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THE DYNAMICAL BASIS OF EMERGENCE IN NATURAL HIERARCHIES

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Abstract

Since the origins of the notion of emergence in attempts to recover the content of vitalistic anti-reductionism without its questionable metaphysics, emergence has been treated in terms of logical properties. This approach was doomed to failure, because logical properties are either *sui generis* or they are constructions from other logical properties. If the former, they do not explain on their own and are inevitably somewhat arbitrary (the problem with the related concept of supervenience, Collier, 1988a), but if the latter, reducibility is assured because logical constructs are reducible, by definition, to their logical components. A satisfactory account of emergence must recognise that it is a dynamical, not a logical property of property of natural systems, and that its basis is dynamical rather than logical composition. Collier (1988a) introduced the concept of *cohesion* as the closure of the causal relations among the dynamical parts of a dynamical particular that determine its resistance to external and internal fluctuations that might disrupt its integrity.

Cohesion is an equivalence relation that partitions a set of dynamical particulars into unified and distinct entities, providing the identity conditions for such particulars. Cohesion blocks reduction of dynamical particulars, and is necessary for dynamical emergence. We will give reasons for thinking that cohesion might be sufficient for emergence as well.

Keywords: emergence, cohesion, hierarchy, dynamics, causation

Introduction

Many kinds of natural things are arranged in a hierarchy of existential dependence: chemical entities depend for their existence on their atomic components, biological things depend on their chemical and physical basis, psychological phenomena depend on biological processes, social occurrences depend on psychological events, and so on. Independent of questions of whether higher level disciplines are merely a special

version of lower level disciplines (i.e. psychology is a specialised branch of the physical sciences), and whether higher level theories can be reduced to lower level theories, there is the question of the ontological relations among objects, properties and processes at different levels (i.e., the number of particular things there are). Are higher level entities merely elaborations of the lower level processes that compose them (their *basis*), or do they introduce something new? Some approaches try to place emergence in novel laws (cf. Klee, 1984), but we believe that emergent entities are logically prior to their laws, and that there may be entities that are emergent without new fundamental laws. In order to explicate emergence, we focus on the individuation conditions for physical properties, objects and processes. Phenomena that are merely elaborations are identical to some conjunctive combination of lower level processes, and are thus *logical constructs* of those processes in the sense that their identity depends on no properties not present in their lower level components.¹ Such phenomena are epiphenomena. Genuinely new entities at higher levels, on the other hand, are emergent.

We argue for a causally based conception of emergence that can help us to understand the causal autonomy, holistic nature, novelty, irreducibility and unpredictability that characterise emergence. This conception assumes that higher levels

cannot differ if lower levels are the same, and supports the explanatory relevance of underlying processes to the emergent entities they compose (next two sections). The key to this conception is the characterisation of a property we call cohesion, which distinguishes emergent phenomena from epiphenomena. This concept is supplemented by recent work on the logic of identity and individuation, together with work on determinism and predictability. We will discuss the sense in which emergent phenomena are novel last.

Getting a hold on emergence

We can get a preliminary hold of the concept of emergence by looking at how it is used. Emergence plays two roles in modern science. On one hand, it has been invoked to mitigate the apparent reductionist consequences of materialism. On the other hand, it has been used to attribute a material basis to phenomena that have resisted reduction to fundamental physics. To satisfy these roles, we can call a property emergent whenever it has a physical basis, but it is not merely a logical consequence of that physical basis.

We reject complete autonomy and separate substances views of emergence because of the relevance of underlying causal processes to the explanation of emergent phenomena. This is particularly striking when emergent phenomena are disrupted by underlying processes, such as when a chemical substance such as a psychedelic or empathsogenic drug alters consciousness in a way previously attributed only to spiritual (supernatural) causes, but is also evident in the fortification illusions of migraine sufferers, stimulated memories during brain surgery, and the effects of brain ablations on perception and behaviour. These unusual effects often point to the physiological basis of normal mental functioning. Similar inferences can be made about the genetic and molecular basis of

¹Cariani (submitted) calls this emergence-through-recombination, which he contrasts with emergence-through-creation. We allow that emergence-through-recombination is weak emergence if the combination is produced by cohesion. Emmeche et al (1997) concentrate on levels of emergence. We are not convinced that there are distinct levels in all cases of emergence, given its basis in individual emergence, but our views would force agreement with Emmeche et al's view that there might "'local' existence of different ontologies". We also agree with the general thrust of their attempt to devitalise emergence through reference to nonlinear systems.

physiology from example of genetic damage or mutations. These impingements of lower level phenomena are limited if the mind and physiology are autonomously emergent (see Christensen et al, submitted) since normal physiology and normal mental activity involve complex phenomena that are not straightforward consequences of lower level phenomena because of the non-linearity of the systems.

