

Emergence In Physics

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The concept of emergence in philosophical discussions is closely connected with the notions of antireductionism, unpredictability, and novelty. In many cases these latter concepts are explicated in mereological terms. Very crudely, something is emergent when it (the whole) is greater than the sum of its parts. Alternatively, the behavior of the emergent whole does not reduce to some function of the behavior of its components. Or, the behavior of the emergent whole is unpredictable given knowledge of the nature of its parts. Or, finally, the behavior of the emergent whole is completely different, new, and unexpected, given knowledge of the nature of its parts. In addition, there is often, again in philosophical contexts, a demand that the emergent feature is not *explainable*, by a theory of the nature of its parts.

Most philosophical discussions focus on the notion of emergence in the context of the mind/body problem, broadly construed: How can the mental, with all of its unique attributes, possibly obtain in a world in which the basic fundamental features are characterized by physical theory. This problem of emergence is intimately connected with the position called nonreductive physicalism.

On the other hand, there have been discussions of emergence (though not necessarily using that term) in the “modern” physics literature at least since the time of the development of kinetic theory and statistical mechanics. [8] Most, though not all, discussions of emergence in physics focus on the question of how the macroworld of our experience can arise out of the behavior of the microconstituents of everyday objects of our experience. Thus, most discussions of emergence in the physics literature as well can be seen as focusing on mereological part/whole questions. However, there are, arguably, non-mereological emergent features of the world, so that one might question the necessity of part/whole relations in a complete characterization of emergence.

This entry will examine very briefly a number of examples that may naturally be considered to be emergent phenomena in physics. Section 1 begins with early attempts to relate the amazingly successful science of thermodynamics (a phenomenological theory that does not address the ultimate constitution of the systems it describes) to theories such as kinetic theory

and statistical mechanics. Section 2 considers issues concerning the nature of measurement in quantum mechanics and the so-called emergence of the classical world. The third section discusses a debate that came to a boil in the 1970s about reductionism in physics. It concerns the nature of fundamental physics and pits high energy theorists against solid state (condensed matter) theorists. From this debate has emerged a new attitude toward theories in particle or high energy physics, namely, that all such field theories may well be “effective,” and that the search for some ultimate theory of everything may be misguided. Finally section 5, addresses some of the mathematical aspects of emergence and, in particular, the nature of a kind of reasoning that often gets employed in arguing for emergent phenomena. It is suggested that many of our everyday experiences of the physical world are experiences of emergent phenomena.

1 Thermodynamic Phenomena

From the point of view of orthodox thermodynamics, a system, such as a gas in a box, is a continuous blob of stuff. The theory is phenomenological in that it describes (and explains) the observable behavior of various systems like gases, while it remains agnostic about the internal constitution of those systems. Historically, thermodynamics developed alongside speculation concerning the nature of the systems. However the quantities or properties of state appearing in thermodynamic equations are independent of any specific claims about the ultimate constitution of those systems. [8] Similar claims hold as well for the phenomenological theory of hydrodynamics, where the equations governing fluid flow are also continuum equations.

On the other hand, kinetic theory and statistical mechanics aim, in part, to explain the observable behavior (so well-captured by thermodynamics), in terms of more fundamental principles or laws governing the behaviour of the constituents of thermodynamic systems. At base this is a reductive project: the goal is to explain the success of thermodynamics in terms of a more basic theory. This project has been, and continues to be, extremely successful.

Nevertheless, a cursory survey of work relating thermodynamics to statistical mechanics will reveal vast problems with the reductive program. Some of these problems have to do with philosophical issues about how to properly understand what it is for one theory to reduce to another. [18, 4, Chapter 9] [Also, article in REP on reduction.] But other problems are more technical. Even if one could resolve some of the more philosophical issues and agree upon a unique conception of intertheoretic reduction, maybe not all of thermodynamic phenomena can be fully captured by statistical mechanics.

That is, maybe some thermodynamic phenomena are genuinely emergent.

One issue concerns the pervasive temporal asymmetry that is characteristic of most processes we observe around us. For instance, we seem to be able to stir cream into our coffee, but never seem to be able to stir it out. This temporal asymmetry is expressed by the second law of thermodynamics which states that the entropy of an isolated system is a temporally nondecreasing quantity.

One reason to maintain that these asymmetries may be emergent, is the extreme difficulty (if not impossibility) of deriving or otherwise accounting for a time-asymmetric law—the second law—in terms of the more fundamental dynamical laws of kinetic theory or statistical mechanics which are *symmetric* in time. Many attempts have been made, but it is fair to say that these reductive arguments remain both largely programmatic and problematic. [18, 1, 19] sklar REP, Uffink REP.

