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REENTRANT EMERGENCE

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Introduction

Despite its long history, there is no agreed-upon conception of emergence. One might claim that a common idea of emergence seems to be that something termed a "system" gives rise to, or possesses, characteristics termed "properties," which latter are absent or unmanifested in whatever individual components the system consists and are thus "emergent" from the system itself. However, types of systems discussed run a gamut from purely mental entities (e.g., O'Connor and Jacobs 2003) to simple tools (e.g., Maturana and Varela 1980). "Properties" is similarly unconstrained (e.g., properties as content: Weiskopf 2008, p. 360; Terhune 2008, p. 2; and properties as characteristics: Japaridze 2006; Johnson-Laird 2006, p. 125). The so-called (e.g., Fodor 1975) special sciences, such as biology, psychology, sociology, and even chemistry (e.g., Luisi 2002) have all claimed some properties as emergent. However, the enormous literature dealing with various types of systems characterized as emergent can be divided, roughly speaking, into two classes of descriptions of emergence. One might be termed "structural" and the other "functional." The first characterizes emergent systems in terms of their components and their interrelationships (e.g., Earley 2003), while the second characterizes them in terms of their effects on other systems or elements (e.g., Ryan 2007, Wong 2006). There is generally no mention of possible internal structures of the system in the latter, and if there is, it is in vague and/or abstract terms, while the former emphasizes internal structures over clear characterizations of the effects of emergence. Thus, a conception of emergence like Kim's (e.g., Kim 1999) is functional, while explicit descriptions of small-world networks, chaotic systems, or other types of complex internal organizations in mathematics, physics, and computer science (e.g., Atay and Jost 2004; also, see the Appendix) are structural. The structural-functional distinction will play a part in the analysis of emergence later in this paper.

Kim has devoted considerable effort to explicating and deflating the concept of emergence (e.g., Kim, 1999; Kim, 2006). He presents a thoroughgoing materialist argument for emergent properties as, effectively, complexes of simpler properties awaiting analysis. Kim argues that if there are emergent properties, they are causally ineffective (i.e., epiphenomenal). Are there truly emergent *physical* properties that arise solely from physical interactions? If we cannot answer this question explicitly, then it seems that the problem of emergence devolves to that of finding ways to bridge the well-known "explanatory gap" (e.g., Levine 1983). The last holdout of a causally effective emergent system or property would seem to be "mind" or "consciousness," if we follow Kim. Since there is currently no theory showing how either of those might be reducible to neural activity, one can still assert, at least, that they "emerge" (or, similarly, "supervene"; see, e.g., Kim 2006, p. 550) from that activity.

Thus, while Kim and others have provided abstract analyses of emergence (e.g., Delehanty 2005, Elder-Vass 2005, Gillett 2002, Humphreys 1997, Kim 1999, Kim 2006, Welshon 2002, Wong, 2006) that attempt to deny or weaken purely physical emergence, that denial is based on general functional properties. That is, when a system manifests emergence, its emergent properties have certain functional characteristics: they are (a) in some sense unpredictable[1] from those of the lower-level entities underlying them (e.g., Kim 1999, pp. 8–10), and/or (b) they possess "new causal powers" (Kim 1999, p. 5) that are not possessed by those lower-level entities. Given that characterization, his conclusions seem correct. If we want emergent properties per se to be causal, we must be unsatisfied: either they collapse to their original causes, or we can only characterize them as mental properties. If we are physicalists, those latter must also collapse, and the same holds for their unpredictability. If we are not physicalists we must, according to this argument, embrace epiphenomenalism. As Kim has pointed out, beyond objections amounting to the claim that the calculations would be immensely complex, no properties have been characterized that are clearly nonexistent on a "micro" level and/or which "use up," as, e.g., Humphreys (1997, p. 10) wishes to claim, the causal powers of the properties giving rise to the emergent properties. That leaves epiphenomenal properties, and if mental properties are the only subset of those latter taken seriously, the term "emergence" then becomes merely a shorthand reference to the explanatory gap.

Kim's analysis (e.g., Kim 2006, p. 558) is correct in (a) regarding emergence as fundamentally a causal phenomenon, but incorrect in (b) claiming that a system comprised of components with distinguishable causal effects will ultimately be describable ("causally reducible" [CR]) to the causal properties of those components. That is, we can say:

> (i) if emergent properties are properties of complexes, i.e., not of causally singular (CS) entities, then those emergent properties are CR to the properties of the complex's elements, which is equivalent to:
> (ii) if emergent properties are not CR to the properties of the complex's elements, then those (former) properties are not properties of complexes; rather, they are properties of CS entities: they are "causally opaque."

From the above, it follows that systems with the property of "causal opacity," i.e., which *present* themselves as unanalyzable into components (where a "component" is an entity distinguishable within a system), are *effectively* single elements. The key terms here are "present" and "effectively." Nonreducible, "emergent" properties are consequences of *epistemologically* CS elements. Such elements are not, so long as they are understood to be unanalyzable, causally reducible. If they were understood to be analyzable, then their properties would be reducible, given Kim's arguments, to the causal properties of the elements making up the system. Reducibility, and emergence, are in this conception epistemic.

Systems, understood as single entities, will have causal properties that cannot—*while the systems are thus understood*—be reduced to those of their components. To find and describe systems that are *effectively* singular is to show how and under what circumstances other systems interact with them as singular entities. This is the equivalent of providing a functional characterization of how, *relative to those interactions*, the former systems' properties are "emergent." Thus, "causally singular" cannot be taken as an ontological property; it is characteristic of only certain classes of physical interactions, and is in that sense an epistemological property. In other words, if our only known interactions with a system inform us that this system is a singular entity, then that system is effectively CS, and our theories, based only on such observations, must assume that. Thus, emergent systems can be termed "causally opaque" in the above sense.

