# What are Emergent Properties and How Do They Affect the Engineering of Complex Systems?

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**'Emergent properties' represent one of the most significant challenges for the engineering of complex systems. They can be thought of as unexpected behaviors that stem from interaction between the components of an application and their environment. In some contexts, emergent properties can be beneficial; users adapt products to support tasks that designers never intended. They can also be harmful if they undermine important safety requirements. There is, however, considerable disagreement about the nature of 'emergent properties'. Some include almost any unexpected properties exhibited by a complex system. Others refer to emergent properties when an application exhibits behaviors that cannot be identified through functional decomposition. In other words, the system is more than the sum of its component parts. This paper summarizes several alternate views of 'emergence'. The intention is to lend greater clarity and reduce confusion whenever this term is applied to the engineering of complex systems.**

*This paper was motivated by observations of a recent workshop on Complexity in Design and Engineering held in Glasgow, Scotland during March 2005. It builds on the analysis presented by the other papers in a special edition of Elsevier's Reliability Engineering and Systems Safety journal. These other papers are indicated by references that are not accompanied by a numeric index.*

## 1. Introduction

Complex systems can be characterized in several different ways. At a superficial level, they are hard to design and understand. These conceptual problems often stem from the multiple interactions that occur between many different components. Marashi and Davis define complex systems to 'contain many components and layers of subsystems with multiple non-linear interconnections that are difficult to recognise, manage and predict'. Taleb-Dendiab, England, Randles, Miseldin and Murphy provide an example of this 'face-level' complexity in the design of their decision support system for post operative breast cancer care. The Neptune system combines a 'situation based calculus' with a 'grid architecture' to provide distributed support to a large and diverse user population. However, Solidova and Johnson provide examples of second order complexity where relations between sub-components change over time. They cite the difficulty of predicting the complex temporal flows of interaction in response to rapidly changing properties of both systems and environment. As Wears, Cook and Perry observe in their contribution on healthcare failures 'The incident emerged from the interaction of major and minor faults which were individually insufficient to have produced this incident. The design problem here is that validation of individual device design is an insufficient basis from which to conclude that use in context will attain the design performance levels'.

It seems clear that complexity poses growing challenges to systems engineering. For example, Gott (2005) has recently identified what he calls the 'complexity crisis'. He finds that, "…driven by markets that demand ever-increasing product value and functionality, manufacturers have embarked on continuous product improvement, delivering more features, more innovation and better looking products". He goes on to argue that "coping with the resulting design complexity while maintaining time to market and profitability is the latest challenge to hit the engineering industry". Bruseberg provides examples of this interplay between technical difficulty, project management issues and the economics of systems development in her study on the use of 'Commercial Off The Shelf' (COTS) software components for the UK Ministry of Defence (MoD). In her case, complexity stems from the need to satisfy system safety requirements using components that were not designed for safety-critical applications. Similarly, Felici's paper looks at the socio-technical challenges created by the need to maintain safety margins in European Air Traffic Management as the number of flights are predicted to double by 2020 without significant increases in infrastructure investment.

Wulf (2000) has identified complexity as one of the most significant "macroethical" questions facing the US National Academy of Engineering "the key point is that we are increasingly building engineered systems that, because of their inherent complexity, have the potential for behaviors that are impossible to predict in advance". A recurring theme in this paper will be the 'surprise' that engineers often express following adverse events. This is illustrated by Basnyat, Chozos and Palanque's analysis of a complex mining accident and by Felici work on the Űberlingen mid-air collision. Both incidents revealed traces of interaction between operators and their systems that arguably could not have been anticipated using current engineering techniques.

