Developing a conceptual model for exploring emergence

Diane M McDonald[1,2] **and George RS Weir**[2]
Information Resources Directorate[1],Computer and Information Sciences[2]
University of Strathclyde
D.McDonald@strath.ac.uk, George.Weir@cis.strath.ac.uk

1. Current perspectives on emergence

Emergence is a fundamental property of complex systems and can be thought of as a new property or behaviour which appears due to non-linear interactions within the system; emergence may be considered to be the 'product' or by-product of the system. For example, within social systems, social capital, the World Wide Web, law and indeed civilization in general may be considered emergent, although all within different time scales. As our world becomes increasingly more interconnected, understanding how emergence arises and how to design for and manage specific types of emergence is ever more important. To date, the concept of emergence has been mainly used as an explanatory framework (as used by Johnson 2001), to inform the logic of action research (Mitleton-Kelly 2004) or as a means of exploring the range of emergent potential of simulation of real complex systems (Axelrod 2003). If we are to improve our ability to manage and control emergence, we need first to directly study the phenomenon of emergence, its causes and consequences across real complex systems.

The informal definition above is indicative of the current level of understanding of emergence. Despite a vast range of accounts in the literature (e.g. Holland 1998; Kauffman 2000; Johnson 2001; Strogatz 2003; Fromm 2004; Crutchfield 1993; Bedau 1997, 2002; Shalizi 2001; Kubik 2003), there is no agreed definition, let alone theory, of how emergence arises. Much of the confusion stems from differences in vocabulary and perspectives across disciplines – emergence has been variously described as events which are surprising, the result of non-linear dynamics, novelty, hierarchy and the product of evolution. While some formal models of emergence based on grammars (Kubik 2003) or computational mechanics (Crutchfield 1993) do exist, the most common concept when discussing emergence is that of Agent-Based Modelling (ABM) (Casti 1997; Holland 1998; Epstein 1999). ABM aims to replicate the complex nature of physical, biological and social systems which adapt over time forming Complex

Adaptive Systems (CAS); multiple, possibly non-homogeneous 'agents' are represented as identifiable components which behave in an autonomous and goal-directed manner. ABM is not a direct model of emergence, rather the computer simulation of ABM aims to replicate emergence as observed in real complex systems.

The ability of current models fully to portray emergence in all its possibilities has been questioned (Gross and Jeffries 2001; Kauffman 2000; Fontana 2003; Funtowicz & Ravetz 1994). Reasons range from the lack of understanding of the inner working of CAS (Strogatz 2003), through intrinsic limitations of programming constraints (Gross and Jeffries 2001) to the claim that the behaviour observed in real complex biological and social systems is uncomputable (Rosen 1991). As Funtowicz & Ravetz (1994) point out, current conceptual models of emergence are too simplistic or general to be useful when examining real life social systems – they do not adequately replicate the range of types of emergent phenomena observed in real physical, biological and social systems. Improved understanding and modelling of emergence is required.

Emergence by its nature is problematic to model. It is the product of interconnections and interaction making it dynamic and unpredictable; entities, interactions, their environment and time are key contributors to emergence, however there is no simple relationship between them. For example, how do novel system entities, such as the appearance of life, eyes or language appear? Examination of literature shows that different types of emergence exist – the self-organised structure of birds flocking is quite different from the emergence of the first self-reproducing cells – at least in terms of the creativity of the system. The question is, how and why do these different types of emergence arise? For example, self-organisation, while linked with the appearance of hierarchical structures and system wide properties does not account for the emergence of true novelty (Gross and Jeffries 2001) or semantics and meaning (Pattee 2001). Are there underlying generalisations which can be drawn about the occurrences of different types of emergence, which can be applied to real systems? This is after all one of the underlying principles of Complexity Science. Another little understood issue is how emergent properties or dynamics appear to influence the behaviour of the constituent entities of the system – displaying what Campbell (1974) describes as downward causation. The inner workings of such 'closed causal loops' (Rosen 1991) are still unclear, presenting a fundamental modelling problem.

In order to address the issues with the modelling of emergence and develop a useful investigatory model, a 'back to basics' approach was adopted. A new model was derived by examining the literature to see what an emergence model should usefully include. A conceptual modelling approach was adopted because, as Järvelin & Wilson (2003) suggest, it allows a useful representation of salient features pertaining to the issues under investigation. Such a model does not necessarily have the explanatory power of formal models, rather it "provides a working strategy, a scheme containing general, major concepts and their interrelations. It orients research towards specific sets of research questions." (Järvelin & Wilson 2003). Initial review led to the hypothesis ***H0****: A novel, domain neutral conceptual model which takes cognisance of the texture of emergence will provide a useful framework for exploring and improving understanding of emergence*.

