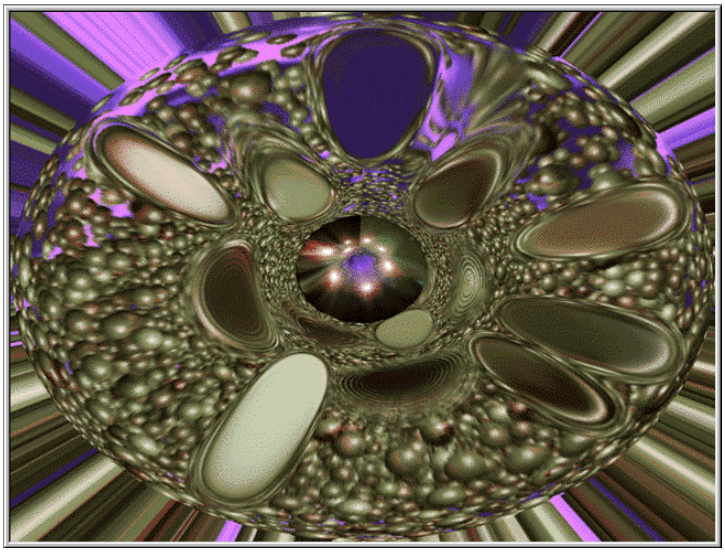
EXPLOITING THE PHENOMENA OF EMERGENCE



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EXECUTIVE SUMMARY

1. Phenomena are said to be 'emergent' when they arise from interactions among the parts of a complex 'system' in a manner that is not always apparent by examining the components in their inactive state. Emergence seems to create powerful positive and negative effects (often appearing as tangible phenomena which persist over time) almost out of 'nothing'. In reality, emergent phenomena are a collective property of interacting 'systems' which are manifested as higher levels of organisation, abstraction and apparently sophisticated behaviour. The aim of this paper is to show that further investigation of this behaviour could provide humans with a way of exploiting the phenomena of emergence to provide useful 'tools' for the military and commerce.

2. Common examples of emergent phenomena are 'standing waves' (such as those which form as apparently stationary clouds over hilltops in windy conditions or 'stopper waves' in fast-flowing rivers); 'virtual' capabilities such as that of the "very-long baseline" radar dish shown here (which behaves as one large dish even though it is made from many smaller, cheaper ones); Saturn's rings; the complex, apparently unified and sentient behaviour of ants' nests and the features of creatures at the macro level expressed from the interaction of genes at a micro level. Even human consciousness may be an emergent phenomena.

3. Why does the phenomena of emergence need to be researched? Well, it is widely accepted that emergent phenomena exist and that their effects are highly significant, yet there is inadequate science available to help represent emergent phenomena during the design and construction of complex systems (especially before they are activated as part of the real world). Indeed, despite approaches such as dynamic systems theory, the nature of the phenomena of emergence is so poorly understood that there is barely a suitable language available to use to describe it, let alone a set of formal methods available. Also, there is little real understanding of how the phenomena of emergence could be exploited positively as a tool - say as a military force-multiplier or to give a competitive edge in commerce - the promise is there but it has never been fully realised.

4. The human race has managed pretty well to date - but the exponential growth in communication, mobility and information technology is creating an ever more uncertain, chaotic, complex and heterogeneous world. The conventional approaches to engineering systems, which rely on the systems being closed, linear, optimised, hierarchical and 'static', do not work on complex systems - indeed such systems are beyond 'conventional' scientific modelling. The "so-what" about this is that if we do not learn how to exploit phenomena (such as that of emergence) then *we may never know about some of the capabilities that are waiting to be used because they exist at a higher level of abstraction - one that conventional approaches will never reveal to us*.

5. It is curious that we are creating ever more complex software to perform essentially simple tasks. In contrast, nature does the converse, with effective behaviour emerging from simple interactions among 'live-ware'. How is this done? Can the principles involved help us deal with our increasingly complex human systems? Clearly, the phenomena of emergence is part of this puzzle, but how does it relate to other phenomena such as self-organisation, number, information, complexity or chaos theory, human intelligence, sociology and culture etc?

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CHAPTER 1. EMERGENCE AS A PHENOMENA

OVERVIEW

6. The human race seems obsessed with overcoming challenges, shaping our world and striving for novelty by conceiving of future states and then enacting them with dramatic effect. However, we are often frustrated in this endeavour by our inability to accurately perceive what the future state of the world will be as a result of our collective actions. We have developed and evolved many strategies to help predict the future - all of which (be it formal systems such as mathematics or informal representations such as art and language) are a form of modelling.

7. Despite the use of these strategies we are still surprised at the many, varied and apparently unexpected outcomes which occur when we transition our schemes from their models into reality. But should we be so surprised? Foremost among our techniques is deterministic modelling based on a Newtonian view of the world. There is a view, however, that determinism is a myth - to quote Prigogine [1]:

> "The basis of the vision of classical physics was the conviction that the future is determined by the present, and therefore a careful study of the present permits an unveiling of the future. At no time, however, was this more than a theoretical possibility. Yet in some sense this unlimited predictability was an essential element of the scientific picture of the physical world. We may perhaps even call it the founding myth of classical science."

8. Indeed, the deterministic experimental conditions of the science laboratory are not a microcosm of the real world - they are atypical of it - Joseph Ford [2] makes the point more whimsically:

> "Unfortunately, non-chaotic systems are very nearly as scarce as hen's teeth … Algorithmic complexity theory and non-linear dynamics together establish the fact that determinism actually reigns over quite a finite domain; outside this small haven of order [the 'laboratory'] lies a largely uncharted, vast wasteland of chaos where determinism has faded into an ephemeral memory …"

9. So, even if the universe behaves like a machine in the strictest mathematical sense, it can still happen - indeed it is inescapable (as Paul Davies easily proves [3]) - that genuinely new and in-principle unexpected phenomena will occur. The conclusion must be that various kinds of emergent phenomena exist, are inevitable and that we need to look beyond classical science and deterministic models and methods to understand, and then be able to harness, emergent phenomena.

10. Why is this significant now? Currently there is an exponential growth in mobility and in the use of communication and information technology (IT) in dispersed and open environments. Our world, though 'loosely connected', is increasingly highly inter-connected and this provides a myriad vectors for the rapid propagation of 'unexpected behaviours' throughout the planet. This is creating an ever more uncertain, chaotic, complex and heterogeneous world where, more and more, we see cases of major (unexpected and deleterious) effects on commerce and on the human race[1]. This trend is also true in the military, which is both more reliant on IT and is increasingly connected to the commercial world and the open information environment of the Internet and so is vulnerable both to attacks from an opponent and to the erratic behaviour of the commercial world.

[1] The rapid breakdown during the UK petrol crisis, violent stock market swings, the rapid spread of "Love Bug" etc.

11. The "so-what" about this is that if we do not learn how to exploit phenomena (such as that of emergence) then *we may never know about some of the capabilities that are waiting to be used because they exist at a higher level of abstraction - one that conventional approaches will never reveal to us*. The aim of this research then, is to unravel some of these threads and to then to derive principles and insights into the workings of our increasingly complex world which could lead to the generation of tools which can enable us to do more with less by exploiting the phenomena of emergence - say as a military force-multiplier or to give a competitive edge in commerce - the promise is there but it has never been fully realised.

WHAT IS EMERGENCE?