The difficulties involved in conceiving causally independent domains in a common world, together with the evidence for physical determination of all but the most fundamental phenomena justify the *principle of supervenience* (Kim, 1978; Rosenberg, 1978; 1985): If all specific micro-physical facts are fixed, then all other facts are also fixed.² Boolean closure of B, will also share all the properties of P', the Boolean closure of P.

If emergence entails radical indeterminism, then Supervenience rules it out. Nagel, however, (1961, 377) pointed out that although emergence is sometimes associated with radical indeterminism and/or separate substances, this association is not essential. If there is a way to allow for novelty and irreducibility without assuming indeterminacy, emergence may be a useful concept in spite of supervenience of the physical.

All emergent phenomena (if any exist) have a physical basis. However properties might be directly emergent from other, higher level bases, so:

E: A property P is *emergent on* a basis family of properties B if and only if P is supervenient on

B, however P is not merely the effect of B.

E is intentionally vague in order not to exclude any of a wide range of intuitions. The notion of being *a mere effect of* will be clarified in what follows. With **E**, we can define emergent entities and laws: An entity (an object or a system) is emergent just in case it would not exist if it had no emergent properties. Emergent laws are laws involving emergent properties essentially. Something is hierarchically emergent if and only if its emergence implies the existence of a new level of existential dependence.

Strong emergence has an additional computational condition that covers all computational consequences of the basis, and not just its causal consequences:

SE: A property P is *strongly emergent on* a basis family of properties B if and only if P is supervenient on B, however P is not merely the effect of, nor is it deducible from the B.

Not being merely the effect of B might appear to be implied by non-deducibility, but it is not. There are phenomena that are merely the effect of the basis, but are not deducible from the basis.

Candidates for hierarchical emergence include physical, biological, mental and social phenomena. Some of these candidates are more typical than others. Perhaps the most typical are intentionality, biological functionality, and human community. Less typical candidates are molecules, thermodynamic phenomena (especially so-called dissipative structures), chaotic phenomena, self-organising systems, and auto-catalytic phenomena (in particular self-replication). Another, very recent, candidate for emergence is so-called emergent computation (Forrest, 1991; Langton, 1991). We will argue below that emergent computation simulates emergence, but is not really emergent (cf. Cariani, 1991). Candidate emergent phenomena can be contrasted with

² Kim (1978) relies on a general metaphysical position that the world is determined by its physical structure, whereas Kincaid (1987) suggests that supervenience is empirically based. We believe that the metaphysical and empirical reasons are each sufficient independently, but combined they are stronger than either alone. Each answers certain doubts otherwise left open by the other.

obvious epiphenomena. The apparent motion of the marquee lights of a theatre is a good example. Since emergence is a causal situation, and causation cannot be directly observed, not surprisingly, candidates for emergence are also candidate epiphenomena. The fundamental issue of emergence is to distinguish true emergence from epiphenomena.

Natural Hierarchies

A hierarchy is defined by an intransitive relation that implies some sort of inclusion. A natural system (unlike an artificial system) is an organised entity whose parts are causally inter-related in a regular way so that no parts are causally isolated by the causal laws governing the system; i.e., the system is causally individuated by internal causal relations that retain system integrity (its cohesion profile, see discussion below, as well as Collier and Hooker, 1998 and Christensen et al, in preparation) being stronger than its causal interactions with other elements, including fluctuations in its components.

