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LOOKING FOR EMERGENCE IN PHYSICS[1]

abstract

Despite its recent popularity, Emergence is still a field where philosophers and physicists often talk past each other. In fact, while philosophical discussions focus mostly on ontological emergence, physical theory is inherently limited to the epistemological level and the impossibility of its conclusions to provide direct evidence for ontological claims is often underestimated. Nevertheless, the emergentist philosopher's case against reductionist theories of how the different levels of reality are related to each other can still gain from the assessment of paradigmatic examples of discontinuity between models in physics, even though their implications must be handled with care.

keywords

emergentism, ontological emergence, epistemological emergence, reductionism, physics, singular limits

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1. Introduction

Emergentism, in its various forms, is the view according to which there are features of reality (properties, objects or laws) that are irreducible to the lower-level basis from which they emerge, in the sense that they are more than just the result of the combination of the system's parts and their interactions. These features are paradoxically (or so it seems) both *dependent* on and *autonomous* from their emergence base, i.e. from the lower-level that brings them about. They are dependent in the sense that they cannot exist unless the lower-level structure is in place, but they are autonomous insofar as that structure does not suffice for the novel features that arise to be fully explained and predicted. This inexplicability and unpredictability is, of course, in the eyes of the beholder and amounts to what is commonly known as epistemological emergence. Still, metaphysical or ontological emergence can be assumed to underlie this apparent underivability, in which case there is a radical discontinuity in the hierarchical organization of reality, whereby the causal effects of emergent phenomena in the world cannot even *in principle* be accounted for by the causal powers of the lower-level structure on which they depend (Kim, 1999; O'Connor & Wong, 2005).

This type of theory has been developed in very many areas, from different scientific branches to philosophy. In the latter field, its study ranges from metaphysics and the philosophy of mind (in which the focus has been mainly on the relationship between mental/conscious entities and their physiological substrate – Kim, 1993; Searle, 1992), to philosophy of science in general (where the focus is on whether certain theories are reducible to others or not – Bedau, 1997), to philosophy of physics (where emergence seems to be a good conceptual tool for explaining nonlinear phenomena – Andersen, 1972) and philosophy of biology (where the main interest is top-down causation in self-organizing systems – Arp, 2008).

What is common in all these fields is the opposition to the reductionist ideal of a Lego world where the elements of the bottom-most domain provide necessary and sufficient conditions for the phenomena taking place at higher levels of organization. According to reductionism, the lower-level properties and laws of a system determine its upper-levels properties and laws. The instantiation of the former necessitates the instantiation of the latter. This implies, as a consequence, that the scientific domain that explains the lower-level occurrences is *in principle* sufficient to explain the upper-level ones (Sober, 1999). Emergentist views all counter this

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perspective with various examples that are used as evidence for the existence of upper-level phenomena that challenge microphysical explanation, not only in practice, but allegedly in principle.

However, needless to say, there is no uniformity in the way the concept of emergence is used and in the candidates that are accepted as good examples of emergent phenomena (Bedau & Humphreys, 2008).

In this paper, I chose to focus on the debate about emergence going on in philosophy of physics, hoping to show its relevance to the general discussion.

2. Emergence in Physics

A commendable tendency in the past years in philosophy of science has been to develop accounts of emergence that move away from armchair metaphysics and anchor philosophical analyses in scientific theory and practice.

Philosopher and physicist Robert Bishop, for example, has been working in questions of Emergence and Complex Systems for many years. Alone (2005, 2009) or together with theoretical physicist Harald Atmanspacher (2006), Bishop developed an account of what he calls "contextual emergence", which is a relation between different levels of description (in its epistemological form) or between domains of reality (in its ontological form), whereby the description, properties or behaviors of the lower domain provide some necessary but no sufficient conditions for the novelty existing at the upper-level. The remaining conditions must be provided by the context, which includes the stability conditions of the emergent states and observables (i.e. the conditions that guarantee their existence and persistence), which are not given by lower-level descriptions. Bishop uses several examples as evidence for the ubiquity of contextual emergence, from the domain of quantum chemistry to that of human society. All of them have to do with scale transformations: how the laws of microphysics give rise to the laws and properties of the macro world.

