PERSPECTIVE OPEN

Defining emergence in physics

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The term emergent is used to evoke collective behaviour of a large number of microscopic constituents that is qualitatively different than the behaviours of the individual constituents. This usage is appealingly intuitive but problematically ill-defined: it is vague concerning what qualifies as a large number and what constitutes a qualitative difference. In some contexts, an anthropic definition is offered—something is qualitatively new if it cannot be straightforwardly understood in terms of known properties of the constituents. Among the many shortcomings of this definition, perhaps the most glaring is that it implies that as soon as something is understood it ceases to be emergent; this would mean that understanding the emergent properties of quantum materials (a major focus of this journal) would be oxymoronic.

More broadly still, the modifier ‘emergent’ sometimes appears simply as a colloquial indication that a particular property is of great fundamental importance, and thus newsworthy and highly fundable. Consequently, the term has become somewhat politically charged arising in debates over which subfields of physics are more fundamental; those that are the most reductionist which focus on the physics of the smallest constituents, or those that are least sensitive to microscopic details and thus focus on universal emergent behaviours. Integrating its uses across disciplines, the proper definition of emergence becomes even less clear. In evolutionary biology, emergence often refers to a dynamical process by which new species or new biological structures emerge. In certain philosophical contexts, a form of strong emergence is used to account for the apparent logical gap separating that which is determined by the laws of physics from such basic human characteristics as identity, the existence of a soul and free will.

Clearly, no single definition of emergence can encompass all the uses that the word has enjoyed. Here we discuss a sharp definition of the narrow concept of emergence in physics; we give a mathematically precise meaning to the notion of ‘qualitative difference.’ We propose the following:

An emergent behavior of a physical system is a qualitative property that can only occur in the limit that the number of microscopic constituents tends to infinity.

To flesh out this definition, let us apply it. The distinguishing features of distinct phases of matter, such as spontaneously broken symmetries or topological order, are surely emergent in the above sense. Given that the microscopic physical laws are reversible, the existence of irreversible processes that lead to an increase in entropy is likewise emergent. Hydrodynamics is explicitly concerned with the behaviour of fluids at scales large compared with all microscopic scales. Consequently, all distinct hydrodynamic behaviours, including laminar flow, turbulence and shock waves, are emergent. Critical phenomena represent another distinct form of emergent properties.

On the other hand, merely quantitative distinctions between properties are not, in this sense, emergent. The distinction between highly correlated electronic materials and their weakly correlated brethren is, definitionally, quantitative. There is an emergent property that distinguishes unconventional and conventional superconductors, e.g., those with and without gap nodes on the Fermi surface, respectively. However, by itself, the distinction between high temperature and low temperature superconductors is quantitative, not qualitative.

Recognition of the existence of qualitative distinctions between the physical properties of microscopic and macroscopic systems necessarily informs the way we try to understand both aspects. Emergent properties can only be inferred from an understanding of the properties of the microscopic constituents if the analysis is sufficiently subtle to allow for new properties to arise; for instance, spontaneously broken symmetries can only be understood by explicitly exploring asymmetric solutions of the symmetric equations that encapsulate the physics at a microscopic scale. Conversely, the relative insensitivity of the macroscopic behaviour of systems to the precise microscopic interactions is a barrier to making unique inferences concerning the correct microscopic description that gives rise to the observed behaviours. This is why we turn to the brute force experimental approach of CERN rather than relying on very precise low-energy experiments to infer physics at high energies.

Another element requiring clarification is what is meant by the ‘number of microscopic constituents tend[ing] to infinity,’ or in other words ‘the thermodynamic limit.’ Infinity is an abstraction. Real systems always have a finite number of constituents. When that number is large, it is possible to make increasingly accurate approximate predictions based on reference to the infinite number limit. For instance, a persistent current in a superconducting ring actually has a finite rate of decay. However, since the rate vanishes exponentially with the size of the system, the associated caveat rapidly becomes irrelevant for all practical purposes. It is commonplace for a macroscopic ring to have a decay rate that can be experimentally bounded to be less than one over the life of the universe!

Now, let us broaden our discussion so as to explore the wider applicability of our definition in contexts beyond physics. The sometimes-inexplicable behaviour of crowds is often blamed on emergence; a group of angry citizens is more likely than is an individual to lynch a perceived wrongdoer. However, this ‘new’ collective behaviour is not truly new. Individuals, too, commit murder. A nation’s economy can seem to have a life of its own. Although microeconomics is directly related to decisions made by individuals, macroeconomics is strongly cooperative. In macroeconomics, there are bubbles and trends, and sudden changes in national wealth that are difficult to associate with the actions of one or a few individuals.

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This brings us to the ultimate emergent phenomena—life and consciousness. Putting aside the possibility of a mystical spark of life, we are left with a peculiar dilemma in applying our definition. Although living organisms contain a vast number of constituent atoms, that number is finite. Here we see the dangers of extending our definition beyond the realm of physics. To preserve our cherished notion that there is a sharp distinction between the animate and the inanimate, it would be necessary to posit that there exists a critical level of microscopic complexity (say around the level characteristic of the largest viruses and the smallest bacteria) at which *life* begins. If, however, life and consciousness are sharply defined only in the thermodynamic limit, then we are only approximately alive and operationally conscious.

COMPETING INTERESTS

The authors declare no conflict of interest.

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