Helbing, 2010; Allen et al., 2011; Andriani and McKelvey, 2011; Lopez Moreno, 2011; McKelvey et al., 2011b; McGlade et al., forthcoming).

At one end of this dynamic is Type 1 emergence, by far the most common type of complexity found in management journals, along with the Metaphors for Complexity writing. Most complexity modellers work within a single discipline, so whatever emerges in the new level can only be explained within the confines of his/her discipline [see for example, Latane et al. (1994) and Kijima (2001)]. Such studies are only predictive of situations in which real-world behaviour is as simple as the analyses these models can account for.

At the other end of the spectrum is Type 4 emergence, which recognises that the rich and intricate nature of self-organised agents can be only be described through a multi-disciplinary and multi-methodological approach. That is, each progressive type of emergence has the potential to incorporate more agent heterogeneity and more causal intricacy. On the one hand, this richness may only be achieved by integrating methods and disciplines. This is exemplified by the fact that all the Type 1 (and Type 2) complexity models we reviewed are based on a single agent-modelling platform, whereas Carley’s ORGAHEAD model of Type 4 emergence involves a combination of three such platforms – CAs, GAs, and neural networks (see note 8). Lebaron’s (2000) ABM of stock-market trading also includes a CA, GA, and a neural net. His model has now been applied to setting up a worldwide logistics ‘electronic auction market’ in which containers and/or cars act as traders in the model searching for the quickest or cheapest route from, say, Japan to Rotterdam (Wycisk, et al., 2008; McKelvey et al., 2009; Illigen et al., 2011).

To this continuum we add the recognition that greater explanatory power leads to greater scientific validity, a correspondence now virtually taken for granted by philosophers of science. This argument leads to our first proposition:

**Proposition 1** The higher the degree (type) of emergence in a study, the more scientific validity the explanation will have when applied to living systems.

The most complete models of emergence show the indeterminate nature of self-organised entities. Rather than the familiar single-level ABM results in many Type 1 models, Type 4 studies reflect the constantly coevolving and adaptive quality of emergence. As much as emergence studies can describe the generative processes leading to ‘organisations becoming’ (Tsoukas and Chia, 2002), these Type 4 studies will have more connection to the real-world implications of emergence than their deterministic, equilibrium-based counterparts (Stevenson and Harmeling, 1990). Thus,

Proposition 2 The higher the degree (type) of emergence in a study, the more practitioner validity the explanation will have.

Clearly, narrative-style research has far outpaced the modellers in accounting to the full complicatedness of emergence. Rather than implying that thick-description research should stop, we argue that management needs to put far more attention on agent-based modelling than it currently does. Although we should be aware of the problem already being faced in physics and economics – that ‘math or computational modelling nerds’ may lack the intuitive understanding that their narrative colleagues may enjoy – this is no excuse for our field failing to work harder to train the kinds of modellers who can bring modelling technology into our Type 4 cell. Furthermore, since we cannot put firms and societies into labs (what physicists do with molecules and biologists can do with mice or rats), the only way we can test what philosophers of science call ‘*counterfactual conditionals*’<sup>10</sup> is to create agent-based computational simulations. Hence:

Proposition 3 Organisation and management studies will only improve in scientific (epistemological) legitimacy at the rate at which agent-based computational modellers advance into modelling Type 4 emergence.

One significant limitation of narrative-style research is that narratives tend to be discipline-specific. In contrast, as described above, it is the multi-disciplinary quality of Type 4 emergence that gives it scientific *and* practitioner validity; that is, it is the use of ‘hermeneutics-style’ methods for  $N = 1$  research (Hendrickx, 1999; Boisot and McKelvey, 2010; Benbya and McKelvey, 2006, 2011). This is why Simon (1999) argued that a comprehensive study of emergence is necessarily multi-disciplinary, a claim reflected in Gell-Mann’s (1988) insistence that the Santa Fe Institute be a multi-disciplinary research entity. One of the most powerful aspects of agent models is that the agents can be given rules drawn from any discipline, an approach artfully reflected in the recent study by Contractor and his colleagues (Contractor et al., 2000). We summarise this argument with the following:

Proposition 4(a) Organisation and management studies will improve in *scientific validity* only at the rate at which agent modellers draw key variables from a multi-disciplinary basket.

