PART I

Foundations

A

Key Concepts

1

Complexity and Systems Thinking

Yasmin Merali and Peter Allen

> Once the whole is divided, the parts need names.
> There are already enough names.
> One must know when to stop.
> Knowing when to stop averts trouble.
> Tao in the world is like a river flowing home to the sea.
>
> Lau Tsu, Tao Te Ching

INTRODUCTION

Systems thinking has evolved over the millennia as people have looked for ways to articulate the features of the world around them in a coherent manner.[1] Starting from the definition of a system as an integrated whole made up of interconnected parts, various formalizations of systems thinking in a way that would be of interest to managers have emerged over time as people have looked for ways of rationalizing their interactions with the world. These formalizations give us a set of ontological and epistemological devices that have been used to define what the world is, to explain how it works, and to define and justify interventions that are intended to change, control or constrain the future behaviour of that world.

The ancients debated the role of structure, form and composition[2] in determining the behaviour of social, physical and natural systems, and engaged with the transience of system phenomenology,[3] and we find these themes recurring in modern theories of systems behaviour. Successive schools of systems thinking have focused on specific aspects of systems properties, and developed an apparatus to confront the challenges of their time in dealing with complexity.

In this chapter we track the evolution in the Western scientific tradition of systems ideas to deal with complexity, and reflect on the developments that are most likely to be influential in shaping management thinking from here on.

Our account takes us from Bertalanffy's biologically inspired GST (General Systems Theory), through the cybernetics of the Macy Group and the analytical ethos of systems engineering, the theories of self-organization and self-production in chemistry and life, to the present day engagement with the ideas of complexity science.

This trajectory crosses and re-crosses traditional divisions between the physical, biological and chemical sciences, and it takes us from the Newtonian predictability of the trajectories of complex dynamical systems in space to the present day challenges of dealing with the unpredictable trajectories of complex dynamical systems in space-time. We shall see how the different conceptualizations of systems and their complexity have affected the ontological and epistemological assumptions for successive models for managing complexity in socio-economic contexts.

SYSTEMS THINKING

Based on the definition of a system as an integrated whole made up of interconnected parts, axiomatic to traditional systems thinking are:

- the existence of a distinct entity that can be identified and explicitly defined as 'the system' or 'the whole';
- the composition of 'the whole' from a number of *inter-connected* parts; and
- the existence of distinctive properties that can be ascribed to 'the whole' but not to any of the individual parts that constitute 'the whole' (i.e. 'the whole' is more than the sum of its parts).

Systems thinking is often defined by its contrast to the Cartesian paradigm which is characterized by the belief that the behaviour of the whole can be understood entirely from the properties of its parts. Systems thinking, on the other hand, asserts that systems cannot be understood by analysis – the properties of the parts can only be understood within the larger context of the whole.

The composition (what the components are (made of)), structure (how the components are connected) and organization (how the components interact to maintain the coherent existence of the system as a distinctive 'whole') of a system together define the identity of the system at any given moment. As we shall see, these three aspects have received varying degrees of attention in the different families of systems thinking and practice that have evolved in diverse fields and been adopted and adapted by management thinkers to deal with complexity over the years.

General Systems Theory

The formalization of modern day systems thinking goes back to Ludwig von Bertalanffy's formulation of the General Systems Theory (GST) in the first half of the twentieth century as

> … an important means of controlling and instigating the transfer of principles from one field to another, and it will no longer be necessary to duplicate or triplicate the discovery of the same principle in different fields isolated from each other. (Bertalanffy, 1968)

In his exposition of the GST in 1940, Bertalanffy argued that the laws of classical physics that could be applied to predict the behaviour of physical systems were based on assumptions of systems closure and equilibrium dynamics that did not hold for biological systems. So, for example, whilst the Second Law of Thermodynamics states that the entropy (associated with the degree of disorder) of an isolated (closed) system which is not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium, living systems are open systems capable of maintaining ordered steady states under non-equilibrium conditions. This sets the stage for subsequent developments in systems thinking directed at understanding the dynamics that underpin the maintenance of order in open systems. Bertalanffy provided a point of connection for other developments in the study of open systems in diverse fields.

In the management field, systems thinking began to erode the Newtonian paradigm of a clockwork universe governed by deterministic laws of nature. Developments in the earlier part of the twentieth century were predicated on the design paradigm for management and problem solving. The emphasis was predominantly on the design of organizations as systems that could be regulated and controlled by management intervention. Later developments signalled a shift away from the design paradigm, as organizational scholars began to engage with ideas of self-organization, emergence, adaptation and co-evolution as mechanisms to explain the unintended consequences of designed management interventions.

The science of cybernetics, Maturana and Varela's conceptualization of autopoiesis (Maturana and Varela, 1973) and Prigogine's work with dissipative systems (Prigogine, 1967) are amongst the most influential forces in the evolution of ideas about the management and organization of systems. Cybernetics focused on mechanisms for control and co-ordination in machines and organisms, and gave rise to management theories for organizational design in the first part of the twentieth century. Maturana and Varela focused on the patterns of process and organization that defined living systems, and their work has been influential in the development of theories of self-organization and the maintenance of identity in social systems (Luhmann, 1990; Merali, 2002). Prigogine's work was influential in the development of ideas about the dynamics underpinning organizational transformation – shifting the focus from being to becoming.

THE DESIGN PARADIGM

In this section we look at the contributions of cybernetics and systems engineering to management thinking. Both approaches grew out of the research activity in the Second World War, and were influential in the development of management ideas about the way in which organizational structure and control mechanisms could be designed in order to meet the challenges of managing large, complex systems.

Whilst systems engineering focused on controlling complexity by breaking down large organizational structures into smaller, more manageable ones, cybernetics raised the attention of managers to the organizing *principles* that governed the nonlinear dynamics of structurally stable systems.

Cybernetics: patterns of control

The cybernetics movement began during the Second World War. Norbert Weiner coined the term cybernetics from the *kybernetes* (steersman) and defined it as a new science of 'control and communication in animal and machine'. The conceptual framework for cybernetics was developed in the Macy meetings (the first of which was held in 1946). The multidisciplinary membership of the Macy group included Weiner, von Neumann, McCullough, Shannon Mead and Bateson. Their agenda of developing a self-guiding, self-regulating machine ran alongside an interest in discovering the common principles of organization in diverse systems and in understanding the neural mechanisms underlying mental phenomena to create an exact science of the mind. Subjects like complexity, self-organization, connectionism and adaptive systems had been initiated already in the 1940s and 1950s.

The participants of the Macy conferences went on to make a number of important contributions to the fields of computer science, artificial intelligence, cognition, philosophy, information theory, economics, and ecology. John von Neumann's invention of cellular automata and self-reproducing systems has been incorporated into modern-day complexity science modelling approaches.

A major contribution of cybernetic movement to management science in the early part of the twentieth century was the conceptualization of feedback loops between system components as regulating mechanisms for the system's performance. The overall regulatory mechanism for the system is based on the existence of a circular arrangement of causally connected components – the output of each component either has a positive or negative effect on the output of the next component. The overall behaviour of the system depends on the cumulative effect of all the links between its components – a system containing an odd number of negative links will display a self-balancing behaviour, whilst one that has an even number of negative links will display a self-reinforcing exponential runaway behaviour.

The fundamental contribution of this conceptualization to general systems theory was the distinction of the *pattern of organization* from physical structure.

The early developments in management science based on cybernetic principles focused on the exploitation of negative feedback loops for the self-regulation of systems and the maintenance of stability. The importance of positive feedback mechanisms only entered mainstream management thinking in the 1990s along with the interest in understanding the network dynamics underpinning discontinuities in the competitive landscape.