Once one is able to observe that a system is comprised of multiple components, then and only then can one decide that it is causally reducible. It will be shown below that there are systems that behave in some circumstances as CS systems, and in other circumstances as systems of elements; that is, "holistic," so to speak, under some classes of interactions, multiple under others. Kim's position seems to assume that the reducibility of any physical system is ultimately knowable; it will be argued that it is not decidable, in general, that this is the case. If that argument is true, then epistemological emergence is a viable position and ontological emergence is not.

This conception is in some sense similar to Humphreys's and many others' proposals. "Basic" properties (those of the system's components) may be characterized as "hidden," and only systemic properties manifest themselves. However, without a clear physical mechanism by which basic properties may disappear, such explanations are unsatisfying (e.g., see Wong 2006). While we might agree with Elder-Vass (2005, pp. 321–323) and his division of reducibility to "explanatory," types, e.g.,

> it should be clear that this argument in no way denies that we may be able to explain the relationship between higher and lower levels. It is not the attempt to explain higher-level properties that is reductionism's fault; it is the belief that explanation entails elimination (p. 322)

and "eliminative" types, e.g.,

> eliminative reductionism argues, in effect, that certain higher-level properties and events can be fully explained by properties at the lower level. This, in turn, when combined with the dictum that to be real is to be causally effective, can be taken to imply that the higher-level properties and entities, having no causal impact other than that of their parts, have no real existence, at least as entities in their own right, (p. 322)

Elder-Vass does not provide clear, specific mechanisms for achieving emergence. In order to accomplish that, concepts derived from properties of complex physical systems must be employed.

Emergent Systems and Relaxation Time

A physical system can be characterized as a set of physical entities which are mutually interacting, such that any entity in that system will ultimately, even if indirectly (i.e., with another element of the system as intermediary), interact with any other entity. How then are boundaries established between systems? Boundaries can be described on the basis of their dynamical interactions. The concept of relaxation time (RT) is an important one in understanding the idea of system boundaries, and of reentrant emergence. In the physics of strings, the relaxation time is the length of time in which the vibration of a string decays to a point where its effect on other strings or on the medium in which it vibrates is considered insignificant, a context-dependent but meaningful and measurable interval (see, e.g., Vilela et al. 1997, p. 2). This concept can be generalized to any system whose influence on other systems decays with time. The relaxation time, then, is the interval during which one system's interaction with others is significant, as far as those other systems are concerned, and after which it is not. It is also possible to generalize this concept beyond physical systems, but that is beyond the scope of this paper (see also Atkins 1991, pp. 307–309, for a general discussion; and see, e.g., Cerf 2006, Genet and Delord 2002, Wetmore et al. 2007 for applications in biological systems, and Murray 1989, pp. 190–193, for a more mathematical analysis). Relaxation times can establish system boundaries, and two sets of entities are members of two different systems if the RTs of the interactions between the sets are significantly different than the RTs of the interactions within the sets, where "significantly" is, as above, arbitrary and context dependent, but functional. The entities interacting within a system are its "components."

(A) *A "reentrant emergent" (RE) system is characterized, in general, by faster internal relaxation times than those of another system interacting with that RE system*. More precisely, if we take the example of two systems which are interacting, O (observing system) and S (system being observed), we can discriminate two classes of interactions: the interactions within each system (WO and WS), and the interactions (I) between O and S. In order for S to be RE relative to O, the relaxation time of any I must be longer than the totality of those of WS.

(B) The components of an RE system are *mutually interacting* in the sense that every component will interact with every other component in the system, although that interaction may be indirect, i.e., through an intervening component within that system. In addition, intrasystemic interactions (WS) are reentrant processes, in that the interactions of one component with others necessarily involves an interaction back to the original component, analogously to the process of inductive recursion in logic or mathematics employed, e.g., in the generation of the integers (e.g., Kleene 1959, but for complications and implications of "recursion," see Vitale 1989).

(C) In addition, the components of an RE system complete their mutual interactions (WS) *before the RT of its interactions (I) with an external system*. That is, the internal RTs of the RE system are sufficiently rapid relative to that of its interactions with an external system that they are complete before any single external interaction is complete. The concept of RT, then, is central to this conception of emergence.

Given A, B, and C, the RE system is unified in the sense that every interaction between its elements depends on all intrasystemic interactions within that overlapping set of RTs: no such interaction can be described in isolation if the "grainyness" of an O's temporal resolution of S is longer than the RT of S. That unification results in interactions that cannot be ascribed to the causal properties of any single component of the RE system S, since it has interacted with the other components in that system before any single interaction with an external system is complete. Since the causal properties of its individual components cannot be distinguished in these circumstances, the RE system *is effectively a singular element*, and its properties are thus emergent, *relative to O*.

There are many examples of such systems, and history shows that until such systems are "broken down," they are treated (and usually conceived of) as singular elements. While we can write mathematical descriptions of some of these systems in terms of their components after discovering those components, the fact that these systems are recursive implies that in some contexts an RE system is not even theoretically causally reducible, even though post hoc (if it has been "teased apart") it is "describably" reducible. In general, until an RE system can be broken down into its components through interactions that violate A and/or

B, none of those components can be interacted with as individuals; their individual causal properties are indistinguishable from those of the other components of the system: they are "hidden" as individual causal elements.