## 2. Engineering Complexity in a Historical Context

Complexity is not a novel phenomenon. Galileo's Dialogues Concerning Two New Sciences describes how a column of marble was stored on two supports at either end. The masons knew that these columns could break under their own weight and so they placed another support at the mid section of the beam. They were satisfied with their work until the column broke at exactly this mid-point. One of the interlocutors in the Dialogue's makes observations that have a great deal in common with modern descriptions of emergent behaviors in complex systems; the failure of the column was "a very remarkable and thoroughly unexpected accident, especially if caused by placing the support in the middle". One of the end supports had decayed over time while the middle support had remained hard so that half of the beam projected into the air without any support. Petrowski (1994) states that it is 'to this day a model of failure analysis' and goes on to point out that if the supports had been placed at the extreme eights of the column then the maximum bending stress would have been up to double that of the beam resting on its end points alone. Arthur D. Little (1915) one of the pioneers of chemical engineering argued that the basic unit operations in any process are relatively simple. However, "the complexity of chemical engineering results from the variety of conditions as to temperature, pressure, etc., under which the unit operations must be carried out in different processes, and from the limitations as to material of construction and design". Such quotations remind us that environmental and contextual views of engineering complexity have very early roots.

It is possible to distinguish between the elegant 'complexity' of early engineering and the 'messy complexity' of modern systems. As Marashi and Davis note 'An effective and efficient design could not usually be achieved without a proper understanding of the relationship between the whole and its parts as well as the emergent properties of the system. A wicked and messy problem like engineering design has many interlocking issues and consequences which may be unintended. The vast range of stakeholders involved in an engineering design project, e.g. public, client, construction team, designers, financiers, managers, governmental agencies and regulating bodies; and their changing requirements from the system, escalates the complexity of the situations. Furthermore, the objectives change in response to the actions taken and each attempt for a solution changes the problem situation'.

The introduction of information technology and integrated manufacturing techniques has broken down boundaries between subsystems to the point where the behavior of many systems cannot adequately be modelled in terms of individual components. Changes in one area of a system quickly propagate themselves to many other areas in ways that seem impossible to control in a reliable way. The North American electricity black-out of August 14th 2003 provides a good example of this 'messy' complexity. Few could have predicted the way in which deregulation of an industry might combine with the diseased branches of several trees to bring down a vast network of power distribution across two nations. However, not all modern systems possess this 'messy complexity'. Felici argues that 'nuclear or chemical plants are well-confined entities with limited predictable interactions with their surroundings. In nuclear and chemical plants design stresses the separation of safety related components from other systems. This ensures the independence of failures…In contrast; ATM systems operate in open and dynamic environments. Hence, it is difficult to identify the full picture of system interactions in ATM contexts'.

## 3. What is Emergence?

Emergent properties are often used to distinguish complex systems from applications that are merely complicated (Johnson, 2003). They can be thought of as unexpected behaviors that stem from interaction between the components of an application and the environment. Emergent properties can be beneficial, for example, if users adapt products to support tasks that designers never intended. They can also be harmful if they undermine important safety requirements. However, there is considerable disagreement about the nature of 'emergent properties'. Some include almost any unexpected properties exhibited by a complex system. Others refer to emergent properties when an application exhibits behaviors that cannot be identified through functional decomposition. In other words, the system is more than the sum of its component parts.

### *The British Emergentists and Layered Views of Complexity*

The recent preoccupation with emergent properties has many strands. One area of research has renewed interest in the parallels between complex technologies and biological systems. For example, Holland (1998) and Gershenfeld (1999) put a new spin on the work of philosophers such as J.S. Mill (1884): "All organised bodies are composed of parts, similar to those composing inorganic nature, and which have even themselves existed in an inorganic state; but the phenomena of life, which result from the juxtaposition of those parts in a certain manner, bear no analogy to any of the effects which would be produced by the action of the component substances considered as mere physical agents. To whatever degree we might imagine our knowledge of the properties of the several ingredients of a living body to be extended and perfected, it is certain that no mere summing up of the separate actions of those elements will ever amount to the action of the living body itself". Mill based his arguments on distinctions between heteropathic and hompathic effects. Homopathic effects arise where causes acting together are identical to the sum of the effects of those causes acting in isolation. For example, forces acting on an object can have the same effect when applied in combination or separately. In contrast, heteropathic effects describe emergent properties seen in complex biological and chemical systems. These conjoint actions cannot be characterised by the sum of any individual causes. For example, the addition of sodium hydroxide to hydrochloric acid produces sodium chloride and water. It is unclear how such a reaction could be characterised as the sum of individual components.