Two of the most prominent developments derived directly from the cybernetic movement in the field of management are Jay Forrester's System Dynamics and Stafford Beer's Viable Systems Model.

System Dynamics

System Dynamics grew out of Forrester's work on applying the theoretical apparatus of control theory and the nonlinear dynamics associated with the feedback mechanisms of cybernetics to 'enterprise design' in the 1950s.

It is predicated on the development of models that define an enterprise in terms of the structure of the feedback loops underpinning its dynamic behaviour. The focus of the model is on the long-term patterns and internal organizing structure of closed information loops and their role in controlling and regulating the enterprise's behaviour in response to exogenous stimuli and endogenous fluctuations.

Over the years there has been a proliferation of modelling tools for System Dynamics to enable the representation of the causal structures of problems in terms of stocks and flows and feedback loops. The overall pattern of the feedback relationships is defined. The use of such tools has been important in promoting the use of System Dynamics models to design policy interventions and to test the potential of these interventions to effect desirable outcomes by affecting the relative potency of feedback loops. In particular, by supporting the modelling and simulation of complex systems with large numbers of variables within multiple interacting feedback loops, System Dynamics enables decision makers to explore the potential of their interventions to generate unintended consequences. In practice, the predictive power of System Dynamics simulations and their utility for designing interventions is limited by the extent to which a persistent set of feedback mechanisms and their causal effect can be defined for the lifetime of the model.

In systems where it is possible to accurately identify the pattern of feedback loops and the assumption of structural stability holds – i.e. new variables and equations do not appear during the time that the 'simulation' represents, System Dynamics models can be useful, and their predictions meaningful. However, this is no longer the case if the assumption of structural stability ceases to hold – e.g. if new mechanisms and innovations appear, or resources and factors that were not even included in the original model suddenly become important, or people change their behaviour. So, a System Dynamics model may be useful within the time span that its structure actually agrees with that of reality, but could be very misleading if this strong limitation was neither stated nor understood.

The Viable System Model

The Viable System Model (VSM) also originated in the 1950s, and was conceived by Stafford Beer as a generic blue-print, or template, for the organizing structure of any autonomous system. According to Beer, any organization can be defined in VSM terms as a set of systems nested within systems, embodying a recursive organizing structure.

The generic VSM template comprises a configuration of what Beer defines as the:

> … five necessary and sufficient subsystems interactively involved in any organism or organization that is capable of maintaining its identity

> independently of other such organisms within a shared environment. (Beer, 1985)

The generic VSM template is replicated at all levels of detail within the nested structure: the organizing architecture is fractal in nature, displaying the self-similar VSM template at every level.

Labelled as 'Systems 1–5' the subsystems respectively take care of the primary function of the organization, information and communication, governance, environmental monitoring, policy and strategy. According to the VSM theory, an organization is viable if and only if it has this specified inter-related set of management functions embodied recursively at all levels of organization. If any of the subsystems are absent or defective, the viability of the organization will be compromised.

VSM has been widely used for organizational diagnosis and design: its fractal nature unifies its application at all scales to define the management structures for maintaining a cohesive organizational structure and identity. Beer's own work on the diagnosis of socio-political systems illustrates the grand scope of VSM applications.

System Dynamics and VSM conform to a *design* worldview based on assumptions of structural stability, such that desired behaviours of complex systems can be brought about in a largely deterministic manner by management interventions on feedback loops. This view has sometimes been criticized for 'reifying' some temporary description, and for not taking into account the non-rational behaviour of human actors and the emergent aspects of collective behaviours. This criticism has been even more strongly levelled at the other strand of systems thinking (Systems Engineering) that grew out of the research activity from the Second World War.

The engineering of systems: constructing complex structures

In addition to the emergence of the cybernetic movement, a more analytic approach to dealing with complexity also grew out of the operations research activity in the Second World War, based on the definition of systems in terms of hierarchical structures and modular organization. At any level in the hierarchy the system could be partitioned into a set of interacting subsystems, which could themselves be decomposed further into subsystems at successively more granular levels of detail. The technical and management challenge lay in the partitioning of projects, systems and development work without losing the holistic view of the system. The conceptual challenge lay in the definition of boundaries and interfaces in a way that would preserve the integrity of the reassembled whole. This strand of systems thinking, typified by Systems Engineering and Software Engineering (often classified as the 'hard' systems approaches) focused on the internal consistency of modularized systems, whilst Soft Systems Methodology focused on the problematic definition of the 'whole' for human activity systems.

Systems Engineering

Systems Engineering as an approach and methodology grew in response to the increased size and complexity of systems and projects, it:

> recognizes each system is an integrated whole even though composed of diverse, specialized structures and sub-functions. It further recognizes that any system has a number of objectives and that the balance between them may differ widely from system to system. The methods seek to optimize the overall system functions according to the weighted objectives and to achieve maximum compatibility of its parts. (Chestnut, 1965)

This engineering approach to the management of complexity by modularization was re-deployed in the software engineering discipline in the 1960s and 1970s with a proliferation of structured methodologies that enabled the analysis, design and development of information systems by using techniques for modularized description, design and development of system components. Yourden and DeMarco's Structured Analysis and Design, *SSADM*, James Martin's Information Engineering, and Jackson's Structured Design and Programming are examples from this era. They all exploited modularization to enable the parallel development of data, process, functionality and performance components of large software systems. The development of object orientation in the 1990s exploited modularization to develop reusable software. The idea was to develop modules that could be mixed and matched like Lego bricks to deliver to a variety of whole system specifications. The modularization and reusability principles have stood the test of time and are at the heart of modern software development.

Introducing the axiological dimension: soft systems thinking

Whilst the cybernetic approaches had their roots in the desire to construct a self-guiding, self-regulating machine and create a science of the mind, and both VSM and System Dynamics have been used to explore aspects of social systems, none of the approaches covered so far dealt explicitly with human values and motivation.

Peter Checkland's conceptualization of the Soft Systems Methodology (Checkland and Scholes, 1990) grew out of his critique of the way in which systems engineering methods neglected the human dimension of the context within which systems were conceived and used. Soft Systems Methodology (SSM) is important in the history of systems engineering because of its explicit treatment of human purpose and value-based perceptions. Whilst the systems engineering approaches focus on the efficacy and internal consistency of systems specifications and their development – i.e. building the system right, SSM focuses on the often contested question of what the 'right' system should be. Subsequent attempts have been made to fuse SSM with the structured approaches of systems engineering, but SSM remains at its most powerful when used freely as an approach for exploring, making sense of, and defining multiple views of problem situations and their potential solutions.

SSM can be used both for general problem solving and in the management of change. Its primary use is in the analysis of complex situations where there are divergent views about the definition of the problem situation (e.g. How to improve health services delivery; How to manage disaster planning; When should mentally disordered offenders be diverted from custody? What to do about homelessness amongst young people?), and the transformation that it needs to undergo.

In SSM the problem situation is viewed as a human activity system with multiple stakeholders having different perceptions about the system and its purpose. In the early stages of the method each stakeholder is engaged in defining explicitly what the problem situation is, and what transformation it must undergo to achieve a more desirable state of affairs. As part of this exercise each stakeholder has to make explicit the *Weltanschaaung* (the 'world outlook' and value assumptions) that the transformation definition is based on. Each stakeholder then goes on to define the activities that must be undertaken to deliver the transformation, along with the requisite resource requirements and criteria for evaluating the effectiveness, efficacy and efficiency of the proposed transformation. The different stakeholder 'models' of transformation are then fed into a collective debate and discussion with the objective of arriving at a decision about the way forward that would be systemically desirable and culturally feasible.