12. It could be said that we call phenomena 'emergent' when we don't understand them, and this may be true in some circumstances. However, there are clear cases where the phenomena of emergence generates outcomes which are definitely "more than the some of the parts". So what would be a suitable definition of 'the phenomena of emergence? As with many other 'difficult' concepts there are almost as many definitions of the phenomena of emergence as there are workers in the field:

- A property possessed by a system, but not by its components. A property possessed by a system that is not a direct consequence of the nature its components. A property possessed by an evolved system that could not be predicted before the system evolved. [4]
- The appearance of a property or feature not previously observed as a functional characteristic of the system. Higher level properties are regarded as emergent [5].
- Phenomena are said to be 'emergent' when they arise from interactions among the parts of a complex 'system' in a manner that cannot readily be predicted by examining the features of the components in their static state.
- Composite services may interfere with each other either destructively ('feature interaction') or constructively ('emergence'). Which is which is not an objective distinction but depends on the observer's context [6].
- Emergence is a powerful effect which seems to create higher forms of organisation (often appearing as tangible, ordered phenomena which persist over time) apparently (because of our ignorance) out of 'nothing'.
- When these recurring patterns are regularly associated with events of interest, we call them emergent properties. [7]
- Emergent phenomena could be seen as the tangible or intangible manifestations of 'strange attractors' in complex systems.
- The phenomena often have no 'meaning' unless one is an observer (at a higher level of abstraction / organisation) outside the system being observed.

13. Features of Emergent Phenomena. The definitions above imply some apparent features related to emergence as follows (the frequent use of 'quotes' in the text below reflects the imprecise nature of language in this context. To assist, I have used an ants' nest as an example):

a. 'Components'. There some components / agents / elements / parts which are either assembled or which function together as a part of some 'system'. There must be more than one component (viz: the ants).

b. Sensors and Effectors. Every component in a system can have sensor(s) and effectors which enable interaction across their own boundaries.

c. <u>'Substrate'</u>. The components operate in a substrate / context / framework which supports their activities (viz: the ants nest, its passages, food stores etc and the surrounding environment).

d. <u>The Structural Attribute</u>. How the components are arranged within the substrate / environment - (from unconnected to cohesive).

e. <u>Interactions</u>. Interactions take place between the components at various levels of complexity and sophistication and are mediated through many types of tangible and intangible mechanisms (viz: chemical / pheromone messaging between individual ants and to the whole nest, touch, individual and collective behaviours, 'crowd' movement). Note that:

- structural attributes are effected through communications, eg ants may be physically unconnected but use pheromones to effect communications - they are thus connected in a manner[2].
- interactions also take place between the components and the substrate and between collections of components in this 'system' and those in others (see 'Boundaries' below).

f. <u>'Boundaries'</u>. Some notion of boundary for the overall 'system' can be discerned - even if it cannot be defined precisely (viz: is the boundary of an ant colony drawn about the furthest extent of all of its individual members or is it more local to the nest itself?). A boundary may be applied in one place such that whole-system-level interactions (viz: battles between competing ant colonies) can be discerned and, if defined at another level, then component-level interactions will be discerned.

g. <u>The Emergent Phenomena</u>. These are as described above and may be generalised as having the fundamental characteristic of being tangible or intangible 'patterns' that persist [8] over time even though the generators of the patterns themselves may be continually changing (viz: an ant foraging party 'reaching out' to collect a source of food has an ever-changing membership of ants or the water molecules moving through a stationary standing wave).

h. <u>Observer(s)</u>. Clearly, some phenomena will emerge whether or not there are observers present (leaving aside metaphysical argument here), however, other emergent phenomena are an artefact of the observer [9] and only have meaning in the substrate of the observer (viz: the perception that the ant's nest is 'angry' if poked with a stick relates to the emotions attributed down to it, from the human social world, by the observer).

14. <u>Observations about Emergent Phenomena</u>. Clearly, emergent phenomena can be beneficial or harmful, though the phenomena should not be seen as defining or characterising a system in total as the emergent phenomena are just one of the collective properties of the 'system'. Nevertheless, further observations can be made about the manner in which emergent phenomena arise as follows:

a. <u>Lack of Reversibility and the 'Arrow of Time'</u>. Some hold the view that emergent phenomena are not reversible - any cause and effect linkage is one-way, but this is strongly disputed [10]. However, even if we could reverse the 'arrow of time' we would not necessarily see emergent phenomena 'unwind', this is because a differently ordered set of interactions would now take place (in the "poking an ants' nest with a stick" example, the nest would appear to calm down for no reason just before we removed the stick).

[2] It is possible to synchronise the behaviour of chaotic systems by message passing - eg: two pendulums on a wire.

b. Lack of Central Control. Emergent phenomena are not dictated in advance or controlled or co-ordinated centrally (top-down), instead they usually arise bottom-up and are observed at a higher-level.

c. Lack of Dependence on the Existence of Individual Components. Emergent phenomena will persist despite changes in components of the same 'class' - eg: the generators of the patterns themselves may be continually changing (viz: an ant foraging party 'reaching out' to collect a source of food has an ever-changing membership of ants or the water molecules moving through a stationary standing wave are always changing though the standing wave remains). Indeed, components can be added and removed without the whole 'system' being decommissioned.

d. Entropy vs 'Information' and Increasing Structure and Organisation. Emergent phenomena add to structure in the universe. Despite the Second Law of Thermodynamics stating that entropy always increases towards featureless uniformity, some see (though others disagree [10]) that there is opposite trend at work in the universe - that of increasing structure and organisation at ever higher levels of abstraction manifested through emergent phenomena - the so-called 'optimistic' arrow of time [11]. This may be being achieved by the fact that there are causation mechanisms at work which would not contradict the Second Law. As Donald MacKay [12] says:

> "…whereas in classical physics the determination of force by force requires a flow of energy, from the standpoint of information theory the determination of form by form requires a flow of information. The two are so different that a flow of information from A to B may require a flow of energy from B to A …"

This viewpoint is strongly related to the "Levels of Abstraction" discussion below.

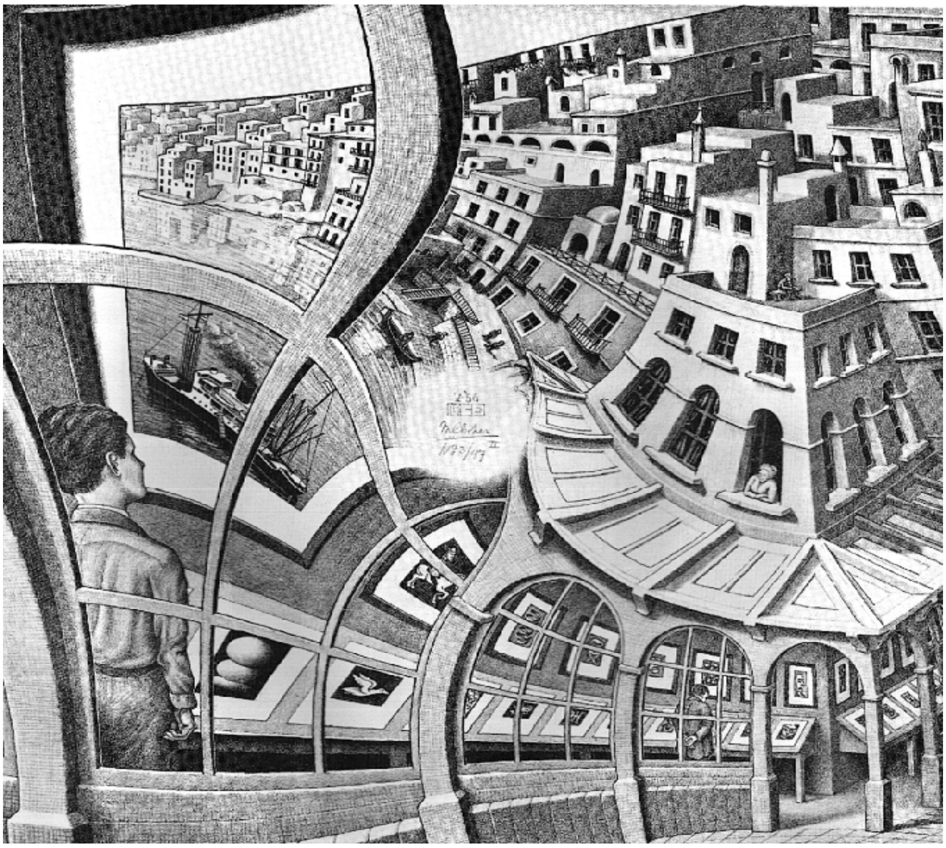

Figure 1: Print Gallery, by M C Escher (lithograph 1956)

e. Levels of Abstraction (the Observer observed). As already mentioned above emergent phenomena may have no 'meaning' [3] at the level at which they are generated. Though this sounds like the beginning of an endlessly infinite regress of no value, it is actually a crucial point to understand if the phenomena of emergence is to be exploited. For example, Popper [13] represents this by his description of "World 1 .. World 3 entities"[4]. This kind of idea might be described as follows:

> That there exist higher levels of abstraction at which a simplified representation of the activities of a lower level can be meaningfully manipulated by an observer *outside the system*.

