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Book Review

Review of Tim Maudlin's "Philosophy of Physics: Quantum Theory"

Travis Norsen

Smith College, Northampton, Massachusetts 01063, USA

E-Mail: tnorsen@smith.edu

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Tim Maudlin's latest book – "Philosophy of Physics: Quantum Theory" (Princeton, 2019) – is certain to become an influential and widely-read text on the continuing struggle to make physical sense of quantum mechanics. The book is a sequel, or perhaps just a companion, to Maudlin's 2015 "Philosophy of Physics: Space and Time", but the new "Quantum Theory" volume stands perfectly well alone; readers interested in delving into Maudlin's illuminating perspective on quantum theory need not work through the earlier volume first (though many would undoubtedly enjoy doing so at some point, and the earlier book does provide relevant background to some of the issues raised at the very end of the new book).

In general, the new book reflects Maudlin's characteristic tenacity in following Einstein's advice to make things as simple as possible, but never simpler. The book, that is, is highly readable and will be accessible to anyone interested in its subject matter, including undergraduate philosophy students with a sparse technical background in physics; but the treatment is also ruthlessly honest in presenting the physics in an accurate (if not-too-technical) way. Indeed, although one will not learn the mathematics of quantum theory from this book, one will acquire, from Maudlin, a far more accurate understanding of the status of that mathematics than one can get from any traditional physics textbook.

The book is carefully and thoughtfully organized, beginning with an essentialized overview of the empirical basis of quantum mechanics, which Maudlin summarizes via eight carefully-chosen experimental scenarios. In addition to more standard things (like single-electron interference, Stern-Gerlach, and EPR), I especially appreciated here the inclusion of the "double slit [experiment] with monitoring" (in which the position of a proton registers the passage of an electron through either the upper or lower slit) and also the GHZ setup. Both of these provide the basis for important later discussions of the sort one cannot find in other extant books on the foundations of quantum mechanics.

The second chapter provides an overview of the quantum mechanical formalism, which Maudlin stresses is more a "recipe" for making empirical predictions than it is a proper physical theory. Here Maudlin does a nice job of maintaining his audience's motivation, for what might otherwise feel like the chore of laying the minimal mathematical groundwork needed for the rest of the book, by staying focused on how the quantum formalism accounts for the (real or expected) results of the eight experiments from the previous chapter. The concreteness of those

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experimental scenarios – and the occasional illustrations – help keep the narrative flowing and accessible despite the math.

After a short third chapter to which I will return below, we are then treated to three full-chapter-length presentations of versions of quantum mechanics which are not mere prediction recipes, but full-fledged candidate theories: the spontaneous collapse theory (of Ghirardi, Rimini, Weber, and others), the pilot-wave theory (of de Broglie and Bohm), and the many-worlds theory (of Everett). Maudlin discusses the spontaneous collapse theory first, as a plausible way of converting the standard quantum recipe into a proper theory, using this also as an opportunity to introduce "the problem of local beables" (which is a problem for the orthodox version of "quantum theory", the problem being, in a nutshell, that it doesn't include any). The pilot-wave theory is then presented as the playing out of the other side of Bell's alternative: "[e]ither the wavefunction, as given by Schroedinger, is not everything or it is not right." Everett's theory is then introduced as a perhaps-unanticipated third way out of Bell's dilemma.

I found these three chapters – which are in some sense the core of the book – very rewarding and satisfying. Each one provides both a clear "big picture" appreciation for why someone would consider the theory appealing and/or promising, and also a detailed explanation of how, exactly, the theory accounts for the empirical observations summarized in the eight experiments. Even people who are already familiar with the theories will learn something from Maudlin's presentation, as I did, for example, about the "peculiar thinness of the local beables at the microscopic scale" (p. 115) in the "flashy" version of GRW, and the extent to which the ontology problem in the many-worlds theory "has been obscured by a linguistic labeling trick" (p. 196). I also learned a tremendous amount from Maudlin's summary and critical analysis of the sprawling literature on attempts to understand/derive Born rule probabilities in the context of the many-worlds theory. There is also considerable illumination on offer in Maudlin's explanations of how the pilot-wave theory accounts for the double slit experiment with monitoring.