Whilst SSM (along with other approaches arising out of the more general socio-technical school of management and critical systems thinking) was important in pointing to the importance of human and social values and perceptions in decision making and its outcomes, it remains within the design paradigm. Its focus is on specifying and designing the 'right' system intervention to achieve a desired state of affairs. Whilst it highlights the messiness of human activity systems and acknowledges the diversity that is accommodated in social organization, its design is to enable all stakeholders to see the whole, diverse problem space, and to take a collective decision about the best way forward.

Models in the design paradigm

Making models of complex systems and situations is a powerful way of understanding and testing the assumptions that we make about the structure and dynamics of systems.

We understand situations by making creative, but simplifying assumptions. We define the domain in question (the boundary) and by establishing some rules of classification (a dictionary) that allow us to say what things were present and when. This means that we describe things strategically in terms of words that stand for classes of objects. The value associated with an element in a model (e.g. number, price) may be both related to the internal state of the element and also affected by processes or mechanisms that link it to other elements. This allows us to understand the changes in a variable in terms of both internal conditions and also the changes that occur in the values of the other variables within the system. If the purpose of defining the system is to achieve an explanation of the linked changes in the values of the different components, then we need to include within the system the majority of causal links possible, and allow weaker links to be left in the environment. In other words, there may be a succession of levels of description corresponding to the natural clustering of linkages, such as for example, atoms, cells, organisms, groups, firms, industries, economies, societies up to the planet. The point is that in using a systems approach to characterize a situation, there are really three levels of description involved: the internal nature of the elements; the different variables in interaction making up the 'system'; the effects and links connected to the system environment.

The staging posts in the evolution of systems thinking have all been associated with different types of assumptions about what constitutes a 'good enough' abstraction of reality as a basis for the development of models that would allow us to:

- make predictions about future system states; and
- define interventions in the present that would generate desired behaviours of the system at some future point.

In Figure 1.1 we show how successive assumptions are made in the development of models in order to 'understand' the real situation. On the left-hand side we have the 'cloud' of reality and practice. Approaches like SSM engage with this by attempting to capture and systematize descriptions of perceptions of reality from different stakeholder perspectives.

The 'science' of modelling begins by deciding on a boundary within which an explanation will be attempted, in the context of the environment outside. The second assumption is that of classification. The elements present within the boundary are classified into types, so that potentially, previously established behaviour and responses of similar types can be used to predict behaviour. In examining any evolving system of interest over some long time, however, it will be found that qualitative evolution has occurred in which some types of component have disappeared, others have changed and transformed, and others still have appeared in the system initially as innovations and novelties.

Figure 1.1 shows us how starting from 'reality' on the left, about which no assumptions have been made, different types of representation and model can be made providing that the necessary assumptions hold (Allen et al., 2007). These different representations pass from one of pure acceptance through various intermediate views to one of complete deterministic certainty when prediction is believed possible. In the development of these representations and understandings of a

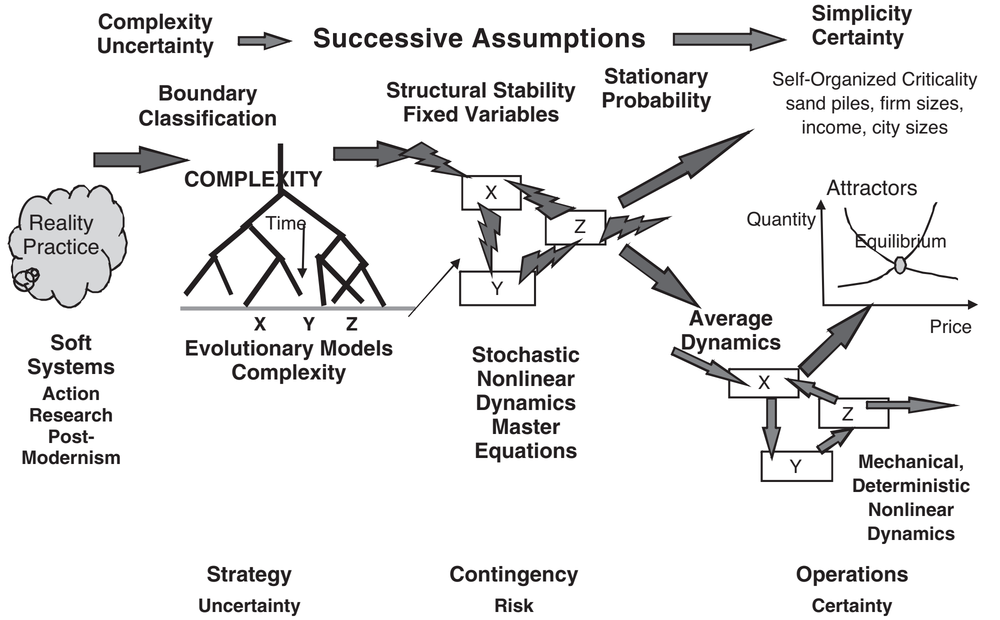

Figure 1.1 Successive assumptions that lead to various 'scientific' understandings of a situation

situation, the inherent openness of the future is constrained by two basic assumptions:

- the closure of the system to unknown outside influences; and
- the homogeneity and fixity of the classes of internal elements.

If these two assumptions can reasonably be made, then in fact the system may well behave in a predictable way. It really reduces to saying that providing nothing new happens in the environment and that system elements continue to act as they have been, we can predict the future. However, such an approach may work for artefacts that are only used in environments for which they were designed, but not for living things which can learn, get bored and be creative. Also, even the first assumption implies that all the interactions between system and environment are known and held within given bounds. But in reality, our system is an 'intellectual construction' which captures some, or many or most of the interactions between it and the environment but is constrained by the bounded rationality imposed by the modeller: it does not include the things that the modeller does not know about, or considers to be irrelevant. Indeed, it is through events and crises that some of the things we did not know will reveal themselves.

The assumptions are specifically shown in Table 1.1.

If we are interested in understanding the behaviour of the existing system then we can simply take the inventory and description now, and consider the 'working' of the components, bearing in mind the way that different aspects and elements are connected. This assumes structural stability and takes us away from open, evolutionary change, to the effects of running a fixed set of processes.

By considering only the present and assuming structural stability of our current system, we can generate models that govern the dynamics of the probability distributions of the different variables. Such models are

Table 1.1 The general complexity framework

Number	*Assumption made*	*Resulting model*
1	Boundary assumed	Some local sense-making possible – no structure supposed.
2	Classification assumed	Strategic, open-ended evolutionary – structural change occurs. Statistical distributions part of the evolutionary process can be multi-modal.
3	Average types	Operational, probabilistic, nonlinear equations, master equations, Kolmogorov equations – assumed structurally stable. Statistical distributions can be multi-modal or power laws.
	First pathway	
4	Statistical attractors	Self-organized criticality, power law distributions.
	Second pathway	
4	Average events, dynamics of average agents	Deterministic mechanical equations, system dynamics – assumed structurally stable. No statistical distribution.
5	Attractors of nonlinear dynamics	Study of attractors, catastrophe theory. Nonlinear dynamics with point, cyclic or chaotic/strange attractors.

systems models that are very useful in studying the resilience and risk of collapse of organizations or structures as a result of fluctuations in the environment and within the system. These models take into account not only the 'average' dynamics of such systems but their different possible futures in which luck can play a positive or negative influence. In other words, such models can consider how some particular shock or internal event may disturb the behaviour of the system, taking into account all possible sequences of events – including those that are possible but improbable. Resilience and contingency planning is not just about how a system will respond to a particular shock or disturbance but the relative probabilities of different possible pathways into the future – some corresponding to a return to normal functioning and others to different kinds of failure or collapse.