Mill's ideas indirectly led to the development of the 'British Emergentists'. Although their work was not directly intended to guide the engineering of complex systems, many of their ideas have implicitly helped to shape current debates in this area. The emergentists proposed a layered view of complexity in which the world is divided into different strata. At the bottom are fundamental physical laws. On this foundation we can observe chemical, biological, psychological and social interactions at ever increasing levels of organisational complexity. Research in physics, therefore, investigates fundamental properties and laws that are broadly applicable. The remaining 'special sciences' focus on properties that emerge from complex systems. These emergent properties can be influenced by behaviors at lower levels in this layered approach. In engineering, therefore, we can identify behaviors that cannot be understood in terms of the individual observations of underlying physical phenomena. They can only be considered in terms of their collective actions at the higher systems level.

An immediate problem with this layered approach to complexity is that many properties stem from interaction between systems and their environment. Paternò and Santoro make this clear when they analyse the impact of context of use on interaction with safety-critical systems. While standard emergentist approaches look at general relationships between different layers in complex systems. Engineers must, typically, focus on specific relationships between a system and its environment. The underlying ideas in the emergentist approach do not readily suggest a design method or development technique.

### *Alexander and the Challenge to Functional Decomposition in Risk Assessment*

There are several different theories about how relationships are formed between the layers of a complex system. For Mill and later philosophers such as Broad, higher-level emergent properties in complex systems stem from, and are in addition to, lower level causal interactions. Hence we can talk about both the ways in which crowds behave at an organisational level and at the level of individual actions that influence wider patterns of group behavior. The distributed cognition observable in teams of system operators is often quite different from the sum of the individual cognitive resources displayed by each individual user. Although the sum may be more or less than the individual parts of a complex system, in Mills view, it is still possible to reason about properties of the higher level systems in terms of the properties possessed by their component parts.

The second explanation of interaction between levels in complex systems was proposed by emergentists, such as Alexander (1920). They argue that the appearance of novel qualities and associated, high-level causal patterns cannot be directly expressed in terms of the more fundamental entities and principles. In this view, it makes little sense to talk of human cognition in terms of individual neurons. Consciousness is intrinsically a systems level property quite distinct from the underlying physiology of lower level components. The term emergence is often used to reflect the limitations on our understanding of complex systems. This strand of thought is strongly associated with engineering studies of 'messy' complexity, mentioned in previous paragraphs. Although the work of Alexander and his colleagues is not primarily intended to address the engineering of complex systems, the implications are clear. The idea that there are properties of systems that cannot intrinsically be understood in terms of lower level concepts seems entirely at odds with many contemporary approaches to engineering. For example, this would suggest that there are many risks that cannot be identified by following the functional decomposition that is implicit within techniques such as FMECA.

Some authors, including Pepper (1926), have attacked the concept of emergence in complex systems. For example, it can be argued that unexpected or novel macroscopic patterns of behavior do not reveal special forms of 'emergent' properties. Instead they simply illustrate problems with our understanding of a complex system. The limitations in our knowledge could be addressed if we augmented our theoretical understanding to include the conditions in which novel phenomena occur. It would then be sufficient to construct more complex laws that specify behavior when the new variables are not satisfied and the 'novel' behavior when the variables are satisfied (O'Connor and Wong, 2002). This approach creates a number of problems. For example, the papers of this special edition describe a great range of emergent phenomena in several different application domains ranging from healthcare to aviation. Pepper's would characterize their behavior using of dozens of disjoint laws, each of which would describe system properties in a very small set of circumstances. By extension, we might also argue for the presence of emergent properties whenever there is discontinuity in microscopic behaviors unless we can develop an elegant theory that relies more narrowly on the basic properties of the system.

