Ruetsche on the pristine and adulterated in quantum field theory*

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It might seem that philosophy of science has fallen on hard times. When not being pilloried by famous scientists, philosophy of science receives scant attention from the educated public. This is not to say that work in philosophy of science is not flourishing; but surely what is flourishing most — in terms of number of jobs, number of publications, etc. — is the philosophy of the specific sciences, such as physics, biology, etc.. So does "general philosophy of science" have a future? Will that subject cease to exist, to be completely replaced by philosophical investigation of the specific sciences?

Judging by its title, Laura Ruetsche's book *Interpreting Quantum Theories* would seem to confirm the trend towards fragmentation in philosophy of science. And indeed, the book does discuss quantum theory in great detail and depth; it would certainly make for difficult reading for somebody with no college-level training in physics. But if you thought that Ruetsche's book adds another nail to the coffin of general philosophy of science, then you thought wrong. Ruetsche's book is set apart from many of the recent books of the philosophy of physics, not only in its engagement with the quantum theory of infinite systems (including quantum field theory), but also in its explicit engagement with questions from general philosophy of science. In fact, while Ruetsche does much to advance our understanding of the quantum theory of infinite systems, her challenge to the "received view" of what it means to interpret a scientific theory will be of interest to anyone working in any sub-field of philosophy of science.

The claim that general philosophy of science has something to say for foundational work in the particular sciences was defended by Larry Sklar in his book *Theory and Truth*. Similarly, philosophers such as Arthur Fine and Bas van Fraassen have argued that work on the foundations of physics bears directly on the big questions in general philosophy of science (e.g. realism vs. antirealism). Ruetsche's book continues in the tradition of Sklar, Fine, and van Fraassen, but with perhaps the most sophisticated engagement with mathematical physics that we have ever seen in a "philosophical" monograph. To my knowledge, no monograph has ever contained both the phrases "no miracles

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argument" and "Connes' classification of type III factors," much less shown how they are related to each other.

So, Ruetsche's book operates on two levels. On the first level, Ruetsche discusses foundational issues in the quantum theory of infinite systems. On the second level, Ruetsche puts forward an argument about what philosophers of science should be doing. Beautifully, these two levels are intertwined throughout the book. However, for the purposes of this review, it will be helpful to separate the strands. First, I will sketch Ruetsche's argument against what she calls "extremist" interpretations of QM_∞. Second, I will discuss Ruetsche's argument that *sans* an extremist interpretation, QM_∞ demands a revision of scientific realism.

According to Ruetsche, philosophy of science must constantly reevaluate itself and its maxims in the light of the complexities of real-life scientific theories. Her case in point is the quantum theory of infinite systems (QM_∞), a theory of notorious mathematical and conceptual difficulty. Ruetsche's main claim is that the traditional conception of *how to interpret a theory* cannot make sense of the complexities of QM_∞. Although her argument for this claim occupies the entire book, we are provided along the way with a pedagogical introduction to QM_∞, as well as with many sub-arguments of independent interest.

As Ruetsche points out, the standing conception of *how to interpret a theory* is based on a metaphor from mathematical logic: one gives meaning to a formal theory — or "interprets" it — by assigning meanings to the symbols so that all the sentences of the theory come out as true. Similarly, the standing conception would have us take a physical theory as a partially interpreted formal calculus, which we can then endow with meaning by describing how the world might be such that the theory is true. Notice that in both cases, there is a clear distinction between two phases: in the first phase, the theory is constructed *qua* formal system; in the second phase, the theory is interpreted or "endowed with content."

This standard conception of interpretation lies behind the copious literature on the interpretation of elementary quantum mechanics. It is typical in this literature first to describe the "statistical algorithm" of quantum mechanics — i.e. a recipe for computing the probabilities of measurement outcomes. Only after a formalism for computing such probabilities has been constructed does the question arise, "what does this theory say?" Giving an answer to that question is the task of interpreting quantum mechanics.

Obviously, we philosophers have had some trouble in agreeing on an interpretation of quantum mechanics. But at least we seem to agree on what needs to be done, i.e. we agree on what formalism needs to be interpreted: the states are vectors in a Hilbert space (or, more generally, density operators), and the quantities are Hermitian linear operators on that Hilbert space. But when we come to QM_∞, everything goes haywire. For the typical case in QM_∞ it's not even clear what the right sets of states and quantities are! So, it seems like philosophers cannot even get started on QM_∞, because the mathematical physicists haven't told us yet what formalism we should interpret.