If our conceptualisation of natural hierarchical systems is correct, then closure conditions should be helpful identifying natural hierarchies. For example, the biological hierarchy from the cellular metabolic system to ecosystems is defined by the component relation, which is scalar (cf. Salthe, 1985 re scalar and specification hierarchies). If we throw in genetic information, we find it is distributed throughout the ecosystem, and is not contained at any level of the hierarchy, since selection implies mutual information of the genes and environment, so the causal closure of genetic information includes environmental factors (Collier 1998a; in review; Brandon, 1990). We should have used the genetic replication and transcription system, which is a subsystem of the cellular metabolism. One of the greatest advantages of the cohesion account of emergence is that it

distinguishes between abstract systems and causally based systems, forcing identification of the appropriate level for system properties. In the above example, naive identification of properties tends to make genetic information in general a property at the organismic, cellular, or even some intracellular level, whereas causal closure requires that it is at the ecological level (at least). On reconsidering, we might decide that we are interested in genetic information in general, so we stay at the ecological level, or we might decide that we are really interested in a much more restricted genetic system involving replication and transcription. If the two levels are confused, as might happen if the causal closure requirements are ignored or suppressed, it might easily be falsely inferred that an explanation of gene replication and transcription was a full explanation of genetic information.

Examples of properties that we often take to unify natural hierarchies and place the levels in relation to each other are size, structural constitution, control, and function. Only the last three are candidate properties for natural systems; size is not itself a causal property. Control and function are questionable as well.³ It is important not to confuse hierarchies with different unifying properties. Many things, like genetic information, are ambiguous with respect to their hierarchy, and a single subsystem can be a member of more than one hierarchy (Collier, 1988b). Reducibility of elements in one hierarchy should not be confused with reducibility in general. For example, the flight function of a bird's wing is composed of lift and propulsion functions, but these are not located in separate structural components, as they are in contemporary aeroplanes. The (admittedly unlikely) possibility of reducing a bird's wing to its anatomical components does not directly

³But see Christensen, 1996 and Christensen et al, in preparation.

imply that flight is not emergent from the propulsion and lift functions.

For emergent levels, we can ask which properties, objects and processes are reducible and which are not. To decide these issues, we need a criterion of reducibility. There appear to be robust hierarchies whose higher levels are not merely effects; the higher levels are themselves causally efficacious. Donald Campbell (1974) suggested that higher level phenomena can exert what he termed *downward causation* on lower level phenomena. His idea is that the constraints created by higher level organisation make the lower level entities behave in ways that they would not otherwise. This is probably the most important type of interlevel interaction between causally robust levels.

Avoiding seduction by language

On logical empiricist accounts of science (the Received View, Suppes, 1976), reduction across levels, theory reduction, methodological unification, prediction and explanation are unified into a common logical framework, in which the relations are founded on deductive relations among empirical properties. This approach ran into insurmountable problems in identifying unequivocal empirical properties (Kuhn, 1971; Feyerabend, 1975; Suppes, 1976). To avoid these problems, we concentrate on the dynamical relations among entities at different levels, and set aside problems that arise from epistemological and linguistic limitations. This allows us to focus on our problem more directly, and to avoid red herrings such as using logical concepts like supervenience alone to resolve the problem (Collier, 1988a). Later in this section we will argue that it is a philosophical howler to try to use logical concepts alone to resolve a problem that is fundamentally about causal relations.

Nagel thought that emergence in hierarchical systems was a property of knowledge, predictability and deducibility.⁴ He held that if we have complete knowledge of some object O constituted of parts standing together in some complex relation R, except that we do not know R, and some property P of O cannot be predicted (deduced from knowledge), then P is emergent, and O is an emergent entity (Nagel, 1961, 367). Nagel cited Broad as supporting the unpredictability formulation of emergence (1961, 368), though our reading of Broad makes him out to be closer to Campbell. In any case, Nagel concluded that the doctrine of emergence is a doctrine about formal facts, and that emergence is relative to a theory.

Nagel observed that from the combined theories of hydrogen and oxygen alone we cannot deduce statements about water unless the term 'water' is appropriately included in the language of the combined theory. He assumed that to predict the properties of some entity is to deduce statements about it from previously accepted statements. That water is hydrogen oxide is not deducible from the theories of hydrogen and oxygen alone. Thus, Nagel allows that water could be emergent from hydrogen and oxygen. Anything with a synthetic composition is emergent in this way. If, however, we define water as hydrogen oxide, then the composition of water is not emergent; it is a defined term in the combined theories of hydrogen and oxygen. This justifies Nagel's claim that emergence is theory relative.