This is discussed at some length by Hofstadter [14] and beautifully illustrated by the Escher drawing at Figure 1 above showing a young man in a gallery observing a picture which includes himself observing a picture of himself …. we, because we are outside the system, can observe and reflect on this paradox - possibly itself an emergent phenomena.

ARE THERE DIFFERENT TYPES OF EMERGENCE?

15. There appears to be a view that there may be different types of emergence and that they relate to the way that they arise - the following are some examples of differing viewpoints:

> "… we seem to have (for all practical purposes at least) two kinds of 'emergence': There is the 'designed' (and the question is, should we apply the term 'emergent' to this) and the 'evolved'. Related to this distinction seems to be some concept of predictability. Some kinds of emergence, it is claimed, can't be predicted or planned for. The distinction rests on either:
>
> a) what we can predict / know or hope to know (in a reasonable time).
> b) what it is logically possible to predict / know." [15]

and:

> "As we see it here emergence is just the same as holism. An emergent structure is a holistic structure. We should emphasise, that from this refined notion of holism, it does not follow that `the whole' cannot be analysed, nor that it is always impossible to deduce the properties of the whole from its constituents and the observational mechanisms. Thus, within the general framework proposed here, one must distinguish between two different kinds of emergence:
>
> A. Deducible or computational emergence. There exists a deductional or computational process or theory 'D' such that an emergent phenomena 'P' (observed in a higher-level system) can be determined by 'D' from the lower-level system.
>
> B. Observational emergence. 'P' is an emergent property, but cannot be deduced as in (A) above.
>
> (Clearly, further refinements are possible!). As argued in larger detail in Baas (1994a, 1996), examples of deducible emergence include some compositional structures in engineering constructions, non-linear dynamical systems, phase transitions, nontriviality of

[3] The phenomena may be real but some of the meaning attributed to a phenomena may be subjective or interpreted in a way which makes sense to the observer.
[4] Popper describes "World 1" as the physical world and "World 2" as the "world of our conscious experiences" whereas "World 3" is the world of the logical contents of books, libraries, computer memories, and the like.

complexity of manifolds in topology, and the Scott model of the [[lambda]]-calculus. In these cases, the various properties can be decided by well-defined procedures, so can be seen as instantiating an algorithm leading to a set of properties. Examples of observational emergence include `Gödel sentences' in a formal system (this the truth function; cf. Gödel's theorem), and the property of membership of the Mandelbrot set and most Julia sets. Furthermore, it was indicated that the eventual semantic non-compositionality of a language would imply that the meaning of sentences in such a language was observationally emergent." [16]

16. Certainly greater understanding is required of where we are talking about emergence as:

- a substitute for something interesting that we don't understand, or
- as 'weak' emergence (ie: as something 'inevitable' - evolution or 'unfolding'), or
- as 'strong' emergence (where we are talking about a truly novel outcome which can't be predicted from observing the elements of the system), or
- as a useful, higher-level metaphor for some aspect of complex behaviour.

17. Certainly there are phenomena which emerge directly from interaction at the physical level (standing waves etc), but there also appear to be conceptual emergent phenomena observed at the level of human consciousness. It seems possible therefore that there may be a continuum of types of emergent phenomena (depending on their tangibility or intangibility, the 'systems' from which they arose, the mechanisms of interaction / underlying theories at work, the nature of the observer / observation, the level of abstraction or other factors) and that characterising and classifying the types and their differentiating features may just be a time-wasting exercise - or extremely valuable. Currently, I feel this should be a topic for further research.

EXAMPLES OF EMERGENT PHENOMENA

18. Common examples of emergent phenomena are legion and include (roughly ordered from the physical level to abstract conceptual levels):

- 'standing waves' (such as those which form as apparently stationary clouds over hilltops in windy conditions or 'stopper waves' in fast-flowing rivers);
- the persistence and stability of Saturn's rings;
- 'virtual' capabilities such as that of the "very-long baseline" radar dish (which behaves as one large dish even though it is made from many smaller, cheaper ones),
- the multiplicity of combinations of carbon, hydrogen and oxygen and the many and varied properties of the organic substances which result;
- the sudden, unexpected and catastrophic failure of complex systems as a result of a small event (as happens in types of heart attack), which may be as a result of a phase change in a local system - but with global effects;
- the self-maintenance of a living cell is based on the structure of the cell and the functionality of its molecules: Though in general each type of macromolecule in virtue of its chemical properties (characterisable by chemical analysis) can enter into reactions with an infinite set of possible molecules, in the living cell each molecular species is committed to one or a small number of reactions that defines its specific function within the cell's metabolic system (e.g., catalysis of a part of a specific metabolic pathway);
- well developed sequences of 'reverberating assemblies' of neurones in vision systems;

- the absence of tripodal animals in nature arising from the interaction of stability / manoeuvrability features;
- the features of creatures at the macro level expressed from the interaction of genes at a micro level;
- the complex, apparently unified and sentient behaviour of ants' nests;
- the 'glider' in Conway's 'Game of Life', though the position and existence of each cell of the glider is decided deterministically, the existence of the glider, its mode of behaviour and the existence of 'glider guns' (which generate gliders) cannot be determined in advance;
- the collective properties of information systems such as their robustness, flexibility - so-called "quality attributes" [5] ;
- having a winning edge in commerce;
- the collective agility and adaptability of a command system composed of humans and artificial devices;
- human intelligence and introspection and cultural and social phenomena. Some think that consciousness itself is an emergent phenomena "Consciousness is not a property of individual neurones, it is a natural emergent property of the interactions of the neurones in nervous system of the body in an environment. It makes a structure that is related to lower level interactions as well as higher level thoughts, and it represents a new observational mechanism of the entire system." [17] - something which is difficult to prove conclusively!

EMERGENCE - SOMETHING USEFUL?

19. In 1965 Stuart Kauffman [18] was interested in how gene switching could result in cell differentiation. At this time it was perceived that a single feature did not relate simply to a single gene but that features related to combinations of 'modifier genes' being 'switched on or off' (this mechanism, where a gene has more than one effect, is called 'pleiotropism'. There are other effects such as 'polygenes', where a feature won't appear unless there several sets of genes present; or 'epistatis', where one gene will mask the expression of others etc). To investigate this, Kauffman carried out the following experiment:

a. He set up a network of 100 nodes (to represent a set of genes - for this experiment think of them as light bulbs) which could be switched on or off according to a set of 16 Boolean rules.

b. He wired up the connections between the 'bulbs' and between their rules at random such that (in the manner of a cellular automata) the state of a single bulb depended on the state of two other 'bulbs' and the applied rule (all having been selected at random).

c. The network was operated, step by step, and Kauffman hoped that it would converge on some dynamically repeatable state cycle which might be deemed to be representative of the 'expression' of some stable and persistent feature from the genes.

d. Intuition suggests that the state cycle might be a long time in coming - it is worth while asking the reader to guess at how many iterations might be required before a stable state emerged (100, 10000, millions? - in principle as each bulb can be in one of two states so the number of iterations could, in theory, be $2^{100} = 10^{30}$).

