

DISCOURSE ON EMERGENCE: PART I (FOUNDATIONS)

The following paper is part one of a three-part treatise on the concept of emergence. The aim of this paper is to establish the foundations of this concept via a review of the literature. First, a popular definition of emergence is introduced and a brief historical background to the concept is described. Second, basic system-theoretical concepts associated with modern formulations of the notion of emergence are presented. Third, some phenomenological issues (concepts of emergence and types of emergent) are discussed. Finally, a formal framework for emergence is examined and the distinction between emergent computation and computational emergence is clarified.

KEY WORDS: Emergence, systems-theory, phenomenology, formalisms, computation

1. INTRODUCTION

Like the legendary phoenix rising from the flame, the concept of emergence has begun to again enjoy popularity within scientific and philosophical discourse. A number of factors have motivated reconsideration of this idea including renewed interest in connectionist (as contrasted with symbolic) models of cognition (Clark,89), the emergence of the discipline of artificial life with its bottom-up modeling methodology (Langton,89), and, perhaps most significantly, the need to resolve the "hard problem" of phenomenal consciousness (Chalmers,96). Yet, despite renewed interest, and in spite of ubiquitous usage, the concept of emergence remains elusive, a fact which is marked by the lack of uniformity regarding its definition. In this survey paper, which is the first in a series of three papers on the topic of emergence, an attempt has been made at establishing and clarifying some of the basic foundations associated with the concept. In the second survey paper, various epistemological and ontological issues associated with the concept are investigated while in the third and final position paper, a detailed critique of the concept is attempted and proposals for its reconstruction are outlined.

1.1. Definition: Emergence

Popular scientific and philosophical discourse holds that the essence of the concept is traceable to an observation made by the ancient Greeks:

the whole is more than the sum of the parts.

However, this statement is at best incomplete since it does not clarify the distinction (if any) between emergence and related concepts such as holism and self-organization (the semantics of which are investigated in Part III of this treatise). More importantly, it does not describe the way(s) in which a whole is more than the sum of its parts since it fails to clarify the ontological¹ and epistemological² issues associated with the concept. (The part-whole problem is addressed again, briefly, in Part II, §3.4). An attempt at articulating a more precise definition of emergence has been made by Mayr (1982) who maintains that

"emergence denotes the appearance of new characteristics in wholes that cannot be deduced from the most complete knowledge of the parts, taken separately or in other partial combinations." (p.63)

This definition is clearly an improvement on the original maxim since it addresses both the ontological and the epistemological issues associated with the concept. However, it also clearly does not constitute a formal definition of emergence. In an attempt at constructing such a definition, various philosophical schemes which provide the basis for modern formulations of emergence will be briefly discussed in order to trace the development of the concept to its modern systems-theoretical forms. The objective is to examine the various issues associated with the concept and thereby provide a basis for the epistemological and ontological critique of emergence presented in Part III.

1.2. Historical Background

It is to Chapter VI of J.S.Mill's A System of Logic Ratiocinative and Inductive (1843) that perhaps the first implicit reference to the concept of emergence in a modern scientific context can be traced. Mill describes what he calls heteropathic laws as "laws of combined agency [which] are not compounded of the laws of the separate agencies" (p.375) and goes on to state the following:

"as a general rule, causes in combination produce exactly the same effects as when acting singly: [however,] this rule, though general, is not universal: that in some instances, at some particular points in the transition from separate to united action, the laws change, and an entirely new set of effects are either added to, or take the place of, those which arise from the separate agency of the same causes³: the laws of these new effects being again susceptible of composition, to an indefinite extent, like the laws which they superseded [emphasis added]." (p.376)

However, the earliest documented use of the term 'emergence' is attributed to the philosopher of science George Henry Lewes in the middle of the nineteenth century (Kenyon,41). Lewes anticipated the epistemological conclusions drawn from modern research into the behaviour of complex non-linear⁴ dynamical systems by distinguishing between resultants and emergents: in the former, the sequence of steps which produce a phenomenon are traceable whilst in the latter they are not. Thus, according to Lewes, emergence is a statement of the epistemological limitations of phenomenal observation. In the twentieth century, the concept of 'emergence' was formally introduced by C.Lloyd Morgan in Instinct and Experience (1912) and a theory based on the concept was developed in his Emergent Evolution (1923). Like Lewes, Morgan regarded the distinction between resultants and emergents as inductive and empirical, and not metaphysical. Emergence was understood as implying that the higher orders of being produced in the evolutionary process were not mere resultants of what went before and were not contained in them as an effect is in its efficient cause; hence, emergentism was not equivalent or reducible to mechanism. Blitz (1992), who has extensively researched Morgan's philosophy of emergent evolution, maintains that it consists of three premises:

- (i) evolution is a universal process of change productive of qualitative novelties

- (ii) qualitative novelty is the emergence of a property not possessed by any of its parts
- (iii) reality can be analyzed into levels consisting of systems characterized by emergent properties

However, Morgan's scheme was purely descriptive and did not provide an explanation for the phenomenon of emergence (Collingwood, 45). It was in Samuel Alexander's Space, Time and Deity (1920) and J.C. Smuts' Holism and Evolution (1926) that the first attempts at an explanatory framework for emergent evolution were made. On Smuts' view of emergence, nature is permeated by an impulse towards the creation of wholes; novelty, the defining characteristic in Morgan's scheme, is considered as merely a derivative phenomenon. Alexander, on the other hand, anticipated modern notions of self-organization (Part III) and functionalism⁵ by identifying emergence with the tendency for things to arrange themselves into new patterns which as organized wholes possess new types of structure and new properties or 'qualities'. The connection to functionalism is implied in the conception that quality depends on pattern (organization, form or structure).

1.3. Towards a Theory of Emergence

One of the earliest presentations of the concept is that due to Broad (1925) who provides the following outline for a theory of emergence:

- (i) there are certain wholes, composed (say) of constituents A , B , and C in a relation R to each other;
- (ii) all wholes composed of constituents of the same kind as A , B , and C in relations of the same kind as R have certain characteristic properties;
- (iii) A , B , and C are capable of occurring in other kinds of complex where the relation is not of the same kind as R ;
- (iv) the characteristic properties of the whole $R(A, B, C)$ cannot, even in theory, be deduced from the most complete knowledge of the properties of A , B , and C in isolation or in other wholes which are not of the form $R(A, B, C)$.

This scheme is complemented by Pepper (1926) who identifies emergence as a kind of change different from that of random changes ("chance occurrences") and mechanistic changes ("shifts"):

"emergence .. is a cumulative change, a change in which certain characteristics supervene upon other characteristics, these [latter] characteristics being adequate to explain the occurrence on their level." (p.241)

Supervenience is the idea that a higher level phenomenon is causally dependent on a lower level phenomenon for its existence: for example, mental phenomena are causally dependent on the occurrence of physical events in the brain. However, the supervenience relation between a mental event and the associated physical event does not imply a one-one mapping: many physical brain states can support the same mental

state; thus, mind is said to be multiply-realizable. As Klee (1984) states, there are "multiple distinct determinative micro-bases for the same macro-property" (p.56). Hence, there is a close relationship between supervenience and functionalism. Pepper's cumulationist formulation implies, however, that emergents (the products of a process of emergence) must be epiphenomenal or non-causal; thus, the possibility of 'downward' causation (Part II, §3.3) is rejected a priori.

According to Pepper, the theory of emergence involves three propositions:

"(1) there are levels of existence defined in terms of degrees of integration; (2) there are marks which distinguish these levels from one another over and above the degrees of integration; (3) it is impossible to deduce the marks of a lower level from those of a higher." (p.241)

On this basis, the concept of emergence, originally conceived in terms of the relations between parts and wholes, is readily recast in systems-theoretic terms: for example, Pepper's propositions are directly associated with three issues: (i) complexity (§3.5), (ii) types of emergent (§4.2), and (iii) the limits of reductionism (Part II, §2.3).

2. BASIC CONCEPTS

In this section various concepts associated with contemporary theories of emergence derived from cybernetics and systems theory are briefly examined.

2.1. Systems

The idea of a system is a basic concept within modern theories of emergence and a conceptual prerequisite of functionalism.

Defⁿ: a system S (or internal environment) is (1)

S_C	a set of components c_p where $p \in P$ (some finite index set)
$S_R : S_C \rightarrow S_C$	a set of relations r_q where $q \in Q$ (some finite index set)
$S : S_C \times S_R$	a network of relations between components

A system may be viewed as performing a function if (i) a second set of components and relations defining the environment E external to S is specified and (ii) an input-output (coupling) relation between E and S is defined:

Defⁿ: an environment E (or external environment) is (2)

E_C	a set of components c_m where $m \in M$ (some index set)
$E_R : E_C \rightarrow E_C$	a set of relations r_n where $n \in N$ (some index set)
$E : E_C \times E_R$	a network of relations between components

Defⁿ: an input-output (coupling) relation $I_R - O_R$ is (3)

$I_R : E_C \rightarrow S_C$ a set of relations r_i where $i \in I$ (some index set)
 $O_R : S_C \rightarrow E_C$ a set of relations r_j where $j \in J$ (some index set)

Thus, the system maps a set of inputs (from the environment to the system) to a set of outputs (from the system to the environment). This input-output mapping defines the functional pathways of the system. However, this description is incomplete since only the topology (structure) of the system-environment coupling has been specified. In order to complete the description it is necessary to define each component and each relation. Furthermore, as Heylighen (1993) states, "no absolute distinction can be made between internal and external, that is, between system and environment. What is 'system' for one process is 'environment' for another one." (p.3) Hence, the system-environment coupling relations are relativistic irrespective of whether the relativism is functional (ontological) or observational (epistemological). The relations between a system and its environment are shown in Figure 1.