Bishop is in good company, as voices have been rising in the attempt to tell philosophers and unexamined reductionists that real-world science does not actually have any models that drill down from many-body physics to some mythical microphysical state and that, in fact, productive scientific models largely ignore such thinking altogether. According to nobel laureate Robert Laughlin, for example, the idea that one might in principle deduce the goings-on in the domains of chemistry, biology and other special sciences from a complete knowledge of particle physics is totally unfounded and, even though reductionism is a belief that is central to much of physical research, "the safety that comes from acknowledging only the facts one likes is fundamentally incompatible with science. Sooner or later it must be swept away by the forces of history" (Laughlin & Pines, 2000, p. 264).

Let us now look at some examples of emergence in physics that have been put forward in the literature. The examples challenge the reductionist ideal from different fronts: first, the need for singular limits, for example in the transition from quantum to classical mechanics (section 2.1), is used to call into question the idea that a macro-physical state can be derived from a micro-physical equation. Second, the case of criticality, which is an example of universality (section 2.2), questions the assumption that a macro-physical state has a unique microphysical basis, which is commonly taken as a consequence of a reductionistic world. Finally, the phenomenon of liquidity (section 2.3) highlights the role of stability conditions which are often not provided by the underlying emergence base.

2.1. When a Macro State Cannot Be Derived From a Micro Equation

The transition from quantum to classical mechanics is a mysterious one. Mathematically, these two realms are separated by singular limits (mathematical expansions in which some quantities are assumed to tend either to zero or to infinity), which means that the transition between the formalism that describes the behavior of particles at the quantum level (the Hamiltonian dynamics) and the equations used in the field of many-body physics is discontinuous. The behavior before and after that transition is qualitatively different and has to be described by a totally distinct equation. And in order to move from one equation to the other, Planck's constant is assumed to tend to zero, which is a mathematical trick that departs from reality (where it is actually non-zero). Hence, between the classical and the quantum domains there is a radical epistemological gap which can be bridged only with the help of a formal artifact.

This can be illustrated with the example of molecular shape. Isomers are molecules that share identical chemical formulas but have different spatial arrangements which give them very different properties. According to Bishop, these are good candidates as examples of contextually emergent phenomena since the specific structure into which a certain quantum description (the so-called Hamiltonian) will evolve at the chemical level cannot be deduced from quantum mechanical data alone.

> Even though QM [i.e. quantum mechanics] contains necessary conditions in terms of nucleons, electrons and their properties, fundamental force laws and so forth, observables relevant for molecular structure do not exist in the domain of QM. For such observables to obtain, an additional context not given by QM must be specified (Bishop, 2009, p. 177).

Only with the help of heuristic formal procedures, like assuming the nucleus of the atom to be stationary and infinitely larger than the electron mass, can one derive the equation encoding molecular shape.[2] This means that the chemical context (the stability conditions of a "clamped nucleus" together with the ratio of the electron mass over the nucleus mass tending to zero) must be fed into the mathematical treatment of the quantum mechanical information. It is thanks to these constraints that come from "outside" the quantum realm that the quantum correlations between nuclei and electrons are broken and classical position and momentum observables, as well as molecular shape, can arise.

2.2. When a Macro State Is Compatible With Multiple Micro States

Several natural phenomena share with the previous case this feature of being theoretically dependent on mathematical tricks, such as the postulation of the infinite or null value of certain observables that we know to be finite. They are cases in which the appearance of the macro property is not a mere quantitative derivation from a smaller scale to a larger scale, but rather a qualitative transformation which can be explained and predicted (at least on the basis of the models and theories presently available to us) only through the artificial normalization of singular limits.

According to Robert Batterman, a leading figure in Philosophy of Physics, emergence happens precisely there where singular limits cause our theories to break down. And as a matter of fact, our most important physical theories are asymptotically related in pairs:

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[2] This "clamped-nucleus" assumption is part of the so called Born-Oppenheimer "approximation". Mathematically, it corresponds to an asymptotic series expansion in which the parameter ε (= electron mass/ nuclear mass) diverges to zero, that is, the nuclear mass is assumed to be infinitely large with respect to the electron mass.

$\text{Lim}_{1/c \to 0}$ (special relativity) → Newtonian mechanics
$\text{Lim}_{\lambda \to 0}$ (wave optics) → ray optics
$\text{Lim}_{h \to 0}$ (quantum mechanics) → classical mechanics.

This can be interpreted as an indicator of the inadequacy of our theories and models, or instead as a “source of information”. Batterman has been arguing for the latter attitude for several years now:

> If it were not for the singularities that appear in our theories and models we would have no understanding of the emergence at different scales of distinct and apparently “protected” states of matter (2011, p. 1040).

