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COMPLEX THINKING: THE EMERGENCE OF EVERYTHING?

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ABSTRACT
The science of complex systems has tended to assign a central role to the concept of emergence. But how precise or coherent is this concept? Three alternative approaches to answering this question are discussed. Firstly, we examine specific examples of emergence, using the Pauli Exclusion Principle as the main case study. Secondly, we survey alternative kinds of definitions of emergence that have been offered in the literature. Thirdly, we address the possibility that the concept of emergence is in some sense undefinable. We conclude that emergence remains problematic, in particular because it is difficult to circumscribe a concept that avoids two extremes whereby either nothing is emergent (i.e. the concept is vacuous) or everything is emergent (i.e. the concept is trivial).

Keywords: emergence, complexity, definition, Pauli Exclusion Principle, ontology, epistemology

Introduction

Over the past decade or so, there has been an enormous rise in interest among scientists in issues concerning complexity, complex systems, cellular automata, and the like. To a large extent this interest has not been reflected in the philosophical community. My topic in this paper concerns one key concept that often features centrally in discussions of complex systems. This concept is emergence.

Consider the following excerpt from a recent survey paper by the director of the Institute for the Study of Complex Systems (ISCS):

> "If 'complexity' is currently the buzzword of choice for our newly minted millennium – as many theorists proclaim – 'emergence' seems to be the explication of the hour for how complexity has evolved. Complexity, it is said, is an emergent phenomenon. Emergence is what 'self-organizing' processes produce. Emergence is the reason why there are hurricanes, and ecosystems, and complex organisms like humankind, not to mention traffic congestion and rock concerts. Indeed the term is positively awe-inspiring. As physicist Doyne Farmer observed: "It's not magic … but it *feels* like magic.""[1]

Why focus philosophical attention on emergence? One reason is already illustrated by the quotation given above, namely the alleged *significance*

[1] Corning [2002, p. 1].

of emergence and of emergent phenomena. In some ways, the pressure to demonstrate this significance has mutually conflicting effects. One way a phenomenon can be significant is to occur frequently across a wide range of important contexts. Conversely, the significance of a phenomenon can also lie in it being unusual, special, rare. As we shall see, each of these features has been claimed by theorists for the concept of emergence.

The following anecdote may help to illustrate the predicament. In June 2002 I attended the 4th International Conference on Complex Systems in Nashua, New Hampshire. One of the core themes of the conference was emergence. About halfway through the week-long conference, an audience member stood up during the question period following a talk and asserted that there are, in fact, *no* genuine cases of emergence. This provoked animated discussion and led to an ongoing debate during the remainder of the conference, with people on both sides of the issue. As a (then) outsider to the complex systems community, I was startled by the lack of consensus about this apparently very basic question. It was as if I had gone to a paleontology conference and halfway through a debate had broken out over whether dinosaurs ever existed! This episode is but one illustration of what I think is a more general phenomenon: there is widespread usage of the term "emergence" in the complexity literature, yet little agreement over what it means or how it might be precisely defined. This leads me to my core question: what is "emergence"?

My question is meant as a philosophical request for clarification. As such, there are several potential approaches to trying to answer it. One approach is to provide paradigm *examples* of emergence in action, exemplars which illustrate what the concept is and how it works. A second approach is to formulate an explicit *definition* of the term "emergence." And a third and final approach is to give arguments for why no genuine clarification of the term is possible. In what follows I shall spend some time considering each of these three approaches in turn.

Section 1: An Example of Emergence?

I shall take my main (alleged) example of emergence from Harold Morowitz's 2004 book, *The Emergence of Everything*. In the early chapters of the book, Morowitz stresses the link between emergence and what he describes as "pruning rules." Here are three sample quotes:

> "[S]cientists have looked for ways of pruning the space of possible solutions or sets of allowable solutions. This may lead to surprises in the system trajectories, giving rise to novel behaviors. These are the emergent properties of the system, properties of the whole. They are novelties that follow from the system rules but cannot be predicted from properties of the components that make up the system."[2]

> "[N]ature yields at every level novel structures and behaviors selected from the huge domain of the possible by pruning, which extracts the actual from the possible.

[2] Morowitz [2004, p. 13].