This theory relativity of emergence, though, is a property of language, not of

⁴Nagel (1961, pp. 375-376) observed that new properties can evolve from prior simpler properties. He called this *historical emergence*. The new properties arise from organic or functional organisation of the parts that limit their future development. This is just the formation of a new level exhibiting Campbell's downward causation. Thus we do not treat historical emergence separately.

objects. It is misleading to speak of the emergence of water when this follows merely from a particular way of using the word. It would be more correct to speak of the emergence of 'water', where this is understood as a property of the term within a certain language and theory. Water, if it is emergent, is emergent because of some facts about water, not about our theories of water. Perhaps, on Nagel's view, the correct theory would determine whether water was emergent, depending on the role of the term in the theory, but it is not clear that there need be any difference between two theories, one in which water is emergent in Nagel's sense, and the other in which it is not, that could be decided by empirical evidence. In any case, Nagel's account of emergence in hierarchies does not illuminate what it is about water, if anything, that makes it emergent. This is the howler that we alluded to at the beginning of this section.

Cohesion: the basis of dynamical identity

Perry (1970) pointed out that the relation between the parts of a thing which makes them parts of the same thing is not the identity relation (in itself a relatively trivial, albeit important, logical relation), but a relation he came to call the *unity relation*. For many things the unity relation is artificial, but spatio-temporal continuity is an important criterion for natural physical objects (Wiggins, 1967). This catches the intuition that the parts of natural objects move together through space. This coherency might be due to (1) chance, (2) correlated independent causes, or (3) causal interactions among the parts. Most of us would be prepared to dismiss presumed objects based on chance correlations as mistaken or illusory. The constellations are a good example. So are apparent images of rabbits in clouds. But the other two make genuine phenomena.

Some examples of objects whose unity comes from correlated independent causes are rainbows, the images in motion pictures and on computer screens, and a salvo of bullets or a shotgun blast. What characterises these phenomenal objects is their illusion of being unitary. They are really epiphenomena of underlying causes. Their higher level properties (such as size, orientation, duration, intensity, not to mention apparent causal interactions) are not their own, but are logical sums of the effects of their components. Another example is the possible epiphenomenal character of the mind. Epiphenomenalists hold that the mind is just systematically correlated with a large number of independent electro-chemical events. Epiphenomena are not merely coincidental, but they are not proper things, either. They are merely the effects of underlying or common causes. They get their coherence from the regularities of their underlying causes, but have no internal binding.

Examples of objects whose unity relation is causal interaction among its parts are rocks, animals, and swarms of bees. These objects are held together by causal interactions that constitute their organic unity. We call this their *cohesion*. Cohesion represents those factors that causally bind the components of something through space and time, so it acts coherently and resists internal and external fluctuations.⁵ The causal relations involved in

⁵Cohesion is a causal condition, and fits the analysis of causation in terms of transfer of information in (Collier, 1998b). On that analysis, transfer of information is the identity of a particular token of information across space and/or time. Cohesion is just that information that is required for the identity of the dynamical object or property of interest. For more detail on cohesion, see (Collier 1988a; Christensen et al in preparation; Collier and Hooker, submitted). Our cohesion may be similar to Humphreys (1997) *fusion operation* [.*]. It plays much the same role in our somewhat similar approaches. However we disagree that lower level properties disappear except in specifics, and we do not see how fusion could be other than

cohesion may be stronger or weaker; no object is indestructible. The existence of cohesion, however, is not a matter of degree. Cohesion creates a stability that an object would not have otherwise. It makes the object resistant to changes and fluctuations in its parts.

Cohesion cannot be observed directly; therefore it might be doubtful whether a given object is cohesive. Any direct cause can be imitated by epiphenomenal causes, so there are no strict observational criteria for direct cohesion. The existence of cohesion can be decided only by discovering the nature of the cause of the coherency of the object. *Prima facie*, cohesive things like rocks can be distinguished from non-cohesive things like motion picture images by empirical means. This can be done by testing their stability under various conditions, and coming up with a *cohesion profile* that averages the various possible cohesion disrupting influences weighted by their probabilities. A cohesive system has a cohesion profile such that it is more cohesive with itself than it is with any other system or subsystem, and it is stable against typical external or internal random perturbations. Cohesion is thus relative to the physical context of the system, but it is not a subjective matter. We will assume in what follows that this sort of testing for cohesion can be done (for more details, see Christensen et al, in preparation).

