Title
Interpreting Quantum Theories

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Laura Ruetsche, *Interpreting Quantum Theories*. Oxford: Oxford University Press. Pp. xvii, 377.

Most philosophical work on quantum physics has concerned simple systems. And for good reason. Even one or two particle systems can exhibit the striking features we have come to associate with quantum physics—features such as entanglement, interference, and non-locality. But as far as physics goes, such systems barely scrape the surface. In particular, they have only a finite number of *degrees of freedom*, which means their states are characterized by a finite number of independent parameters. The systems studied in fields such as high energy particle physics and many-body physics, meanwhile, have *uncountably* many degrees of freedom. They are far more complicated than the usual philosophical fare.

This is untroubling as long as the conceptual heart of quantum physics can be effectively condensed down. But what if philosophers' toy systems are fundamentally different from realistic ones? That would be a problem. And indeed, as Laura Ruetsche convincingly argues in *Interpreting Quantum Theories*, systems with uncountable degrees of freedom—what Ruetsche collectively calls QM_∞—*are* fundamentally different from the systems that have become the stock and trade of philosophy of physics, in ways that change the interpretational project.

Ruetsche's book does two things exceedingly well. The first is to provides a (comparatively) accessible and philosophically-oriented introduction to the algebraic approach to quantum physics, which is essential for understanding QM_∞. This is a valuable contribution. The algebraic approach is the setting for much recent philosophical work. And yet learning it is notoriously difficult, as even pedagogical texts are aimed at research-level mathematicians. Ruetsche's book is technically demanding, but it works to bring non-mathematicians along. It is, without a doubt, the best place to enter this literature.

Second, the book sets the agenda for future work on QM_∞, by effectively and judiciously drawing important foundational questions out of a sprawling and difficult physics literature. In this regard, it is a close cousin to John Earman's excellent *Bangs, Crunches, Whimpers, and Shrieks*, which has had a significant influence on subsequent philosophy of spacetime physics.[1] Philosophers of physics will be addressing the questions Ruetsche has raised, in many cases for the first time, for years to come.

Interpreting Quantum Theories centers on what might be called the *problem of inequivalent representations*. The quantum theories that philosophers are accustomed to are set in a mathematical structure known as a (separable) Hilbert space, which is an at-most countably infinite dimensional complex vector space. Rays in a Hilbert space represent possible states of a physical system, and self-adjoint operators on that Hilbert space correspond to properties of the system.

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1 John Earman, *Bangs, Crunches, Whimpers, and Shrieks* (Oxford: Oxford University Press, 1995).

To treat QM_∞, meanwhile, physicists pass to a generalization of this formalism. Now one begins with an abstract algebra of operators corresponding to the various properties associated with the system. States in this more general framework are linear functionals on the algebra whose value at each operator is interpreted as the expectation value of a measurement of that property in that state.

The trouble with this more general framework is that the interpretational tools of Hilbert space quantum theories do not directly apply. Some solace comes from recognizing that any (appropriate) algebra of operators admits a representation in terms of the operators on a Hilbert space. This suggests that one can always move back to the more familiar Hilbert space formalism. But this is a pyrrhic victory. In general these Hilbert space representations are neither unique nor empirically equivalent. In particular, these inequivalent representations, interpreted in the familiar way, yield disagreements about which algebraic states are physically realizable.

Faced with this situation, Ruetsche presents several principled options—what she calls “pristine” interpretations of QM_∞. The two most significant are what she calls “Hilbert Space Conservatism” and “Algebraic Imperialism”. The Conservative claims that, for a given system, there is one true Hilbert space representation, which should be interpreted in the familiar ways. The Imperialist, meanwhile, insists that only the abstract algebra matters: the physical states are the algebraic states, properties correspond to the operators in the algebra, and if our old methods do not apply, so much the worse for our methods.

At this level of description, the Imperialist may appear to have the advantage, since she need not fret over which representation to choose. But there’s a catch. As we have seen, there is a sense in which the Imperialist generally recognizes a broader range of possible physical states. But the Conservative allows for more *properties*. This is because when one represents the abstract algebra as operators on a Hilbert space, the operators in the representation naturally approximate additional operators on that Hilbert space, in a way that is unavailable in the abstract setting. Thus each interpretation suffers from limitations the other does not.

To adjudicate between the interpretations, Ruetsche takes them to the trenches, to see which provides the resources to support the actual explanatory and representational practices of physics. After a masterful survey, she concludes that *neither* interpretation has all of the requisite resources. In particular, she argues, physicists regularly make essential use of operators that are only available to the Conservative, while making equally essential use of multiple inequivalent representations—which only the Imperialist can support. More, the particular mix of Conservatism and Imperialism varies between applications, apparently ruling out a stable interpretation of the formalism that can be articulated independently of the messy details. We are left with what Ruetsche calls “adulterated” interpretations.

Philosophers’ practice notwithstanding, it might seem unsurprising that we cannot separate our interpretation of physical theories from the pragmatics of their application to the world. After all, we are interested in these theories only insofar as they are successfully applied. But Ruetsche believes the problem is more acute. It is not merely that pragmatic considerations enter the debate between the Conservative and the Imperialist. Ruetsche argues that there may not be *any* consistent, general interpretation of QM_∞ compatible with practice. And this, she claims, makes realism about QM_∞ untenable.

The idea that the applications of a broad class of our best physical theories undermine their consistent interpretation in a way that renders realism incoherent is striking. Insofar as Ruetsche's case is convincing, it should have serious repercussions for general philosophy of science—both because it bears on important debates, and because it shows how generalist questions depend on the details of particular scientific theories and their applications. Indeed, Ruetsche's skepticism about the terms of the realism debate and her radical particularism *should* influence general philosophy of science. But that said, her argument ultimately leaves room for disagreement.

Ruetsche's basic claim is that Conservatism and Imperialism each support practices that the other cannot, and that both kinds of practice are essential. But there is an important asymmetry here. The Conservative suffers because she fails to represent putative physical possibilities appealed to in practice. The Imperialist, meanwhile, needs to justify that in certain applications, she may limit attention to a subset of the physical possibilities her interpretation admits, and then use resources that only make sense in those limited regimes.

The trouble is that the Imperialist's opportunism is neither unusual in physics nor difficult to motivate. In spacetime physics, for instance, properties such as the total mass of the universe or global time can only be defined in very special cases. And yet such properties are used in practice, because often the salient spacetimes are precisely the ones in which these quantities make (approximate) sense. To make her case that adulteration in QM_∞ undermines realism, Ruetsche would need to establish that the representation-dependent quantities used in applications of QM_∞ are different in kind from analogous quantities that appear throughout physics. And here it is not clear that she succeeds.

None of this undercuts the importance of the book, however. Indeed, Ruetsche acknowledges that her argument may depend on how one understands idealization in physics. And even if one takes the view just described, there is a great deal of work to do on how Imperialism *can* support the practices Ruetsche identifies—work that will surely proceed within the framework Ruetsche has laid out, by addressing questions Ruetsche has raised. And so, wherever our study of QM_∞ takes us, Ruetsche's book is sure to play a central role.

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