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[5] Some authors use the 'quality' in preference to 'emergence' as emergent properties conveys the sense of features that are unpredictable and only identified once a system is created, whereupon action to control these properties can then be undertaken. For this reason the term quality attributes is preferred.

e. In practice the network converged (on average) onto a repeating 3 / 4-step cycle after about 10 iterations (this occurred even if the random assignments were changed).

f. The network was converging on a periodic attractor which was manifested as an emergent phenomena: a stable state cycle.

This experiment was an example of the creation of a stable emergent phenomena generated from self-organisation in a complex system.

20. **The lesson here is profound - that out of tremendous complexity at one level can emerge a simple, manageable and useful 'representation' at a higher level.**

21. One could foresee an example where, if that network had represented a set of 100 possible choices facing a commander in a military campaign, then the stable set of cycling behaviours ('calculated' in milliseconds rather than hours) might be able to represent a winning strategy, a set of enemy courses of action, or a predictable set of states to be avoided. **It would be an aim of this research to find out if it will be possible to employ the phenomena of emergence in this useful manner**.

CHAPTER 2. UNDERSTANDING THE PHENOMENA

HOW DO EMERGENT PHENOMENA ARISE?

22. In general terms, it is well understood in that emergent phenomena arise in systems with the features described in Chapter 1 above (ie: with components, substrate, interactions and where synergy, antagony and holism etc are at work). However, the mechanisms which cause emergent phenomena to arise can be found in many different circumstances:

- deterministic situations,
- open systems with non-linear interactions,
- far-from equilibrium situations,
- situations where there are large collections of limits,
- situations where there are high degrees of feedback,
- situations involving open-ended evolution and adaptation over time in heterogeneous environments,
- in fact, just about anywhere …

The implication here is that once the ingredients are in place emergent phenomena seem to arise 'spontaneously' (even relentlessly and unavoidably) without anyone having to do anything - but is this true? I feel this should be a topic for further research.

HOW DOES EMERGENCE RELATE TO OTHER PHENOMENA?

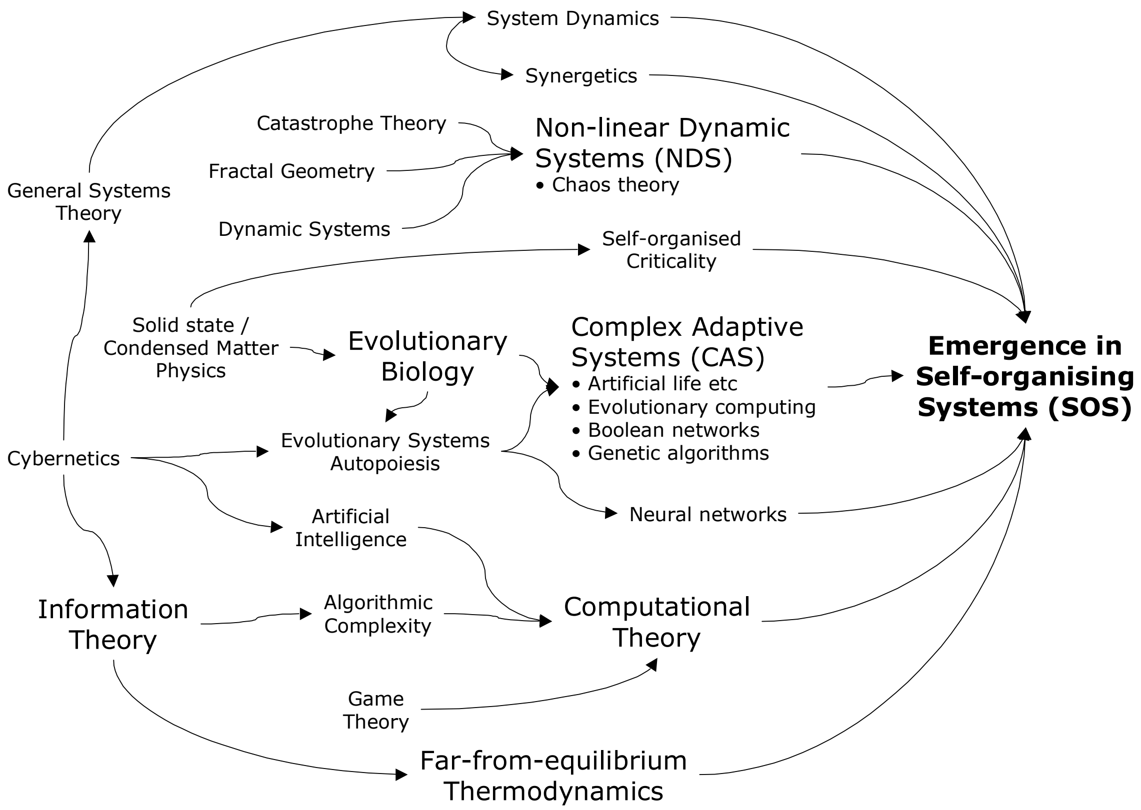

Figure 2: Emergence in Relation to other Phenomena

23. Other 'Magic Numbers'. In becomes apparent from Figure 2 above (which is a suggested set of relationships) that the phenomena of emergence does not exist in isolation and that, as pointed out in para 19, it is a general manifestation which arises owning to many types of mechanisms. However, there are apparent invariants to be found in these systems (such as Langton's Lambda parameter discussed below) which appear to express some universal truth and other such 'magic numbers' exist in many fields of endeavour. For example, in the fields of 'deterministic chaos' studied by Mitchell Feigenbaum [19] he discovered the so-called 'Feigenbaum Numbers' (2.5029… and 4.669201…) which relate to the onset of chaos. There is the possibility that these numbers (and other similar constants) may relate to transitions between types of emergent phenomena or may have other significance - pursuing this topic will be a core research task - some initial thoughts are included below.

24. Langton's Lambda Parameter. As emergent phenomena arise from interactions (which implies an exchange of 'information') there are optimum conditions under which this occurs and there do seem to be principles at work which would change the nature of the onset and the 'fierceness' of the propagation of the effects.