This is the essence of calculating risks and attempting to design systems that are resilient and capable of dealing with possible events and fluctuations. Such applications are of great importance for logistics, supply and demand networks and production systems. Systems models can be developed that can be used to examine their performance and also their resilience and the risk of failure under various circumstances. Structural stability and essentially fixed structural elements can be assumed if, for example, the systems are designed and owned by single agents. Of course, if the different elements should be managed by different agents with their own motives and learning capacity, models can be used to explore the effects of different assumptions of what these might be. In any case, these probabilistic dynamic models have been developed in the natural sciences and can be applied to help explore, design and make decisions in human complex systems.

If the events considered are discreet, then the running is according to a probabilistic dynamics, and we have what is called stochastic nonlinear dynamics, where different regimes of operation are possible, but the underlying elements never change nor learn, nor tire of their behaviours.

In Table 1.1 we have set out two pathways to greater simplification and easier understanding. The first pathway is to assume that we can use average rates instead of probabilities for the events, in which case we arrive at deterministic system dynamics. This is in general, nonlinear dynamics and may be cyclical or chaotic or at equilibrium, but what happens is certain, simple and easy to understand.

The second pathway is to suppose that the dynamic probabilities move rapidly to equilibrium – to a stationary distribution. This is a particular way to define a 'system' since it is one in which the interactions are assumed to maintain the form of the distribution. The work of Bak on sand piles led to the idea that this stationarity expressed that the system attained a self-organized criticality. So, for example, the probabilities of earthquakes, or of cities or firms of different sizes is considered to result from systemic interactions that will tend to restore the stationary distribution should it be disturbed. For many years the work of Zipf on word frequencies and on city sizes showed from the data that the distribution in question was particularly simple – a seemingly fixed negative power law governing the probability of finding a city of a given size. The US distribution of city sizes for example between 1790 and today has been described by a Zipf exponent of varying between 0.98 and 0.75 which is a remarkably stable curve. However, this apparent stability hides a great deal of dynamics since individual cities have occupied very different places in this scheme. Similarly, for firm sizes, although the overall curve for US firms is fairly stable the fate of each individual firm is still quite dramatic ending of course, as all things must, in extinction. While these ideas are interesting it is difficult to see how management can use these results in any way to make decisions. Rather it is true that agents struggle to attain their ends whatever that may be, and the interactions of the system seem to enmesh them in a fairly stable collective outcome. However, recently Toyota overtook General Motors as the largest automobile producer and so the distribution is in fact populated by large amounts of dynamic change and the probabilistic nature of the distribution by no means reduces agents to impotence. Bad management or lack of effort will simply hasten the demise that is the overall outcome that the distribution promises.

This discussion exposes some of the limitations associated with the assumptions of structural stability, equilibrium assumptions and the use of average types and distributions to describe system properties. In the next sections we look at how systems thinking in the second part of the twentieth century shifted away from assumptions of structural stability to focus on the dynamics of open, out-of-equilibrium systems and the importance of microdiversity in heterogeneous populations.

THE SCIENCE OF COMPLEX SYSTEMS: COMPLEX ADAPTIVE SYSTEMS

The later part of the twentieth century saw a questioning of the popularity of centralized, hierarchical management control, accompanied by a growing concern about the unintended and unforeseen consequences of planned management interventions.

Herbert Simon's articulation of bounded rationality in decision making and Mintzberg's articulation of strategy as emergent (Mintzberg, 1978) were important milestones in management thinking. Both pointed to the limitations of the planned approaches of decision makers in ensuring expected outcomes of management action, and fuelled the search for alternatives to the design paradigm.

As early as 1957, Simon highlighted the limitations in informational and cognitive scope and capacity of managers to make optimal decisions in complex situations, due to bounded rationality:

> boundedly rational agents experience limits in formulating and solving complex problems and in processing (receiving, storing, retrieving, transmitting) information. (Simon, 1957)

Simon's work was perceived at the time as a challenge to develop better optimization techniques within the design paradigm, but in fact it pointed to the more profound issue of whether it was *ever* possible to develop an optimal plan.

By marking the distinction between planned strategy and strategy in action Mintzberg's concept of emergent strategy highlighted the contextual complexity for strategic action. He proposed that *actual* strategies *emerge* from the *dynamics of interaction* between the organization and its environment. This idea brought with it notions of organizational learning and evolution over time. In the organizational behaviour literature, there was a growing interest in the role of self-organizing groups and front-line inventiveness in enabling transformation and innovation whilst maintaining organizational integrity in dynamic competitive contexts.

The rapid adoption of the Internet and related technological advances in the 1990s highlighted the networked nature of society and economics, characterized by increased informational complexity and scope for greater uncertainty and unpredictability associated with the consequences of management action. The global inter-connectedness and network dynamics made it difficult to define the requisite system boundary and parameters of structural stability within the deterministic design paradigm (Merali and McKelvey, 2006).

These developments generated the interest of management scholars in the 'new' science of complex systems which enabled the formalization of ideas of adaptation, emergence, self-organization and transformation.

Self-organization, emergence and adaptation

In systems thinking the idea of emergence was originally expressed in the context of systems as hierarchical, nested systems of systems – the philosopher C.D. Bond coined the term 'emergent properties' for properties that emerge at a certain level of complexity but do not exist at lower levels (Capra, 1996). Scientists in the second half of the twentieth century brought to the fore the importance of the open nature of systems and provided insights about the dynamics of emergence, inspiring management scholars to develop models of organizations as complex adaptive systems. Complex adaptive systems are systems that adapt and evolve in the process of interacting with dynamic environments. Adaptation at the macro level (the 'whole' system) is characterized by emergence and self-organization based on the local adaptive behaviour of the system's constituents.

Three of the most influential developments in systems thinking about emergence and self-organization in open systems came from the physical and life sciences: Prigogine's work on dissipative structures in chemical systems along with Eigen's hypercycles and Haken's articulation of Synergetics, Maturana and Varela's concept of autopoiesis in living systems, and the articulation of evolutionary dynamics in artificial life and ecosystems. All of these highlight that self-organization is not the result of *a priori* design, it surfaces from the interaction of system and the environment and the local interactions between the system's components. This capacity for the spontaneous *creation* of order through *intrinsically* generated structures is captured in Stuart Kauffman's (1993) expression 'order for free', in the notion of Prigogine's dissipative structures (Prigogine, 1967), Haken's Synergetics (Haken, 1973), Eigen's hypercycles (Eigen and Schuster, 1979) and in Maturana and Varela's theory of autopoiesis (Maturana and Varela, 1973).

Dissipative structures, autocatalysis and synergetics

In the 1960s Ilya Prigogine and his colleagues demonstrated that energy input to an open system with many interacting components, operating far from equilibrium, can give rise to a higher level of order. Running a particular chemical reaction where nonlinear catalytic effects were present gave rise to the spontaneous formation of stationary or moving patterns of colour ('dissipative structures') that either maintained themselves in a stable state far from equilibrium, or evolved to produce new patterns.

Close to equilibrium the chemical kinetics can be described by the linear equations of classical thermodynamics, but as the chemical reaction is driven further from equilibrium by pumping in reactants, the system reaches a critical point at which it 'jumps' spontaneously from homogeneity to a moving or stationary coloured pattern. Prigogine modelled this phenomenon using nonlinear chemical kinetic equations receiving matter and energy from the outside. In this explanation, changes in the internal structure (observed as instabilities and the jump to the new structural form) are the result of local fluctuations in the densities of chemicals amplified by positive feedback loops. He called the emergent, ordered structures 'dissipative structures'.