A shorter final chapter reflects on the prospects for reconciling the various candidate (non-relativistic) quantum theories with some notion of fundamental relativity and with characteristically relativistic phenomena such as particle creation and annihilation. One important lesson that emerges from this discussion is that even theories that make identical empirical predictions need not share the same status vis a vis compatibility with relativity. Although this chapter raises more questions than it resolves – the reader is truly brought to the current frontier of knowledge – it is nevertheless satisfying as a final illustration of the fact that the different candidate theories surveyed in the book really are distinct physical theories with distinct prospects for growth and development.

The one criticism I would make of the book is that it doesn't go quite far enough in recognizing and implementing an important distinction that, as far as I know, Maudlin introduces here for the first time. The distinction I have in mind is the one between "the wavefunction and the quantum state", which is the title of the book's third chapter. As Maudlin explains:

> "The term 'wavefunction' is used in different ways in different discussions of quantum theory, but throughout this book, we will be fastidious about its meaning. A wavefunction is a purely mathematical item used for calculational purposes in the quantum recipe. Specifying a wavefunction for a physical system means associating a particular mathematical object with that system, no more and no less." (p. 37)

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In the third chapter, Maudlin argues quite convincingly (first based on the intuitive explicabilitly of interference phenomena, and then by rehearsing the more rigorous theorem of Pusey, Barrett and Rudolph) for the so-called psi-ontic approach, in which the wavefunction is understood as representing some physically real aspect or property of individual systems. This – whatever it is, exactly, that wavefunctions are *about* – is what Maudlin refers to as the "quantum state": "[o]ne might maintain that the wavefunction represents some physical feature of individual physical systems, in which case we will call that feature the *quantum state* of the system." (p.37)

If the wavefunction represents some physically real aspect of individual systems, rather than just, say, someone's incomplete knowledge of the state of the systems, then we have to take the structure and time-evolution of the wave function – including for example the collapse process that is part of the standard quantum recipe – seriously. This explains why Maudlin views the spontaneous collapse theory in the way I described it above: a plausible way of converting the standard quantum recipe into a proper theory. It is the most straightforward way of combining the standard quantum recipe's two conflicting rules about how wavefunctions evolve (the Schroedinger equation and the collapse postulate) into a single unified time-evolution law.

But even having established that the map (the wave function) is a map *of* some territory (the quantum state), we still need to be careful to distinguish the map from the territory. Maudlin is generally sensitive to this point, but also sometimes seems to read properties of the territory (the quantum state) off from properties of the map (the wavefunction) in a way that seems questionable to me. For example, in discussing Einstein's commitment to separability (the idea that "the physical states of spatially separated systems [should] be specifiable independently of one another" (p. 81), Maudlin seems to assume that quantum states are not (necessarily) separable, because wavefunctions are not (necessarily) factorizable. But it's not clear to me why this should follow. Couldn't an entangled (non-factorizable) wavefunction be providing some kind of abstract, indirect representation of a perfectly separable quantum state (of some admittedly unknown sort)?

Relatedly, at several points Maudlin makes statements along the following lines: "the quantum state is itself not anything that exists in physical space" (p. 111), "the quantum state is not a local beable" (p. 115), "the wavefunction is not straightforwardly connected to physical space-time, nor is the quantum state" (p. 137), "[t]he quantum state is a real, nonlocal entity" (p. 171). But how do we know this? It seems to be implied that the quantum state cannot be a thing (or set of things) that exist(s) in physical space, because the wavefunction is, mathematically, a function on an abstract high-dimensional (non-physical) space. But this seems like a case of conflating the map with the territory. It also seems at odds with what we know about such abstract spaces from less controversial areas like classical mechanics. For example, a point in 3N-dimensional configuration space (or 6N-dimensional phase space) in classical mechanics provides an abstract, indirect representation of the configuration (or state) of stuff that exists in physical space, namely, N particles. Are we really certain that the quantum mechanical wavefunction does not similarly represent a physically real quantum state that is more mundane than we've thought possible? Could the quantum state be something that *does* live in ordinary physical space, and which has just been described in a weird, indirect, abstract way with the wavefunction?