> The pruning rules are the least understood aspect of this approach to emergence, and understanding them will be a major feature of the science of the future."[3]

> "[The computational approach is] to select solutions or families of solutions by fitness rules or other selection criteria often defined by introducing pruning algorithms. Theories of this kind are successful if the … solutions generated under the constraint of rules and pruning lead to behaviors with some kind of agreement or resonance with the world of observation. Such outputs are called emergent properties of the system."[4]

One question here is whether the notion of a "pruning rule" is itself transparent enough to help in clarifying emergence. For one thing, Morowitz always talks of pruning rules in the context of models. But what are supposed to be the real-world analogs of pruning rules? In the course of the whole book, only one explicit example is presented, which is the Pauli Exclusion Principle. When describing the allegedly emergent properties of the periodic table of chemical elements, Morowitz writes

> "The pruning relations that severely limit the eigen states (allowable atomic configurations) of matter are the solutions to the Schrödinger equation and the Pauli exclusion principle. The emergent behavior is the content of the science of chemistry: the periodic table of the elements, the rules of covalent bonding, etc."[5]

What exactly is the Pauli Exclusion Principle (PEP)? One way of stating it is as follows:

> PEP No two electrons in an atom can have the same four quantum numbers.

As Morowitz describes it, PEP follows from the more general mathematical rule that functions representing states of two electrons must be antisymmetric. This in turn follows (although Morowitz does not mention this) from a more general rule which covers all fermions (i.e. particles with ½-integer spin).[6]

So much for the content of PEP. The key question is what makes PEP special, and thus a candidate for creating emergent properties. How, in other words, is PEP different from a typical law of nature such as Newton's Law of Gravitation? In answering this question, let us first dispose of two potentially distinctive features of PEP which do not seem to be relevant here. Firstly, PEP is quantum mechanical in nature. It is hard to see, however, how this can be the operative feature linking PEP to emergence. (Indeed, if anything, the association with quantum mechanics may give rise to the suspicion that one mystery (emergence) is being 'explained' by invoking another mystery (quantum mechanics), as – for example – Roger Penrose has done with his attempts to root consciousness in the

[3] *op. cit.*, p. 14.
[4] *op. cit.*, p. 19.
[5] *op. cit.*, p. 55.
[6] This is in contrast to bosons, which have integer spin, and which do not obey PEP.

peculiarities of quantum mechanics.[7]) Secondly, at several points in his exposition Morowitz refers to PEP as a "selection rule." It should be noted that this term has quite a specific meaning in physics (and rather different, evolutionary overtones in biology). In the context of physics, a selection rule is a restriction on the space of possibilities arising from underlying symmetries, which correspond to conserved properties of the system. An example is Noether's Law, which states that continuous symmetries always give rise to conserved properties (e.g. angular momentum). In this technical sense, it is not even clear whether PEP *is* a selection rule: it relies on antisymmetry, not symmetry; and it is discrete, not continuous.

So what feature or features of PEP might provide the necessary link to emergence? Morowitz makes three central claims about the nature of PEP:[8]

(i) PEP is *unrelated to the other laws of physics*.

(ii) PEP has *nothing to say about the behavior of individual electrons*.

(iii) PEP is a *nondynamical* principle, but it influences the dynamical behavior of electrons.

One problem here is that Morowitz is not himself a particle physicist. The consensus among the several particle physicists I have consulted is that (i) is false, (ii) is true – though not especially significant –, and (iii) is unclear. Let us take the three claims in order.

(i) PEP is *unrelated to the other laws of physics*.

There is a sense in which this is true in quantum mechanics. However it is false in quantum field theory. (Quantum field theory is a theory for many-body systems which allows for the creation and annihilation of particles, unlike quantum mechanics.) In quantum mechanics, the antisymmetric rule of PEP must be added 'by hand.' It is not 'forced' by the underlying formalism of the theory. The opposite is true in quantum field theory; in fact, dropping antisymmetry for half-integer-spin particles leads to violations of causality. Hence it seems fair to say that PEP does follow from other aspects of the theory in quantum field theory (assuming that probabilities are preserved).[9]

(ii) PEP has *nothing to say about the behavior of individual electrons*.

This is true in the sense that if there is just one electron in the system there is nothing to exclude. But if this is all that is meant then the point can be made less confusingly by saying that the properties imparted by PEP on a single electron are *relational*. In this sense, the laws of genetics similarly have nothing to say about isolated (sexually reproducing) organisms.

[7] Penrose [1989].

[8] *op. cit.*, pp. 55–6.

