# Review of Richard Healey, *Gauging What's Real: The Conceptual Foundations of Gauge Theories*

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September 11, 2009

I loved this book. It's not an easy read, but it's deeply rewarding – an important monograph and a useful reference, all in one. Its 2008 Lakatos Prize was well-earned. *Gauging What's Real* is also a book that metaphysicians should take notice of, because it overlaps with – and often challenges – much of the literature on natural properties and Humean supervenience.

But noticing Healey's book is one thing, and comprehending its depth is quite another. The learning curve is very steep – steeper than necessary, perhaps. It would be outrageous to recommend that a non-specialist pick up *Gauging What's Real* without a "prep course" in the philosophy of gauge theory. So let me first provide, insofar as space allows, a prep course and a list of introductory readings.

The place to begin is Lange (2002), which discusses the metaphysics of classical field theories. By the end of Chapter 2, you will have learned that electromagnetism employs a vector quantity called the *potential* (one component is measured in the familiar unit of volts). The curious thing about the potential is that its value is of no predictive significance. Only certain derivatives of this quantity matter in the calculation of experimental predictions. As Lange notes, the "classic" response to this fact has been to deny that the potential is physically real, appealing instead to the electric and magnetic fields as the theory's fundamental ontology.

If you don't finish Lange's book (I recommend that you do), make sure to skip ahead to page 285 of the final chapter, where he briefly explains the Aharonov-Bohm effect. This experimentally-measured phenomenon casts considerable doubt on the "classic" ontology of electric and magnetic fields. It turns out that electromagnetism can influence a measurable feature of quantum particles (their complex phase) even in regions with zero electromagnetic field. This motivates Healey's main project: the search for a new ontology, beyond just the field, for electromagnetism.

With Lange under your belt, you'll be prepared for the first six pages of Healey, before he starts talking about fiber bundles.

This is a bit of a problem with the book, pedagogically – Healey breaks out the mathematical big guns before he needs to. Much of what needs explaining, including Aharonov-Bohm, would benefit from an informal first-pass look which he doesn't provide. Fortunately, there does exist an accessible introduction to the math Healey employs: Chapter 3 of Maudlin (2007). Healey would surely ask that you take Maudlin's philosophical claims with a grain of salt, but I imagine he'd agree that this chapter provides an excellent introduction to fiber bundles, pitched specifically at the "core" philosopher.

That's the last of the assigned reading. Now on to Healey.

His first four chapters form a self-contained study of classical (that is, non-quantum) gauge theories. Since the Aharonov-Bohm experiment depends crucially on the interaction of electromagnetism with a quantum particle, this may seem like an artificial distinction. But I urge the reader not to be tempted by such thoughts. The metaphysical upshot of Aharonov-Bohm rests on the fact that the local values of the electric and magnetic fields do not determine the results of the experiment. Similar results could be achieved in purely classical physics, *if* there were a classical complex field that interacted with electromagnetism, and whose complex phase differences were measurable. In our world, as it turns out, the only such "field" is the wavefunction of a quantum particle – but that seems to be a metaphysically contingent feature of our world. So the metaphysical implications of Aharonov-Bohm extend to at least some classical worlds, and do not essentially depend on quantum theory.

What are those metaphysical implications? Healey argues that the worlds described by classical gauge theories are not made up of fundamental fields localized at points, but instead exhibit a sort of holism. There are three lines of response available to the Aharonov-Bohm example. One is to retain the classic ontology of fields, but allow them to act instantaneously at a distance. This may sound unpalatable at face. Moreover, as Healey notes it doesn't make much sense (for technical reasons) to respond in this way to the Aharonov-Bohm effect in gauge theories more complicated than electromagnetism, such as the theory of chromodynamics that describes the strong nuclear force.

One response that does work – technically, at least – is to accept the unobservable potential as a real and fundamental physical quantity. This view breaks down into a number of versions, but Healey argues that they all fall prey to the same problem: they entail that electromagnetism is indeterministic. The problem arises as follows. Suppose I hand you a specification of the electromagnetic potential everywhere at some time $t$. To figure out the potential that should result at some $t'$ (either before or later), you'd naturally seek a solution of the theory that obeys Maxwell's equations, which codify the known laws of electromagnetism. Then you'd check what value the potential takes on at $t'$. The problem is that there are infinitely many distinct solutions to the equations, each with a different potential at $t'$. These solutions are all empirically equivalent, so usually we ignore the differences between them. But if the potential is a fundamental quantity, we'd better stop ignoring such differences – and we are left with a bizarre sort of unobservable indeterminism.

This argument has been around for some time, but Healey backs it up with a new, entirely original argument. He shows that if one accepts some plausible assumptions of David Lewis's account of how theoretical terms refer, it is impossible for us to construct terms that refer to values of the unobservable potential. Thus, even if the interpretations Healey opposes are correct, the fundamental physical facts according to these interpretations cannot be expressed in any of our theories.

Healey thinks we can do better, by taking the third of the three options I mentioned. He offers an ontology for electromagnetism and other gauge theories that he calls the "holonomy interpretation." The distinguishing feature of this interpretation is its holism: rather than being localized at points, the fundamental physical quantities inhere in closed loop-shaped regions of spacetime. These properties do not generally supervene on the features of the points making up the loops.

All this has so far been restricted to classical gauge theories. Healey goes on in the second half of his book to discuss the technical difficulties and ontological prospects of *quantum* gauge theories. I'm afraid these four chapters will resist comprehension by non-specialists, but for the specialist community they will prove invaluable. (The rest of my review will probably elude the non-specialist, too, for which I apologize.)

That said, the question of how to quantize gauge theories is so deeply vexed that, inevitably, a few important approaches are ignored. Where possible, Healey is careful to work within the framework of algebraic quantum field theory, a decision I applaud given the unique mathematical precision of this approach compared with other forms of quantum field theory. But he is not always clear about the tension that exists between this approach and some of the quantization schemes he discusses. For instance, he begins by discussing quantization that involves gauge-fixing (that is, imposing a deterministic equation of motion on the potential). This otherwise-excellent discussion neglects the fact that research by Franco Strocchi has shown that these forms of quantization, at least in the standard textbook form which Healey presents, are incompatible with the algebraic approach. Gauge-fixing methods are widely employed, and I don't think they should either be omitted or quickly dismissed from a discussion like this. But Healey's book would have benefited from some discussion of the alternatives to the algebraic approach (e.g., effective field theories), which are currently needed to make sense of methods like gauge-fixing.

Readers interested in alternatives to the quantization schemes discussed by Healey should look in two places. The major approach he leaves out (perhaps because it involves a discrete picture of spacetime) is lattice gauge theory. Thorough discussions can be found in any number of textbooks. The other, far less well known scheme is one due to Thirring and Narnhofer (1992). These authors suggest a way around the no-go theorems of Strocchi by proposing an algebraic gauge quantum field theory that employs non-separable Hilbert spaces. This approach has the interesting consequence that the potential is not even defined as a physical quantity on the resulting quantum field theory, laying to rest (if correct) the dispute about whether the potential is physically real. But it is far from clear that Thirring and Narnhofer's approach will bear fruit, any more than the many alternatives discussed by Healey. I'm mainly thankful that our author treats quantum gauge theory the way it ought to be treated – as an open question. He can be forgiven for overlooking a couple of the many possible answers.

## References

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Maudlin, Tim (2007), *The Metaphysics Within Physics*, Oxford: Oxford UP.

Thirring, W. and N. Narnhofer (1992), “Covariant QED Without Indefinite Metric,” *Reviews in Mathematical Physics* 4:Special Issue 197–211.