### *Predictive Approaches to Emergence in Accident Investigation*

The contemporary philosophy of emergence has been heavily influenced by *predictive approaches;* emergent properties are system level features that could not have been anticipated. For example, Wears, Cook and Perry describe healthcare vulnerabilities that cannot easily be anticipated by designers 'in particular, some forms of failure emerge from the interactions of independently designed and implemented components'. They go on to present a case study 'of such an emergent, unforeseen failure and use it to illustrate some of the problems facing designers of applications in health care'.

Predictive approaches are orthogonal to Alexander's ideas. For instance, there are many systems level properties that are not directly related to system subcomponents but which might be predicted. Alexander might call these properties emergent but this attribution would not fall within the definitions adopted by predictive approaches. For example, ‘risky shift’ occurs when greater risks are accepted by groups than would have been taken by individual team members. In other words, the level of acceptable risk shifts towards the more risk preferring members of the group. Such behaviors are emergent in Alexander’s terms because they are closely entwined with the behavior of groups. However, in a predictive sense they need not be emergent because they can be anticipated. Designers can, therefore, take steps to guard against these behaviors that might otherwise compromise the engineering of complex systems. For example, risky shift can often be detected by external reviews of team-based risk assessments.

The predictive approach to modern theories of emergence raises questions about the perspective of the person making the predictions. Designers and engineers never have ‘perfect knowledge’ about the systems and environments that they work with. Information about a complex system may be distributed in such a way that some properties may be emergent for a group that lacks key information whereas the same features of a complex system might easily have been anticipated by co-workers with additional data. It is, therefore, often assumed that emergent properties are those that cannot be predicted by individuals who possess a thorough knowledge of the features of, and laws governing, the parts of a complex system and its environment (O’Connor and Wong, 2002). This relativism has important implications in the aftermath of major accidents. In retrospect, it is easy to argue that any behaviors that were not anticipated during the design of a complex system were emergent simply because they had not been predicted. This interpretation ignores the important caveat that emergent properties must be assessed with respect to a thorough knowledge of the system and environment in question. Under the predictive view, to argue that an accident was caused by an emergent property is to accept that the behavior could not have been anticipated by an individual with “a thorough knowledge of the features of, and laws governing, the parts of a complex system and its environment”. All too often, engineers have issued warnings about possible accidents that have been ignored until after an adverse incident has occurred (Johnson, 2003). Such failures cannot be described as emergent properties under this predictive interpretation.

Popper and Eccles (1977) have extended studies into emergence and unpredictability by investigating the non-determinism that often characterizes complex systems. Designers often fail to determine the behavior of application processes. For example, environmental conditions can introduce the non-determinism that prevents accurate predictions about complex systems. In a layered view, non-determinism can also stem from interactions with the layers both above and below a particular level. Apparently random behaviors can arise when we have failed to understand underlying systems. Early 19th century bridge builders such as John Scott Russell, struggled to predict the performance of suspension bridges because they did not sufficiently understand the way in which the positioning of crossbars could affect the modes of vibration that affected particular designs. Without any sufficient theory, the best that could be done was to use experimental methods as a means of mapping out the apparent non-determinism that was observed when some bridges failed whilst others succeeded (Petrowski, 1994). This analysis seems to contradict Anderson’s view in which there are emergent properties that cannot be understood in terms of the underlying layers in a complex system. In contrast, if we view emergence as strongly related to non-determinism then it might be possible to ‘control’ or at least anticipate emergent properties by understanding the source of any non-determinism, for example, by studying the underlying properties of lower level components within a system. The non-deterministic approach to emergence, therefore, need not reject functional decomposition as a primary tool in the engineering of complex systems.