[9] Another way of explicating the above point is in terms of position functions. (Dr. Leonidas Pantelidis (personal communication)).

A second, more technical, objection to claim (ii) is that it confuses an epistemological point with a metaphysical one. Electrons have spin ½, which – given PEP – means that a 2π rotation brings the state back to minus itself (i.e. its wavefunction picks up a phase of -1). However, probabilities in quantum mechanics are related to the square of the wavefunction, hence the only way to observe this phase change is to have one electron interfere with another one. This does not imply that PEP "has nothing to say" in the single electron case, only that what PEP says cannot be verified without having the single electron interact with other electrons.

(iii) PEP is a *nondynamical* principle, but it influences the dynamical behavior of electrons.

Something is dynamical, in the physicist's sense, if it is related to force. PEP does not depend on the existence of forces, so in this sense it is non-dynamical. Also, there is a sense in which PEP does have dynamical consequences. It implies, for example, that the probability of two electrons being in a certain pair of positions decreases as those positions get closer.[10] Thus (iii) does seem to be basically accurate as a claim about PEP. The question remains, however, of why being a nondynamical principle with dynamical consequences makes PEP such a prime candidate for producing emergent behavior. Unfortunately, Morowitz says nothing in his book that casts light on this mystery.

Section 2: A Definition of Emergence?

My complaint against Pauli's Exclusion Principle is not that it fails to generate emergent phenomena – I have remained neutral on this issue. Rather it is that nothing very illuminating has been said about *why* PEP is such a paradigm case of emergence. The broader point here is that examples in themselves are unlikely to illuminate a given concept. A proposed example may be rejected by some, and even if it is accepted, at least provisionally, there still tends to remain the above sort of why-question. Examples provide good test-cases for candidate definitions, but they cannot fully replace the definition seeking process.

What, then, are the prospects for a philosophically satisfying definition of emergence? I mentioned at the beginning of this paper the tensions arising from theorists' desires to show the *significance* of emergence. If too many kinds of phenomena are emergent then the concept becomes less distinctive, more commonplace. If, on the other hand, emergent phenomena are too few and far between then the concept becomes esoteric and irrelevant. At the fullest extremes in these two directions lie pitfalls which must be avoided when defining any substantive concept: these mirror-image pitfalls are *vacuousness* and *triviality.*

(i) Vacuousness: a concept, F, is vacuous if nothing is F

(ii) Triviality: a concept, F, is trivial if everything is F

[10] This makes PEP dynamically equivalent to a repulsive force (in a classical system).

Another way of putting the definitional question, then, is as follows: is it possible to come up with a reasonably precise definition of emergence which does not include *everything* (i.e. is non-trivial), but does include *some* things (i.e. is non-vacuous)?

Space precludes all but a very general sketch of the possibilities for defining emergence. The scattered literature on emergence includes a large number of proposed definitions, characterizations, and criteria for emergence, as well as various ways of slicing the concept up into different sub-concepts. For clarity of exposition, I shall classify kinds of definition into three broad categories: ontological, epistemological, and complexity-related.

2(A) Ontological Definitions of Emergence

Perhaps the most common phrase associated with emergence is the claim that, in a genuinely emergent system, "The whole is more than the sum of the parts."[11] Unfortunately this is more of a slogan than a precise definition. For one thing, it is unclear whether this is supposed to be just a necessary condition for emergence, a sufficient condition, or both. For another thing, the key terms in the slogan are not transparent. What does 'more than' mean? What does 'sum' mean? Consider two systems each of which consists merely of four coins arranged on a table:

(i)	C	C	(ii)	C	C	C	C
	C	C					

The systems (i) and (ii) have qualitatively identical parts: each consists of four coins of the same size, shape, etc. Are these two systems more than the 'sum of their parts'? In one sense, at least, it seems we should answer yes. If we take the term "sum" here seriously, then it should share the basic properties of the mathematical operation of summation. For finite numbers of inputs, a mathematical sum has two important properties. Firstly, it is a function, so the same inputs are mapped onto the same outputs. Secondly, the arrangement (including the order) of the inputs makes no difference to the overall output. In the above case, systems (i) and (ii) have the same inputs, just arranged differently, but different outputs. Hence (i) and (ii) are more than the sum of their parts.