FIGURE 1

Essential to definitions (1)-(3) is that S be finite while E can be finite or infinite: if both S and E were infinite, it would be impossible to distinguish the system from its environment; S would be identical to E (and vice-versa). On the above definitions, system and environment are conceptually similar with respect to form (or structure). This is consistent with an autopoietic (or self-generating) systems perspective (Maturana,80) in which the connection between organism and environment is viewed in terms of a network of perturbation relations between coupled systems⁶.

The link between systems and emergence may be stated as follows: emergence occurs during the becoming or coming-into-being of the system-environment duality. A system, as defined above necessitates description at two levels: the component (or parts) level and the system (whole or functional) level. Furthermore, the coming into being of systems fulfills one of the requirements for emergence, viz. non-reductionism, since system descriptions cannot be epistemologically reduced to descriptions at the component level, even if causality is strictly 'bottom-up'; components (parts) are only identifiable with respect to systems (wholes) and vice-versa. (The ontological possibility of 'top-down' or retroactive causality is discussed in Part II, §3.3; in this latter case, it is not only description which is two-level but causation as well.) However, this view of the link between systems and emergence is incomplete since it fails to distinguish emergence from chaos, whereby the latter is meant simply the unpredictability that arises as a consequence of the non-linear properties of certain dynamical systems such as Newtonian n -body systems. In order for a system to qualify as genuinely emergent, it must possess properties which its components do not possess and these are broadly of two kinds, viz. structural and functional (§4.2).

2.2. Hierarchies

The two-level description of systems leads directly to the notion of a hierarchy. Simon

(1981) defines a hierarchy as

"a system that is composed of interrelated subsystems, each of the latter being in turn hierarchic in structure until we reach some lowest level of elementary subsystem." (p.196)

It is important to note, however, that this recursive definition is motivated by purely epistemological concerns; it states how a system may be observed or interpreted. Ontological issues, for example, how the system is causally organized or produced, are not addressed. Adopting the causal perspective enables two different approaches to hierarchy construction to be identified, viz. top-down and bottom-up.

2.2.1. Top-down (designed or planned):

the system subsists as an a priori potentiality in the Platonic sense of an abstract transcendent form (structure) or mental artifact (concept) awaiting actualization in matter; consequently, the system-environment boundary is pre-defined.

2.2.2. Bottom-up (emergent or evolutionary):

the system comes into being as an a posteriori teleological actuality, form (structure) and telos (function) arising as a consequence of the establishment of a coupling relation between components. Systems become separable and identifiable from their environments once partial or relative causal closure is established (assuming this is possible) in the former (Part II, §3.1).

2.3. Partitionings

System hierarchies must be distinguished from system partitionings: in the former, both the set of subsystems and their interrelations is necessarily specified, while in the latter, specification of the subsystems alone is sufficient. Figure 2 shows the difference between hierarchies and partitionings.

FIGURE 2

It should be noted, however, that systemic structures other than hierarchies and partitionings are possible: for example, Hofstadter (1979) describes a system of 'tangled loops' or heterarchies in which the relations between levels are non-linear and characterized by a high degree of feedback. As Heylighen (1993) states,

"all fundamental types of abstract order which can be found in emerging systems, such as hierarchies, symmetries, periodicities, cycles, partitions, etc can be generated by the recursive combination of extremely simple 'closure' operations [and] the emergence of cyclical distinctions .. may lead to heterarchical, non-linear architectures." (p.5)

2.4. Near-Decomposability

Simon (1981) maintains that multi-level hierarchies constitute the most stable and efficient structures for systems of even moderate complexity (§3.5): the time required for a system to evolve by natural selection is much shorter (logarithmic) if the system is structured as a series of levels of subsystems rather than composed from the primitive system components. Simon further maintains that the bottom-up construction of hierarchies tends to produce systems which are either decomposable or near-decomposable, systems in which the intra-subsystemic interactions are strong (high cohesion) and the inter-subsystemic interactions negligible or weak (low coupling) respectively. Near-decomposability ensures that the short-term behaviour of each of the component subsystems is approximately independent of the short-term behaviour of the other components; in the long term, the behaviour of any one of the components depends in only an aggregate (or statistical) way on the behaviour of other components. Near-decomposability facilitates abstraction and reductionism (Part II, §2.3) by an appeal to the "empty worlds hypothesis", viz. most things are only weakly connected to most other things; hence, "for a tolerable description of reality only a tiny fraction of all possible interactions needs to be taken into account." (p.221) However, what constitutes a 'tolerable' level of description varies depending on context, the level of precision required being motivated by relevance to either the observer/interpreter or/and organizer/producer of the system.