At this point, Ruetsche reminds us of something that we shouldn't need to be reminded about: philosophy (of science) should be continuous with science. In particular, there is no strict division between the task of constructing a formal system to accommodate the phenomena, and the task of interpreting that formalism. In particular, philosophers can and should be involved even in the first stage of formalizing or regimenting QM_∞, because doing so is not different in principle from interpreting the theory.

To reiterate, QM_∞ is not completely clear about what formal apparatus should be taken to represent reality. For example, suppose that we want to describe the "free Boson quantum field." As usual for quantum theory, we need a Hilbert space whose vectors represent the states of the field. Where do we find this Hilbert space? One possibility is to take the space of solutions to the classical Klein-Gordon equation, and then define a notion of multiplication by complex numbers (which we need, because the state spaces of quantum systems are *complex* vector spaces). Unfortunately, there are at least two distinct natural ways to define multiplication by complex numbers, giving us two distinct possibilities for the Hilbert space of the free Boson field. Well, maybe these two Hilbert spaces are just notational variants of each other? Unfortunately, no: it can be proven that these two choices of Hilbert space give "inequivalent representations" of the canonical commutation relations, and as Ruetsche argues at length (in §2.2), these inequivalent representations give physically inequivalent theories.

Here we encounter a minor crisis in the foundations of quantum field theory, a crisis which has motivated a large proportion of the philosophical literature on QFT in the past two decades — by Ruetsche herself, as well as by Rob Clifton, John Earman, Fred Kronz, and Tracy Lupher, among others. And let's not forget that QFT is our fundamental theory of the constitution of matter! If we can't even say clearly what this theory is, then how are we supposed to interpret it, and how are we supposed to derive metaphysical morals from it?

It is clear that this crisis in QFT was an initial motivation for Ruetsche's book. But Ruetsche's solution to the crisis is a "meta-level" solution: instead of offering yet one more proposal within the ambit of the standard approach to interpreting physical theories, Ruetsche argues that no interpretation within this framework will work, and that we need to change the rules of the game.

As you might expect, there are two sorts of responses — within the ambit of the standard approach to interpreting physical theories — to the minor crisis: one sort of response tries to find reasons for privileging one particular choice of state space, and the other sort of response tries to show that the different choices of state space are, in some sense, equivalent. (It's interesting how these two sorts of responses coincide with traditional realist and anti-realist strategies: the realist inflates our epistemic abilities in order to keep up with ontology; the anti-realist deflates ontology so that our epistemic abilities keep up with it.) Ruetsche then makes two long, sustained arguments: first she argues that neither of these "extremist" responses can allow QM_∞ to do what it has been claimed to do. Second, Ruetsche argues that the standard conception of how to interpret a theory would require adoption of one of these "extremist" responses, and she concludes that the traditional conception must be abandoned. Let's look at these two arguments in turn.

The two extremist interpretations of QM_∞ are described in Chapter 6 and given the titles "Hilbert space conservatism" and "algebraic imperialism." As a reminder, conservatism is the view that whenever we're using QM_∞ to describe something, then we should be using one particular Hilbert space. Imperialism claims that we don't need to choose between the competing Hilbert space descriptions, because they are "descriptive fluff" (to borrow a phrase from John Earman). The consignment of the Hilbert space to the realm of fluff is motivated by a mathematical result derived by Irving Segal. Segal's result shows that all of these competing Hilbert space descriptions have a piece of structure in common; in fact, Segal invented a new branch of mathematics in order to describe this piece of shared structure: the theory of C^*-algebras.

Let's be a bit more clear about Segal's idea. The theory of the free Boson field — the most simple quantum field theory — requires operators $\phi(x)$ and $\psi(x)$, one for each point x of space; moreover, these operators are required to obey the canonical commutation relations:

$$\phi(x)\psi(x) - \psi(x)\phi(x) = i\hbar I.$$

As mentioned above, there is more than one Hilbert space that carries operators satisfying these relations, and these Hilbert spaces yield physically inequivalent quantum theories. But Segal's idea is to restrict attention to a smaller set of quantities: those that can be constructed from the field operators $\phi(x), \psi(x)$ by standard algebraic operations (sums, products, scalar multiples), and by taking limits relative to a very fine topology (one in which few sequences converge). If we use A to represent the algebra obtained by implementing this process on the first Hilbert space H, and A' to represent the algebra obtained by implementing the process on the second Hilbert space H', then Segal shows that there is an isomorphism $f : A \to A'$. For Segal, the isomorphism f provides the mathematical justification for saying, on the one hand, that it doesn't matter which Hilbert space H or H' we use, and on the other hand, that the operators in the algebra A (equivalently A') represent all the "real" physical quantities.