Another reason to think certain thermodynamic phenomena are emergent can be found in the fact that everyday (and not so everyday) systems exhibit phase transitions and singular behavior. We are all familiar with the change of water from its liquid to its solid phase in our freezers and from the liquid phase to the vapor phase in our tea kettles. Similar transitions occur in magnets, from the ferromagnetic phase to the paramagnetic phase, etc. These qualitative changes in the states of matter, likewise, can be taken to be emergent, as it proves very difficult (if not impossible) to reduce them to the underlying microphysics without appeal to certain infinite idealizations. [16, 5] The new states of matter are genuinely novel from the point of view of the underlying fundamental theory whose focus is primarily on the interactions of the finite molecular components of the macrosystems.

By my lights a the unifying feature that may lead one to think of these thermodynamic phenomena as emergent is the possibility that one may fail to find a satisfactory explanation of them *solely in terms of the more fundamental theory of statistical mechanics*. This explanatory failure is a consequence of the lack of a smooth correspondence between the two theories—one at the macroscale, the other at the microscale. Nevertheless, and this is one feature distinguishing discussions of emergence in physics from those concerned with mental phenomena, emergent physical phenomena such as phase transitions need not be completely mysterious. The claim (though this is a matter of controversy) is that there *are* physical explanations for these phenomena despite the lack of smooth correspondence between theories and despite the explanatory inadequacy of the more fundamental theory. [4, 3, 5]

2 Quantum Measurement

The interpretation of the quantum measurement process has been an important foundational problem since the inception of the theory. [See REP entries on superposition, QM measurement] The problem arises because a macroscopic measuring apparatus can evolve, upon interacting with a quantum system in a superposed state, into a superposition of that apparatus' pointer states. However, the apparatus is never found in such a superposition: one only sees “classically allowed” pointer states at the macrolevel. One way (though, surely, not the only way) to think of the measurement problem is to think of it as a problem of accounting for how the classical macroworld always emerges despite the fact that the world is fundamentally quantum mechanical.

Numerous proposals have been offered to “solve” or dissolve the measurement problem. Suffice it to say that there is no universal agreement as to how best to account for the fact that our classical world view dominates, despite the truth of the quantum theory. Some recent proposals involve appeal to so-called decoherence according to which the environment itself destroys the quantum mechanical superpositions and singles out the preferred classical pointer states. [20, 12] Others involve changing the quantum evolution equation by adding some kind of nonlinear term to the Schrödinger equation. [13]

Interestingly, a number of investigators have argued that the entangled states arising as a result of an interaction between one system and another (possibly though not necessarily macroscopic) system *themselves* should be considered emergent. The two systems can interact with one another such that the composite system is represented by a state vector from which it makes no sense (according to orthodox quantum mechanics) to attribute well-defined states to the individual systems. This holds even if the two systems are localized in spacelike separated regions of spacetime. See [14, 15] for a discussion.

In the context of the emergence of the macroscopic, however, the real issue is how the classical macroworld always results from an underlying quantum reality. This suggests that a fruitful way to understand this emergence and, consequently, the persistence of the measurement problem, is in terms of a failure to find (or the impossibility of there being) an appropriate correspondence relation between quantum mechanics and classical mechanics. Such a view enables one to fit this example of emergence with the others discussed in this entry. Section five, below, makes this connection somewhat more

explicit.

3 High Energy Physics vs. Condensed Matter Theory

In the 1970s a debate among physicists about the nature of fundamental physics came to a head. To some extent the proximate cause of this was financial: Should large amounts of money be invested in high energy projects like the Superconducting Supercollider, at the cost of failing to fund “non-fundamental” research in solid state or condensed matter physics? However, philosophically, the debate is really about the nature of the reductionist program in physics and about what really counts as fundamental physics. [11] To a certain extent, this debate continues today, with stalwart reductionists still searching for a Theory of Everything (string theory, perhaps, being the latest incarnation).

A number of physicists—while accepting the view that in some sense reductionism is true (namely, in the sense that all systems ultimately must obey the fundamental laws of theories “below” them on some appropriate hierarchy of theories)—nevertheless maintained a strong conviction that “higher” level phenomena can be emergent. The levels of the hierarchy are typically delimited in terms of energy scales. The higher the energies, the more basic the physics. (Since higher energies equate to smaller length scales, one can also think of the more basic physics as being the physics of smaller and smaller things.)