Also in the 1960s Herman Haken developed his science of *Synergetics* (Haken, 1973, 1978), based on his work with lasers, demonstrating the self-organization of an incoherent mixture of lightwaves of different frequencies and phases into a coherent laser light of one single monochromatic wavelength. The synergetic mechanism was taken up by Beer in his formulation of Syntegrity as a method for team-based problem solving (Beer, 1994).

In the 1970s Manfred Eigen speculated that the origins of life may lie in interacting autocatalytic cycles (hypercycles) that evolved by passing through instabilities and creating successively higher levels of organization characterized by increasing diversity of richness of components and structures for natural selection to act on.

Prigogine, Eigen and Haken's discoveries of self-organizing systems are all characterized by:

- stable states that are far from equilibrium;
- development of amplification processes through positive feedback loops;
- the breakdown of stable states through instabilities that lead to new forms of organization;
- continual flow of energy/matter through a system; and
- mathematical description in terms of nonlinear equations.

As Capra (1996) points out, in nonlinear thermodynamics the 'runaway' positive feedback loops that had always been regarded as *destructive* in cybernetics now appear as a source of new *order* and complexity in the theory of dissipative structures.

Dissipative structures demonstrated how self-organization and the emergence of structures (such as oscillating colours, spiral waves, etc.) at a completely different level to that of the molecules creating it, could occur spontaneously. The patterns were in the range of centimetres while the molecules that formed them were of the order of a hundred million times smaller. All that was required was a system of interacting elements (in this case molecules and atoms) that are open to flows of energy and matter. This gives us a science that includes history both in the organization and structure that has emerged, together with its relationship with the environment: in the words of Prigogine and Stengers: *'where classical science used to emphasize permanence, we now find change and evolution.'*

The nonlinear equations that describe the system's dynamics have a number of possible solutions, and the path that the system takes will depend on the system's history and the prevailing environmental conditions at that precise moment. As the system is in a constant state of flux, the combination of system state and environmental conditions is unique for each dissipative structure, and this means that over the longer term it is *impossible* to predict what the next system state will be.

It is this impossibility of prediction that distinguishes complex adaptive systems from chaotic systems. The term 'chaos' has been popularized in the managerial literature on dynamism, innovation and creativity, and is often used to refer to a state of disorder and randomness out of which arises a new order. However, technically a chaotic system is a *deterministic* system that has parts of its trajectory that are not stable so that its future is very sensitive to its precise path and current state. In practice the degree of accuracy (of measurement of start conditions) needed in order to predict an outcome is likely to be impossible to obtain. Chaotic systems share properties with complex systems, including their sensitivity to initial conditions. However, in the study of chaotic systems, the systems' dynamics are generally described by a small number of variables interacting in a nonlinear fashion, whilst complex systems have many degrees of freedom.

The scientific study of open systems has led to the science of complexity – that is the science of evolutionary change, adaptation and self-transformation. It deals with systems that can undergo spontaneous, symmetry breaking transformations corresponding to qualitative change with new emergent features, capabilities and processes and do not simply grow or decline within a fixed set of dimensions. It is easy to see the appeal of such a science for those in search of systemic principles to explain the dynamics of socio-economic systems: it has the potential to address the ideas of path dependency, creativity, disruptive change, unpredictability and self-determination that are characteristic of human activity systems.

This approach for open systems presented a major contrast to the equilibrium dynamics of traditional Newtonian physics, and brought to the fore the importance of system/environment interactions. For management scholars it suggested the possibility of a novel paradigm for the organization of complex social systems – one in which individuals did not have sight of the whole problem space, there was no central co-ordinator, and yet their local interactions resulted in the emergence of a coherent collective behaviour in the face of environmental perturbation. We shall see the impact of these ideas on current thinking about competition and the evolving competitive landscape in a later section.

Autopoiesis

Whilst the discovery of dissipative structures in the natural sciences provided the conceptual frame for understanding the dynamics of self-organization and transformation, the biological sciences provided a novel perspective on sustainability, life and the maintenance of organizational integrity.

The cybernetic movement had already launched a stream of research on the development of machine intelligence, and von Neumann's work with cellular automata forms an important component of experiments with artificial life to the present day. The von Neumann machine was a theoretical machine which, by following precisely detailed instructions, could fashion a copy of itself. The concept was then improved when Ulam suggested that the machine be built as a collection of cells on a grid. The idea intrigued von Neumann, who drew it up – creating the first of the devices later termed cellular automata.

Maturana and Varela's theory of autopoiesis had its roots in the cybernetic world: they examined the mathematical models of self-organizing networks from cybernetics, and using cellular automata, they developed the model of self-producing organization that is at the heart of their theory. Maturana and Varela (1973) identified *autopoiesis* (self-production) as the defining characteristic of all living systems. The term is sometimes used in a more general sense to refer to self-organizing systems with nonequilibrium dynamics capable of maintaining stability over long periods of time.

According to their definition, the system is open to the flow of energy and materials, but maintains its integrity and identity by organizational closure:

> Living systems [are] organised in a closed causal circular process that allows for a change in the way the circularity is maintained, but not for the loss of the circularity itself.

In keeping with the cybernetic tradition, their definition distinguishes between the organization (abstract description of pattern of relations) and structure (physical relationships between components, physical embodiment of its organization)**.** They define the living system as a network of networks of (self-producing) production processes, identifying three types of relations (*relations of constitution*, *relations of specification* and *relations of order)* that must obtain between components in order to maintain the substance, form and integrity of the autopoietic *unity* over time. The autopoietic *unity* is a self-referential, self-regulating, self-producing, self-organizing entity capable of maintaining a stable state under nonequilibrium conditions. The autopoietic 'network of processes of production' is realized by components interacting with each other through structural coupling and neighbourhood relations of variable strength. Perturbations in the environment are sensed by boundary components and appropriate adjustments are propagated through the network. Individual components make adjustments relative to their local neighbourhood relations to maintain a stable global *organization.*

The mechanism of structural coupling allows the system to learn and to generate new behaviours in response to environmental changes whilst preserving its overall pattern of network relationships. The system interacts with both its internal and external environment through structural coupling, responding to environmental changes with structural changes which will in turn alter future behaviour of the system as a whole.

In the management field, autopoiesis has provided an important conceptual framework for thinking about boundary phenomenology and the processes of self-organization that allow learning and creativity whilst maintaining organizational integrity and identity in the face of environmental perturbations (Merali, 2002).

In sociology Niklas Luhmann developed the theory of autopoiesis to study social systems as networks of networks of communication:

> Social systems use communication as their particular mode of autopoietic reproduction. Their elements are communications that are … produced and reproduced by a network of communications and that cannot exist outside of such a framework. (Luhmann, 1990)

The dynamics of the system is defined in terms of self-amplifying feedback loops, and network closure gives a shared system of beliefs, explanations and values – a context of meaning – which is continually sustained by further conversations. In Luhmann's approach, communication acts include self-production of roles and boundaries (of expectation, confidentiality, loyalty, etc.), which are maintained and renegotiated by the autopoietic network of conversations.

The autopoietic construct illustrates the combination of path dependency and innovation that have characterized the evolution of systems thinking: in it we can see clearly the connection between the cybernetic movement of the Macy conferences, and the self-organizing principles of complex systems science articulated by Prigogine, Eigen and Haken. Its impact on the field of management has been largely at the conceptual level – as metaphor, model and, as in Luhmann and Merali, theory for making sense of the systemic properties of individual organized forms and their persistence.