Ruetsche, following Aristides Arageorgis, calls the Segal-style proposal "algebraic imperialism," but it might more appropriately be called "algebraic Ockhamism," or "algebraic structuralism," or something like that. In any case, algebraic imperialism tries to avoid an underdetermination problem by reducing the number of facts about which one needs to make a commitment.

The problem with Hilbert space conservatism is obvious: the conservative owes us a reason for privileging one particular Hilbert space over the others. Ruetsche calls this the "problem of privilege," and discusses it extensively in §6.2. She supplies further arguments against conservatism in Chapters 9 and 10, where she deals with cases where two different Hilbert spaces, say H and H', come equipped with two different particle notions. She argues that no particle notion can be fundamental in QFT, and consequently that general metaphysical considerations cannot solve the problem of privilege.

But what's the problem with algebraic imperialism? In short, the problem with algebraic imperialism is the problem that commonly plagues the Ockhamists: in trying to minimize the number of posits needed to explain a phenomenon, there is always a danger that one does violence to the explanandum. In this case, Ruetsche carries a heavy burden of proof: she needs to convince us that there are phenomena that cannot be explained by the algebraic imperialist.

Ruetsche's argument against imperialism occupies Chapters 12–14, and makes use of two applications of QM_∞: first, Ruetsche argues that quantum statistical mechanics' explanation of phase coexistence cannot be reproduced by the imperialist. Second, Ruetsche argues that quantum field theory's explanation of spontaneous symmetry breaking cannot be reproduced by the imperialist. I will look here only at the first argument, since it is the technically simpler of the two. (Ruetsche herself places more stock in the second argument, since it doesn't involve any controversial idealizations.)

Quantum statistical mechanics (QSM) purports to be able to explain why materials undergo phase changes at certain critical temperatures. Ruetsche considers one particular and well-understood case of this phenomenon, namely the spontaneous polarization of a ferromagnet. Here the task is to make sense of the idea that the ferromagnet has more than one ground state, a fact which cannot be accommodated in elementary quantum mechanics.

To cut straight to the punchline, distinct ground states of the ferromagnet live in different (inequivalent) Hilbert spaces. So, you might think that imperialism actually has the explanatory advantage, since it doesn't privilege one of the Hilbert spaces. Indeed, more is true: the imperalist deems as physically possible any state of the abstract algebra A of observables, and every vector in every Hilbert space gives rise to such a state! So, the imperialist very explicitly endorses the physical possibility of these distinct ground states of the ferromagnet. So where, according to Ruetsche, does the problem arise? The problem, in short, is that the imperalist doesn't recognize enough quantities.

What do we mean when we say that there are "distinct ground states?" Surely we mean that there are two ground states and they differ in some way. But in the physical world, two states differ only if some quantity has a different value. So, if there are two ground states, then there should be some quantity Q that has a different value in the two states. Indeed, this is (intuitively) the case for the ferromagnet: the different ground states disagree on the value of the global polarization of the magnet.

But here, according to Ruetsche, is the rub for the imperialist: the global polarization quantity is not in the abstract algebra A, and so is not recognized as a physical quantity. So, perhaps the imperialist cannot, after all, explain the existence of distinct ground states, because he cannot say how such states differ from each other.

If Ruetsche's argument were as simple as this, then the imperialist would have a simple reply: although the imperialist denies that there is a quantity called "global polarization," there are other quantities in the abstract algebra A on which the distinct ground states will disagree. So, there is certainly no problem — in the abstract — with distinguishing between these ground states. Indeed, more is true: there is a sequence (a_i) of operators in A that converge (in an appropriate topology on A) to the operator representing the global polarization, and the different ground states must assign different values to elements in any tail of this sequence.