Just as objects are cohesive, some of their properties are cohesive as well. This must be so, because objects are individuated by their properties. A cohesive property is one that is largely insensitive to fluctuations, either external or internal.

The phenomenological thermodynamical properties are interesting cases of cohesive properties (Collier, 1988a). Although thermodynamics has been reduced to statistical mechanics, it is not true that

thermodynamical states are merely epiphenomena of the states of molecules. In the reduction, the thermodynamic states are averages of the effects of the molecules. It might seem that averages are paradigmatic epiphenomena, being nothing more than a mathematical construct. This is true in many cases, such as the average family, but it is not true for statistical mechanical properties that correspond to detectable thermodynamical properties. The difference is that the thermodynamic properties are themselves causally efficacious. The average family cannot get into a car. Pressure, however, can do work. The causal efficacy of thermodynamical properties depends on the existence of something that physically does the averaging, i.e. cohesion. The average is not merely a construct. It is a result of the spreading of the local effects of individual molecules through space and time by cohesion; of filtering the varied effects of molecular velocities. The pressure of a gas in a container depends on the cohesion of the container walls. If there is no cohesion, there is no pressure. The pressure inside an ideal gas is really a potential waiting to be actualised by some detector that can create the appropriate average.

Or consider a kite, flying in the wind. The lift of the kite is the net effect of the impulses of molecules hitting the kite on its two sides, averaged by the cohesive forces that hold the kite together. It is the averaging process, physically embodied in the interaction of the cohesive kite and the individual molecules that produces the lift, which can be felt as tension on the kite line. The specific motions of the individual molecules are not relevant to the net effect of lift, only their average is. The kite is insensitive to the individual molecular motions, due to its cohesion.

The general insensitivity of the identity of cohesive things to fluctuations in microstates makes reduction inappropriate. Any reduction to microcomponents would have to include much information that is irrelevant to the

causal, as suggested by Hunphreys.

identity of the reduced object and its macroscopic properties. In the example of pressure above, the averaging eliminates much of the information required to define the microstate, effectively dissipating that information. If we allow that the properties that individuate something constitute its identity, and assume that reduction must establish an identity between two differently described phenomena, then reduction of cohesive things to their components is impossible, because this sort of microreduction will inevitably bring in factors that are irrelevant to the identity of the thing supposedly reduced.

It might appear that the problem of irrelevant factors can be avoided by reducing the higher level object to some part of its basis. The problem with this approach is that the relevant part cannot be defined solely with the resources of the lower level. Going back to the lift of the kite, we might think that we can define the lift as some average effect of the impulses of individual air molecules. Surely this average exists. It is important, however, to distinguish between the mathematical object which is the average net impulse of the molecules in the region occupied by the kite and the physical property which numerically equal to this value. The former is a mathematical consequence of the dynamics of the air molecules, but the latter exists only because of the additional cohesion of the kite, which cannot be localised at the microscopic level. The proposed reduction either makes the lift an abstract object (a category error), or else it identifies the lift with an equivalent property that is already at the higher level, requiring the cohesion of the kite for its existence. Cohesive objects have properties that are not merely effects of the properties of their components (though they are that too). They differ from epiphenomenal objects in that, far from being merely effects, they can act as causes as well, independently of the particular contingencies of their composite parts. (We ignore here complications arising from the causal powers of

the perceptual attributes of epiphenomenal objects.) These causal powers create new possibilities (section 7 below). The spatiotemporal binding involved in cohesion distributes the action of cohesive properties. The whole mass of a cohesive object is focussed on its point of collision with another object. The mass of the object acts as a whole, not as a collection of parts.