In the next section we look at the ideas about the way in which other ideas from biology have contributed to our understanding of more complex socio-economic systems involving multiple relationships between many individuals and organizations – we move from looking at the *unity* as an individual persistent, bounded entity to looking at populations of different entities and their co-evolution with the changing landscape.

Adaptation, evolution and co-evolution

In the second half of the twentieth century a number of models and theories developed to link diversity of individuals at the local micro level with population level effects at the macro level. Some of the main contributions to systems thinking in this vein came from models of evolutionary dynamics and the creation of artificial life with cellular automata.

Artificial life

Simulations deploying von Neumann's cellular automata were instrumental in the development of ideas about the way in which a collection of simple entities (later referred to as 'agents')[4] could, by following very simple interaction rules, self-organize into complex structures. This type of modelling was used extensively in the 1960s and 1970s to develop ideas about the origins of life and the organization of biological systems at all scales, ranging from the genome and cellular organization through to organisms, ecologies and social systems.

Craig Reynolds work on the dynamics of flocking was amongst the first biological agent-based models that contained social characteristics (Reynolds, 1987). He tried to model the reality of lively biological agents, known as artificial life, a term coined by Christopher Langton in the 1980s. Models such as these (in which elaborate, stable flocking patterns emerge as individual agents follow three very simple rules for positioning themselves relative to their neighbours) inspired management scholars to look for simple rules that they could deploy to create a self-organizing, adaptive workforce. Experiments showing the spontaneous emergence of novel artificial life forms encouraged them to advocate the organizational forms that were on the 'edge of chaos', aligned with Kauffman's speculation that:

> Networks on the boundary between order and chaos may have the flexibility to adapt rapidly and successfully through the accumulation of useful variations. In such poised systems, most mutations have small consequences because of the systems' homeostatic nature. A few mutations, however, cause larger cascades of change. Poised systems will therefore typically adapt to a changing environment gradually, but if necessary they can change rapidly. (Kauffman, 1991)

Whilst many of the attempts to translate these ideas into management practice were overly simplistic, this strand of work succeeded in providing management scholars with models for conceptualizing the dynamics of self-organization.

Evolutionary dynamics: fitness landscapes

According to the classical theory of evolution, populations adapt to their environment under the pressures of selection. At the individual level, biological fitness is determined by the genetic make-up of individuals, with those that have a good enough fit with the environment surviving to reproduce.

The classical top-down perspective of selection as the driver of evolution has been complemented by complex systems scholars using cellular automata to define mechanisms for the generation of micro-level diversity and defining the 'fitness landscape' or map of the relative value (for survival) of individual genetic endowments. The most common mechanisms for generation of diversity are random mutation and recombination. The evolutionary process is defined as a search in the space of possible genotypes for points that map for a higher fitness. The best known of such models is Stu Kauffman's *NKC* model in which the space of possible genotypes is defined by a network of *N* genes (with *A* possible variants (alleles)) with *K* interdependencies between them (determining the extent to which the potency of each gene is affected by its interacting others) and affected by *C* external interdependencies. As Maguire et al. (2006) explain:

> biologists conceptualize the challenge facing species as a problem of combinatorial optimization – of navigating the landscape in search of higher peaks by sampling points in the space, ascertaining the associated fitness, and moving – then theorize about adaptation, competition and co-evolution using computational experiments. Agents thus, try to climb toward fitness peaks, but run the risk of getting trapped on suboptimal ones.
>
> It is also important to realize that since a new behaviour can have emergent properties and features, in reality the 'fitness landscape' only exists where it is 'populated'. The real fitness, and even the dimensions of performance may change when a new type is actually tried out.

Models of evolutionary dynamics have been deployed in management science as a mechanism for connecting the diversity and interactions of individuals at the local level with the overall system characteristics displayed at the macro-level for a number of different applications including the dynamics of competition, the emergence of dominant designs, the impact of disruptive technologies and organizational adaptation.

Evolutionary drive

'Evolutionary drive' was put forward some years ago (Allen and McGlade, 1987) as the underlying mechanism that describes the change and transformation of complex systems. In this view evolution is driven by the interplay over time of processes that create micro-diversity at the elemental level of the system and the selection operated by the collective dynamic that results from their interaction together with that of the system with its environment.

This co-evolution is seen as a continuous, on-going process and not one that has already 'run its course', as in the case of 'evolutionary stable strategies' (Maynard-Smith, 1982). Because of the ignorance of individuals, and of the universe itself, as to the pay-offs that will occur over time for a given behaviour, there are always new aspects of micro-diversity that can occur, so that co-evolution never reaches an 'optimal' outcome, as in the Game Theory approach. Instead, we see this multilevel exploration and retention process as an on-going process that is occurring in real time, enabling the system to respond to currently undefined changes in the environment. History is still running. Each behavioural type is in interaction with others, and therefore evolutionary improvements may lead to greater synergy or conflict between behaviours, and in turn lead to a chain of responses without any obvious end. And if there is no end, then the most that can be said of the behaviour of any particular individual or population is that its continued existence proves *only that it has been 'good enough' – but not that it is* optimal.

In this review of the ideas that link complexity to the management of organizations the guiding premise is that successful organizations require underlying mechanisms that continuously create internal micro-diversity of ideas, practices, schemata and routines – not that they will all be taken up, but so that they may be discussed, possibly tried out and either retained or rejected. It is this that will drive an evolving, emergent system that is characterized by qualitative, structural change.

It firmly anchors success in the future on the tolerance of, and ultimately organizational understanding of, seemingly unnecessary perspectives, views, and ideas, since it is through the future implementation of some of these that survival will be achieved. In other words the organizational behaviour and the functional types that comprise it *now*, have been created from the competitive and/or cooperative interactions of the micro-diversity that occurred within them in the *past*.

Elements may be of the same type, but differ from each other in detail. Nobody may know whether these differences will make a difference as they are just random variations around a reasonable average. But, consider that there is in fact a 'fitness' landscape which actually reflects better and worse 'fit' of the diverse individuals to the environment. In biological evolution, the variation is caused mainly by genetic and epigenetic variations which lead to phenotypic heterogeneity for which the fitness landscape will provide differential survival and reproduction rates, thus defining and amplifying the 'fitter', and suppressing the less fit. In this way, the existence of mechanisms that provoke genetic and phenotypic variation will automatically produce the exploration of the fitness landscape.

In a competitive market it will be true that differential performance will be defined by customers and investors through the choices they make. Within organizations, however, evolutionary change will require that different performances of different individuals, ideas, practices or routines be noticed, and that what works well is deliberately reinforced, and what works less well discouraged. This differential dynamics is really the 'selection' term of Darwin, operated by the environment, the customers and investors of the market place, or by the beliefs of the upper echelons of the organization. The organization chooses between different possible practices, routines, etc. and the market chooses between different possible products and services made by firms – and the only thing that is certain is that if there is no diversity to choose between, then nothing can change.

Evolution can only occur if there is something that will generate heterogeneity spontaneously. And this is in fact the current ignorance about future outcomes and a lack of commonly agreed norms of how things should be done. This leaves managers with the challenge of deciding how much diversity to support within the organization for the sake of an unknowable future: the real options approach is designed to allow managers to invest in possible futures, but deciding *what* to invest in is still a challenge. The situation is further complicated by its dynamics and the coupling of the internal organization and the environment: the shape of the competitive landscape changes as individual organizations make their moves, and, depending on the dimensions of change, the fitness factors may also change. This brings to the fore the importance of time and timing, and of the information flows between system and environment.