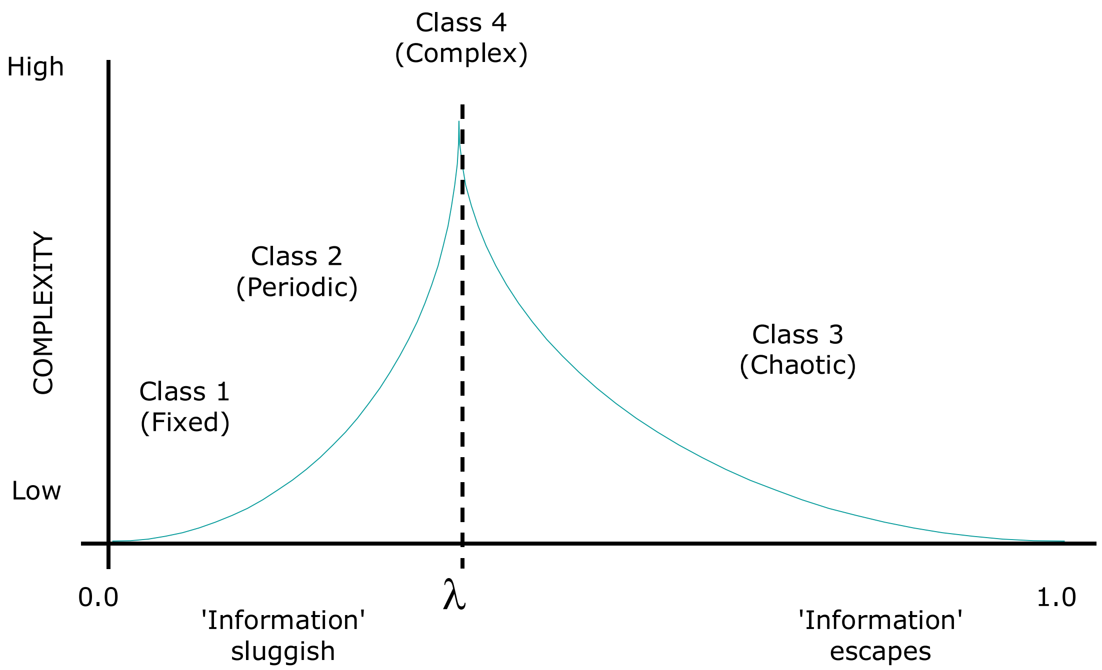

Figure 3: Langton's Lambda Parameter

25. Through his work on cellular automata (CA) and artificial life Chris Langton [20] noticed a pattern to the types of CA which were derived as shown in Figure 3 above. The pattern also related to Stephen Wolfram's [21] system where he had classified CAs into four classes. Langton noticed the following:

a. It became apparent that in situations where the 'information' used by the CAs was constrained to be sparse or 'frozen' few CAs existed - and those that did displayed a narrow 'fixed' behaviour.

b. At the other extreme where 'information' moved too quickly to be captured it 'boiled off' and the few CAs here displayed a chaotic behaviour and had hardly any form.

c. He found that at a set value (about 0.273, where the complexity of the system was at a maximum, available entropy was at an optimum and where there was a phase change) the most diverse and vibrant CAs were to be found - he dubbed this "life on the edge of chaos".

26. It appears the phenomena of emergence is also related to this factor. In principle, this means that we now have a measure which can be applied to the features of a system which generates emergent phenomena, such that some assessment can be made of the likelihood that:

- nothing interesting will happen,
- 'interesting things' may happen (eg: at phase transition),
- the 'system' will generate 'chaotic' emergent phenomena,

27. Interestingly, in the military domain, Col Hugemark of the Swedish War College sees conflict being driven (this is largely the result of the opponent who's actions will impose unpredictable events / outcomes on the 'Battlespace') by the events which occur near phase transitions between states. Conflict is thus the maintenance / influencing of a dynamic tension between opposing 'forces' which try to cause a shift between states to the benefit of one of the participants. The Conflict Model (shown in Figure 4 below) has four basic states manifested through many emergent phenomena:

- Stable, but watching out for indicators of impending imbalance through renewed conflict,
- Changing and preparing for next attack,
- Transitioning to next conflict, defending first till offensive action is required,
- In conflict and looking for a resolution / return to an advantageous stability.

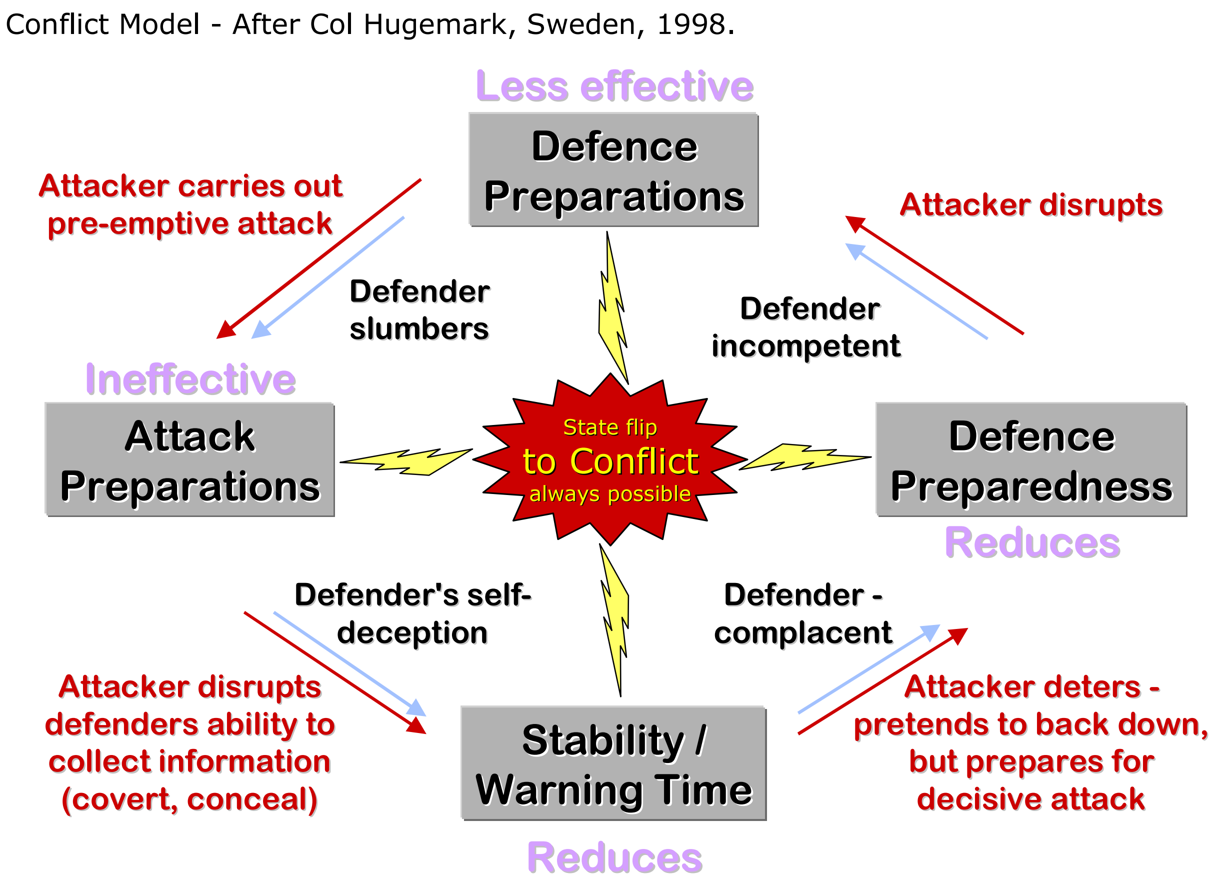

Figure 4: Conflict Model (Military Phase Transition Diagram)

At all times there's a balance between committing forces too early or missing the signs / opportunity and being crushed. Are we forcing the change - or is the enemy? Once a change is apparent, can we get to the next state first to gain an advantage? How would we know we should be changing - are there indicators (manifested as emergent phenomena) that we should use?

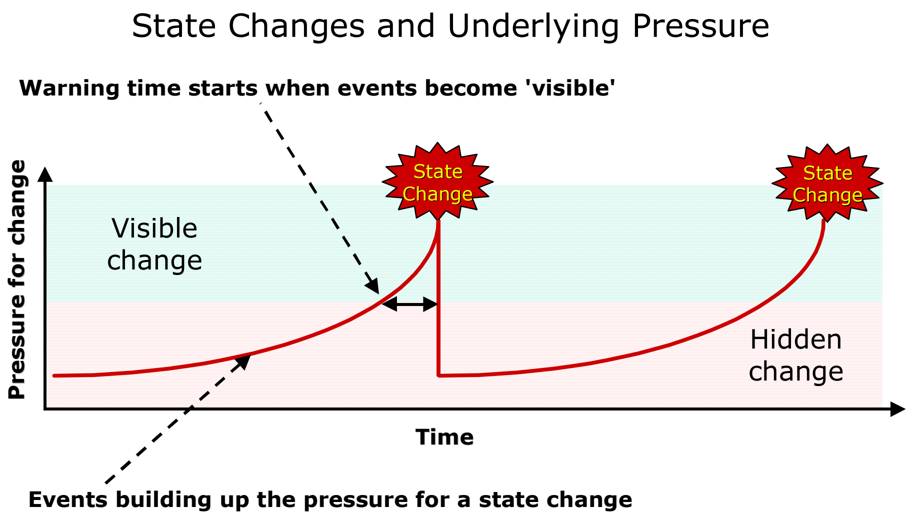

Figure 5: Hidden and Visible Changes

28. Hence, most of the potential military benefits come during the phase transition not when the system is 'at rest'. The model for the state changes appears to be binary (see Figure 5 above), but it is not - the (hidden) pressure increases till a change is observed. One key point here is that the states appear to change suddenly, but that actually an underlying pressure may build up for some time before a state change is observed and it should be noted that emergent phenomena are a manifestation of the underlying pressures.

