# The Physics of Emergence

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*To Hans Primas and Frank Richardson, who both in their own ways have trailblazed paths for understanding the world's richness and complexity.*

# Contents

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# Author biography

## Robert C Bishop

Robert C Bishop studied physics at the University of Texas at Austin under John Wheeler, and philosophy under Fred Kronz and Robert Kane. He has held research postdocs in Freiburg and Konstanz, Germany, and taught philosophy of science and philosophy of physics at the London School of Economics, Oxford University, and Rice University. He is currently Associate Professor of Physics and Philosophy and the John and Madeleine McIntyre Professor of History and Philosophy of Science at Wheaton College.

# Introduction

It isn't unusual among particle physicists to find the belief that elementary particles and forces (or quantum fields) determine everything else in the rest of physics, the whole of chemistry, biology, geology, physiology and (by implication at least) human behavior. It isn't just that physics underlies everything else in the Universe; it's the belief that everything else in the Universe reduces to the play of elementary particles under elementary forces (or the action of quantum fields). Yet, it's equally likely that condensed matter physicists will argue that this is an oversimplified view of physics itself and the relationship of physics to other domains such as biology and psychology.

This book explores these debates in physics. Moreover, it examines cases in physics that appear to lend support to the two sides of the debate by focusing on detailed examples which indicate that the structure of physics and the practice of physics research are both more interesting than is captured in the debates as well as having interesting consequences for how to think about emergence in the domain of physics and beyond. It turns out that stability conditions, global constraints and multiple realizability play particularly important but under-appreciated contextual roles for understanding the physics of emergence.

Reductionist accounts usually maintain that properties and behaviors of systems are nothing over and above the states and intrinsic properties of their 'parts.' Call this *ontological reductionism*. A related thesis is *epistemological reductionism*, the belief that the states and intrinsic properties of their parts ultimately *explain* system behaviors. Furthermore, one can find scientists making confident claims that 'reductionism' is *the* method of scientific inquiry (e.g. [1, 4]).

In contrast, emergence accounts deny one or both of these reductionist claims. Yet, emergence often is either poorly defined, or given a definition that seems obscure or inapplicable to the sciences. Sometimes philosophers and scientists will speak of *strong* or *radical emergence*, meaning some kind of brute bridge laws between elementary particles/forces and biological phenomena, say. Or sometimes radical emergence denotes novel properties and processes that seem to come from nowhere and are independent of elementary particles/forces. Yet, radical emergence is highly problematic and seems irrelevant to the sciences.

Sometimes philosophers and scientists will speak of *weak emergence*, or what I will call *epistemological emergence*, which basically means that biological phenomena, say, aren't explainable or derivable from elementary particles/forces due to some kind of epistemic limitation (e.g. lack of computational or descriptive power). This is a denial of epistemological reductionism, but this situation is ubiquitous; epistemological emergence has no illuminating ontological consequences, being fully consistent with ontological reductionism.

If these were the only options for emergence then this book could end here. Nonetheless, many have looked for some form of *ontological emergence* as a robust alternative to ontological reductionism. Unfortunately, the way the debates are typically framed, the only possibilities for ontological accounts of physical reality are ontological reductionism and radical emergence (e.g. [1, 4]). Given the implausibility of radical emergence and its manifestly disordered picture of the world, ontological reductionism appears to win hands down.

But this is a false forced choice fallacy because the framing leaves out other possibilities for ontological emergence. This book will explore such a form of emergence, known as *contextual emergence* (chapters 3 and 4), originally developed to capture the nuances of inter-scale and inter-domain relations in physics [2, 3]. It offers both a plausible and highly ordered account of the structuring of nature.

A number of objections that have been raised from physics against proposals for emergence (e.g. that genuine emergence would disrupt the lawlike order physics has revealed and violate fundamental laws, that there is 'no room' for any other influences than elementary particles/forces in physics). These objections usually call into question radical emergence as well as presuppose some unexamined assumptions. This book will examine a form of emergence in physics that discards these problematic assumptions. The discussion of emergence herein will be grounded in the details and the context for actual physics explanations, giving physics students, researchers, as well as those interested in physics, the background to be able to explore the physics of emergence for themselves.

Some of the key case studies to be discussed are the relationship between quantum mechanics (QM) and classical physics, QM and chemistry, thermodynamics properties, such as temperature and chemical potential, and statistical mechanics (SM), and micro constituents and large-scale structure (e.g. fluid molecules and convection cells).

It is relatively well-accepted that so-called higher-level concepts such as shape, adaptive behavior, and purpose have no meaning in the domain of elementary particle physics or quantum field theory. It is more surprising to hear that the situation is the same for bread and butter physics concepts such as temperature or chemical potential. Or to hear that it is very often the case in QM that subsystems do not determine the state of the whole system (e.g. entanglement). Such situations challenge typical reductionist intuitions and assumptions as we will see.

## References

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