On the other hand, (i) and (ii) are about as simple as systems can get, and about as uninteresting too. Surely if we can find emergence even in very basic systems of this sort, then the threat of triviality is very real. David Chalmers has similar qualms about the following, more definition-like version of the above slogan:[12]

[11] e.g. "Emergence leads to novelties: the whole is somehow different from the sum of the parts." (Morowitz [2004, p. 20]).

[12] Chalmers [1990, p. 1].

(1) Emergence involves whole systems having properties which are not possessed by any of their parts.

While (1) may sound promising, insofar as it covers instances such as (brain-level) consciousness arising from unconscious neurons, or geometrical patterns arising from the chemical reaction of unpatterned molecules, it also falls prey to triviality. It is not hard to find properties that systems (i) and (ii) each have and yet none of their parts have: for example, having 4 distinct components, or having a total mass of X grams. Indeed it seems that any system will have *some* properties not possessed by any of its parts.

One way to refine (1) so as to avoid this triviality is to place some restriction on the kinds of higher level properties which count. For example, we might try

(2) Emergence involves whole systems having properties which are *qualitatively different* from those possessed by any of their parts.

The idea is that the properties mentioned above in connection with systems (i) and (ii) – having 4 distinct components, having a mass of X grams – are not qualitatively different from properties possessed by individual coins or by subclusters of coins in the systems.

For (2) to be useful as a definition, however, it must be possible to specify what qualitative difference amounts to without invoking emergence. And it unclear whether this can be done. For example, is nonlinear behavior qualitatively different from linear behavior? (In other words, if various linear components interact to produce an overall nonlinear effect, is this emergence?) And what about a lump of fissile radioactive material to which more and more atoms are gradually added: when the mass reaches criticality and a chain reaction ensues, is this a qualitatively different piece of behavior?

2(B) Epistemological Definitions of Emergence

A second widely-used approach is to define emergence for a system by reference to the difficulty of predicting the behavior of the system. For example,

(3) A system is emergent if and only if it is impossible to predict the behavior of the whole just on the basis of the behavior of its separate parts.

Crucial to the force of (3) is whether the impossibility referred to means impossible *in practice* or impossible *in principle*.[13] Each choice has its drawbacks. If we go with the 'in practice' reading then – as many philosophers have complained – we are turning emergence into a highly subjective notion. We can no longer talk about a system being emergent or non-emergent *per se*, but only emergent-relative-to-us. Logically very straightforward systems,

13 e.g. "[T]he behavior of the agents leads to system properties not knowable without running the program." (Morowitz [2004, p.23]).

for example the game of chess, may turn out to be emergent in this subjective sense simply in virtue of being sufficiently computationally complex to exhaust our powers of direct analysis. On the other hand, if we choose the 'impossible in principle' interpretation, we face the prospect of the concept collapsing in the opposite direction to vacuousness. If we think of the 'in principle' stance as taking a God's-eye view, then it may be that nothing is genuinely emergent because everything is in principle predictable. In particular, there would seem to be no room for emergence in a fully deterministic universe.

2(C) Complexity-Related Definitions of Emergence

As has already been mentioned, emergence crops up frequently in discussions of complex systems. One common approach to characterizing emergence is to define it in terms of complexity. A distinction is sometimes made by theorists analyzing the concept of emergence between *synchronic* emergence and *diachronic* emergence. Roughly speaking, synchronic emergence involves the relations between different levels of a system at a given point in time, while diachronic emergence involves the relations between earlier and later states of the same system. Complexity-related definitions of emergence also tend to fall into one or other of these two categories.

Let us consider first synchronic emergence. What is striking about definitions falling in this category is that two quite contrary relations have been invoked. On the one hand, there are definitions along the following lines:[14]

(4) Emergent systems are those in which low-level complexity produces certain very simple behaviors at a higher-level.

The appeal of (4) is twofold. Firstly, it fits well with some of the canonical examples of emergence in complex systems: for example, circadian rhythms in humans, or seasonal fluctuations in air temperature. In such cases the underlying systems (the human organism, the atmosphere) are enormously complex, yet surprisingly simple regularities 'emerge.' Secondly, (4) boosts the claims of complex systems proponents who argue that the evolving field of complexity science is right to look for commonalities across different complex systems in diverse contexts. If the emergence of simple higher-level patterns is characteristic of such systems then the chances of these patterns being shared look better than they might otherwise at first glance.