### *Teleological Approaches to Emergence*

Chalmers (2002) identifies a spectrum of approaches to emergence. At one extreme, ‘emergence’ is used to describe ‘semi-magical’ properties. This captures an extreme form of surprise where higher-level properties of a system cannot be deduced from lower level attributes no matter how sophisticated the analysis or the analyst. At the other end of the spectrum is a more prosaic view in which emergence means little more than properties that are possessed by a ‘whole’ and not by its parts. In this view, almost every non-trivial object possesses emergent properties, including filing cabinets and chairs.

Most applications of the term lie between these extremes. When we talk about emergent properties in biological systems or connectionist networks we are usually referring to behaviors that can, in principle, be deduced but only with great difficulty. Bedau (1997) calls this ‘weak emergence’. Such properties are identified by the degree of difficulty that an observer has in deducing them from lower level phenomena. However, emergence often carries with it the notion that the underlying phenomena are relatively simple. For example, the behavior of a large-scale computer program can be almost impossible to deduce in terms of the underlying binary signals. However, few people would say that the behavior is emergent. In contrast, many authors describe the computational architecture of connectionist networks as displaying emergent properties. Chalmers views emergence as a largely positive phenomena where these simple combinations of simple components buy you ‘something for nothing’. In other words, emergent behaviors in biological systems support behaviors in addition to those provided by individual components. For instance, the visual system supports perception that defies explanation in terms of components such as the retina, cornea etc. Similarly, the genetic mechanisms of evolution are very simple but the results are complex.

Chalmers’ analysis approaches a teleological definition of emergence. These phenomena are associated with systems that possess interesting properties that were not included in the goals of the designer. This teleology is significant because for many working on the biological aspects of emergence, the notion of a ‘designer’ implies some guiding hand that stands at odds with Darwinian views. However, Chalmers (2002) argues that the psychological and relative approach to emergence also allows a non-telelogical approach; ‘in evolution, for instance, there is no "designer", but it is easy to treat evolutionary processes as processes of design’. It is more straightforward to apply Chalmers’ work in the field of engineering where design objectives can be inferred without reference to divine intervention.

### *Bedau and Weak and Strong Emergence*

As mentioned, Bedau (1977) distinguishes between weak and strong emergence. Weak emergence is a macroscopic state which could be derived from knowledge of the system's micro-dynamics and external conditions but only by simulating or modeling all the interactions of the microstates starting from a set of initial conditions.

Bedau's work contributes to recent research in the area of chaos 'theory'. His view of weak emergence characterizes situations in which the longer term outcome of non-linear processes is sensitive to very small differences in initial conditions or environmental factors. However, in weak emergence it is possible for engineers to derive these higher level behaviors from lower levels even if this analysis requires considerable modeling resources.

In contrast, Bedau's work on strong emergence borrows much from the mind-body problems of cognition, mentioned in previous sections. Higher-level behaviors are largely autonomous from underlying layers, just as higher levels of cognition cannot easily be described in terms of neurological processes. These distinctions between weak and strong emergence can also be characterized in terms of causal relationships between the different levels of a complex system. For example, weak emergence can be analyzed using reductionist techniques where complex behaviors at a systems level are caused by properties of underlying components. In contrast, strong emergence relates to a form of 'downwards causation' where behaviors at lower levels in a system are constrained by higher level characteristics. One way of thinking about this is in terms of social interaction. The behavior of a crowd can be simulated in terms of the behavior of individual members. This represents a 'bottom-up' form of weak emergence. In contrast, crowds also act in conformity with rules that govern their behavior as a whole. For instance, if a crowd enters a narrow alley then it alters its movements. Groups entering the constriction will slow their pace in order to avoid hitting or getting to close to others in front. Locally, the crowd self-organises even though for any individual the movements and buffeting may appear random. As Lemke (2000) observes of this form of strong emergence; "Order forms because there are only relatively few solutions to the problem of correlated motions, and when contrasted with an ideal of randomness in which all possible states of motion are equally likely, those few solutions stand out as orderly". It is for this reason that many computer-based evacuation simulators enable their users to specify individual behaviors. These tools also provide facilities for users to place constraints onm crowd behaviors, to simulate the flocking that occurs in the immediate aftermath of some adverse events (Johnson, 2005).