A GENERAL REPRESENTATION OF THE PHENOMENA OF EMERGENCE

29. Developing an acceptable representation of the phenomena of emergence and its relation to the tangible and intangible world will be also be a core research task. As a starting point the diagram shown in Figure 6 below is offered for evaluation.

30. This diagram is an attempt to show how emergent phenomena at the physical level may relate to phenomena at the abstract conceptual level, while at the same time showing the relationship between the natural and artificial world.

31. A key part of Figure 6 is the emphasis on the interactions between the domains shown. It should not be assumed that all interactions are equal. Each type of interaction, at each level of abstraction, will require the development of a suitable set of underlying 'theories' to characterise them.

32. There may well be some 'universal shorthand' for characterising all types of interactions but at this stage it would be foolish to assume this. Indeed, it is clear that it is currently very difficult to 'transform' a viewpoint showing interactions at one level of abstraction into an equivalent one at

another level and that this difficulty is a reflection of the incompatibility of the theories and mechanisms underlying the interactions and their attendant representations at each level.

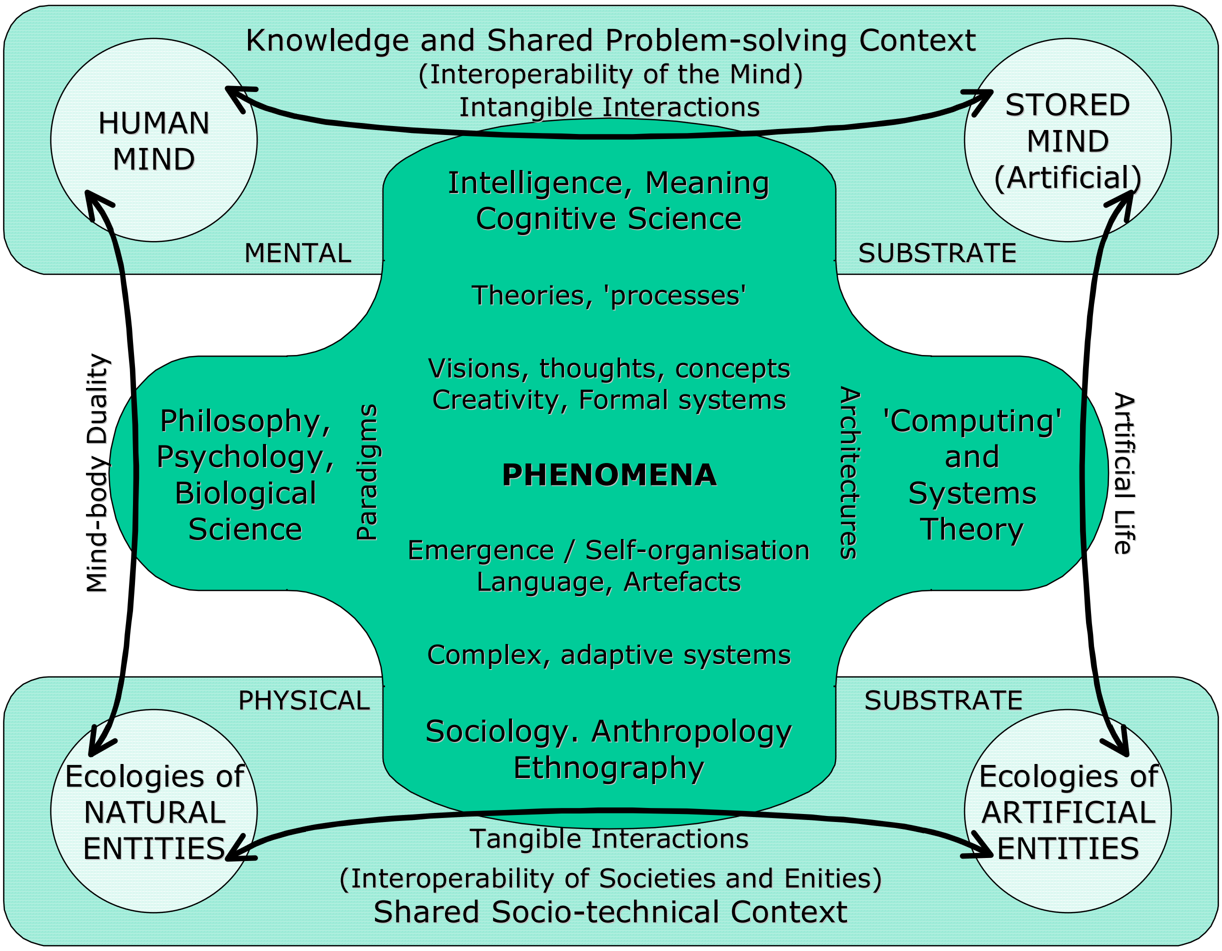

Figure 6: A Representation of the Domain under Examination

DEALING WITH EMERGENT PHENOMENA

33. We are often frustrated in our endeavours by our inability to accurately perceive what the future state of the world will be as a result of our collective actions. We have developed and evolved many strategies to help predict the future - all of which (be it formal systems such as mathematics or informal representations such as art and language) are a form of modelling.

34. In the world of systems engineering the view is that:

> "The systems engineer is always trying to enhance positive emergent properties caused by combining components, and suppress negative aspects of interactions." [22]

In reality that often means that it is easier to suppress the negative by 'locking down' the variables in a system, and in doing so reduce the positive too. The paper has indicated that it wishes to use research into the phenomena of emergence to help change this situation by **providing designers and users with tools to help them actively exploit the phenomena of emergence**. The way that this will be achieved is described in outline below.

CHAPTER 3. EXPLOITING THE PHENOMENA OF EMERGENCE

THE 'SO-WHAT' FACTOR

35. Well indeed, having read all the above - so what? The "so-what" is that:

- almost without exception the natural world (both tangible and intangible) is formed, driven and evolves through the interaction of phenomena which manifest themselves at different levels of abstraction and self-organisation right up to the most rarefied levels of human introspection and beyond.
- almost without exception we do not employ the same mechanisms as the natural world in the creation of our devices, systems and human artefacts and so miss out on all the potential benefits that are waiting to be accrued [23]. As physicist P W Anderson states:

> "I believe that at each level of organisation, or of scale, types of behaviour open up which are entirely new, and basically unpredictable from a concentration on the more and more detailed analysis of the entities which make up the objects … " [24].

The implication is that if we insist on only using 'classical science' and do not learn how to understand, employ (for analysis) and positively exploit phenomena (such as that of emergence) then *we will never know* what capabilities are waiting to be discovered because they exist at a *higher level of abstraction* that conventional approaches will never reveal to us.