Ranged against (4) are definitions which make the simplicity-complexity link in precisely the *opposite* direction. For example,

(5) Emergent systems are those in which low-level simplicity produces certain very complex behaviors at a higher-level.

[14] One example is from Cohen & Stewart [1994, p. 411], who write: "We shall give the name 'simplexity' to the process whereby a system of rule can engender simple features. … Another word with a very similar meaning is Stuart Kaufmann's concept of antichaos: the occurrence of simple large-scale behavior in complicated systems."

What proponents of (5) tend to have in mind are multi-agent systems in which the individual agents interact according to very simple, and often very local, rules. Examples include anthills and groups of birds. Such systems often exhibit seemingly quite sophisticated behavior at the global level – rallying to defend the nest, for example, or flocking in complex patterns. Interesting behavior is somehow arising, or 'emerging', from very basic foundations.

The contrary directions of definitions (4) and (5) provide a nice illustration of the competing pressures to play up the *significance* of emergence. By emphasizing potential commonalities across different complex systems, (4) roots the significance of emergence in its link to simplicity. By contrast, (5) equates simplicity with uninterestingness. What emergence does, on this second view, is somehow produce interesting – and thus significant – complexity from seemingly uninteresting component materials.

What about diachronic emergence? In this case, theorists seem to be in general agreement about the direction of the relation between earlier and later stages in a system which exhibits emergence. The laws of thermodynamics tell is that systems are likely in general, and in the long run, to evolve from more ordered states to less ordered states. In other words, disorder – or entropy – tends to increase. A putative characteristic of emergent systems, by contrast, is that disorder tends to *decrease*.[15] The issue then is how to connect decreasing disorder to the changing complexity of a system over time. Does order enhance complexity or reduce it? Unfortunately for the prospects of a definition of diachronic emergence based on complexity, it seems like there is no general answer to this question other than, "It depends."

It depends on the degree of complexity of the system we start out with. If enough disorder is imposed on an organism it will most likely die. And a dead organism is presumably less complex than a live one, so here increasing disorder decreases complexity. On the other hand, if we impose some disorder on a crystal lattice then it will become more complex, so here increasing disorder seems to increase complexity. The salient difference between the organism and the crystal lies in the comparative simplicity of the latter in comparison to the former.

It also depends on the length of time the system is left to evolve. Consider an array of qualitatively identical iron nails. If they are left alone then they will gradually start to rust. Different nails may exhibit slightly different patterns of rusting, which will render them qualitatively different and hence make the array as a whole more complex. But in the long run all the nails will rust down to a fine powder and the total system of iron powder will be simple, perhaps even simpler than the original array of nails. So here progressive disorder first increases, then decreases the complexity of the system.

[15] See, for example, the title of John Holland's 1998 book, *Emergence: From Chaos to Order*.

The fundamental problem here is that there is no straightforward relationship between complexity and disorder. Highly complex systems in fact seem to consist of a *mixture* of ordered and disordered features. Hence both a significant increase in disorder and a significant decrease in disorder may act to reduce the overall complexity of the system. This balance between order and disorder is reflected in our epistemological interactions with complex systems. Such systems are typically neither completely predictable nor completely unpredictable. A paradigm case here is the weather: many aspects of weather are predictable given our current computational resources – we can make reasonably accurate short-term forecasts, and spot longer-term trends. But for most areas it is impossible to accurately predict what the weather will be like two weeks from now. Indeed one popular approach to defining complexity is based on measuring the difficulty of describing the 'interesting' features of a given system. Highly ordered systems come out as relatively simple, because their main features can be concisely described. And highly disordered systems, for example chaotic systems, also come out as relatively simple, because they have few interesting features to describe.

Section 3: Is Emergence Undefinable?

Our inability to come up with a fully adequate definition of the concept of emergence does not, of course, show that such a definition does not exist. But are there independent reasons for pessimism concerning the definability of emergence? There are certainly plenty of examples in the literature of pessimism of this sort. Thus John Holland writes near the beginning of his book,

> "It is unlikely that a topic as complicated as emergence will submit meekly to a concise definition, and I have no such definition to offer."[16]

Below I shall consider three possible reasons for claiming that emergence is not definable, or at least not definable in any feasible manner.