These notions of strong and weak emergence can be contrasted with the predictive approaches mentioned earlier. Recall that emergence can be connected to non-determinism and that the term 'emergent property' is often used to describe a feature of a complex system that was not anticipated by systems engineers. This creates problems because there are classes of properties that relate to systems level behaviors, which seem to be emergent, but that are also predictable. Further problems arise because emergent properties rely on the subjective experience of people making the predictions. The idea of strong emergence avoids some of the conceptual problems that arise when these emergent behaviors are narrowly tied to predictions about complex behaviors. Strong emergent properties cannot be reduced to the physical laws of causal composition. However, they can still be described in terms of other laws or patterns of behavior. We can still talk about patterns in cognitive behavior even though we cannot explain in detail how those behaviors relate to underlying electrochemical changes in the brain. Clark (2001) argues that emergent phenomena are best understood by observing a 'pattern resulting from the interactions' among multiple elements in a system including aspects of the environment.

## 4. The Engineering Implications of Emergence

The previous paragraphs have provided an initial overview of emergence. The intention has been to provide a more structured, theoretical basis to the engineering of complex systems. In such an abstract and often theoretical discussion it is easy to lose sight of the importance of these ideas for complex systems engineering. Wears, Cook and Perry make the following statement; ‘emergent vulnerabilities, such as arise from the interaction among disparate, independently designed components, seem almost impossible to foresee in anything other than the most general terms. Health care seems especially vulnerable to these sorts of threats for several reasons: 1) The relative youth of complex computer application in the field; 2) The general unfamiliarity of health professionals and managers with methods for reducing vulnerabilities; 3) The fragmented nature of health care “organizations”; 4) The potential subversion of risk information into internal, conflicting agendas; and 5) The lack of formal or regulatory frameworks promoting the assessment of many types of new technologies. These factors are as much social-organizational as they are technological’.

It seems clear, therefore, that emergent properties have considerable significance for the design and engineering of many applications. It is less clear that the philosophical ideas on emergence can make a significant contribution to engineering and design. The ideas are interesting but how can they help engineers? Buchli and Costa Santini (2005) have observed that the process of finding unifying principles either at the microscopic or macroscopic levels of complex systems, is hindered both by the divisions between specialised disciplines and by the problems of language where different concepts share overloaded names. Haken (1999) continues that “despite a lot of knowledge about complex systems the application of this knowledge to the engineering domain remains difficult. Efforts are scattered over many scientific and engineering disciplines". Attempts to establish complexity engineering as a discipline are hindered by basic misunderstandings over common terms such as ‘emergence’. It is unlikely that the ‘concensus making’ advocated by Marashi and Davis will be successful while more basic disagreements complicate the use of common terms.

The confusion created by the (ab)use of common terms can be illustrated by two recent papers on engineering with complexity[1]. The first argued that “emergence is often associated with a ‘surprise-factor’: local interactions result in something unexpected at the global level. Engineering emergence is about removing this surprise”. Such comments illustrate a pragmatism based on the predictive approach to emergence and non-determinism described in previous paragraphs. In contrast, a companion paper went on to demonstrate “…that interacting cell networks are prime candidates to study principles of self-organized pattern formation. In addition, they offer a multitude of possibilities for microscopic interactions that might also be relevant for dynamic communication networks. Examples of interacting cell systems are life cycles of bacteria or social amoebae, embryonic tissue formation, wound healing or tumour growth and metastasis. Then, we show that mathematical modelling

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[1] Engineering with Complexity and Emergence (ECE'05), Paris, Satellite workshop of the European Conference on Complex Systems, see http://complexsystems.lri.fr/

of dynamic cell networks (biomathematics) has developed techniques which allow us to analyze how specific microscopic interactions imply the emergence of a particular macroscopic behavior. These techniques might also be applied in the context of dynamic communication networks". The aim of this work is to transfer observations about the macro behavior of biological systems to the engineering of telecommunications networks using a language of 'self-organisation'. This has much in common with the idea of strong emergence, although the author does not use this term and shows no evidence of having read Bedau.