36. The aim of this research then, is to unravel some of these threads and to then to derive principles and insights into the workings of our increasingly complex world which could lead to us being able to do more with less by positively exploiting the phenomena of emergence as a useful 'tool' which could be applied as a military force-multiplier or to give a competitive edge in commerce - the promise is there but it has never been fully realised. In addition, exploiting emergence positively could lead to the development of 'systems' with the following advantages:

- distributed and robust control (no central world model needed and no single point of failure),
- self-organising and self-optimising (no external control necessary - though still can occur),
- self-healing (resistant to / recovers from disruption),
- adaptable / flexible / agile (robust under varying or uncertain conditions).

MILITARY AND COMMERCIAL CONTEXTS

37. The Military Context. The aspirations and user needs for the battlespaces of the future lay heavy emphasis on the need for a collective (humans and machines) performance which displays certain properties (see the discussion of state_changes in conflict above). However, especially in the area of command and control many of the things that are required (flexibility, robustness, coherent action, implementation of intent etc) can't be bought - instead, they are emergent properties which are manifested when the system elements interact.

a. The approach used to acquire military capability is to specify what is required and then obtain it by recruiting and training personnel, purchasing equipment or by acquiring information and technical know-how.

b. Currently, an attempt is made to design these 'system of systems' [6] in detail with the specification of the features of every element happening in advance. Note here that a single system has an architecture which can be defined as "The architecture of a system is the structure or structures of the system, which comprise components, the **externally visible properties** of those components, and the relationships among them.". Hence, the true architecture of a 'systems of systems' may only be perceivable as a collective emergent property. However, when the Systems Engineering approach is followed, knowledge of the state and composition of every element is required. Then, when the system is activated, it is required to function predictably and any behaviour of the system (initially evaluated through modelling) which does not conform to the required design is ruthlessly eradicated. This approach has a proven, and impressive, track record which can be seen in achievements such as the successful "Apollo" missions to the Moon using the Saturn V rocket. However, such systems are notoriously 'brittle' and quickly fail[7] when circumstances (inevitably) lead to events occurring which are outside the expected specification.

c. In the past the components of such systems were acquired separately (so-called 'closed' or 'stovepiped' systems) and were designed and built to perform a limited range of functions in isolation. This is no longer the case as, increasingly, complex systems are being created by connecting federations of components into open, distributed systems. The components of these systems[8] involve organisations, humans, processes, information, software, hardware (sensors etc) operating in a loosely-connected, dynamic, ever-changing and (especially in the military domain) uncertain environment which is not controlled centrally. Many initiatives aspire to create complex, flexible and robust systems of this type.

d. However, it is quite simply impossible[9] to predict and establish *exactly and rigorously* whether a complex 'system' of this type[10] will display an ideal set of features using mechanistic 'Newtonian' approaches. This is because:

- firstly, the 'system' has no clear boundary;
- secondly, there are strong human and environmental components in the system;
- thirdly, the composition of the system will be changing all the time as entities of different type (class) join and leave the federation;
- fourthly, the state of every component will be varying in an asynchronous manner which is not (and cannot) be controlled centrally, and
- lastly much of the 'behaviour' of the system is emergent.

e. Paradoxically, you can't begin to establish the exact performance of a component until it interacts with the federation and, even then, all that one can establish is an estimate of performance. This is because it is impossible to examine every state under which the component would have to operate as many of the states are emergent and *will not be part of the formally specified design*. It is appearance of these emergent phenomena which leads to the failure of many of the attempts to create complex system noted above and is why 'unwanted' emergence is treated as something to eradicate.

f. So, by embracing the fact (a priori) that the 'system of systems' is a complex, dynamic, uncertain and evolving 'ecosystem' and by employing appropriate approaches it is

[6] A term dating from the American Civil War.
[7] Well known examples - Software: London Ambulance, ATC; Software / hardware: YF22 crash etc.
[8] So-called "socio-technical" systems.
[9] Even evaluating all possible states in something as small as a hundred-node network (where each node can be on or off would take 10^{30} steps (or some 31,000 million years on a 1GHz computer).
[10] The Internet is an example of this type of 'system'.

more likely that the work will lead to a useful analysis of the system's collective capability. For example, if one can prove a degree of insensitivity of the behaviour of each component to the activities of the others, then one may be able to make much more global statements about the performance of the collective system without having to slavishly explore all states of the entire system.

38. The Commercial / Civilian Context. The increasing use of distributed information technologies 'in the wild' (especially in the entertainment domain) introduces every more uncertainty and informality. This results in many more levels of unregulated interaction between the components of the distributed system and from this many novel behaviours emerge (eg: the rise of SMS or the popularity of MP3). However, there is good evidence that the phenomena of emergence can be highly beneficial even in simple applications. For example, from competition between communities of calculating software agents has emerged the best machine-generated number sort routine ever[11] - only one step worse than any human effort. If the companies are to research and deploy distributed information technologies in support of commercial organisations then obtaining an understanding of how to exploit the beneficial elements of the phenomena of emergence is a key enabling technique.

[11] This was done by Daniel W Hillis' "Ramps" - which were co-evolving software parasites.

CHAPTER 4. WHERE NEXT?

INVESTIGATIONS SO FAR

39. I have been gathering information related to this topic since the early 1980s and this year began to write a short paper about "Exploiting the Phenomena of Emergence". As part of this activity I contacted over 130 potential collaborators and interested parties. The main points to come out of the analysis of their replies is that there were a number of people who would like to be involved and that there is some significant interest in this area, a number of potential applications / uses exist and that follow-up action was required (a summary report and possibly some sort of seminar was requested) leading to further research.

APPROACH TO THE RESEARCH

40. A key point to make first is that the biggest danger for research into this topic would be a lack of focus. As has been argued, emergence is potentially a larger topic than science or engineering and possibly bigger even than philosophy. Thus the scope of the research needs to be reduced to something more manageable if it is to be tractable.

41. Hence, the aim of the research would be to attempt to derive the specific principles and insights which would lead to being able to exploit the phenomena of emergence as a useful 'tool' in the specific 'socio-technical' contexts, such as the commercial context of competition for 'resources' in distributed information systems. The approach to the research would be to assemble a multi-disciplinary team to investigate the following topics:

a. Providing further observations about the characteristics of emergent phenomena.

b. Classifying the types of emergent phenomena and their differentiating features and developing a consensus on terminology of emergent properties within the scope.

c. Characterising the necessary conditions under which emergent phenomena arise and relating those conditions to the characteristics and classes of phenomena:

- investigate classes of approach to predicting the potential emergent properties of interconnecting two or more systems (bottom-up), and
- investigate classes of approach to predicting what emergent properties are possible given a system of systems (top-down).

d. Investigating the use of apparent invariants (such as Langton's Lambda factor and of the Feigenbaum numbers in 'deterministic chaos') to 'measure' factors relating to the generation of emergent phenomena in distributed information systems.

e. Investigating the applicability of extensions of classical theories (e.g. to optimum control / optimum filter / organisational management / stability / quantum effects etc).

f. Understanding how to trigger (and subsequently nurture) a certain forms of emergent phenomena 'on demand' to support a specific 'task'. To investigate precursors and constraints and possible 'paths to emergence'.

g. Investigating the characteristics of 'self-organising socio-technical systems' and the organisational mechanisms that are employed.

h. Researching how to exploit the phenomena of emergence in a useful manner in commercial and military applications (mappings between phenomena and their representations in reality.

i. Selecting a challenging test case and using multi-agent systems prototypes as a test-bed for some of the experiments at the conceptual level.

42. Research Outcomes. The expected outcomes of the research would be as follows:

a. Improved understanding of the factors and principles relating to positively exploiting the phenomena of emergence as a 'tool'.

b. A set of formal descriptions encompassing characteristics, classifications, invariants and representations relating to the exploitation of the phenomena of emergence.

c. Initial tools for employing and exploiting the phenomena of emergence with some examples derived from the test-bed research with software agent teams.

d. Report on the potential applicability of the research information derived from the above to commercial capability to how commerce could approach problems of this type.