The first reason, mentioned by Morowitz in the more speculative chapters at the end of his book, is that attempts to reflect upon and to analyze the concept of emergence involve some kind of *circularity*. Morowitz writes,

> "In the emergence approach, we have operated in a circular fashion. … [W]e have started with the mind … and have built a universe of constructs that are then used in an effort to try to understand the mind."[17]

A little later in the book, Morowitz returns to this theme, writing

> "Emergence has in an orderly way moved from protons to philosophers. At this level there is a kind of closing of the loop. … The emerging world turns inwards and thinks about itself."

[16] *op. cit.*, p. 3.

[17] Morowitz [2004, p. 173].

But how significant is this alleged circularity? After all, not all circularity is problematic. (For example, it is not generally considered to be problematic to give deductive arguments in support of the validity of deduction.) Perhaps Morowitz's worry stems from the nature of philosophical inquiry. Like logic and mathematics, philosophical claims can sometimes fall under their own scope.[18] In the case of philosophy this is because its scope of inquiry is by nature general. Hence it may make universal claims such that these claims are part of their own domain of application. In this respect, philosophy is unlike most other disciplines: the claims of biology, for example, are not themselves biological phenomena. Such circularity can lead to paradox. For example, "All generalizations are false," does not seem to be capable of having a truth-value assigned to it on pain of contradiction. But Morowitz has done nothing to show that any such paradoxes threaten the concept of emergence. Even if he is right that the mental apparatus which philosophers use to concoct definitions of emergence itself emerges from lower-level neuronal, molecular, and sub-atomic activity, why should this preclude the possibility of a cogent and paradox-free definition?

The second reason for pessimism about defining emergence links back to our discussion of complexity-related definitions at the end of Section 2. The worry is not that there is any direct circularity in the concept of emergence, but rather that the only way to define it brings in other concepts – such as complexity – which can themselves only be defined in relation to emergence. In other words we end up with a tight circle of interrelated concepts that have so little external underpinning that they are practically useless.

The third reason for pessimism is in some sense a blending of the first two reasons, and is related to Holland's remark, quoted above, that the topic of emergence is "complicated." This may turn out to be a consequence of the close links between emergence and complexity. As we have seen, it is not clear how to understand the claim that emergence is itself somehow emergent, nor why this should pose problems for defining emergence. Perhaps more plausible, however, is that complexity is itself a complex notion. If so, and if it is right to associate complexity with difficulty of description, then this would explain why it is so hard to come up with an adequate definition of emergence. It might also help to explain the intuition that emergence is an 'interesting' and 'significant' phenomenon, as mentioned at the beginning of the paper.

Conclusion

It is hard to see how – as it stands – the concept of emergence can do much in the way of explanatory work in either scientific or philosophical contexts. As we have seen, the concept as a whole is often conflated with various distinct sub-concepts: ontological versus epistemological emergence, synchronic versus diachronic, strong versus weak, and so on. Nor are these sub-concepts themselves generally amenable to straightforward definition. And there is a sense that each new theorist comes into the field 'fresh' and defines his or her own new version of the concept from scratch. It may be that in this respect complexity is actually a more tractable concept than emergence. As with emergence, various more specific kinds of complexity can be distinguished: Kolmogorov complexity, computational complexity, algorithmic complexity, and so on. The difference is that many of these specific kinds have become standard in the literature, and (probably not coincidentally) many of these specific kinds have also been given precise, mathematical definitions.

Furthermore, there is a tension arising from the proclaimed significance of emergence that pulls both in the direction of showing that emergent phenomena are to be found all over the place and in the direction of bracketing off emergence as a unique and distinctive occurrence. A second tension arises from competing aspirations for what the concept should be able to do. Emergent phenomena are supposed to be both genuinely novel but also rooted 'non-magically' in their initial conditions or microstates. Wanting it both ways accounts, for example, for the appeal of "emergentism" in the philosophy of mind. If successful, then treating consciousness as an emergent phenomenon holds out the hope of explaining both the distinctiveness and the metaphysical naturalness of the mental. But the suspicion remains that wishful thinking is, at least in part, replacing rigorous philosophical analysis of the concept. Emergence ends up being whatever you want (or need) it to be … .[19]

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[18] A feature exploited most famously by Gödel in proving his Incompleteness Theorems for arithmetic.

[19] My thanks to Leonidas Pantelidis and to Vijay Balusubramanian for helpful information about the Pauli Exclusion Principle, and to members of the TRICO Emergence Reading Group, based at Bryn Mawr College, for their comments on an earlier version of this paper.