A Verbal Description

Suppose that we have two physical entities interacting with each other, with appropriate relaxation and delay times. That is, suppose that an entity A is caused to generate and to propagate a disturbance (IA) to entity B, which is thus caused to generate and propagate its own disturbance (IB) back to A. In all cases, IA will have a finite effective duration (the relaxation time of A), and in addition take some time to reach B, and to interact with B. Of course, IA cannot normally directly interact with IB, except by interacting with B, as B generates IB. These durations are absolute requirements, insofar as we know, for all physical systems (with the possible exceptions of the propagation time in entangled states, and the time such a state takes to decohere). Any analysis of physical interactions must take these delays and interaction parameters into account.

Case 1: (a) IA reaches B (IA/B) and causes IB; and then
(b) IB reaches A (IB/A) *after* IA has ended, i.e., after the relaxation time of A.

Because IB arrives after A's relaxation time, IB cannot influence the generation of IA by A, since it does not interact with A during the latter's generation of IA. There is no RE state produced.

Case 2: (a) IA reaches B and causes IB; and
(b) IB reaches A *before* IA has ended, i.e., before the relaxation time of A is over.

Thus, this is a case where the RTs overlap. In this case, IB influences the generation of IA by A: IB/A → IA/B.

We now can produce the RE state. The resulting possibilities split again:

(I): IB on A will cause IA to impact B *after* the relaxation time of B, i.e., after IB. Case I leads to a situation with two distinct entities, A and B.
(II): IB on A will cause IA to impact B *within* the relaxation time of B, i.e., during IB: in this latter case:
IB/A → IA/B, and
IA/B → IB/A; an RE state has been produced.

In this situation, there are recursive interactions between A and B, and A and B, as they interact, are dependent, i.e., their interaction cannot be described with independent variables. This is the state termed the reentrant emergent (RE) state. One might also term the RE state a *resonant* interaction between A and B, resulting in a singular element insofar as this class of interactions is concerned.

Now introduce a third element (O) interacting with the system AB. To simplify, assume that O only interacts directly with A in AB, and not (directly) with B. Then we can say that O causes the propagation of a disturbance IO to A (IO/A) while A is interacting with B (IA/B).

If AB is not in an RE state, the only interesting interaction with O would be if O interacted with A such that this pair produced an RE state (AO); but this merely repeats the analysis above. If AB is in an RE state, then, an interaction with O can either be one that results in an RE state with A or not.

(1) If the interaction IO/A does *not* result in an RE state with A, then an observer or external system is interacting with another system that is in an RE state.
(2) If the interaction IO/A *does* result in an RE state with A, then we have the not uncommon situation in which some system incorporates another component into itself: O is now part of the RE system AB (resulting in, say, the system D, consisting of ABO, where D is in an RE state).

What does this imply in terms of causal opacity? In situation (1) here, O cannot "see" A separately from B, because IA/O *includes* IB/A, as we have seen in Case 2, b, II above. The interaction of O with A in AB is not similar (necessarily) to the interaction of O with A either in isolation, or when AB is not an RE system. How, then, does O "know" that there *is* a component A in AB? If this is the only type of interaction O has with AB, then O cannot, in effect, interact with A while A is in AB; its interactions with A are unavoidably contaminated, so to speak, by B's interactions with A. Thus, relative to these interactions with O, AB is a singular, emergent entity (see Figure 1).

There are, of course, scenarios in which this is more complex and less clear-cut: e.g., a situation in which the interactions with AB do not commute, that is, when the interaction of O with the RE entity AB (IO/A) does not have the same results as the interaction of O with the RE entity BA (IO/B). When we observe this, we say that the entity we are observing is nonuniform or asymmetrical. In some of those cases we are then led by theory to look for components, and in some, e.g., magnetic fields or spin states (which have poles or an "up" and a "down") we are not. In addition, the RE state is neither particularly stable nor universal, and gradations of asymmetry and of interaction parameters imply that in some systems an A is "barely" hidden, and in some it is completely hidden relative to some particular classes of interactions. That is, the above discussion has neglected the nature of the disturbance, e.g., IO, implicitly assuming, for the sake of simplicity, that IO would not influence either IA or IB. However, this is not always true, and if IO causes either IA or IB to alter to the extent that the AB RE state changes to a non-RE state, then if O is interacting with A, A will no longer be "hidden," since its interactions with O take place without the recursive influence of B. This is, in fact, the primary methodology by which systems observed and/or theorized to be "simples" are discovered to be in fact complexes. The history of science, as shall be seen, is full of such instances.

The entities in the RE state have been characterized as "effectively a single entity." How is this realized in some actual physical systems? An example of a class of entities arising from RE dynamics is covalent mol-

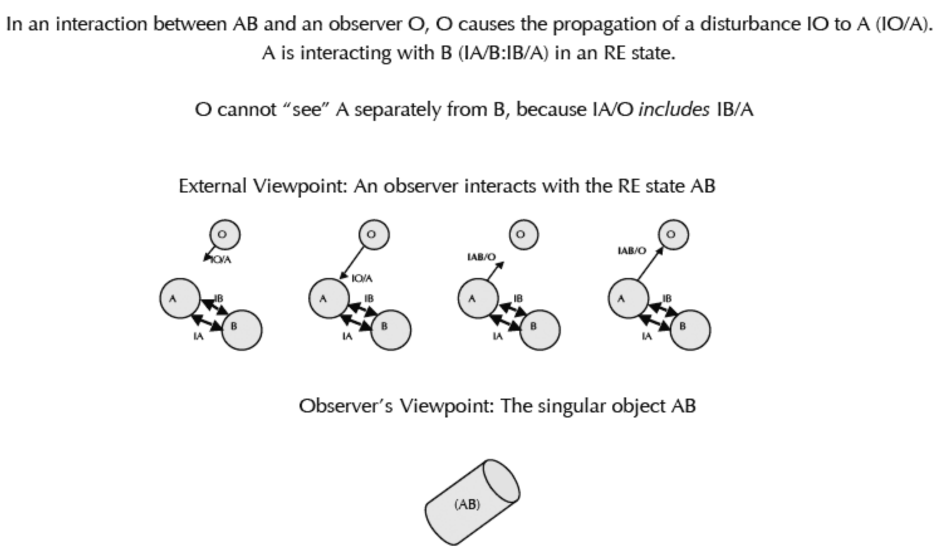

Figure 1. Examples.