UNTAPPED RESOURCES

43. There are a vast set of Internet Links and References as yet not fully collated. These are in addition to the references used in this document. They are available on request from the author.

CHAPTER 5. SUMMARY AND RECCOMENDATIONS

SUMMARY

44. This paper has described emergent phenomena as being persistent and discernible effects which arise from the interactions among the parts of a complex 'system' in a manner that cannot always be predicted by examining the features of the components in their inactive state. The paper seeks to show that these phenomena could be utilised positively as a useful tool and recommends that research takes place to find out how to do this.

45. Emergent phenomena can be seen to arise:

a. directly from a physical 'systems' (eg: 'standing waves' - such as those which form as apparently stationary clouds over hilltops in windy conditions or 'stopper waves' in fast-flowing rivers; 'virtual' capabilities such as that of the "very-long baseline" radar dish - which behaves as one large dish even though it is made from many smaller, cheaper ones and Saturn's rings, even the features of creatures at the macro level expressed from the interaction of genes at a micro level), or

b. at the interaction of the physical and conceptual world (eg: the complex, apparently unified and sentient behaviour of ants' nests and even human consciousness may be an emergent phenomena). Indeed, this type of emergent phenomena tend to manifest themselves as behaviours which only appear at 'higher levels' of abstraction or as novel 'structures' at higher-levels of organisation.

c. where there is no other explanation for the manifestation.

Therefore, these novel emergent phenomena are tangible manifestations of "the whole being more than the sum of the parts". As such they can provide extra functionality or capability to complex systems and they can also provide a way of understanding a complex system by examining its simpler emergent phenomena.

46. Why does the phenomena of emergence need to be researched? Well, it is widely accepted that emergent phenomena exist, that they are highly significant and massively effective. The view is that "The systems engineer is always trying to enhance positive emergent properties caused by combining components, and suppress negative aspects of interactions." and yet there is inadequate science about how this might be done during the design and construction of complex systems before they are activated as part of the real world. Indeed, the nature of the phenomena of emergence is so poorly understood that there is barely a suitable language available to use to describe it, let alone a set of formal methods or any understanding of how the phenomena of emergence could be exploited positively as a useful tool.

47. In other words, the human race has managed pretty well to date - but things are changing as the exponential growth in distributed communication, software mobility and collaborative working creates an ever more chaotic, complex and heterogeneous world. The conventional approaches to engineering systems, which rely on the systems being closed, linear, optimised, strongly hierarchical, non-competitive and 'static', do not work on complex systems - indeed such systems are beyond the limits of 'conventional' scientific modelling.

48. Nature takes a different approach to complex systems with useful behaviour emerging from interactions between 'live-ware'. How is this done? Can the principles involved help us deal with our increasingly complex human systems? Clearly, the phenomena of emergence is part of this puzzle, but how does it relate to other phenomena such as self-organisation, number, information, complexity or chaos theory, fractals, human intelligence, sociology and culture etc? So:

- almost without exception the natural world (both tangible and intangible) is formed, driven and evolves through the interaction of phenomena which manifest themselves at different levels of abstraction and self-organisation right up to the most rarefied levels of human introspection and beyond.
- almost without exception we do not employ the same mechanisms as the natural world in the creation of our devices, systems and human artefacts and so miss out on all the potential benefits that are waiting to be accrued.

The implication is that if we insist on only using 'classical science' and do not learn how to understand, employ (for analysis) and positively exploit phenomena (such as that of emergence) then *we may never know* what capabilities are waiting to be discovered because they exist at a *higher level of abstraction* that conventional approaches will never reveal to us.

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CHAPTER 6. REFERENCES / GLOSSARY AND CONTRACTUAL

REFERENCES

1. On p214 of Ilya Prigogine. *From Being to Becoming: Time and Complexity in the Physical Sciences.* San Francisco - Freeman. 1980.

2. On p4 of Joseph Ford. *How Random is a Coin Toss?* Physics Today. April 1983.

3. On p31 of Paul Davies. *The Cosmic Blueprint.* Penguin ISBN 0-14-024362-3. 1995.

4. In Dave Marsay. *Defence Holarchies*. (DERA Internal). 9 February 1999.

5. For USENET Newsgroup comp.theory.self-org-sys: *Self-Organizing Systems (SOS) Frequently Asked Questions (FAQ)*. Version 2.4 May 2000.

6. On p7 of John H Holland. *Emergence: from Chaos to Order*. Oxford University Press. ISBN 0-19-286211-1. 1998.

7. Jack Cohen and Ian Stewart. *The Collapse of Chaos: Discovering Simplicity in a Complex World*. Penguin Books. ISBN 0-14-017974-0. 1994.

8. Ibid. John H Holland. p215.

9. In Nils A. Baas and Claus Emmeche. *On Emergence and Explanation*. Intellectica 1997/2, No.25, pp.67-83 (also as: the SFI Working Paper 97-02-008. Santa Fe Institute, New Mexico, U.S.A). 1997.

10. J. Bricmont: *Science of Chaos or Chaos in Science?*. In: The Flight from Science and Reason, Annals of the New York Academy of Sciences 775, ed. by P.R. Gross, N. Levitt, M.W. Lewis (The New York Academy of Sciences, New York 1996) pp. 131--175

11. Ibid. Paul Davies. pp20 and 76.

12. On p679 of Donald M MacKay. In Nature 232. 1986.

13. Karl Popper and John Eccles. *The Self and its Brain*. Berlin. Springer International. 1977.

14. On p713 of Douglas R Hofstadter. *Godel, Escher, Bach: an Eternal Golden Braid*. Penguin. ISBN 0-14-00.5579-7. 1980.

15. J.C. Smuts. *Holism and Evolution*. MacMillan 1926.

16. Ibid p5. Nils A. Baas and Claus Emmeche.

17. Baas N A. *A framework for higher order cognition and consciousness*. p. 633-648 in Stuart Hameroff, Alfred Kaszniak and Alwyn Scott, eds. *Towards a science of consciousness*. MIT Press/Bradford Books. 1996.

18. In Stuart Kauffman. *Origins of Order: Self-organisation and Selection in Evolution*. Oxford: Oxford University Press. 1992. Also in *Antichaos and Adaption*. pp 78-85, Scientific American, August 1991.

19. Christopher G Langton. *Life at the Edge of Chaos*. On pp 41-49 of A-Life II. Addison Wesley. ISBN 0-201-52571-2. 1992.

20. Stephen Wolfram. *Cellular Automata as Models of Complexity*. Physica 10D. 1984.

21. Ibid. Paul Davies. pp42 - 51. Mitchell Feigenbaum.

22. Ibid. SOS FAQ. Section 7.2, para 29.

23. On p94 of Brook, Arnold, Jackson and Stevens. *Systems Engineering - Coping with Complexity.* Prentice Hall ISBN 0-13-095085-8.

24. P W Anderson. Science 177, p393. 1972.

25. Bass L., Clements P., Kazman R, The SEI Series in Software Engineering, "*Software Engineering in Practice*", Addison Wesley Longman, Inc ISBN 0-201-19930-0.

26. F J Oddling-Smee. *Multiple Levels in Evolution: An approach to the Nature-Nurture Issue via 'Applied Epistemology'*. In Animal Models of Human behaviour. Ed. G C L Davey. John Wiley and Sons Ltd. 1983.

GLOSSARY / ABBREVIATIONS

CA	Cellular Automata
CCRP	Command and Control Research Programme
FAQ	Frequently Asked Questions
MP3	Motion Picture Expert Group's Audio Layer 3
SIP	Sensors and Information Processing (Department)
SMS	Short Message Service
SOS	Self-organising Systems

CONTRACTUAL

QUOTATION

N/A.

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