We can devise a simple computer program to demonstrate the dynamics of evolutionary drive, by considering a population that initially sits at a low point of a fitness landscape, and then has random variation of individual fitness. Different individual types will grow at different rates, thus defining 'fitness' after the fact. Gradually the population will 'climb' the local fitness landscape because of processes of 'exploration' in character space. Ignorance and consequent randomness are very robust sources of such exploration. Clearly random changes in the design of any complicated entity will mean that tinkering experiments will lead to many non-viable individuals and hence that there is an 'opportunity cost' to behavioural exploration. By considering two populations simultaneously at the foot of the fitness hill, where one population has a higher rate of randomness in character space than the other, we can compare the relative success of different rates of exploration. Initially, the 'explorer' population wins, because, despite its cost in nonviable individuals, diffusing and innovating faster is rewarded by the fitness slopes it discovers. Later, however, when the landscape has been explored and climbed, faster diffusion is no longer rewarded and the more conservative population with less exploration eventually dominates.

Evolution is thus driven by the noise to which it leads. Providing that microscopic diversity (noise) is produced in systems of interacting populations, the interaction dynamics will lead to the retention and amplification of some, and the suppression of others. This process will determine the 'ability to evolve' as well as the particular types of micro-diversity contained in the populations at a given time. This situation reinforces the earlier epistemic theme of our limited knowledge of our own systems. There will never be a completely clear understanding of any evolving system at a given time, because it will always contain micro-diverse elements that may or may not turn out to be successful. The understanding that we can have of reality is obtained by creating a 'system' of interacting entities that are sufficiently correct to describe the current situation, but inadequate to predict the future structural evolution that may occur.

However, understanding the nature of evolutionary dynamics enables us to speculate on the space of possibilities for the future by experimenting on how plausible models of current states may play out under a variety of future conditions.

For a social system, the irreducible uncertainty of the open-ended co-evolution of things means that a messy, micro-diversity is the only insurance against an unknown future, and that social evolution will proceed through successive periods of drift and diversification separated by shorter spans of selective elimination. Evolution and co-evolution only demonstrate what is not viable at a particular time, and do not imply that what remains is an optimal structure that achieves anything in particular. Models can be built that capture the behaviour of multiple interacting individuals and the way in which their beliefs are confounded, reinforced or updated as they struggle to make sense of their changing circumstances. Complex systems models can therefore help us explore the consequences of different possible practices, values and beliefs, perhaps indicating some basic features that will underlie any functioning society.

Modelling complex social systems

Advances in mathematics of complex systems since Newton and Leibnitz' differential calculus have become increasingly sophisticated, and significant developments include statistical mechanics, dynamical systems theory for dealing with nonlinearity, feedback and iterations, and Poincare topology and fractal geometry for studying the qualitative features of complex systems. Whilst analytic methods have always been used for studying system dynamics, most nonlinear equations for complex systems are too difficult to solve analytically, and the advances in computing capacity have advanced the practice of solving by just running them numerically.

Cellular automata and agent-based systems are the most prevalent modelling approaches used for modelling complex social systems. One of the earliest social agent-based models (ABM) in concept was Thomas Schelling's segregation model (Schelling, 1971). Though Schelling originally used coins and graph paper rather than computers, his models embodied the basic concept of ABMs as autonomous agents interacting in a shared environment with an observed aggregate, emergent outcome.

With the growing availability of computers ABMs could become much more ambitious (an early example is Robert Axelrod's model for competing strategies for the Prisoner's Dilemma).

For social systems ABMs have been used to examine phenomena from the societal scale (e.g. ethnocentricism and dissemination of culture and the co-evolution of social networks and culture), issues as designing effective teams, understanding the communication required for organizational effectiveness and the behaviour of social networks at the level of the individual organization (Axelrod, 1997; Carley, 2003). More recently, agent-based simulations have been based on models of human cognition, known as cognitive social simulation (Sun, 2006). The exploitation of ABMs in the management field spans applications in the strategic, operational and organizational domains (Lomi and Larson, 2001; Maguire et al., 2006).

The diffusion of agent-based modelling has been accelerated by the availability of specialized modelling software (StarLogo in 1990, SWARM and NetLogo in the mid-1990s and RePast in 2000). A number of special interest groups and journals have been established focusing on the use of agent-based modelling in the social sciences (reviewed in Bonabeau, 2002; Samuelson, 2005; Samuelson and Macal, 2006).

Epstein and Axtell developed the first large-scale ABM, the Sugarscape, to simulate and explore the role of social phenomenon such as seasonal migrations, pollution, sexual reproduction, combat, and transmission of disease and even culture.

Learning multi-agent models

Agent-based modelling really become complex systems modelling when the agents are open to new ideas (decision behaviours) and can learn over time. This effectively opens the system. Without this, the models themselves are still closed, mechanical systems.

One of the direct uses of ABMs with learning agents is in the study of competitive dynamics. The competitive landscape of a given organization consists, among other things, of other organizations with similar objectives, and so there will be two criteria for fitness: (1) the ability to out compete similar organizations, or (2) the ability to discover other 'niches' which can still command resources, but which escape the competition.

In Darwinian thinking the micro-diversity of agents that occurs is considered to be 'random' and independent of the selection processes that follow, while in human innovation we like to think that there is intentionality, calculation and belief that may, *a priori*, 'channel' diversity into some narrower range.

The openness of an organization to its environment underlines the importance of the 'fit' between an organization and its environment. The 'fitness' of any organization or structure is a measure of its ability to elicit, capture or merit resources from its environment and put them to use for self-perpetuation. In order to maintain 'fitness' in a changing environment then, it will be necessary for the organization to be capable of actively transforming itself over time, requiring that agents change their internal knowledge, behavioural rules and perhaps connections.

Just having noisy agents, or signals with agents with fixed rules, which can be simply described by fixed stochastic equations corresponds to a mechanical model of social systems. Representing learning agents that can give rise to structural change and emergent capabilities takes us from a mechanical model with fixed structure to evolutionary and co-evolutionary models which exhibit full complexity.

The dynamic perspective on competition shifts the emphasis from creating a set of maximally efficient operations that will produce some good or service for a particular market, to developing adaptive capacity in recognition of the reality of openness. Openness exposes the organization to change in supply and demand situations and the continual appearance of new ideas, technologies and competitors. This in turn demands changes in the organization itself, as it is presented with the need to learn and adapt, continually shifting its focus to track change. This discussion of organizational dynamics reinforces the replacement of maximal efficiency with 'sufficient efficiency' combined with sufficient adaptability, but emphasizes the significance of self-organized, organizational change in underwriting this process.

The problem of what constitutes the requisite level of efficiency and diversity to deal with the changing competitive landscape has no single definitive solution, but the use of agent based models allows us to explore the space of possible futures that may evolve from the (albeit limited) set of endowments and actions that we can conceivably attribute to our agents.

CONCLUSION

The evolution of systems thinking, starting from the ancients' distinction between structure and form, has progressed as successive simplifying assumptions have been challenged and new dimensions have been introduced.

Associated with each stage of development are concepts that have influenced management thinking along with powerful methods and models for adoption in management practice. In this chapter we have traced the path from approaches predicated on assumptions of structural stability to the present day engagement with complex systems science and the nonequilibrium dynamics of open systems.

One of the key transitions in the methodological perspectives between the two halves of the twenty-first century has been the shift from assuming structural stability to questioning whether and when it is safe to assume structural stability. In the absence of structural stability the challenge shifts from being one of dealing with uncertainty to one of also dealing with unpredictability.