2.4.1. Historicity

Near-decomposability has been criticised by Wimsatt (1972) who maintains that it fails to distinguish the decomposability or stability of subsystems before they aggregate in the system from their decomposability or stability as isolated components after they have aggregated. Such criticism appears justified in the context of biological systems assuming, as Wimsatt does, geological time, which allows for a process of mutually coadaptive changes under the optimizing forces of natural selection. This important observation has also been made by Kenyon (1941), who points out that a possible consequence of emergent evolution (emergence) is that the parts in the new whole may be modified. For example, a set of components $\{a,b,c,d\}$ might interact to form the emergent whole X . When X is subsequently fractionated (decomposed) along 'natural' hierarchical boundaries, X may reduce to components $\{e,f,g,h\}$ where $\{a,b,c,d\}$ is not isomorphic with $\{e,f,g,h\}$. Thus, emergent evolution redefines the components of the whole via dynamical construction of a hierarchical structure within the whole. This position is consistent with the non-cumulationist account of emergence proposed more recently by Bunge (1969) and discussed in Part II, §3.4.

2.4.2. Relativity

Rosen (1977) maintains that because a system can be decomposed on a number of equally 'natural' partitionings, objective decomposition is impossible. However, Simon (1981) argues to the contrary by appealing to a Kantian position:

"The fact .. that many complex systems have a nearly decomposable, hierarchic structure is a major factor

enabling us to understand, describe and even 'see' such systems and their parts. Or perhaps the proposition should be put the other way round. If there are important systems in the world that are complex without being hierarchic, they may to a considerable extent escape our observation and understanding. Analysis of their behaviour would involve such detailed knowledge and calculation of the interactions of their elementary parts that it would be beyond our capacities of memory or computation." (pp.218-219)

Simon reinforces this objectivist conception of system decomposition by maintaining that "in most systems in nature it is somewhat arbitrary as to where we leave off the partitioning and what subsystems we take as elementary." (p.196) However, this view may be contested on the grounds that it fails to recognize the role of the observer/interpreter who identifies a system by regarding certain phenomena (properties, behaviour etc) as systemic and others as non-systemic according to some relevance criteria. Non-systemic phenomena are considered 'side-effects' and for certain types of system, for example, linear dynamical systems, may be negligible. However, for other types of system, such as non-linear dynamical systems, side-effects can be the source of an exponentially-increasing disorder leading to increasing unpredictability (an epistemological problem) and increasing instability (an ontological problem) of system behaviour.

2.4.3. Locality

Another criticism at a much more fundamental level involves the underlying premise on which the notion of near-decomposability is based, viz. weak inter-subsystemic interaction. Bechtel (1986) refers to this as the "localizationalist" perspective; proponents of this view maintain that although organization is present in a system, it is inessential to the explanation of the system. However, Bechtel contests this position:

"sometimes it is the case that a system performs a task because some part of it performs that task. In such cases a localizationist account is correct .. Moreover, even in cases where the localizationist account turns out to be incorrect, it is sometimes reasonable to begin one's research by trying to find localized components which may perform the task one is trying to explain What one learns about the components of the system may show that no component performs the whole task and may provide critical guidance in developing an explanation that attributes a major role to the integration of the components." (p.34)

2.5. Complexity

Ever since the theory of emergent evolution was first articulated, it has been appreciated that the occurrence of emergence is contingent on the complexity of the substrate. For example, Langton (1990,1991), following a basic insight due to von Neumann (1966), postulates the existence of an 'edge of chaos', a region of self-organized criticality lying between ordered (periodic) and random (chaotic) behavioural regimes to which, it is conjectured, certain kinds of complex non-linear dynamical systems evolve. However, while it is generally accepted that complexity is a necessary condition for emergence, to infer that it is also a sufficient condition does not constitute an explanation; the nature of the relationship between complexity and emergence remains to be clarified. However, the problem is further compounded by disagreement regarding the conceptual basis of the metric by which the complexity of the underlying

substrate (component level) is measured. Edmonds (1995) describes various complexity metrics in the context of a study of the link between complexity and biological evolution while Bennett (1990) presents the following list of metrics gathered from a review of the literature associated with measuring complexity in physical systems:

- (i) Life-like properties
- (ii) Thermodynamic potential
- (iii) Computational universality
- (iv) Computational space-time complexity
- (v) Algorithmic information
- (vi) Long-range order
- (vii) Long-range mutual information
- (viii) Logical depth
- (ix) Thermodynamic depth
- (x) Self-similar structures and chaotic dynamics