Proposition 4(b) Organisation and management studies will improve in *practitioner relevance* only at the rate at which agent modellers draw key variables from a multi-disciplinary basket.

Proposition 4(c) Organisation and management studies improve only at the rate at which the multi-disciplinary basket is filled with narrative-style research that is, itself, fully multi-disciplinary, i.e., hermeneutics.

Given the incredible data-richness of narratives and time-series analyses, practitioners are overwhelmed with bits of information that may or may not be useful in their circumstances. Since narratives are by nature dated, localised, and not generalisable, and time-series data are composed of ‘average’ tendencies not readily applicable to specific situations (especially in power-law distributed rank/frequency distributions (Andriani and McKelvey, 2007, 2009), it becomes extremely difficult to extract from the plethora of potential circumstances crystals of knowledge that are locally valid and practically

relevant. Models are the most powerful way to test *possible* tenets of practise-relevant knowledge, which is achieved by taking locally salient variables, 'tuning' them to a range of potential circumstances, and testing forward into time. Hence:

Proposition 5 Organisation and management studies of emergence will provide increased practical relevance to the degree that ABMs can be applied to issues of local relevance through appropriate modelling experimental-design technology.

## 8 Conclusions

Scholarship in the 21st century is changing, due to the need for interdisciplinary knowledge-creation strategies that span the capabilities of universities, research institutes, and practitioner application (Huff, 2000). At the same time, the rigors and demands of academic scholarship continue to increase, resulting in a dilemma characterised by March and Sutton (1997, p.698):

Organizational researchers live in two worlds. The first demands and rewards speculations about how to improve performance. The second demands and rewards adherence to rigorous standards of scholarship.

Others have lamented the result of this dilemma, namely that management research fails to impact practicing managers (Sussman and Evered, 1978; Whyte, 1989; Rynes et al., 2001; Bennis and O'Toole, 2005; Ghoshal, 2005; Benbya and McKelvey, 2006, 2011; Van de Ven and Johnson, 2006; Gulati, 2007; McGahan, 2007), while at the same time failing to gain legitimacy in the academic community (Pfeffer, 1993). The study of emergence and the methods of complexity can solve this dilemma in two important ways.

First, emergence, as described in the introduction, is an expansive phenomenon that has become important in virtually every management discipline, including organisational behaviour, change and development, organisational theory, entrepreneurship, innovation management, strategy, and others. Some have framed emergence as a generalisable process that can link multiple layers of economics and management (Adams, 1988; Dyke, 1988; Lichtenstein, 2007; Rosser, 2009; Brunner and Allen, 2009), while others suggest that emergence incorporates all the major steps in physical and social evolution (Jantsch, 1980; Mainzer, 1994; Khalil and Boulding, 1996; Chaisson, 2001; Mitleton-Kelly, 2003; Helbing, 2010). It follows that self-organisation and emergence may provide a context that integrates a variety of management frameworks, allowing researchers to draw together some of the disparate threads of management theory and practise.

Second, the Santa Fe Institute's approach to complexity science provides an ideal approach for studying emergence, via longitudinal multi-method narrative studies and ABMs. When linked together via the Semantic Conception (Suppe, 1977, 1989), complexity science, as the modern exemplar of 'normal science' provides a methodology and an epistemology that effectively justifies truth claims about emergence and self-organisation, gaining theoretical validity in parallel with practical relevance (McKelvey, 2003). As such, a complexity science of emergence offers insights into issues that are increasingly important for management scholars, and increasingly relevant to the leaders of our 21st century organisations.