ecules. While particles interact with each other within certain parameters and covalent bonds unite those particles into units with particular "strengths," those units are entities that require some threshold of energetic disturbance to disrupt. But just as there is no such entity as a "covalent bond" in a physically basic sense, there are also no molecules that are, in all interactions, singular entities. Yet so far as normal molecular disturbances and interactions go, molecules behave as singular entities when their components' interactions with other entities occur as described above (i.e., as RE states). Let us take a specific example: the water molecule. Oxygen (O) is a very reactive element, and two oxygen atoms will join very strongly together with what is called a double "covalent" bond consisting of two pairs of shared electrons. When mixed under appropriate circumstances with hydrogen, which is also extremely reactive as an element (H) and is thus nearly always in the form of a molecule consisting of two hydrogen atoms, oxygen and hydrogen combine exothermically to form water (H_2O), a system joined by covalent bonds into an RE state. In this system, a disturbance to one atom will result in very rapid propagation of that disturbance to the other two in the molecule, and the molecule will react to that disturbance as a single entity, because momentum is transferred between the components, very quickly, through electrical fields from their shared electrons and from the charge on their nuclei. When two water molecules interact under normal circumstances, their interaction is described, in part, in terms of mass, angular momentum, dipole moment, and vibrational frequencies, among other factors.

The angular momentum of H_2O, then, due to its being in an RE state, is an emergent property. Suppose that the system was *not* in an RE state relative to some particular exchange of momentum, in which it interacted with an entity much faster than the internal interactions resulting in the RE state. Then, when, say, the O atom in H_2O was impacted by an entity C, a transfer of momentum would occur between the impacting entity and O, *before* O interacted with the two H atoms (or, alternatively, before *their* resulting disturbances returned to the O atom [see above]). In that case, the H_2O molecule per se would have no angular momentum relative to C, because C would only be affected by the momentum of the O atom. *After* that interaction, because the O and H atoms have been interacting, albeit relatively slowly, the molecule would most likely spin around, with some angular momentum. But as far as C was concerned in that interaction, the H_2O molecule consisted of one component: O, although C's interaction with that component, because O is in a system with two Hs, cannot be quite the same as if the O were isolated (e.g., it has a charge in the H_2O system). The angular momentum of the molecule is an emergent property of the molecule as a whole, so long as it interacts within appropriate parameters. This is a good example of the difference between RE and non-RE interactions. The interaction with the O, within RE parameters, must involve the total mass of the H_2O system, the angular momentum of the Hs, etc. If the interaction is outside those parameters, an interacting entity effectively encounters only an O atom, albeit one somewhat different than an isolated O atom.

Given the above analysis, interactions with H_2O cannot result in knowledge of its triple composition unless an inquiry can be conducted outside of its RE parameters. Strong and/or relatively fast disturbances would accomplish this, and those kinds of disturbances, e.g., its electrolysis, or its formation when O and H are burned together, are in fact what led to the discovery that water is H_2O. Other properties of water, e.g., that it expands as it freezes, are also dependent on the H_2O molecules' shape and large dipole moment, as is well-known. In order to manifest this latter property, H_2O must be interacted by other H_2O molecules as unitary systems, and so this is an emergent property as well. Indeed, this property may also satisfy Kim's criterion of "surprising," or so we are informed by the popular press. This criterion ("surprising"), then, is *derivative* from the above structural analysis. Does this derivability mean that therefore ice's expansion cannot be emergent? But if the above arguments hold, one could *not* derive this type of property prior to knowing water's composition, and that necessitates investigating it outside of the RE parameters. That is, ice's expansion is always emergent, but before that latter investigation, it was not, in Elder-Vass's terms, explanatorily reducible, since one could explain the circumstances but not the causes of its expansion. Afterwards it *is* explanatorily reducible. One might in addition ask whether ice's expansion is also eliminatively reducible. Given this analysis of emergence, that phrase must be refined. If "reducible" in the phrase "eliminatively reducible" means that one can explain ice's expansion in terms of its components, the answer is yes, it is, as Kim asserts, eliminatively reducible. If, however, reducible refers to physical interactions, and one asks whether the components of ice (insofar as its components' interactions are concerned, resulting in its freezing) are effectively the atoms comprising water, we must claim that water's property of expansion upon freezing is not eliminatively reducible, since its components are effectively and functionally (for this particular type of interaction) the water molecules, not their atoms.

The surface tension of a soap bubble or a drop of water is another emergent property (also see, e.g., Jiang and Powers 2008, for a discussion of the curvature of lipid membranes). It will only be present if the interactions with that surface, on a scale comparable to the size of the drop, are slower and/or weaker than the RE interactions of the molecules on the surface of the drop with each other. That is, if something hits a soap bubble gently and very fast, it is interacting with nothing more than the soap and water at the area of impact. If it hits the bubble slowly, the whole bubble may vibrate (if it does not break) as a single object. The existence and shape of the bubble are emergent properties, if very unstable ones.