Disagreement over how to measure complexity has led, in at least one case, to the view that it may be impossible to provide an objective definition of the concept (Horgan,95). For example, Von Neumann argued that complexity was the essential characteristic of life. However, Bennett (1990) has criticised this view on the grounds that it does not differentiate between potential and actual complexity; the former is a static, structural concept whilst the latter is a dynamical, control concept (Pattee,73). On the basis of these arguments, it is proposed that complexity should be regarded as an observationally-relativistic measure (Part II, §2.2) in the sense that it is defined with respect to epistemic perspective: the emergent properties of a system in which we are interested define (via selection amongst alternatives) the metric we use to measure substrate complexity. This position is consistent with that of Tallis (1994) who argues against the idea of intrinsic complexity. However, Edmonds (1995) maintains that even relativistic formulations of the concept are problematic on the grounds that notions of complexity can usefully be applied only to constructions within a given language; this leads to a consensually-defined as opposed to objectively-defined concept of complexity. Edmonds proposes the following definition of complexity:

"That property of a language expression which makes it difficult to formulate its overall behaviour, even when given almost complete information about its atomic components and their inter-relations." (p.6)

Edmonds argues that complexity is observationally-relativistic, in particular that it is "only revealed through interaction with the complexity of another system (typically us)." (p.3) It might be argued, however, that since complexity metrics are products of human design or anthropo-artifacts (Ali,97), complexity is a concept which is meaningful only with respect to human artificers (producers); to assert otherwise would be to anthropomorphize, that is, project human characteristics onto non-human entities.

3. THE PHENOMENOLOGY OF EMERGENCE

In the following section, the phenomenology⁷ of emergence is described, various concepts of emergence are discussed and different types of emergent are presented.

3.1. Concepts of Emergence

Similar to the four concepts (as contrasted with types or kinds) of computation postulated by Emmeche (1994), there are various concepts of emergence which can be identified. For example, Pattee (1989) presents the following three concepts:

- (i) syntactic emergence (for example, symmetry-breaking and chaos), characterized by non-symbolic, rate-dependent, continuous dynamical systems;
- (ii) semantic emergence (for example, genetic and cognitive creativity), characterized by symbolic rate-independent, discrete dynamical systems in which it is possible for the emergent to stand for a referent. "Semantic emergence operates on existing data structures that are the result of completed measurements or observations" (p.73);
- (iii) measurement emergence, characterized by the production of a record of some type of classification of the environment in a measuring device.

Cariani (1989,1991) also presents three concepts of emergence:

- (i) Computational (formally based, Platonistic) in which global patterns arise from local micro-deterministic computational interactions; for example, 'gliders' in the Game of Life cellular automaton, swarming and flocking behaviour in artificial ecologies etc.
- (ii) Thermodynamic (physically based, materialistic) in which stable structures arise as a consequence of self-organization in physico-chemical systems far from equilibrium; for example, dissipative structures (Prigogine,84). (However, Anderson et al. (1987) have argued that the structures emerging in dissipative systems are, in fact, unstable.) Simon (1981) postulates a statistical concept of emergence based on the notion of near-decomposability in hierarchical systems.
- (iii) Relative-to-a-model (functionally based, pragmatic) in which emergence is defined as the deviation of the behaviour of a system from an observer's model of it: if an observed system changes its internal structure and behaviour to such a degree that it becomes necessary to modify the observer's model in order to continue to predict its behaviour, then such systemic changes are considered emergent relative to the model.

Emergence-relative-to-a-model is similar to a concept of emergence due to Nagel (1961) who maintains that

"although a property may indeed be an emergent trait relative to some given theory, it need not be emergent relative to some different theory" (pp.370-371)

and further, that

"the distinction between an emergent trait and a nonemergent one .. shift[s] with changes in interest and with the purposes of an inquiry." (p.377)

Umerez et al. (1993) differentiate three forms of the concept of emergence-relative-to-a-model:

- (i) emergence with respect to a concrete⁸ model: error
- (ii) emergence with respect to a concrete theory: change
- (iii) emergence with respect to a concrete paradigm: crisis

(i) necessitates a change in a model, but within a fixed theoretical framework; (ii) necessitates a change in both the model and the theoretical framework, but within the scope of an existing paradigm; (iii) necessitates changing the entire approach (model, theory and paradigm). Umerez et al. associate (ii) with self-organizing behaviour in which the relations between the observables at two levels in a system (substrate and emergent) are fixed or static; this type of self-organization is described as structural emergence. (iii) is associated with functional behaviour and the relations between the observables at the two levels (substrate and emergent) are dynamic.