The paper proceeds as follows: The new conceptual model of emergence is presented in section 2; the testing of the model is described in section 3. Section 4 then discusses the advantages of this approach, addressing issues of reliability, generalisability and transferability and its limitations. The paper concludes (section 5) by summarising the results, identifying the novelty and outlining future steps.

2. Developing the model

2.1. Meta Classes of Emergence

Below, we provide a brief summary of the rationale for the various meta classes of emergence identified through the literature review process. These meta classes – indicated by italics - were first introduced in McDonald and Weir (2005). Features were considered potential meta classes if (i) they were the product of non-linear interactions, (ii) they were domain independent (iii) they were a core building block for system interactions and (iv) they open up new system potential by their existence.

Self-organisation, where detailed organisational structure and new system interactions emerge as a result of the, often very simple, behaviour rules of the system entities, is a well documented feature of real complex systems. The term self-organisation is varyingly used to describe the dynamics of complex systems, emergence or the specific organisational changes brought about through the autonomous entity behaviour. The term *organisation* rather than self-organisation is therefore used in preference and is defined as the structural change in a complex system which arises from nonlinear, possibly noisy interaction. Where this structural change is a collection of parts with ordered asymmetric relationships, we class it as *hierarchy*. The concept of *hierarchy* again is well documented, frequently acting to constrain the degrees of freedom of a complex system.

As Kauffman (2000) observes, some emergence fundamentally changes the complex system in which it appears. For example, the appearance of biological cells radically changed the purely chemical environment on earth leading to life as we know it. Similar step changes occurred with the emergence of new social units in history. Therefore, we define *novelty* as the emergence of a sustainable new entity with distinctly different interaction patterns. For Pattee (2001), the role of memory is crucial in biological systems – "evolution depends, at least to some degree, on control of dynamics by rate-independent memory structures." These memories must first appear before the complex systems may capitalise on them. Therefore, we define the *memory* meta class as frozen structure or processes which arise through non-linear interactions.

Kauffman (2000) in his 'investigation' of life suggests that biological life relies on synergistic coupling which happens in nature through an entity's ability to sample its environment and make use of synergistic opportunities – it uses other entities or processes within the system to do work. This is an example of what we term the emergence of *functionality*, where a new process emerges that carries out 'work' which is used by another entity. Before entities can make use of other entities or processes in this synergistic way, they must be able to detect their existence. When a new ability for sampling of the environment arises through interaction, we define that as the emergence of *measurement*. Related to the emergence of memory is the issue of its accessibility to the various entities of the complex system. Where the non-linear interactions cause this memory or processes within the system to be restricted to certain parts, we describe this as *localisation*. If the localised memory or processes are 'used' differently within the system, then *context* is said to have emerged. Related to this is semantics. As Kauffman (2000, p111) emphasises - "Once there is an autonomous agent, there is a semantics from its privileged point of view. […] we are not far from C.S. Pierce's meaning laden semiotic triad". It is this ability of entities to recognise patterns which trigger specific behaviour, although the original causal pattern may be lost that significantly adds to the creativity of complex systems. This we call *symbolism*.

We discarded certain phenomena found in the literature if they did not meet our criteria. For example, 'surprise' (Roland et al) was discarded as it is related to the degree of understanding rather than any intrinsic quality of emergence. Variation is included within contextualisation. We also have, for two reasons, deliberately excluded concepts such as autocatalysis, reproduction, evolution, dissipative systems and autopoiesis. Firstly, these are specialised forms of processes which emerge and therefore are included under function / process. And secondly, we wish to start afresh – the model if it is to be useful should be able to shed new light on these processes rather than be restricted by these preconceived theories. Domain specific phenomena such as life were excluded to retain neutrality. We suggest however, novelty, memory functionality and processes are components of life, which is still itself to a degree an ill-defined concept.