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## Notes

- 1 Prigogine's focus on dissipative structures, governed by the 2nd Law of Thermodynamics (the inevitable trend of ordered systems toward randomness), was ignored by general systems theorists (von Bertalanffy, 1968; Buckley, 1967; Miller, 1978). As a result, Prigogine's work was also ignored in systems thinking foundational to organisation science (Katz and Kahn, 1966; Berrien, 1968; Baker, 1973).
- 2 An EBSCO-Host search on Business Source Premier, using the terms complexity science or complexity theory or complex adaptive system or self-organisation or dissipative structure or disequilibrium or NK or fractals, from 1991 to 2011.
- 3 Downward, upward, and the four Aristotelian causes: material, final, formal, and efficient. Aristotle looked at causes from the perspective of building a house. A grass hut and igloo differ because each is constructed of different locally available materials – material cause. Cheops' pyramid and Eiffel's tower differ because their vision of what should be built was different – final cause. Their organisational means of accomplishment (getting the job done on time, under cost, and consistent with the vision; use of hierarchy and technology, motivation of workers, etc.), were also different – formal cause. Their use of force and energy differed as well; flowing river and strong backs to get stones to the site vs. use of fire to form cast-iron girders and wheels to transport them – efficient cause. Aristotle's comments on the four causes appear in his book, *Physics*, which is published in Barnes (1995). The latter is the only one that survived into Newtonian, physics-based sciences, including economics (Mirowski, 1989).

Kaminska-Labbé et al. (2011) now point to the coevolution of causalities in organisations, given that all four Aristotelian causes appear in action.

- 4 In biological (living) systems ‘supervenience’ refers to downward causation beginning with coevolving environmental effects that influence the nature of bee hives, ant colonies, buffalo and lion herds, etc., which then influence the nature and survival of the animals, which then can influence the nature of how the animals’ biology evolves – e.g., stronger stings, long legs, bigger hearts and horns, better foraging abilities, etc. In firms we see the equivalent downward causation from industry and competitor-firms’ effects, to firm level, to department level effects, and so on, in parallel with the downward influences to CEOs and other top-level managers.
- 5 Structuration theory involves an even more complex view of emergence, for insofar as individual actions constitute, maintain and occasionally modify institutions, social action can also be said to supervene on institutions (Giddens, 1984).
- 6 The line of work that brings system dynamics closest to complexity is that by Allen (1988, 1994; Allen and McGlade, 1987). Allen typically uses ‘noisy differential equations’ in his models, which is one way to simulate heterogeneous agent behaviour without facing the limitations of monstrous combinatorial search spaces and the not so fast computers of that time. Still, representing expected results of agent interactions with stochastic parameters (not unlike what catastrophe theory modellers do) is not the same as actually assigning interacting agent rules that define their own learning objectives and how they choose to interact with other agents, and then finding out what kinds of self-organised macro structures emerge.
- 7 A power law is the rank/frequency expression,  $F \sim N^{-\beta}$ , where  $F$  is frequency,  $N$  is rank (the variable) and  $\beta$ , the exponent, is constant. This differs from an exponential equation where the exponent is the variable and  $N$  is constant. A power law is simply a set of Pareto-distributed data points plotted on log X- and Y-axes.
- 8 Kauffman does discuss emergent group structures in the context of interacting ecosystems [Kauffman, (1993), p.256–259]. Here regions of ‘order’ (where adaptive change is frozen) and ‘chaos’ (where adaptive change constantly fluctuates) on the CA grid emerge and change size as iterations progress. But this hierarchical emergence is a very minor part of Kauffman’s 700-page book and has not yet occurred in business applications.
- 9 Besides CAs and GAs, neural nets serve as the third primary agent-modelling platform. They stem specifically from brain functioning (Hassoun, 1995). For another sophisticated modelling approach combining all three, see LeBaron (2000).
- 10 What is a counterfactual conditional? If A were to occur, X would occur (Suppe, 1977); or, if we took A out of an experiment would X disappear. This is the only sure way of knowing whether A really causes X, or not. Needless to say, the experiment gets more complicated if there are moderator and mediator variables involved.