The most popular concept of emergence within the philosophy of mind is that due to Churchland (1985) in which emergence is defined as a relation between a phenomenon and two theories describing it:

"A property *P* specified by its embedding theory *T1* is emergent with respect to the properties of an ostensibly reducing theory *T2* just in case

1. *P* has real instances;
2. *P* is co-occurrent with some property or complex feature recognized in *T2*, but nevertheless
3. *P* cannot be reduced to any property postulated or definable within *T2*."

Manthey (1990) supports this view maintaining that "an emergent phenomenon is a product of a hierarchy relation between conceptual levels". What is problematic about this view is that it is unclear whether the emergent relation is objective or subjective: if the latter then emergence depends on the choice of observation frames adopted by the theoretician; consequently, Churchland's concept reduces to the second form of emergence-relative-to-a-model described by Umerez et al. (1993).

3.2. Types of Emergent

There are a number of different types or kinds of emergent reported in the literature; however, many of them are associated with specific concepts of emergence. Emergents are properties (or qualities) arising during a process and fulfilling one of the following conditions (Klee,84):

"Property *P* is emergent at a level of organization in a system, with respect to the system's lower-level microstructure *MS*, when and possibly only when either:

- (i) *P* is unpredictable in principle from *MS* (that is, unpredictable even from an ideally complete theoretical knowledge of *MS* in the limit of scientific inquiry)
- or

(ii) *P* is novel with respect to *MS*

or

(iii) *MS* exhibits a much greater degree of variance and fluctuation from moment to moment than does the level of organization where *P* occurs; *P*'s constant and enduring presence in the system would not seem to be wholly determined by *MS*

or

(iv) *P* has direct determinative influence and effects on at least some of the properties in *MS*."

Interestingly, and as Klee states, (iii) is consistent with both supervenience (§1.4) and functionalism, viz. "multiple distinct micro-bases for the same macro-property" (p.56). More importantly, however, is the fact that (i)-(iii) are consistent with a cumulationist view of emergence while (iv) necessitates adopting a non-cumulationist position (Part II, §3.4).

Emergent properties (or, more simply, emergents) broadly fall into two categories: (i) structural and (ii) functional.

3.2.1. Structural

In the context of a discussion of emergence occurring in systems of distributed, concurrent and asynchronously-coupled computational processes, Manthey (1990) defines the necessary and sufficient conditions for structural emergence⁹ as follows:

Necessary conditions

1. There are at least two processes
2. These processes interact via either memory or synchronization
3. The putative emergent phenomenon [invariant structure] cannot - even in principle - be expressed by a single process.

Sufficient Conditions

1. The phenomenon occurs.

However, Manthey admits that the "delicate issue of observation" (Part II, §2.1-§2.2) is ignored in this scheme.

3.2.2. Functional

Heylighen (1993) identifies at least three kinds of functional emergents, viz. boundaries, organizations, and control relations (Part II, §3.3.1). However, it is an open issue whether such functions are intrinsic (ontological) or extrinsic (epistemological); in the latter case, emergence is relative to an observer. While it is certainly the case that something must have a function in order to be considered a system¹⁰ (§3.1), it does not follow that systematicity is necessarily an intrinsic property of certain configurations

of matter. Even if it is held, following Pepper's conjecture (1926), that there can be no emergent properties other than emergent 'laws', there is still the problem that a law is defined in terms of a set of observables which necessitates the existence of an observer. This leads to the epistemological problem of intrinsic and extrinsic emergence discussed in Part II, §2.1.

4. FORMALISM, COMPUTATIONALISM AND EMERGENCE

In this section, various formalizations of the concept of emergence are briefly examined. Simon (1981) anticipates a formal framework for emergence in his conception of hierarchical systems, viz.

"Hierarchic systems are usually composed of only a few different kinds of subsystems in various combinations and arrangements .. Hence we can construct our description from a restricted alphabet of elementary terms corresponding to the basic set of elementary subsystems from which the complex system is generated." (p.221)

4.1. Basics

In order to explain the behaviour of any whole in terms of its structure (or organisation) and components, the following two independent pieces of information are necessary (Broad,25):

- (i) how the parts behave separately, that is, when not in the whole
- (ii) the law(s) according to which the behaviour of the separate parts is compounded when they are acting together in any proportion and arrangement

Such requirements translate isomorphically into a distributed formal-computational model of the corresponding system (Langton,89), viz.

- (i) a description of the behaviour of each member of a set of *behaviors*, each of which is an automaton (for example, finite state machine (FSM), Turing machine (TM) etc)
- (ii) a description of the set of local *rules* governing the interactions between behaviors (for example, the state-transition rule for the FSM, Turing machine specification etc)

4.2. A Formal Framework for Emergence

Baas (1993,1997) describes a formal framework for emergence involving three components which are arbitrarily defined, viz. primitives, observations, interactions:

Primitives $\{S_i^I\}$ is a set of first-order structures, where $i \in J$ (some index set, finite or infinite).