Perhaps the most famous statement of this emergentist position can be found in P. W. Anderson’s paper “More is Different.” [2] Anderson distinguished between the “reductionist hypothesis” and a “constructionist hypothesis” arguing that

[T]he ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society. [2, p. 393]

Anderson holds that “. . . at each new level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other.” [2, p. 393]

The general idea here is that “new physics” can emerge at energy or length scales quite far from those explored by researchers examining the basic building blocks of the universe. [7] This “new physics” includes the

physics of stuff at everyday energy and length scales. Broadly speaking, these systems are those studied in condensed matter theory. It is odd in a way to speak of the physics of fluids, magnets, glasses, gels, foams, etc. as being new. But the idea is that such materials at these larger scales exhibit novel behaviors—behaviors that require, for their understanding, novel methods and explanatory strategies.

The emergence of the properties of everyday stuff is best characterized in the context of relations between physical theories at different levels or scales. Not only do the theories of condensed matter involve new and different methods and explanatory practices, but they are, in effect, *decoupled* from theories at lower or “more basic” levels or scales. They are, that is to say, largely autonomous. As a result, one can maintain a distinction between “more basic” theory and “more fundamental” physics: One can accept the reductionist position that higher energy, lower level theories are more basic, but still maintain that research into higher level theories counts as fundamental research.

4 Effective Theories

The idea that different physical theories may apply at different length or energy scales suggests that some (or, more radically, all) theories may be *effective*. An effective theory is one that captures the relevant phenomena in a given relatively circumscribed domain. In quantum field theory there has been some success in showing how a theory appropriate for some range of energy scales is related to a theory for another range via a process of renormalization. While renormalization provides a kind of correspondence between theories at different scales, there are good reasons to maintain that such a relation is not one of reduction and, therefore, is compatible with emergence. In part this is because of the relative independence of the physics at the different scales. Renormalization is, in effect, a mathematical scheme for characterizing how the structure of interactions changes with changing scale: it turns out that the domain characterized by some lower energy (or larger length) scale is surprisingly and remarkably decoupled from that of higher energies (or smaller lengths). In other words, the decoupling entails that the higher energy regime does not much effect the behaviours and character of the lower energy regimes.

If one takes this scale decoupling seriously (and there are very good reasons—theorems—for so doing), then one is presented with the following interesting picture of the theoretical structure of the physical world: Different theories apply in different ranges—at different scales. These theories

may form a tower of theories each of which is phenomenological relative to the theory below it at the next higher energy or smaller length. There are two different attitudes one might take toward such a tower or hierarchy. On the one hand, one might endorse the reductionist ideal that the hierarchy must stop somewhere, at some basic theory of everything. (Of course, this reductionist stance is still compatible with the relative independence of adjacent levels in the hierarchy.) On the other hand, one might remain agnostic about a stopping point and endorse, instead, the view that all theories are essentially effective. This latter position is compatible with a rather strong conception of emergence—namely, that virtually everything we see at any one scale is emergent relative to some higher energy (smaller length) scale. [9, 10]

5 Emergence in Physics

As noted above in the entry description, philosophical conceptions of emergence are, typically, grounded in issues about parts and wholes. Properties of wholes are emergent, rather than merely resultant, when (i) they are not reducible to properties of the parts, (ii) they are unpredictable given exhaustive information about the nature of the parts, (iii) they are unexplainable given exhaustive information about the part, and (iv) they have novel causal powers of their own—powers not exhibited by the parts. [17]

While part/whole relations play some role in the examples of emergence in physics considered above, it is fair to say that those relations are not essential. Rather, it seems that issues about (correspondence) relations between theories are paramount; and such intertheory relations need not be mereological in nature. [4] Instead, relations between phenomena examined at different scales play the essential roles in understanding emergence in physics. These relationships are best exhibited mathematically by examining the behavior of theories in various limits. For instance, one can examine the relationship between statistical mechanics and thermodynamics by considering statistical mechanics in the limit as the number of components of a system approaches infinity. And one can examine the relationship between quantum mechanics and classical mechanics in the limit as systems “get big”. In each case, one examines some kind of correspondence relation between pairs of theories and finds that often the correspondence is not smooth in the following sense. The explanations provided by the more basic theory—typically the theory of the microstructure of the systems of interest—often do not tell the whole story about the behavior of the system. The phenomena for which such explanatory gaps arise are reasonably thought of as emergent. (This is one of the

main points argued in [4] and is by no means uncontroversial [6].)

The examples discussed above, particularly in sections one, three and four, support the idea that emergence in physics is best understood in the context of limiting intertheoretic relations. And furthermore, they support the idea that phenomena at one level (characterized by one theory) may be considered genuinely emergent when those phenomena fail to be fully explainable by the theory at next lower level. Though, perhaps more controversial, the same idea may apply in the context of quantum measurement as suggested in section two. On this conception of emergence, in contrast to that typical in the philosophy of mind, emergent *physical* phenomena need not be completely unexplained or ineffable. The mathematical schemes employed, for instance, in the understanding of properties of condensed matter discussed in section three (the renormalization group) do provide nonreductive explanations.

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