Another way to look at the contrast between reducible and nonreducible properties is to consider the differences between linear and nonlinear systems. In a linear system, superimposing trajectories upon other trajectories via linear transformations produces a possible trajectory. The situation is analogous to the superimposition of one epiphenomenon on another. They can be superimposed freely without any interference or interaction. The net effect is a simple sum of the component causes. Another analogy between epiphenomena and linear systems is that linear systems can be analysed as a set of additive parts, or vectors. Each of these parts can be treated independently, without affecting the other parts, or being affected by them. Epiphenomena can be treated as parts in a similar manner. We are all familiar with parts of rainbows, and parts of a movie or computer image. They can retain their form, despite arbitrary segmentation. Nonlinear dynamical systems do not permit superposition by linear transformations. Nor, typically, do cohesive objects. They usually interfere very strongly; consider trying to overlap two rocks! Likewise, in many cases lopping off a part of a cohesive object alters both the part and the rest of the object far beyond the segmentation. Given these correspondences, it seems plausible that cohesive things are nonlinear, and vice versa. The only possible exceptions are systems in which the non-linearities are entirely localised both spatially and temporally, and systems in which cohesion is a linear sum of local effects. We do not know of any real counterexamples

of either sort, though purely ionic salt crystals come close.

Nonlinear systems, by definition, are not fully decomposable. The analogy to cohesive systems is more than superficial. Nonlinear systems involve relations among their parts that cannot be localised. Computing a change in a variable requires information about other variables. If our nonlinear description of the system is an accurate account of its inherent dynamics, this will be true for the system itself. This implies an internal causal structure for the system. If this internal structure is non-local, then the system will be cohesive. Whether or not there are purely local nonlinear systems, we can say that non-local nonlinear systems are cohesive. Certain archetypical nonlinear systems, like implementations of feedback loops, are obviously cohesive. Linear systems are reducible, but non-local nonlinear systems are not. If there are linear cohesive systems, then they would be reducible, and they could not be emergent. A possible example is a system of rigid, elastically colliding spheres. Although some systems, such as billiard balls, might approach this ideal, complete rigidity and elasticity are not found in nature. We must be careful not to confuse the idealisations we use to make nature more tractable with the properties of nature itself. When this is taken into consideration, the evidence for linearity even in simple realistic physical systems is quite weak.⁶

⁶It would be nice to be able to show that cohesion necessarily involves spatiotemporal non-linearity, but we do not currently know how. The analysis of non-local nonlinear systems, will require the presupposing higher level properties. A good example of this is Chandreshankar's treatment of convection in Bénard cells, in which the equations of motion are constrained by conditions required by the known behaviour of convection cells, rather than being derived solely from the motions of particles or the local motion of a continuous fluid (see Collier et al, in review).

The irreducibility of cohesive properties has implications for biology and psychology. Biological organisms are cohesive because of structural and functional connections among their parts that make them immune to the continuing flux in their composition and even their form. They do this not with strong bonds, like rocks, but through relatively subtle interactions with their environments and with themselves (Christensen et al, in preparation). Many of their properties are cohesive, and hence emergent, but others are not cohesive. To tell whether a given property is emergent or epiphenomenal it is necessary to determine its causal basis. For example, the "broken wing" behaviour of some birds in the presence of predators might seem to be a coherent ruse to protect offspring. Closer analysis reveals that it is an instinctive response to certain stimuli. The "protection" property is an epiphenomenon of these underlying causes. Further evolutionary analysis might locate cohesion for the protection function in the cohesive effects of selective forces on the bird's ancestors. If so, the protective function might be promoted to a true emergent property. Note, though, that reference to selection requires inclusion of ecological and population properties to achieve causal closure. To the extent that the broken wing behaviour is cohesive, it is not a property of the individual bird alone. In any case, we cannot simply assume that a behaviour with a coherent effect is emergent. In particular, many higher psychological properties of humans such as belief, intention, and even personal identity should be suspected as epiphenomena until the basis of their cohesion is discovered. Introspection alone cannot be expected to provide any decisive evidence for unity. One of the most useful properties of cohesion is its requirement of closure, making it more difficult to confuse the proper level of a thing, or to ignore significant factors of its dynamical unity.

Despite the irreducibility of cohesive things, the states of their components are explanatorily relevant to their behaviour.

Although a strict microreduction of thermodynamical properties to the mechanical properties of atoms and molecules is impossible, it is possible to do what has been called a *macroreduction* of thermodynamic properties to properties that are described in the language of the mechanical properties of atoms and molecules. Then it can be seen how the states of atoms and molecules are explanatorily relevant to cohesive macroscopic properties (Collier 1988a).