The “protected” states of matter that Batterman is referring to are what Laughlin and Pines (2000) call “protectorates”, which are stable states of matter which are not only mathematically underivable from more fundamental equations without the help of singular limits, but are also insensitive to changes at the micro-level. These protectorates are the units of the phenomenon physicists call “universality”, which is what philosophers dub “multiple realizability”. One example of such a phenomenon is thermodynamic criticality.
The critical point of a fluid is a state in which liquid and vapor can coexist, and it is determined by a specific temperature and pressure (which is different from fluid to fluid).[3] Surprisingly, once they reach their specific critical point, all fluids (as well as magnets) behave in an identical manner, even if their properties are radically different in other phases and even if the values of their critical points are as diverse as 1,040.85ºC/270 atm for sulfur and -239.95ºC/12.8 atm for hydrogen. This macroscopic similarity beyond microscopic differences has been mathematically accounted for by the renormalization group theory (Batterman, 2002, 2011, 2014). This mathematical technique (for which Kenneth Wilson won the Nobel Prize) shows how the molecular details that are specific to each fluid are irrelevant for the macroscopic behavior that it shares with all other fluids.[4] Batterman’s conclusion (2014, p. 15) is that this concrete method for explicating a process whereby higher order patterns arise that are not derivable from micro-structure can be considered as evidence against reductionism.
In the words of Laughlin, who uses examples such as these in his battle against the reductionistic framework often used in physics, it is obvious at the eyes of solid-state physicists, chemists and biologists that nature is filled with phenomena that are insensitive to microphysical variability, the behavior of which is determined by higher organizing principles, and that we may confidently call emergent.[5] This is one of the reasons why “predicting protein functionality or the behavior of the human brain from [quantum mechanical] equations is patently absurd” (Laughlin & Pines, 2000, p. 260).

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[3] As with the previous cases, this phenomenon too is described as the result of assuming a variable to be infinite: viz. the number of particles or the correlation lengths between them (the distance over which one particle can influence another).

[4] The process, developed by Kadanoff, Fisher, and Wilson (cf. Batterman, 2002), is based on an iterated transformation of the Hamiltonian of each system, by which as one gradually changes scale, more and more fine-grained information is lost and the resulting function ends up being the same for all the elements of the universality class in question (a value that is called a “fixed point”).

[5] Laughlin and Pines (2000) provide various examples. Here are two more: “The Josephson quantum is exact because of the principle of continuous symmetry breaking. The quantum Hall effect is exact because of localization. Neither of these things can be deduced from microscopics and both are transcendent, in that they would continue to be true and to lead to exact results even if the Theory of Everything were changed” (p. 261).

2.3. When Macro Context is as Crucial as Micro Structure

But are emergent phenomena exhausted by cases such as these, where we find radical discontinuities between theories? What can physics tell us regarding properties that do not look so mysterious to us?

Liquidity, for example, is a very familiar property (or cluster of properties) which we may resist considering emergent. In spite of its *in practice* unpredictability and novelty with respect to the properties of the components of the liquid taken in isolation (Weisskopf, 1977), the macroscopic properties of liquids (like viscosity or surface tension) and their causal powers seem straightforwardly derivable from the laws governing chemical bonds and other microscopic states and events. What we see at the level of the liquid is not something *over and above* the goings-on at the level of the molecules and their interactions. So reducibility seems possible, almost unavoidable. However, condensed-matter physicists reply, it is not that simple.

The stability of liquids depends on temperature, which *cannot* be derived from the particle's interactions. Even though in the philosophical literature temperature is still cited as a good example of reduction (it is taken to be *nothing but* the mean translational kinetic energy of molecules in a system), it is actually considered to be a case of emergence by most condensed-matter physicists. Temperature is a property that arises out of two mathematical transitions (from particle mechanics to statistical mechanics, and from there to thermodynamics), the calculation of which depends upon mathematical limits (e.g. the thermodynamic limit, which assumes the container of a gas to be infinitely large) as well as on stability conditions which are not available in the underlying domain, such as thermodynamic equilibrium.

Hence the calculation of the macro properties of liquids cannot be made without first establishing the stability conditions upon which the liquid depends, that is, without taking into account the macro conditions that make it so that some laws of interaction rather than others apply.