One can appreciate the delicacy of the RE state in contemplating, for example, the complexity of the conditions necessary for an animal such as a water strider (an insect in the Gerridae family) to maintain its status on top of the surface of water. Viewing this insect closely, on water, reveals the smooth indentations in that surface under its feet, due to its weight, rather than the displacement of water volume around and adjacent to its legs and/or body that would result if the insect were floating, as do boats. That is, one can speak of "volume" down to the level of individual molecules, and the displacement of water down to that level also; individual molecules, as separate entities, are displaced, just as are groups of molecules: volume is not an emergent property of water (see also Kim 1999, pp. 25–26, on this). But one cannot make the same claim about the surface of water. One molecule does not suffice as a surface unless its *interactions* with the surrounding molecules are such that the displacement of that first molecule results in particular exchanges with the molecules next to it, such that its displacement is limited in depth (within certain parameters) by those others. That act of limitation creates the surface, since it involves the other molecules as aspects of the same limitation: the surface is emergent, and as far as a healthy water strider goes, causally opaque. Nonetheless, at present that surface can be causally reduced to individual molecules' interactions, as Kim wishes, because to make that explanation possible, physicists and chemists have broken down the resonant states of water.

Concerning physical systems linked through quantum coherence, in order for these entities to be in an RE state, given infinitely fast propagation of effects, their relaxation times are dependent only on the *duration* of the effects propagated to the other entities in the coherent state, and not on the propagation times. But this alters neither the basic conception of the RE state, nor its possibility in those systems.[2]

Objections and Consequences

One might object to the above on the grounds that the causal properties of such emergent states are not "strong" enough, that they are not genuinely fundamental in the sense of being physical properties which are *always* epistemologically opaque, or better, causally opaque. That is, e.g., there are no physical laws or properties implied by the existence of surface tension that are not, in all situations, clearly consequent on their component water molecules. One problem this type of objection pinpoints is a multiplication of physical properties. There are many accounts of emergence in which so-called "emergent" properties can be as varied as the mass of a particle, or the "sharpness" of a knife. If the sharpness of a knife counts as a true physical property, then the above objection—the multiplication of properties—is simply irrelevant; but surely such an arbitrary creation of qualities is unsatisfactory. What if somehow "properties" are narrowed to include only those facts that can be put in terms of the most basic laws of physics, from which, it is hypothesized, all other physical properties arise? Aside from our current limited knowledge of physics, there are at least two more fundamental problems with this conception. First, there is the assumption (a) that physics, ideally, is the equivalent of a deductive system in mathematics or logic. Given (a), physical situations/facts should at least be consistent with a finite set of basic elements and operations, hopefully as theorems from those basics. However, given the lack of a "theory of everything," there is no clear evidence that nature works this way. Further, if (b) the physical world were literally the realization of a deductive system (one capable of internally formulating proofs), physics is faced with the unavoidable implications of Gödel's theorem (and on this see Wolpert 2008; Hawking 2003; Jaki 1966, pp. 127–129). There may arise "theorems," i.e., physical facts, that are not provably true, i.e., which will be unanalyzable (underivable) from, although consistent with, some finite set of fundamental physical laws. Nothing has refuted such an idea in physics (and on that general issue, see, e.g., Stöltzner 2004; Wilson 2000). If a physical situation or fact cannot be analyzed in terms of the laws normally employed, the natural tendency is to add new, or alter old, laws, and indeed this has sufficed on a case-by-case basis. But given Gödel's theorem, no finite set of "basal" laws will ever give rise to the totality of physical facts. That is, physical situations that are underivable from the known set of physical laws are clearly not reducible in Kim's sense, yet neither are they "emergent" in any clear sense, since they may be simple realizations of laws yet unknown. To require emergent causal laws or properties to be derivable from basic hypotheses seems incorrect, given a characterization of physical reality as a deductive system.

Why is this relevant to the present argument? Kim states, "What all this means is that the supervenience argument [see Kim 1997, pp. 286–287] would generalize only to those nonmental properties, if any, that, though supervenient on other properties, resist functionalization in terms of their base properties" (Kim 1997, p. 297). Kim also wants to equate "functionalization" with reduction (Kim 1997, p. 297). What he is doing, then, is assuming that all physical systems can be "functionalized": "it is not obvious that there are such properties in other special sciences—that is, supervenient but nonfunctionalizable properties" (Kim 1997, p. 297). Thus, if physics (at the very least—Kim includes such sciences as chemistry as well) is universally reducible, as Kim seems to be claiming, then he must hold that it is a system which is somehow an exception to Gödel's theorem. But physics is surely a strong enough system to express basic arithmetic, and so is subject to that theorem, and thus nonreducible physical states, situations, and properties would at least seem possible. In fact, examples of "nonfunctionalizable" properties are easy to come by in physics. So-called "dark matter" is so far inexplicable in terms of the basics of modern physics; physicists are still searching for explanations in terms of what is known. Another well-known example is antimatter; there was no explanation of that in early twentieth-century quantum or relativistic physics until more basics were added to those theories (e.g., Dirac 1958). Earlier, the fundamental atomic particles were electrons, neutrons, and protons, until others were hypothesized, and observed, by techniques involving the breakdown of RE states.