These two papers reflect very different implicit views of emergence. The resulting tensions are most apparent when Zambonelli (2005) argues "It is getting more and more recognized that the exploitation of self-organization and emergent behaviors can be a feasible way to bear the complexities and dynamics of modern systems. However, attempting at defining a practice of engineering such emergent and self-organizing systems in a reliable and repeatable way appears a contradiction in terms". As we have seen, this contradiction arises because engineers freely move from predictive definitions in which emergence is equated to a surprise and definitions of strong emergence where higher-level patterns can be used as design templates. The main aim of this paper is to help future engineers avoid these contradictions. Greater care must be taken when using terms such as 'emergence'. Without this there is little chance of developing the discipline of complexity engineering.

## 7. Conclusions

Complex systems research has been hindered by a lack of precision when people refer to 'emergent properties'. Contemporary views of emergence in philosophy include Chalmers' spectrum ranging from a mystical property to the whole-part relationships in mundane objects including filing cabinets. They also include Bedau's distinction between 'weak' emergence, based on simulation and modeling, and 'strong' emergence relying on downwards causation. As we have seen, problems arise because engineers combine many different aspects of these ideas when referring to emergence in complex systems. They refer to the surprise implicit in predictive approaches while talking about the design of emergent properties. In contrast, we have attempted to ground recent research into complex systems by surveying different approaches to emergence. The intention has been to help engineers avoid some of the paradoxes that arise when inconsistent definitions are used.

Further work remains to be done. For example, engineers continue to extend the concept of emergence in many directions that are not adequately captured by philosophical discourses on complexity. For instance, Eckert, Keller, Earl and Clarkson refer to *emergent changes*, 'which arise from problems with the current state of a design proposal in terms of mismatches with requirements and specification…these can be caused by mistakes, supplier constraints and factors internal to the process such as resources, schedules and project priorities across the company'. Although these changes clearly emerge during manufacturing 'from a mistake or a late modification from the supplier, designers often resent it as avoidable'. Further work is required to determine whether such properties are a particular instance of Bedau's weak emergence, only predictable through advanced simulation techniques, or whether they pose a further challenge to the philosophy of emergence as it relates to engineering and design.

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## Appendix A: Tom Maibaum's Comments on the First Draft

One of the main motivations behind this paper was to provide an overview of different philosophical views on emergence, as they relate to the engineering of complex systems. It is difficult to envisage any survey being 'complete' given the controversial and changing nature of this subject. I have, therefore, extended the initial version of this paper by including comments and criticisms that have been received sine it was first published. The following email from Tom Maibaum makes an important point with respect to non-determinism and under specification that I failed to consider. In retrospect, this omission is all the more regrettable given that it comes from my own discipline!

From Tom Maibaum [tom@maibaum.org], 16th February 2006.

Dear Chris

I have been reading your recent paper on 'What are Emergent Properties ....'. I have some thoughts about it that your paper helped me to place in context and I wanted to share some of them with you.

I have been working on component based design of systems for almost 20 years, using category theory as a setting for describing how components are bound together to make larger components/systems. The binding is basically describing how interaction between components is defined. (It is an example of a coordination mechanism.) We use temporal logic to specify components. Now, if you take a classical example like the dining philosophers, specified in terms of philosopher components and fork (resource) components and 'connectors' to make them work together correctly, then if you ascribe to philosophers the property that if they hungry, they will eventually pick up their forks and eat, when you look at the system of dining philosophers (and forks), a philosopher has an emergent property! It is the property that the philosopher eventually puts his forks down! This is because models of the whole system require that all philosophers eventually eat and this requires neighbouring philosophers to eventually release the resources required to do this.