But Ruetsche's argument is more nuanced. First of all, I was being sloppy when I said that the sequence (a_i) in A converges to the global polarization operator. In fact, A is not complete in the relevant topology, and (a_i) is a Cauchy sequence with no limit point in A. So, the global polarization operator does not live inside A, but in a completion $A^=$ of A relative to a specific topology. So, does the imperialist really mean that all operators in $A^=$ represent physical quantities? No, he cannot mean this, because $A^=$ is not shared across all of the possible Hilbert spaces $H, H', H'', \dots$. In other words, taking $A^=$ as the set of physical quantities is tantamount to choosing one particular Hilbert space H, a choice that the imperialist has already foresworn.

Furthermore, there are states of the abstract algebra A relative to which the expectation values of the sequence (a_i) of operators do not form a convergent sequence of real numbers. Thus, the imperialist cannot treat the sequence (a_i) as a surrogate for the global polarization observable, because this sequence does not give well-defined expectation values in every state.

What is the imperialist to do? At this point, I can tell you what they actually do, where "they" denotes the mathematical physicists who work with QM_∞: they declare that only a proper subset of the states on A are physically possible. Without going into details, an appropriate choice of the subset of physically possible states brings the quantities and states back into harmony: there are enough states to describe all situations we encounter, and there are enough quantities to distinguish the features of these states.

So why not just make this small addendum to imperialism: not all states on A are physically possible, but only a subset thereof, which must be chosen based on specific features of the system under investigation. I'll lay my cards on the table and say that this addendum is probably the right way to go. But the addendum has a problem: it does not lead to a "pristine interpretation" in Ruetsche's terminology. According to Ruetsche, an interpretation of a physical theory is *pristine* if in identifying the physically possible words, it invokes only, "general principles of metaphysics and epistemology" (p. 4). But this addendum to imperialism requires one to invoke contingent factors in order to whittle down the state space; as such, this addendum "adulterates" imperialism.

One might think that adulteration is a bad thing, and indeed it has been treated as such — according to Ruetsche — in most work on the interpretation of quantum theory. But Ruetsche's argument is intended to show that one must adulterate in order to give an adequate interpretation to QM_{∞}.

Back to the big picture, what does all this have to do with general philosophy of science? According to Ruetsche, the ideal of pristine interpretation is motivated by scientific realism, and specifically by the sort of scientific realism that rests on the "no miracles" argument. Recall that the no miracles argument says that the success of a scientific theory T would be a miracle if T weren't at least approximately true. Ruetsche claims, however, that while the no miracles argument might look plausible in the abstract (with T a free variable), it can start to look fishy when T is replaced with a specific scientific theory. For example, let T be elementary quantum mechanics, which is obviously successful, at least at making predictions. But does that success give us reason to think that quantum mechanics is (approximately) true? The problem here is that quantum mechanics is only partially interpreted, and so we would have to endow it with content — i.e. interpret it — before we could believe or disbelieve it.

In the case of elementary QM, there are pristine interpretations, e.g. the Everrett interpretation, Bohmian mechanics. So, one might think that the success of QM gives us reason to believe one of these interpretations. Now, QM_{∞} is even more empirically successful than elementary QM, so shouldn't we also believe QM_{∞}? But if we were convinced by Ruetsche's arguments, then there is no pristine interpretation of QM_{∞} that underwrites its empirical success; there are only various adulterated interpretations that work for specific applications and contexts.

What is the upshot for general philosophy of science? Some might think that the upshot is a strong argument against scientific realism. But Ruetsche doesn't ever suggest abandoning realism; rather, she suggests that realism must adapt itself to the complexity of current scientific theory. At this stage, it starts to become unclear to me what Ruetsche is proposing as a modified scientific realism. One possibility is that she is proposing a sort of contextualized realism, according to which we should believe our individual theories, but should not attempt to supply a single interpretation — or metaphysical account — that encompasses all these theories. Such a contextualized realism is probably the most phenomenologically adequate account of current science, since the size of the research community has made it practically impossible to unify all the diverse strands of knowledge. But, in my opinion, contextualized realism is more of a stop-gap than an ideal for which we should aspire.

In selecting out a few threads from Ruetsche's book, I have not come even close to doing justice to its rich contents. Beyond the points I have covered, there are entire chapters devoted to the modal interpretation applied to QM_∞, to spontaneous symmetry breaking, and to phenomenological particle notions. Each of these chapters by itself makes an important contribution to philosophy of physics; but amazingly, Ruetsche ties them each to the overarching argument against pristine interpretations, and for a modification of traditional scientific realism.

I hope to have given you some sense of the sophistication of Ruetsche's book. It is a book that repays close study, and which should be discussed extensively by philosophers in the years to come.