Unpredictability

So far we have established that cohesion can account for and explain irreducibility, individuality, downward causation and holism, and the explanatory relevance of lower level phenomena, but we have not yet addressed unpredictability or novelty. If unpredictability can be established, novelty would follow. We will argue that unpredictability is less relevant to emergence than it might seem: emergent entities may or not exhibit unpredictable behaviour, dependant on the kind of property examined and their location in their state space. First, however, we will explore the intuitive tendencies to ground emergence in unpredictability.

Broad believed that unpredictability was essential for emergence; indeed he defined emergence in terms of the non-deducibility of characteristic properties of compound entities (Broad, 1925, 61). His reasons for this rest on the basis that, although general laws may be constructed to deduce the behaviour of dynamical transactions, we have no right to assume that the same holds for more complicated transactions such as chemical reactions. For example, Broad (1925, 66ff) thought that the laws governing silver chloride are, so far as we know, unique and ultimate, even though the properties of silver-chloride are completely determined by silver and chlorine.

We feel this approach errs because determination of chemical properties is contingent on the general level of specialised knowledge in the fields of chemistry, physics and related disciplines. This suffers from the same problems as Nagel's account in not getting at the basis of emergence, but also in being dependent, not on language, but on knowledge. As this knowledge increases more can be deduced about the properties of unobserved or theoretical compounds. This now occurs with industrial regularity in chemistry. Moreover, new compounds are created specifically for desired, predicted characteristics.

It is well known that local nonlinear systems can exhibit apparently unpredictable behaviour of local variables. This behaviour is called *deterministic chaos*, since existence and uniqueness of a trajectory can be shown, but, within the overall constraints on the system, arbitrarily small errors in measurement or control can cause arbitrarily large deviations at later times. Errors in real measurement of initial conditions are amplified such that the prediction of future state is wildly in error and as such is no prediction at all. However, given their initial conditions, any point on their trajectory *can*, at least in principle, be calculated to an arbitrarily high accuracy. Specifically, for any point in the trajectory at time t_1 and any j , that point can be calculated to within radius $\epsilon_{1,j}$ if the initial conditions are localised within $\epsilon_{0,j}$. These systems are not a priori unpredictable.

An instrumentalist approach may be to draw a line at the limit of accurate measurement of properties and declare all systems below that line as unpredictable and hence emergent. This, however, is prone to the continual retreat of the line as the scientific epistemic pool increases and techniques improve and to suffering, as Broad did, progressive reclassification of emergent entities.

Predictability appears to be an epistemological issue but this is so. In nonlinear chaotic systems individual points on a trajectory can be calculated to arbitrary accuracy, the whole trajectory cannot. The prediction of the later evolution of the whole system is impossible (Ford, 1983). True unpredictability arises when we move up a level, and consider the behaviour of whole trajectories. If there are multiple attractors, it is impossible to predict which attractor the system is in. Consequently, single level (non-cohesive) systems, though they may have unpredictable properties, are never emergent, since the novelty is produced discontinuously, and there is no distinction between mere change and emergence. The parsimonious hypothesis is that there is change, but not emergence.

There are deterministic nonlinear systems with multiple attractors, for which the attractor the system is in is unpredictable if the system passes through chaotic regions in its phase space, assuming the system isn't in a permanent transient state. It is predictable that one or another trajectory matches the system (except for a set of initial conditions with measure 0), but no process we can carry out can determine which one it will be, except waiting to see. Again, the attractors are non-local objects, since they depend on properties of whole trajectories. Consequently, they can be manifested only in the presence of cohesion. The higher level behaviour of such systems (which attractor captures the system), can therefore be both irreducible and unpredictable. The important point here is that attractors are only epiphenomenal unless they have some causal powers themselves, dependent on cohesion. The most interesting cases from the perspective of emergence are ones in which the cohesion arises within the system itself, as it does in convection cells.

A champion of the unpredictability criterion for emergence might argue that unpredictable capture produces the only

genuine emergent phenomena. Against this, we would argue that deterministically chaotic nonlinear systems often have regions in their phase space that are quite orderly and predictable, and that the difference between these regions and others depends on accidental initial and boundary conditions. A single system can pass in and out of orderly and chaotic regions, in orderly regions subject to predictable capture, and in chaotic regions capable of unpredictable capture. Such accidental differences between predictable and unpredictable capture cannot distinguish between emergent and non-emergent systems. Otherwise the same physical properties could be emergent or non-emergent, depending only on histories. On the other hand, cohesion is central to the dynamical explanation of attractor capture in both cases. For this reason, we prefer to reject the unpredictability criterion, and allow both strong and weak emergence.