Now, this property was not precluded for philosophers, but not all models/executions of philosophers have this property. So one way of looking at this is that the 'social' interaction of the philosophers (and forks) excludes some potential models of components as not supporting the 'social' behaviour of the components. This relates to what you referred to as 'nondeterminism' in your paper. It is NOT nondeterminism, which is to me an aspect/attribute of a model of computation, like in a Turing machine. What you are referring to is what I call UNDERSPECIFICATION. That is, the model/implementation you are interested in is not fully determined by the specification. (This is what SE is about: reducing underspecification by development steps. This is the classical reference to 'introducing implementation detail' in SE books.) Now, many people get nondeterminism and underspecification mixed up. It is a terrible mistake to make.

Let me give you another, simple, illustration. Suppose you specify sets of somethings, say using first order logic. You use a FUNCTION symbol called 'choose' that, when applied to a non-empty set, gives you back some value in the set. Almost everyone calls this a nondeterministic function. But it is not, because no such animal exists in first order languages. It is a function proper that is underdetermined. So, an implementation might fix on the minimum value in the set as the 'right' implementation. So, if in your implementation you apply choose to the same set at different points during execution, YOU WILL ALWAYS GET THE SAME VALUE! Of course, the implementer might change the implementation on you overnight, and tomorrow you will get a different value applied to the same set, say the maximum. But he is within his rights to do this as it satisfies the specification. The implementation is in no way nondeterministic. A nondeterministic mechanism (of computation) is used in languages like Prolog, where choose would be defined as a relation and Prolog would generate for you ALL THE VALUES IN THE SET in some sequential and apparently nondeterministic order.

Nondeterminism as an internal computational mechanism is to do with randomness and is an external mechanism of choice for users (that may not be truly random).

Why have I gone into the distinction between nondeterminism and underspecification in such detail? Well, it is because I believe that emergent behaviour is intimately related to the latitude for deciding properties for components provided by underspecification. Underspecification is an inherent property of engineered artefacts (as we cannot fully describe everything and all aspects of our artefacts). It is also an inherent aspect of natural phenomena to the extent that we cannot fully describe entities in nature, so we 'underspecify' them.

Now back to the dining philosophers example. Clearly the property of a philosopher always eventually putting its forks down is valid only in some of the models/implementations. The problem of engineering of complex systems is that, at the level we are now discussing it, the 'choosing' of the subclass of models determined by the context in which a component is put IS ITSELF UNDERSPECIFIED. There are a multitude of possible choices for such emergent properties we could observe when we put systems together. The problem for the engineer is to find standard ways of putting components together so as to reduce the chaos of choosing these emergent properties. The whole area of feature interaction in telephony was essentially an example of the chaos of emerging phenomena emerging! :-) Here we had these various components/features, that had emergent properties that resulted exactly because of underspecified interactions with the rest of the system. These people then spent a decade sorting out what this meant for the discipline of component based telephony.

Of course, systems of components also have properties that were not exhibited by individual components. The obvious example of this is deadlock. This is inherently a global property and cannot be reduced to a component property. (It corresponds to the idea that the context of the component eliminates ALL models of the component.) So there are properties that cannot be studied only at the component level and could be characterised as emergent properties of conglomerates not predictable by studying only component parts. (The emergent properties discussed in the examples above were properties of individuals/components.) However, these global properties still depend crucially on underspecification (and clearly not on nondeterminism).

As a conclusion, one might say that the problem of emergent properties in engineered artefacts is centred on the nature of underspecification of components, environment, and the nature of interconnection and coordination and how these forms of underspecification are handled in engineering. (Of course, INCORRECT specification is also a problem!)

Regards

Tom