The science of complex systems has given us the conceptual and methodological equipment to tackle issues of emergence, self-organization, evolution and transformation, to elucidate the mechanisms by which micro-level properties can give rise to macro-level behaviours, and to explain the generation of novel structures and behaviours over time.

The developments in evolutionary dynamics have challenged two other methodological constructs that dominated systems thinking in the earlier era. The emphasis on open systems and the concept of co-evolution have entailed re-thinking the construct of the boundary and the separation of concerns between system and environment. The recognition of micro-diversity, outliers or 'noise' in the generation of alternative evolutionary pathways has challenged the use of average values to define variables, and this in turn has challenged the relevance of many of the statistical approaches for modelling the dynamics of social systems.

Historically systems' thinking has its roots in philosophy and the natural and biological sciences. The application of systems concepts to social systems has been an important component of management science. The scientific understanding of the being and becoming of biological and physical systems has been variously deployed in the management field as metaphor, analogue and true description of social systems.

Some of the objections to using concepts from the natural sciences to explain human social systems have focused on the inadequacy of these concepts to deal with issues of free will, intentionality and purposiveness. However, the recognition exists that there are collective phenomena and systemic properties that can be ascribed to human activity systems. Systems' thinking gives us the possibility of choosing and using abstractions to make sense of the dynamics that underpin the behaviour of individuals and collectives. Complex systems thinking is attractive because it gives us the concepts that have been used to characterize social behaviour in the human sciences (e.g. emergence, adaptation, evolution, transformation, path-dependency, learning, diversity, serendipity), and allows the possibility of developing models that capture some of the richness and diversity of human existence. The complex systems modelling approaches allow us to experiment with possible worlds in which consequences of our actions play out over time. In doing so we need to be aware of the dangers of bounded rationality and its influence on the choices that we make about the abstractions we deploy, and the assumptions we make about the data that we test these against.

Over time the focus of systems' thinking has shifted from structure (reflected in the use of modularization to deal with complexity), to organization or form (accentuated in the cybernetic approaches) to the network dynamics of adaptation and transformation (within the paradigm of complex systems science). Each of these 'phases' has given us concepts, tools and methods for understanding and dealing with complexity in the world as we understand it.

For management science, systems' thinking is a framework that includes these different approaches and allows us to deal with the idea that the component parts of a system can best be understood in the context of relationships with each other and with other systems, rather than in isolation.

NOTES

1 Capra (1996) attributes the root meaning of the word 'system' with its holistic connotations to the Greek *synhistanai* (to place together).

2 For example, the Pythagorean distinction between matter and substance, and the Aristotelian distinction between *matter* and *form*.

3 For example, Heralcitus' observation that we cannot step in the same stream twice.

4 Whilst the origins of agent-based models go back to the von Neumann machine, it is probable that the first use of the word agent is by John Holland and John H. Miller's (1991) paper *Artificial Adaptive Agents in Economic Theory* which is based on an earlier conference presentation of theirs.

REFERENCES

Allen, P.M. and McGlade, J.M. (1987) Evolutionary drive: the effect of microscopic diversity, error making and noise, *Foundation of Physics*, 17(7): 723–728.

Allen, P., Strathern, M. and Baldwin, J. (2007) Complexity and the limits of learning, *Journal of Evolutionary Economics*, 17: 401–431.

Axelrod, R. (1997) *The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration*. Princeton: Princeton University Press. ISBN 978-0-691-01567-5.

Beer, S. (1985) *Diagnosing the System for Organizations*. UK: Wiley.

Beer, S. (1994) *Beyond Dispute: The Invention of Team Syntegrity*. Chichester: John Wiley.

Bertalanffy, L. von (1968) *General Systems Theory*. New York, NY: Braziller.

Bonabeau, E. (2002) Agent-based Modeling: Methods and Techniques for Simulating Human Systems. Proceedings of the National Academy of Sciences 99, May 2002. pp. 7280–7287.

Carley, K.M. (2003) In Pattison, P. ed. *Dynamic social network analysis: Workshop summary and papers:* 133–145. Washington, DC: The National Academies Press.

Capra, F. (1996) *The Web of life: A New Scientific Understanding of Living Systems.* New York: Anchor Books.

Checkland, P.B. and Scholes, J. (1990) *Soft Systems Methodology*. UK: Wiley.

Chestnut, H. (1965) *Systems Engineering Tools*. Wiley. ISBN 0471154482.

Eigen, M. and Schuster, P. (1979) *The Hypercycle: A Principle of Natural Self-Organization*. Springer Verlag.

Haken, H. (1973) Synergetics: cooperative phenomena in multi-component systems. *Symposium on Synergetics, 30 April to 6 May 1972*. Stuttgart: Schloß Elmau.

Haken, H. (1978) *Synergetics – An Introduction*. Berlin: Springer Verlag.

Holland, J. and Miller, J.H. (1991) Artificial Adaptive Agents in Economic Theory, *American Economic Review Papers and Proceedings*, 81: 365–370.

Kauffman, S. (1991) Antichaos and adaptation, *Scientific American*, August 1991.

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

Lomi, A. and Larson, E. (eds) (2001) *Dynamics of Organizations: Computational Modeling and Organizational Theories*. Menlo Park, CA: MIT Press.

Luhmann, N. (1990) The autopoiesis of social systems. In N. Luhmann (ed.), *Essays on Self-Reference*. New York, NY: Columbia University Press.

Maguire, S., McKelvey, B., Mirabeau, L., and Óztas, N. (2006) Complexity science and organization studies. In S. Clegg, C. Hardy, and T. Lawrence (eds), *Handbook of Organizational Studies* (2nd edn). Thousand Oaks, CA: Sage, pp. 165–214.

Maturana, H. and Varela, F.J. (1973) Autopoiesis: the organization of the living. In H.R. Maturana and F.J. Varela (eds), *Autopoiesis and Cognition: The Realization of the Living*. Boston Studies in the Philosophy of Science 42. Dordrecht: D. Reidel.

Maynard-Smith, J. (1982) *Evolution and the Theory of Games.* Cambridge University Press. ISBN 0-521-28884-3.

Merali, Y. (2002) The role of boundaries in knowledge processes. *European Journal of Information Systems,* 11: 47–60.

Merali, Y. and McKelvey, B. (2006) Using complexity science to effect a paradigm shift in information systems for the 21st century. *Journal of Information Technology*, 21(4): 211–215.

Mintzberg, H. (1978) Patterns in strategy formation. *Management Science*, 24(9): 934–948.

Prigogine, I. (1967) Dissipative structures in chemical systems. In S. Claessons (ed.), *Fast Reactions and Primary Processes in Chemical Kinetics*. New York, NY: Elsevier Interscience.

Prigogine, I. and Stengers, I. (1984) Order out of Chaos. New York: Bantam Books.

Reynolds, C.W. (1987) Flocks, Herds, and Schools: A Distributed Behavioral Model, in Computer Graphics, 21(4) (SIGGRAPH '87 Conference Proceedings) pp. 25–34.

Samuelson, D.A. (2005) Agents of Change: How agent-based modeling may transform social science. OR/MS Today. February (Operational Research and Management Science).

Samuelson, D.A. and Macal C.M. (2006) 'Agent-Based Modeling Comes of Age,' OR/MS Today, August. (Operational Research and Management Science).

Schelling, T.C. (1971) Dynamic models of segregation. *Journal of Mathematical Sociology*, 1, 143–186.

Simon, H.A. (1957) *Models of Man*. New York: Wiley.

Sun, R., (ed.) (2006) *Cognition and Multi-Agent Interaction: From Cognitive Modeling to Social Simulation.* Cambridge University Press.