Novelty

The novelty of emergent phenomena lies in the acquisition of new capabilities. For strong emergence, novelty is equivalent to unpredictability, but we need a different account of novelty if weak emergence is to be novel. Again, we go back to the distinction between epiphenomena and emergent phenomena. Epiphenomena depend for their apparent causal powers on the lowest cohesive levels, and all capabilities are inherent in those levels. The illusory motion of dots on a computer screen is a capacity of the underlying program and hardware, as is the capacity for any apparent interaction of those dots. Figures that can be formed from those dots, and all *their* possible epiphenomenal interactions are also present in the capabilities of the underlying program. When cohesion arises at higher levels, however, the potential is created for the formation of new cohesive structures or

properties formed through causal interactions amongst the old ones. Emergent phenomena are novel because they create new capabilities. It is as if the formation of figures alters the original computer program to give it new capabilities that it would not have if the figures had not formed (there is no obvious reason this would not be possible). Note that the formation (or pre-existence) of cohesion underlies the unpredictability found in strong emergence, so the conditions for novelty in both strong and weak emergence are based fundamentally in cohesion.

A reductionist might argue that cohesion itself does not create new capabilities; what really happens is that cohesion limits the way the system can behave (this is reminiscent of Campbell's downward causation). Consequently, weak emergence would not involve novelty. We have argued that cohesion makes reducibility at best irrelevant to identity, since the details of lower level activity are not important to what is going on at the level in question. Cohesion tends to screen higher levels off from the effects of distant levels through its stabilising influence. Furthermore, we find it more natural to speak of the acquisition of new capabilities through the formation of cohesive structures than to speak, as the reductionist must, only of new capabilities limiting the possible behaviour of the system. This is particularly apparent in learning, in which new connections formed allow us to do new things that we could not do before. The reductionist is bound to say that learning restricts our capabilities by ruling out possibilities that we had before. We find this completely counterintuitive. All cohesion is both limiting and enabling. One or another may dominate, but at least there is always something new.

It has been previously noted that in more strongly emergent systems, the lower level relations can vary more widely and complexly (Collier and Hooker 1998, Christensen et al 1998). Such systems may

have many possible states through which they move, interacting with their environment, without losing their identity or autonomy. Stronger cohesive systems are less adaptive and usually exhibit less original properties. Novelty arises in weakly cohesive systems as a result of the adoption of new possible states in response to external feedback. If its environment remained static, we possibly would not witness novelty in a particular cohesive system. This, however, is rarely the case.

Conclusion

The basis of emergence is cohesion. Cohesion distinguishes epiphenomenal objects and properties among those that are candidates for emergence, and allows us to classify questionable cases appropriately. Cohesion makes microreduction impossible: If the individuating properties of a thing are cohesive, then it is not identical to some additive construction out of its components, since any such construction will have properties that are irrelevant to the identity of the thing. Independently of whether reduction of cohesive things is possible, they will have novel capacities that are not found in their components. Cohesion satisfies all the requirements for an account of emergence, except unpredictability, and it is the basis of at least one species of emergence. Strong emergence is the more intriguing, but even weak emergence has interesting consequences for a number of current issues on the borderline between science and philosophy. Strong emergence requires cohesion, and unpredictability can be historically accidental for a given property, so cohesion is again of focal interest. Nonetheless, it is closer to classical characterisations of emergence. Against this is the possibility of the difference between this sort of emergence and weak emergence depending on circumstances that are historically accidental for the emergent

properties. Restricting emergence to these cases allows the same property to be emergent or not, depending on how it originated. The simpler cohesion criterion does not have this problem, but still allows a plausible account of novelty. When cohesion is generated within the system itself in strongly emergent systems we get the closest to the idea of a system which unpredictably produces new capabilities for itself. Perhaps this is the only true emergence, since it is impossible to explain away reductively. We propose, however, that once one form of emergence is admitted, that there are there is little reason not to admit weaker forms as well, given the common focus on cohesion.

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