2.3 The Model

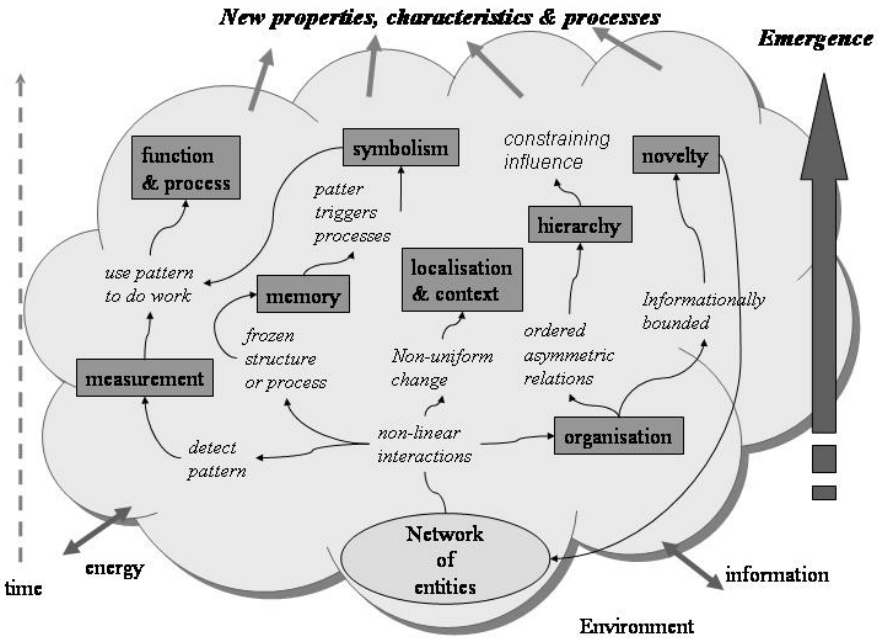

Figure 1: New conceptual model/framework of emergence.

Combining the meta classes with the basic components of complex systems identified in section 1, we arrive at our new conceptual model of emergence, illustrated in **Figure 1** above. The meta classes represent the core building blocks and creative steps of emergence within complex systems. Specific emergent phenomena are built up from a combination of various meta classes. The meta classes illustrate the texture of emergence and we do not require that each emergent phenomenon belong to a specific class, nor must each meta class be a component of the emergence. The meta classes are not disjoint. For example, hierarchy may be considered a specialised subset of organisation. Hierarchy is included because its constraining effect helps distil new emergence from more chaotic dynamics.

3. Testing the model

As the aim of the model was to challenge existing conventions and develop a useful exploratory framework for emergence in real systems, the model was necessarily speculative and subject to change as investigation progressed. While to a large degree, it is the lessons learnt through the development and testing that are important rather than the initial model itself, it was important not to waste time using an inappropriate or false model. To address this challenge and the need to test both usefulness and accuracy, a two stage strategy was adopted**:** (i) the plausibility of the model was tested and (ii) its usefulness as a framework for exploring emergence in real complex systems was assessed by its application in real complex systems to test pertinent hypothesis.

3.1. Plausibility testing

Two aspects required testing: firstly, that the conceptual model is fit for purpose – it is both a valid model of emergence and actually captures the types of emergent behaviour observed in real complex systems and secondly, that the manner in which it does is useful – it aids generation of new insight. The first plausibility requirement was addressed by analysing the fit of the model to existing accounts of real complex systems. Three systems – physical, biological and social - were analysed in detail, examining how their adaption over time matched the various meta classes. The results, displayed in Table 1 below, showed a correlation that supported the appearance of the meta classes as expected. For example, symbolism and measurement were not expected to be found in the evolution of the physical universe.

	Structural	***Memory***	***Novelty***	***Process & Function***	***Measure-ment***	***Symbolism***	***Localisation & context***	***Hierarchy***
Universe	√	√	√	√			√	√
Life (single-celled)	√	√	√	√			√	
Life (multi-celled)	√	√	√	√	?		√	√
On-line communities	√	√	√	√	√	√	√	√

Table 1: Analysis of meta classes found in sample complex systems.

To address the second plausibility requirement, a focus group was used to test the perceived usefulness of the meta classification in tackling identification and understanding of emergence. The group was asked to consider emergence within the context of a university community. Discussion focused on how emergence is currently identified and whether a meta class approach could help improve that. The discussion supported the proposal that a meta class approach could provide useful insight.

