The emergence of *Emergence*

Mark Hereld
Mathematics and Computer Science
Argonne National Laboratory
(Dated: March 5, 2020)

Reductionist thinking has had its day (!!!). Emergence offers a perspective on the universe that induces an entirely different structure on the theories describing its inner workings and in particular their relationships across scales. How might development of this idea impact the practice of science and engineering research and development at DOE laboratories on a timescale of a few decades? In addition to providing a worthy target for fundamental research itself, an emergence-driven approach promises several boons to the process of discovery that will manifest as a restructuring of the enterprise. Perhaps we can benefit by embracing it early and enthusiastically.

Paraphrasing [1], when a global behavior arises from the interactions of its local parts and that global behavior cannot be traced back to those individual parts we are witness to *emergence*. We know of a large diversity of mechanisms by which this can happen in disciplines spread across physical scales: cosmology, sociology, transportation, organismal biology, genetics, and particle physics. One often [perhaps always] finds that this transition to surprising and new behavior occurs when the number of component entities grows large [2]. The transition to large N begets a collective system that for all intents and purposes is a new frontier of science, with new possibilities for invention and exploitation.

This descriptive barrier between scales appears to be universal, and has the awkward (but defining) consequence of requiring new laws to be discovered to describe each new level of reality.

It is clear that temperature, for example, is an emergent quantity only valid for large ensembles of microscopic matter. It is less widely appreciated that so-called fundamental constants like the charge on the electron are emergent consequences of the measurement process [3]. That is, they are not fundamental after all (in the conventional sense). In fact, the idea has been floated that perhaps everything is emergent. In the *upward* direction (from the constituent entities to large-N aggregates) this does not cause one much intellectual agita. In the *downward* direction, toward QCD and QED from macroeconomics, that no bedrock exists on which everything is built does inspire vertigo. Whether or not it is true that this hierarchical layering of natural phenomena is infinite in both directions, the broad patterns of emergence repeat themselves up and down the scale.

Reimagining the process of discovery. How might a shift in perspective, from reductionist to emergentist, effect the scientific and engineering R&D enterprise?

While there remains a hierarchy of dependencies in the emergentist POV, its nature is changed with this shift. In place of the traditional progression from the *fundamental* at the bottom and a sequence of the *merely derived* as one moves up, imagine a landscape of new behaviors described by the nature of their emergence from finer grained constituent systems.

Increased focus on the machineries of emergence would catalyze development of common language and tools to facilitate development and exploitation of models. Enabling cross-fertilization between disciplines up and down the emergence hierarchy, the process of discovering laws governing emergent phenomena might be systematized to a degree far beyond what is possible today. Beyond deepening our understanding of the structure of the natural world, these advances would give us new ways to design systems to benefit society in any number of ways: drug discovery, energy production, resource management, automation, and perhaps on frontiers not yet imagined.

While the notion and principles of emergence are embedded in a large and growing number of examples, there is much work to be done to bring order to this all-encompassing terrain of natural phenomena. In the coming decades it is quite possible that the landscape of science will be shaped by the perspectives taking form now [4], leading to a new and broader understanding of where lie the scientific frontiers, efficient methods for sussing out models in new systems, and important advances in the ways that we engineer systems to deliver materials, processes, and energy.

[1] T. De Wolf and T. Holvoet, Emergence versus self-organisation: Different concepts but promising when combined, in *Engineering Self-Organising Systems*, edited by S. A. Brueckner, G. Di Marzo Serugendo, A. Karageorgos, and R. Nagpal (Springer Berlin Heidelberg, Berlin, Heidelberg, 2005) pp. 1–15.

[2] P. W. Anderson, More is different, Science **177**, 393 (1972).

[3] R. B. Laughlin, *A different universe: Reinventing physics from the bottom down* (Basic Books (AZ), 2005).

[4] M. A. Bedau and P. E. Humphreys, *Emergence: Contemporary readings in philosophy and science.* (MIT press, 2008).