Also, some physical properties, normally considered fundamental in conventional physics, are clearly derived from combinations of other physical properties (see also, e.g., Morrison 2006). Thus, an accelerating charge is the only way known to produce magnetism (no magnetic monopoles have yet been discovered), yet it is a nonaccelerating charge that is "fundamental," as we normally regard physics. Magnetism requires a mass that is charged and a force applied to it, resulting in acceleration; that is, three fundamental properties—mass, charge, and force—must be combined in a particular manner. If, e.g., magnetism can be "reduced," in some sense of that term, to other basic properties, it becomes difficult to characterize just what "fundamental" means. If this were not true, we would not be hunting magnetic monopoles. Further, magnetic interactions are mediated by photons, which consist of electrical and magnetic fields. Thus, while magnetism is mediated by a multicomponent system, that very system is partially comprised of the field it mediates. The magnetic field is a fundamental entity, and so its properties must be basic, and should be so considered until we are reasonably sure that magnetic monopoles cannot exist; we might *then* consider magnetism causally reducible. Similarly, the history of chemistry—illustrating that the existence of the atomic constituents of molecules, and the molecular constituents of substances, was speculative until various direct and indirect means were employed to break molecules and substances apart—demonstrates the same alteration of the notions of "fundamental" (see, e.g., Earley 2006).

The assumption, then, that it is knowable whether any entity is reducible is both theoretically and practically untenable. To require new causal powers, or unpredictability, does not merely burden us with the empirical limitations determined by our present state of knowledge and what can be inferred from it, but with the intrinsic limitations on knowledge, and thus reducibility, which are consequences of Gödel's theorem. However, these restrictions are irrelevant to the criteria of functional indivisibility or causal opacity resulting from RE states.

One of the motivations behind the attempt to characterize emergent properties is to explain mind in physical terms: to cross the explanatory gap. Directly addressing that question is beyond the scope of this paper.[3] The above analysis, however, if it demonstrates that there is at least one type of truly emergent physical system, forces us to reframe questions such as, "Is mind an emergent property of physical systems?" or, "Are qualia emergent properties of physical systems?" One might ask instead whether mind may be an emergent *system* in the physical realm: a set of RE states resulting from particular configurations of, e.g., neurons. Investigating those configurations might then enable one to claim that while mental properties were underivable from systems causally opaque when observed through some particular classes of interactions, the possibility is open that such properties are derivable as the result of other classes of interactions, if the latter appropriately resolve the causal opacity. RE states might well be achieved in neural networks, realized, e.g., as types of Hebbian cell-assemblies, or in more modern analyses, of "neural groups" (e.g., Izhikevich et al. 2004, Wennekers 2007, Tort et al. 2007) with specific parameters of interaction. One might speculate as to the properties of the resulting "emergent neural entities" (ENEs), i.e., the cell-assemblies or groups that are effectively single "virtual neurons," so to speak, comprised of sets of neurons united by appropriate relaxation times into unitary RE states. At this point, descriptions of these putative ENEs should not enable us to cross the explanatory gap, since those descriptions are of neural interactions understood through concepts that have failed to achieve this goal for over a century. Approaches such as Parravano's (2006), however, may indicate other lines of attack (see Appendix).

APPENDIX: MATHEMATICAL DESCRIPTIONS

This Appendix was written for two purposes: first, to illustrate some of the variety of approaches to emergence, and to show that many of these are not the classical ones of biological or psychological systems, and second, to demonstrate that the approach to emergence taken in this paper is quantifiable, and not merely analytically describable. Although there are no precise mathematical descriptions of these states for the purpose of illustrating what might be termed the causal "blending" discussed above, there are many descriptions of recursively interacting dynamic systems from which such blending can be inferred, and from which descriptions can be constructed. For example, the mathematics of interacting radiative oscillators is one such class.[4] There is a huge literature dealing with what are termed "coherent" and "stochastic" resonance, phenomena having to do with arrays, usually of radiative oscillators, which mutually interact through the absorption and emission of periodic signals (see, e.g., Kim and Lim 2001; Boccaletti et al. 2005). The description of resonant systems is usually through a variety of nonlinear equations (the Ginsberg-Landau, the Kuramoto-Daido, and other variants) leading to chaotic states. Because these equations are extremely complex and nonlinear, they cannot for the most part be solved, but must be modeled through approximation and computer simulation. In addition, although observers can be considered systems themselves, the odds are that they are not comprised of the same components as the systems they are observing. Thus, a description of "asymmetric coupling," in which the two (usually identical) systems interact with different coupling amplitudes and/or phases, is most relevant in this context. Bragard (Bragard et al. 2003; see also Boccaletti et al. 2005) and others analyze one such system, but treatments of the interactions of two such systems have not been described.[5]

However, it is possible to refine the description of a "network" (see, e.g., Jalan et al. 2005 for one of a number of possible standard descriptions) such that any one element in that network may be considered an observer, and treated as such by taking into account the delay due to the finite speed of information transfer between that element (the Observer) and the others in the array. Thus, Parravano treats a network of elements that are coupled together by identical interactions, "observed" by another element in the network (Parravano 2006, p. 768). This treatment is reminiscent of the above characterizations of resonant interactions, yet the internal viewpoint of the Observer element leads to somewhat nonstandard results. Patterns of resonance emerge that cannot be found through other types of analyses. Unfortunately, Parravano does not work out, by varying the delay times ("ml_{jk}" against "t_{ijobs}" in Equation (3), Parravano 2006, p. 768), how the interactions of this element with the system varies as the internal and external delay and relaxation times vary, and so he cannot model emergent interactions in the sense described here. The intervals ml and t in his formulation express instantaneous values. That is, they characterize interactions—with finite transmission times—as occurring without relaxation times. Since emergence is dependent upon the lengths of the various relaxation times, as well as the transmission times, even Parravano's treatment is not yet adequate to describe emergence.