3.2 Usefulness and Hypothesis

In order to test the usefulness of the meta model as an investigatory framework for real complex systems, the original hypothesis ***HO*** was broken down into ***H1:*** *The 'meta' classes provide a useful framework for exploring and improving understanding of emergence in social systems* and ***H2:*** *Examining the 'meta' classes and how they develop will provide valuable insight into the mechanics of emergence, aiding development of a theory of emergence.*

The usefulness of the model (**H1**) could be best tested by its practical application. This was achieved by development of an investigatory tool derived from the conceptual model framework, followed by its application to real complex social systems (2) to identify their emergent characteristics. The tool consisted of semi-structured interviews designed to explore the existence and causal factors of each of the meta classes. The open ended questioning allowed for additional, unanticipated emergence types to be identified. The tool was applied to investigate emergence in 'Complex Learning Communities'. Its application proved successful with both a range of emergence and its netlike causal structure identified (McDonald 2005). Respondents also reported it as being a useful exercise as they were asked to consider things from a different angle. Thus, the evidence gathered supported **H1**.

H2 was further split into a number of sub-hypothesis concerning how the meta classes were expected to appear within the systems under investigation. For example, *H2-2: Measurement is a precondition for the emergence of new functionality*. The data gathered from the tool application was then used to test these hypotheses. Again, the evidence gathered supported **H2**.

4. Discussion

The concepts on which a good conceptual model are built should, according to Järvelin and Wilson (2003) (i) meet basic scientific requirements of precision, accuracy, simplicity, generality and suitability for expressing testable propositions; (ii) represent essential features (objects, relationships, events) of the research area; and (iii) differentiate and classify the phenomena in ways that lead to interesting hypothesis (research problems). To this, we add our criterion (iv) provide a useful framework for investigating emergence in real complex systems. The extent to which these criteria have been met is discussed below.

The model was deliberately designed to be generalisable and domain independent and Occam's razor was applied in selecting the meta classes. Simplicity was also an important design criterion, although the meta class concept did introduce a new 'level'.

This it is argued is important as it provides insight into the texture of emergence which is an improvement over more formal grammar based models. The testing described in section 3 suggested that the meta model was sufficiently apposite and suitable for generating testable propositions (the hypotheses).

The analysis of the model's applicability across physical, biological and social systems, combined with its successful application within learning communities lends credibility to its claim to represent the essential features of emergence. However, it should be born in mind that complex adaptive systems are essentially creative – their 'adjacent possible' is ever changing (Kauffman 2000) and novel building blocks of emergence may appear. This suggests that the model should eventually be coupled with a formal calculus of emergence, if such a model is feasible – the meta model providing the more accessible context, the calculus providing a more rigorous base.

One of the advantages of our meta model is that it affords differentiation of the different meta classes and probing of how these might be linked. It also addresses Kubik's (2003) criticism of existing models - "definitions [of emergence] lack a common basis of comparison. It seems they overlap in some way, but it is unclear how" – by providing a set of criteria by which other models can be tested. If they cannot reproduce these classes under the relevant circumstance then other models' appropriateness should be questioned. The ability to structure the investigation of emergence in real complex systems, while still remaining open to unanticipated factors proved useful. And while the model was tested within learning communities, its domain independent nature means that it could equally be used as a framework to develop investigatory tools for other social, biological and physical contexts. Indeed, although a principal driver for the model was to facilitate investigation of emergence in real complex systems, the model is equally applicable to investigating emergence simulated within ABM.

The process of developing the model was an important part of the learning experience in itself. The meta model is to a degree a speculative, concept testing tool, which meant that it evolved as the research progressed. Enabling this to happen while maintaining scientific soundness meant that a two stage testing approach was adopted. As Patton (2002) observers, this is in reality a common, but unacknowledged part of the scientific process, where experience feeds back, refining and enriching the model.

5. Conclusion: Summary, novelty and next steps

In this paper, a new conceptual model of emergence - based on meta classes of emergence - was introduced. This model offers a practical, useful framework for investigation of emergence and its causation in real complex systems as well as aiding the generation of insight into the theoretical mechanisms of emergence. It also meets the requirements of a good conceptual model and enabled the derivation of a useful investigatory tool. The novelty in this work lies in our meta class approach and the corresponding investigatory framework for emergence in real complex systems. An additional benefit is that it may act as a comparator for other, more formal models of emergence. Our next steps are to (i) use the model to explore emergence in other domains, (ii) develop and explore the relation of specific meta classes across domains and (iii) investigate how this model could be applied to improve the simulation and theoretical modelling of emergence.

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