Observations $Obs^I(S_i^I)$ denotes the properties of structure S_i^I registered by the observational mechanism Obs^I which may be internal or external to the system.

Interactions

Int^I is the set of interactions between the elements of $\{S_i^I\}$ allowed by $Obs^I(S_i^I)$.

$S^2 = R(S_i^I, Obs^I, Int^I)_{i \in I}$, where R is the result of interactions between primitives and S^2 is a second-order structure.

First-Order Emergence

P is an emergent property of S^2 iff $P \in Obs^2(S^2)$, but $P \notin Obs^2(S_i^I) \forall i$.

The validity of the above framework might be contested on the grounds that it assumes properties to be objectively definable a priori the interactions of the subjects (structures) with which they are associated: for example, on Elstob's view (Part II, §3.2), properties arise during interactions and are contextually-determined by the interaction; hence, they are only determinable a posteriori the interaction.

Baas differentiates between concepts of emergence on the basis of computability or decidability:

- (i) *deducible* (or *computable* or *decidable*) *emergence* - in which there is a deductive or computational process D such that $P \in Obs^2(S^2)$ can be determined by D from (S_i^I, Obs^I, Int^I) . Obs is algorithmically defined.
- (ii) *observational* (or *undecidable*) *emergence* - in which P is an emergent property which is non-deducible. Obs is non-algorithmic, for example, the truth function in formal systems capable of supporting arithmetic; such systems have statements whose truth value cannot be deduced within the system (Gödel incompleteness theorem).

Deductive emergence in formal or computational systems is epistemically relative, describing the extent to which the 'Platonic landscape' defined by the attractor-space (or basin of attraction field) of the system has been 'mapped' by an observer. (This holds only for finite computational universes or infinite computational universes which are algorithmically compressible.) Simon (1981) alludes to deductive emergence in asserting that "all mathematics exhibits in its conclusions what is already implicit in its premises ... Hence all mathematical derivation can be viewed simply as change in representation, making evident what was previously true but obscure." (p.153) Furthermore, the non-algorithmic nature of Obs can be effectively (practically) overcome using Myhill's theorem (Arbib, 69); hence, on the computationalist view, it is conceivable that observational emergence might reduce to deducible emergence.

4.3. Computationalism

Broad (1925) maintains that the difference between mechanistic and emergentist theories lies in that the latter does not arise through substituting certain determinate values for determinate variables in a general law which connects the properties of any whole with those of its separate constituents and with its structure. However, the distinction between emergentism and mechanism is obscured in many computationalist theories of emergence. For example, Darley (1994) presents a rigorous definition of emergence based on the concept of computational complexity. Emergence is viewed as the result of a phase change in the amount of computation necessary for optimal

prediction of certain phenomena:

"emergent phenomena are those for which the amount of computation necessary for prediction from an optimal set of rules, classifications and analysis, even derived from an idealised perfect understanding, can never improve upon the amount of computation necessary to simulate the system directly from our knowledge of the rules of its interactions." (p.412)

A similar position, viz. simulation as the optimal means of prediction in emergent systems, is argued by Rasmussen et al. (1995). Darley views emergence in computational systems of finite size and finite time as analogous to undecidability in systems of infinite size and time capable of supporting universal computation. Furthermore, whether a system is emergent or non-emergent is an undecidable proposition. Hence, the term 'emergence' may be regarded as an epistemological statement on the undecidability of certain classes of computational phenomena. However, this view fails to distinguish emergence from mere chaos.

4.4. Emergent Computation and Computational Emergence

As stated in §3.1, computational emergence necessitates a computational substrate. By contrast, emergent computation (Forrest,90) necessitates a computational ontology for both substrate and emergent, that is, the phenomenon emerging from a computational process is a computational product; hence, emergent computations constitute a subclass of computationally emergent phenomena. Of course, it is trivially the case that the products of computational emergence will themselves be computational since it is assumed that no new ontological kinds are generated in the process. (Hence, a commitment to a non-accumulationist metaphysics.) However, Forrest's position is much stronger, being motivated by ideas such as the notions of virtual machines and embedded computer hierarchies: an emergent computation refers to the production either of (i) components which can be used in the construction of a virtual machine or (ii) the virtual machine itself. The concept of emergent computation can be understood at three levels:

- | | | |
|-------|---------------------|---|
| (i) | <i>substrate</i> | a collection of agents (or behaviors), each following explicit instructions |
| (ii) | <i>emergent</i> | interactions among the agents (according to the instructions) giving rise to global patterns of behaviour at the macroscopic level, that is, epiphenomena |
| (iii) | <i>interpretive</i> | natural interpretation of the epiphenomena in computational terms |

This concept of emergence is consistent with the notion of global constraints in systems with computational substrates described in §3.3.2. Even if the question of the epiphenomenality or otherwise of emergents is ignored, interpreting the epiphenomena in computational terms is a contentious issue because there are at least two possibilities with respect to any such interpretation, viz. (i) computation "in the eye of the beholder" (extrinsic emergence) and (ii) computation inherent in the system itself (intrinsic

emergence) (Part II, §2.1).