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NOTES

1. Predictability (or its reverse) is taken here to be functional rather than structural because it implies particular types of interactions, which in turn determine emergence. How systems are found to function—how they interact with observers—determines access to their structure. The consistency of structure and function is affirmed, but emergence being consequent on structure is not. Emergence is consequent on interactions in particular contexts; thus, on function, and structural knowledge follows. That is, emergence is not an ontological but an epistemological characterization. This will be explained further below.

2. It is tempting to discuss here the applicability of the RE conception to quantum computation, and to critique approaches such as Penrose's (e.g., Penrose 1991), by arguing that neural systems manifesting RE are, on a macro level, at least reasonable approximations to the micro (quantum) level neural dynamics necessitated by that type of theory. Lack of space precludes this, however.

3. This is the first of several papers on this topic. The intent here is merely to lay the conceptual groundwork for further work.

4. Another possible way of precisely describing this kind of interaction is through chemical reactions. One may produce nonequilibrium reactions that behave in very complex ways, including oscillations in the concentrations of the reactants and products. When two similar reactions in different containers are allowed to interact, a variety of chaotic effects ensue. The effect termed "phase death," in which the ongoing oscillations in reactant concentrations halt and enter a steady state as long as the two solutions interact in a very special regime (e.g., see Yoshimoto, Yoshikawa, and Mori 1993; Crowley and Epstein 1989), may be similar to the above. However, most models using this Brusselator design employ two identical coupled systems, and that is not the situation, in general, of interest here. In addition, there is a large literature dealing with "clustering" in physics and physical chemistry (e.g., Khanna and Jena 1992; Walter, Akola, Lopez-Acevedo, Jadzinsky et al. 2008) relevant to the atomic interactions described above.

5. Suppose there were two "unidimensional fields obeying complex Ginsburg-Landau equations" (Bragard, Boccaletti, and Mancini 2003, p. 1). Bragard analyzes multiple cases of such fields interacting with various phase and amplitude relationships, leading to complex coupling effects. These two fields are the equivalent of one multiple-component system, since most physical systems are comprised of nonidentical components. Therefore, for two systems to interact to describe emergence, one would need a description of the interactions of three such fields, at a minimum. Specifically, one would be asking under what circumstances were there cases in which the interaction between set A of one field with set B of two other such fields would be such that the A-B interaction could be described (a) as the interaction between A and B, in which the components of B could not be separated, as described above, or (b) reasonably accurately as the interaction between A and only one of the component fields of B. The areas in the resulting state spaces would define the states in which A did, and did not, respectively, effectively interact with an emergent singular system.

REFERENCES

Atay, F., and J. Jost. 2004. "On the Emergence of Complex Systems on the Basis of the Coordination of Complex Behaviors of Their Elements," *Complexity*, vol. 10, pp. 17–22.

Atkins, P. 1991. *Quanta: A Handbook of Concepts* (Oxford, U.K.: Oxford University Press).

Boccaletti, S., C. Mendoza, and J. Bragard. 2005. "Synchronization of Spatially Extended Chaotic Systems with Asymmetric Coupling," *Brazilian Journal of Physics*, vol. 35, pp. 411–417.

Bragard, J., S. Boccaletti, and H. Mancini. 2003. "Asymmetric Coupling Effects in the Synchronization of Spatially Extended Chaotic Systems," *Physical Review Letters*, vol. 91, p. 064103.

Cerf, R. 2006. "Catastrophe Theory Enables Moves to Be Detected towards and away from Self-organization: The Example of Epileptic Seizure Onset," *Biological Cybernetics*, vol. 94, pp. 459–468.

Crowley, M., and I. Epstein. 1989. "Experimental and Theoretical Studies of a Coupled Chemical Oscillator: Phase Death, Multistability, and In-Phase and Out-of-Phase Entrainment," *Journal of Physical Chemistry*, vol. 93, pp. 2496–2502.

Delehanty, M. 2005. "Emergent Properties and the Context Objection to Reduction," *Biology and Philosophy*, vol. 20, pp. 715–734.

Dirac, P. 1958. *The Principles of Quantum Mechanics* (London: Oxford University Press).

Earley, J. 2003. "How Dynamic Aggregates May Achieve Effective Integration," *Advances in Complex Systems*, vol. 6, pp. 115–126.

______. 2006. "Chemical 'Substances' That Are Not 'Chemical Substances,'" *Philosophy of Science*, vol. 73, pp. 841–852.

Elder-Vass, D. 2005. "Emergence and the Realist Account of Cause," *Journal of Critical Realism*, vol. 4, pp. 315–338.

Fodor, J. 1975. *The Language of Thought,* ed. J. Katz, D. Langendoen, and G. Miller, Language & Thought Series (Cambridge, Mass.: Harvard University Press).

Genet, S., and B. Delord. 2002. "A Biophysical Model of Nonlinear Dynamics underlying Plateau Potentials and Calcium Spikes in Purkinje Cell Dendrites," *Journal of Neurophysiology*, vol. 88, pp. 2430–2444.

Gillett, C. 2002. "Strong Emergence as a Defense of Non-reductive Physicalism: A Physicalist Metaphysics for 'Downward' Determination," *Principia*, vol. 6 pp. 89–120.

Hawking, S. 2003. "The Impossible Puzzle," *New Scientist*, vol. 178, p. 34.

Humphreys, P. 1997. "How Properties Emerge," *Philosophy of Science*, vol. 64, pp. 1–17.

Izhikevich, E., J. Gally, and G. Edelman. 2004. "Spike-timing Dynamics of Neuronal Groups," *Cerebral Cortex*, vol. 14, pp. 933–944.

Jaki, S. 1966. *The Relevance of Physics* (Chicago: University of Chicago Press).