Molecular shape and criticality are considered to be good candidates for emergence because of the irreducibility of their macro description to the underlying quantum properties. This happens also in the case of liquids, since they cannot exist unless there is a certain sort of symmetry breaking induced by temperature, which in turn depends on conditions that can be provided only at the macro level. Therefore, if molecular shape and criticality are emergent, liquids should be considered to be so as well.

3. From Epistemology to Ontology in Physics

What the aforementioned examples show is that the reductionist ideal of macro properties being derivable from microscopic features and laws is not grounded in scientific practice. Scale transformations are highly problematic and many aspects of reality seem to simply pop up when a certain threshold of complexity is crossed, which mathematically corresponds to unphysical singular limits.

But is this not a merely epistemic matter? Even if we cannot predict upper-level phenomena on the basis of our lower-level knowledge, this does not imply that we are dealing with ontologically irreducible features.

As a matter of fact, besides the misunderstandings caused by the lack of agreement regarding the definition of emergence to which I alluded briefly in the introduction, another major source of confusion, especially in the scientific community, is the lack of clarity concerning the distinction between epistemological and ontological forms of emergence. Epistemological emergence is a relation existing between theories or models of the world. Ontological emergence is a relation existing between objects or properties in the world. Even though the latter implies the former, the inverse is not true. Epistemological emergence is no guarantee for ontological emergence. The impossibility of reducing a certain theory, with which we explain a certain upper-level domain, to a lower-level theory may be due only to our lack of knowledge of the details and intricacies of that lower level, its parts and the relations obtaining between them. Our theories may be incomplete.

If the epistemic irreducibility we found in the cases described in the previous section were to express a deeper ontological irreducibility, that would mean that there is a spontaneous and unexplained symmetry breaking at a certain point in the evolution of the system, whereby new properties with new causal powers come about. Isomers with different boiling points and densities, critical points in which new visible phenomena such as opalescence take place (the fluid becomes opaque and colored), temperature with different effects on macroscopic bodies (such as melting). If our epistemic limits express true ontological irreducibility, these examples, as well as many others, which might be more or less familiar and more or less complex, all seem to be cases of causally new and irreducible, hence emergent, macro features.

However, it is very hard to apply the epistemological/ontological distinction to physics. Physics does not have the pretense of *knowing* reality. All physics does is designing models that are quantitative, predictive and falsifiable. Whether those models correspond to the actual objective truth is something physics cannot tell us. Such an instrumentalist approach, which is the physicist's default standpoint, can make it hard on the philosopher to extract useful information from physical theory and practice for her metaphysical speculations. Of course, philosophers of a realist inclination would consider it legitimate to move from epistemological facts about physical theorizing to facts about the world. However, they would be moving alone. Physicists would hardly approve of such an extrapolation, which would hence be missing the safety net provided by the scientific method and the credibility that comes with intersubjective agreement.

But philosophers do not give up easily on what might be a fruitful dialogue. Even if physics only provides us with models of the world, one can still hypothesize a laplacean demon, a universal and omniscient calculator, whose complete and truthful knowledge of a certain system might be sufficient to explain all its macro properties. Could such a calculator predict the formation of a certain molecule in a fluid with such and such initial and boundary conditions? Granted, the conceivability of this omniscient being is traditionally used as an argument for universal determinism, not ontological reductionism, the truth of which it assumes from the start. Still, this theoretical exercise serves as a way to flesh out what can otherwise seem too abstract a hypothesis and allow physicists to more easily explicate their case against it.

Unfortunately, they will likely find the idea of a laplacean demon to be inapplicable to current physical science for several reasons. First, because in the world of particles at the subatomic scale, classical physics does not apply. Only once a certain measurement is made, is the system in a well determinate state; before, in general, it is considered to be in what is called a superposition of states. There is no way of knowing with absolute certainty all the information that fully characterizes a physical system: if we know precisely where a particle is located – its position in a certain spatial coordinate –, we will miss all knowledge about its momentum (in the same coordinate), and vice-versa.[6] The laplacean demon, therefore, cannot do his job in the quantum realm.

Second, because the *in practice* impossibility of calculating all the information contained in any macro system, not to mention the whole universe, is considered by physicists to be an *in principle* impossibility. It is presently established that no computer can ever accurately solve the equations describing the total energy of a system with more than ten particles at the quantum level (Laughlin & Pines, 2000, p. 160), because the interactions, which grow with the

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[6] This is, of course, an extreme example of the renowned Heisenberg uncertainty relations.

factorial of N (number of particles), are intractable. So to imagine a universal calculation of the evolution of an ideal "system of the world" just sounds plainly absurd.