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If this is a possibility, it is highly relevant to "the problem of local beables" for the spontaneous collapse and many-worlds theories, and could shed light on the otherwise-puzzling status of the quantum state for the pilot-wave theory as well. In the context of Everett's theory, Maudlin discusses, and is I think rightly critical of, the idea that local beables might somehow be understood to "emerge" from the quantum state. But what if local beables don't have to "emerge", because the quantum state *is* local beables in the first place – just represented in an indirect and puzzling way, that we have not yet deciphered, via the wave function? I do not think this possibility has been convincingly ruled out.

Admittedly I do not have a concrete proposal in mind here. (Or, more precisely, the best concrete proposal I've been able to come up with – in which the wavefunction represents an infinite collection of interacting fields in physical space – is a little too cumbersome and ugly, even for my unsophisticated taste.) But still, it seems worth pointing out that there is a bit of a gap in the reasoning – from "the wavefunction is mathematically nonseparable" to "the quantum state is itself not anything that exists in physical space" – even if only to encourage efforts to more rigorously close the gap.

I come back to this. In the same way that Maudlin rightly regards the phenomenon of interference as a powerful argument that the wavefunction represents some actually-existing quantum state, I regard the phenomenon of interference as a powerful argument that the quantum state in some way includes something like fields that live in physical space. What other sort of thing, after all, can exhibit interference in the region behind a pair of slits? More people, I think, should devote more attention to the project of finding models of the quantum state which render such interference phenomena physically comprehensible by providing the sort of direct and literal description that, I suspect, the wave function fails to provide.

I'm not sure how Maudlin would feel about this proposed project, of seeing whether we might, after all, be able to understand the wave function as a description of some sort of collection of local beables . In the book, he does argue – convincingly in my opinion – that we need shoulder no obligation to fit the quantum state into some pre-existing Aristotelian category (pp. 92-93). It would hardly be surprising, after all, if the most novel and surprising scientific discovery of the 20th century had not been fully anticipated by Ancient Greek metaphysicians, even the best of them. It may, that is, turn out that the quantum state is a genuinely novel sort of thing (as fields were in the 19th century) that we will simply need to learn to live with. As Maudlin has so convincingly argued elsewhere, our metaphysics should fit itself to the legitimate findings of science, not act as a straitjacket on science. But I do worry about the possibility of being so open to the idea of the quantum state being some weird new thing, that might not fit into any existing box, that we don't even bother *trying* to make sense of it in familiar physical terms.

So, on this one point, I maybe have a mild disagreement with Maudlin about how best to implement, in practice, some principles we seem to agree about. But this point is both subtle and quite marginal to the overall thrust of the book. The only reason I've gone into it here is that book reviews which don't find something to criticize are typically boring and worthless!

So let me close by recapturing the big picture. Maudlin's new book will make an excellent primary text on the foundations of quantum mechanics for philosophy students, and will also make an excellent and desperately-needed supplement to the standard quantum physics texts of physics students. It is the kind of book that can be read and enjoyed, for pure pleasure, by interested laypeople of unusual intelligence and sophistication – and also profitably studied by people who are already experts in physics or philosophy. The book will undoubtedly be loved

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by some and also hated by many (e.g., those whose preferred theories do not meet Maudlin's clearly-articulated and, in my opinion, entirely reasonable standards). But everyone will recognize this as a profoundly important book, which will set the terms of subsequent debate in the field. And the field will make forward progress as a result.

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