Additionally, it is conceivable that non-computational substrates might give rise to phenomena which are interpretable as emergent computations; in fact, this is precisely how computers can themselves be viewed: computers are material artifacts emerging as a consequence of human design activity. Ontologically, their operation is governed by physical laws; however, epistemologically, their behaviour can be given a functional interpretation. Temporarily ignoring the possibility of a computationalist interpretation of the laws of physics (Fredkin,90), this constitutes at least one instance of the emergence of computation from a non-computational substrate; in this case, the efficient cause of the phenomenon - the means by which the computer comes into existence - is a human artificer (producer). If the various concepts of computation identified by Emmeche (1994) are accepted, it may be possible to extend the list of computational emergents arising from non-computational substrates. This gives rise to the notion of heterogeneous emergent computation wherein a substrate with one kind (concept) of computational ontology facilitates the emergence of a global phenomenon of a different kind of computational ontology; accepting the validity of Emmeche's scheme, this may be the case in the natural world. However, as Emmeche has argued, such a position ultimately rests on the attribution of computational properties to natural phenomena (as contrasted with the computationalism intrinsic to computational artifacts, viz. computers) and this attribution is metaphysical in nature.

Finally, emergent computation may also be interpreted as 'environmental' computation since in systems capable of supporting such emergence, it may be argued that information processing occurs by the components in the system (the 'organisms' or local systemic level) acting on the system as a whole (the 'environment' or global systemic level) (Millonas,94).

5. SUMMARY

In this review paper, various concepts associated with emergence have been identified such as phenomenal hierarchies, complexity, concepts of emergence and types of emergent. In addition, it has been shown how these concepts can be translated into equivalent systems-theoretical constructs, thereby allowing for the encapsulation of the phenomenon of emergence in formal/computational frameworks. However, in the context of this investigation (more specifically, with respect to Part III of this treatise), what is perhaps most important is the assertion that emergence can be viewed as either (both) an epistemological or (and) an ontological phenomenon. This assertion motivates the examination of the philosophical issues associated with the concept of emergence which is presented in Part II.

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1. Concerned with the being or existential nature of things.
2. Concerned with how things are known, understood, explained etc.
3. This concept of emergence is consistent with both cumulationist (or inclusivist) and non-cumulationist (Bunge,60) emergentism as described in chapter 5.
4. *Linear* systems obey the *superposition principle* since they are decomposable into independently analyzable components and composition of understanding of the isolated components leads to *full* understanding of the system. The principle does not hold for *non-linear* systems since in this case, primary behaviours of interest are properties of the *interactions* between components as contrasted with properties of the components themselves; isolating the components *necessarily* leads to the disappearance of interaction-based properties (Langton,89).
5. The Oxford Companion to Philosophy (1995) defines functionalism in the following terms, which have been generalized to account for the application of this philosophical position to phenomena other than the mental:

"The theory that the condition for being in a mental [or vital or material] state should be given by the functional role of the state, that is, in terms of its standard causal relationships, rather than by supposed intrinsic features of the state. The role is normally envisaged as being specified in terms of which states (typically) produce it and which other states and behavioural outputs will (typically) be produced by it when the state interacts with further mental [or vital or material] states .. and inputs."
6. Maturana and Varela (1980) reject the definition of autopoietic systems in conventional systems-theoretical (that is, input-output) terms maintaining that the correct characterization of the organism-environment relation is in terms of exo-systemic perturbations and endosystemic organizational homeostasis. However, their point is moot since irrespective of interpretation, such relations do in fact exist.
7. Phenomenology as understood in the context of the present discussion should not be confused with its technical use within philosophy as described in chapters 1 and 6; in the current context, phenomenology simply refers to the identification of a concept of emergence and its associated emergents (products), that is, a metaphysics and the phenomena which follow. More precisely, a phenomenology is defined by a *concept* of emergence and specification of *types* of emergent.
8. A *concrete* model is a model of a physical system.
9. In this context, a structural emergent is simply a stable configuration in space-time irrespective of whether this configuration is static or dynamic (periodic).
10. Contrary to the assertions of Maturana and Varela (1980), this holds for autopoietic as well as non-autopoietic systems since the former have organizational-homeostasis as their function. Hence, it is argued, functionality is essential to systemicity.