Third, because the theories we have that describe and explain macro properties on the basis of molecular properties are statistical in nature. They do not express the sort of one-to-one causality relations we would like a laplacean demon to have access to. This means that a really carefully imagined omniscient being would have to have a theory set that is fully coherent across scales, which is something we are nowhere near to achieving and cannot even know is possible.

A philosopher may tend to react to such arguments with dismay and call attention again to the hypothetical nature of the laplacean demon that need not suffer from the physical limitations of our brains, theories and actual computers, but the dialogue with the physicist will likely have come to a halt.

It seems like the philosopher and the physicist are talking past each other. The former aims at inferences about the ontology underlying our theories, which the latter will never be able to provide. *In principle* reductionism is impossible to prove and so is non-derivability.

4. Weakening the Reductionist's Case

Even if we ignored the distance between the epistemological and the ontological levels, we still could not use as arguments what science might be able to reveal in the future, but only what it is able to verify right now. And even that is extremely difficult to generalize.

Every microphysical law, which is an abstract construct formulated by theoreticians in as simple and context-free a way as possible, is tacitly implying that its application depends on the absence of outside influences (influences from upper levels of organization). What happens in a laboratory, then, is the testing of such abstract physical laws in equally aseptic environments, carefully designed to exclude any disturbing factor. However, outside these controlled setups, things get very messy. Even though the results of the experiments often corroborate the laws we wish to test, they cannot confirm their applicability to real-case scenarios where the boundaries between organization levels are loose and causal interactions between them much more likely (Dupré, 2001).

Hence, it would be fallacious to infer from the results of experimental scientific research such a strong metaphysical assumption as reductionism, which would require us to be able to ascertain with profound detail what happens in increasingly complex and ever changing contexts. Evidence for reductionism should consist in the verification that the behavior of all complex systems (from chemical, to biological, to neurological, to psychological, to social), in real-case situations, can be fully explained by microphysical laws, which is something that cannot even be done at a molecular level.

While one single case attesting to the failure of the *universal* claim of reductionism would suffice to falsify it, the same argument cannot be applied to emergentism, which is committed only to the existence of *some* irreducible phenomena. We would not need to survey the whole natural realm in order to prove it true; one relevant case of irreducibility would be enough.

In this sense, even if the epistemological emergence of many-body properties and the radical mathematical discontinuity between theories at different levels cannot prove the truth of ontological emergentism, they do come in handy as *circumstantial* evidence against the ontological reducibility of the macro to the micro.

In short, given the impossibility of using physics to prove their ontological claims, what both reductionists and emergentists must do is try to make the case for the higher implausibility of their rival position. That is much easier for a weaker, existential claim (emergentism) than for a strong, universal one (reductionism). And while the empirical evidence we have surveyed in section 2 cannot prove the truth of ontological emergence, it can shed strong doubts on its alternative and thus make the case for emergentism stronger.

5. Conclusion

Let us sum up. All the examples used in this paper consist in systemic properties that are *qualitatively* different from the properties of the parts. They can be calculated once we know the stability conditions that allow them to persist, but the singular limits that separate the theories that describe them render it impossible to explain the whole only on the basis of the parts. Nevertheless, the fact that we cannot know whether this epistemic irreducibility corresponds to an ontological gap rather than to mere limitations of our models prevents us from being able to assert conclusively whether these are cases of ontological emergence or not. In the end, the move from the epistemic to the ontological level of analysis is a matter of personal preference and intuition. Physics is silent about what is really *there* and so all it can do to help the emergentist's case is tell her that ontological emergence is not an absurd anti-scientific hypothesis. It is actually plausible, if our theories are true, since the way our models relate to each other is exactly what one should expect if ontological emergence were the case.
Brian MacLauglin has famously said:

> Given the advent of quantum mechanics and these other scientific theories, there seems not a scintilla of evidence that there are emergent causal powers or laws (1992, p. 23).

As we have seen, this statement is highly questionable. Despite the advent of quantum mechanics and other scientific theories that allow us to explain the behavior of the smallest portions of matter we know, there is much more than a few "scintillas of evidence" that there are emergent causal powers and laws in the world. And they might be much more common than usually supposed, even though reductionism cannot be disproven.

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