Jalan, S., R. Amritkar, and C-K. Hu. 2005. "Synchronized Clusters in Coupled Map Networks. I. Numerical Studies," *Physical Review E*, vol. 72, pp. 016211–1 - 11–15.

Japaridze, Giorgi. 2006. "Introduction to Cirquent Calculus and Abstract Resource Semantics," *Journal of Logic and Computation*, vol. 16, pp. 489–532.

Jiang, H., and Thomas R. Powers. 2008. "Curvature-Driven Lipid Sorting in a Membrane Tubule," *Physical Review Letters*, vol. 101, pp. 018103–4.

Johnson-Laird, P. 2006. "Models and Heterogenous Reasoning," *Journal of Experimental & Theoretical Artificial Intelligence*, vol. 18, pp. 121–148.

Khanna, S., and P. Jena. 1992. "Assembling Crystals from Clusters," *Physical Review Letters*, vol. 69, pp. 1664–1667.

Kim, J. 1997. "Does the Problem of Mental Causation Generalize?" *Proceedings of the Aristotelian Society*, vol. 97, pp. 223–330.

______. 1999. "Making Sense of Emergence," *Philosophical Studies*, vol. 95, pp. 3–36.

______. 2006. "Emergence: Core Ideas and Issues," *Synthese*, vol. 151, pp. 547–559.

Kim, S-Y., and W. Lim. 2001. "Effect of Asymmetry on the Loss of Chaos Synchronization," *Physical Review E*, vol. 64, p. 016211.

Kleene, S. 1959. "Recursive Functionals and Quantifiers of Finite Types I," *Transactions of the American Mathematical Society*, vol. 91, pp. 1–52.

Levine, J. 1983. "Materialism and Qualia: The Explanatory Gap," *Pacific Philosophical Quarterly*, vol. 64, pp. 354–361.

Luisi, P. 2002. "Emergence in Chemistry: Chemistry as the Embodiment of Emergence," *Foundations of Chemistry*, vol. 4, pp. 183–200.

Maturana, H., and F. Varela. 1980. *Autopoiesis and Cognition: The Realization of the Living* (Dordrecht, Netherlands: Kluwer Academic Publishers Group).

Morrison, M. 2006. "Emergence, Reduction, and Theoretical Principles: Rethinking Fundamentalism," *Philosophy of Science*, vol. 73, pp. 876–887.

Murray, J. 1989. *Mathematical Biology* (New York: Springer-Verlag).

O'Connor, T., and J. Jacobs. 2003. "Emergent Individuals," *Philosophical Quarterly*, vol. 53, pp. 540–555.

Parravano, A. 2006. "Looking at Map Networks with Time Delay Interactions from a Local Perspective," *Physica A*, vol. 371, pp. 767–772.

Penrose, R. 1991. *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics* (New York: Penguin Books).

Ryan, A. 2007. "Emergence Is Coupled to Scope, Not Level," *Complexity*, vol. 13, pp. 67–77.

Stöltzner, M. 2004. "On Optimism and Opportunism in Applied Mathematics: Mark Wilson Meets John von Neumann on Mathematical Ontology," *Erkenntnis*, vol. 60, pp. 121–143.

Terhune, D. B. 2009. "The Incidence and Determinants of Visual Phenomenology during Out-of-Body Experiences," *Cortex*, vol. 45, pp. 236–242.

Tort, A., H. Rotstein, T. Dugladze, T. Gloveli et al. 2007. "On the Formation of Gamma-coherent Cell Assemblies by Oriens Lacunosum-moleculare Interneurons in the Hippocampus," *Proceedings of the National Academy of Sciences USA*, vol. 104, pp. 13490–13495.

Vilela, P.M., R. Moscoso, and D. Thompson. 1997. "What Every Musician Knows about Viscoelastic Behavior," *American Journal of Physics*, vol. 65, pp. 1000–1003.

Vitale, B. 1989. "Elusive Recursion: A Trip in Recursive Land," *New Ideas in Psychology*, vol. 7, pp. 253–276.

Walter, M., J. Akola, O. Lopez-Acevedo, P. D. Jadzinsky et al. 2008. "A Unified View of Ligand-protected Gold Clusters as Superatom Complexes," *Proceedings of the National Academy of Sciences*, vol. 105, pp. 9157–9162.

Weiskopf, D. 2008. "The Origins of Concepts," *Philosophical Studies*, vol. 140, pp. 359–384.

Welshon, R. 2002. "Emergence, Supervenience, and Realization," *Philosophical Studies*, vol. 108, pp. 39–51.

Wennekers, T. 2007. "A Cell Assembly Model for Complex Behaviour," *Neurocomputing*, vol. 70, pp. 1988–1992.

Wetmore, D., E. Mukamel, and M. Schnitzer. 2007. "Lock-and-Key Mechanisms of Cerebellar Memory Recall Based on Rebound Currents," *Journal of Neurophysiology*, vol. 100, pp. 2328–2347.

Wilson, M. 2000. "The Unreasonable Uncooperativeness of Mathematics in the Natural Sciences," *The Monist*, vol. 83, pp. 296–314.

Wolpert, D. H. (2008). "Physical Limits of Inference," *Physica D: Nonlinear Phenomena*, vol. 237, pp. 1257–1281.

Wong, H. 2006. "Emergents from Fusion," *Philosophy of Science*, vol. 73, pp. 345–367.

Yoshimoto, M., K. Yoshikawa, and Y. Mori. 1993. "Coupling among Three Chemical Oscillators: Synchronization, Phase Death, and Frustration," *Physical Review E*, vol. 47, p. 864.