Review of Alyssa Ney, *The World in the Wave Function* (Oxford: Oxford University Press, 2021; 269pp).

David Lewis famously quipped that he was willing to take metaphysical lessons from quantum mechanics only when it cleaned up its own act by providing interpretations or modifications of the formalism shorn of appeal to consciousness, irreducibly macroscopic notions, or outright instrumentalism. By the 2000s multiple approaches to quantum mechanics had been developed to a degree which met Lewis's challenge: dynamical-collapse theories, Bohm-style hidden-variable theories and Everett-style many-worlds theories, for all their respective problems and challenges, all offer ways of understanding quantum mechanics that metaphysicians can reasonably engage with. And so the last twenty years have seen a resurgence in the metaphysics of quantum mechanics, the question of what ontology and ideology is appropriate to a quantum universe. The metaphysics of quantum mechanics is not independent of the quantum measurement problem, but does not coincide with it either: there is a widespread view that adopting, say, the Everett interpretation still leaves significant ontological questions undecided, and conversely, a given answer to those questions might answer them for a dynamical-collapse theory too.

Wavefunction realism has become a leading contender for the metaphysics of quantum mechanics, particularly in the case of dynamical-collapse and Everettian approaches. The starting point is non-relativistic quantum mechanics expressed in configuration space: mathematically, the subject matter of the theory is a complex function of 3N variables, evolving under the Schrodinger equation (perhaps interrupted by occasional stochastic collapses). Traditionally those 3N variables are interpreted as the 3 coordinates of position of N particles – but in wavefunction realism, they are interpreted as points in a new, high-dimensional space. Quantum mechanics, according to the wavefunction realist, fundamentally concerns the undulations of the wavefunction in this space; three-dimensional goings on are emergent, high-level, derivative.

Alyssa Ney has been a leading figure in the development of wavefunction realism for most of its existence. Her papers advocating and developing the position have been highly influential, and the present book can be seen as the culmination of this line of her research and is the definitive statement of wavefunction realism as of 2021. Despite its comparative brevity the book is too rich to be adequately described – far less critiqued – in this brief review; my goal is to give an overview of the main themes and arguments, and to make a few critical remarks along the way.

The World in the Wavefunction is not formally divided into parts, but it can profitably be thought of that way. Chapters 1-3 develop the core case for wavefunction realism. Chapter 4 defends the position from the frequent criticism that it is restricted to nonrelativistic physics, by providing a version of wavefunction realism appropriate to quantum field theory. And chapters 5-7 are an extended exploration of how the observed 3-dimensional world can be understood as emerging from a high-dimensional fundamental reality.

The case Ney makes in chapters 1-3 for wavefunction realism is modest and cautious. In chapter 1 she provides a fairly standard – though elegantly expressed – case for the *prima facie* plausibility of wavefunction realism simply based on the fact that standard formulations of quantum mechanics are written in 3N dimensions, and on the (related) fact that entanglement means we cannot interpret quantum mechanics simply in terms of spatially localized particles and nothing else. But in chapter 2 she explicitly argues against any attempt to strengthen these plausibility arguments into reasons why wavefunction realism *must* be adopted; indeed, she provides a detailed and sympathetic taxonomy of the alternatives to wavefunction realism that have been developed, all of which she regards as entirely viable.

(Chapter 2 of the book could profitably be used as introductory reading for a general graduate course on quantum metaphysics.) For Ney, the question of which metaphysics to adopt is a standard metaphysician's question, to be answered by weighing strengths and weaknesses of the various alternatives against one another.

In chapter 3, Ney identifies two such strengths for wavefunction realism. Firstly, it is *separable:* we can specify the complete state of the Universe point-by-point on the fundamental space, without any need to appeal to irreducible holism. Secondly, it is *dynamically local*: expressed in 3N-dimensional space, the Schrodinger dynamics involve no action at a distance.

Ney makes the case for separability at length. Her case for dynamical locality is brief: she regards it as a straightforward consequence of the fact that the Schrodinger equation is a differential equation, so that the rate of change of the wavefunction at a point x depends only on the wavefunction arbitrarily close to x. But I think there is more worth investigating here: after all, the non-relativistic Schrodinger equation may be a differential equation, but it is a *parabolic* differential equation, with no maximum speed of propagation: the rate of change of the wavefunction at x may depend only on a neighborhood of x, but the value of the wavefunction at x an arbitrarily short time later depends on the wavefunction everywhere in space. (And this is not – or not straightforwardly – just an artifact of ignoring relativity.)

But in any case, why think that a separable, local theory is preferable to the alternative? Ney claims that separability and locality are more intuitive and lead to a more comprehensible ontology – and she makes an unabashed defense of intuitiveness and explicability as theoretical virtues. She is quite explicit that her reasons are pragmatic: intuitive theories benefit students and teachers; they are better suited to help us develop new theories; they speak better to the reasons why many students (Ney included) want to study physics in the first place. The implied metaphilosophy here is fascinating and it would be good to see it developed further in subsequent work: Ney seems to reject the mainstream modern approach to ontology (in which these pragmatic virtues are not obviously relevant to the *truth* of wavefunction realism) in favor of something neo-Carnapian where (so far as I can see) the goal of a quantum ontology is to help us get a deeper understanding of quantum mechanics, and that's all there is to it. This also fits naturally with the pluralism she urges, in which approaches other than hers can also be valuable.

Chapter 4 – on relativistic generalizations of wavefunction realism – attempts both a conceptual and a technical task. The conceptual task is to argue that wavefunction realism *per se* is not wedded to any particular theory or choice of Hilbert-space basis within the theory: rather, wavefunction realism is *any* strategy that reifies a high-dimensional space in order to produce a separable local quantum ontology. If so, there is no block in principle to a relativistic generalization of the approach: we just need to find some appropriate high-dimensional space to describe the quantum state in relativistic quantum theory.

The general philosophical point is well taken and convincingly defended (though it's important to note that while arbitrary choices of Hilbert-space basis will give a *separable* theory, there is no reason to assume they will give a *dynamically local* theory: even something as simple as shifting from the position to the momentum basis in nonrelativistic quantum mechanics transforms the Schrodinger equation into something explicitly nonlocal). Unfortunately I don't think Ney succeeds in giving a clear statement of the high-dimensional space she has in mind for quantum field theory. This is one place where her laudable goal of making the book intelligible to non-specialists becomes problematic: she makes many suggestive and interesting comments on quantum field theory but there is no explicit, precise, mathematical statement of her view that can be contrasted with the explicit, precise mathematical representation of the state in nonrelativistic quantum mechanics as a complex function on 3N-dimensional space.

In the last part of the book – concerned with the emergence of ordinary three-dimensional ontology – Ney begins (chapter 5) by rebutting influential arguments by Maudlin, Allori, Goldstein and others that it is empirically incoherent for a physical theory not to make precise, non-emergent, non-derivative statements about matter in three-dimensional space (for a theory not to have a *primitive ontology*, to use the standard term for it). Ney argues – persuasively, to me – that it is perfectly compatible with the way science usually works for a theory to make statements about the observable only in an indirect, derivative way, so that while it might be a *desideratum* for a theory to have a primitive ontology, it is not compulsory for it to do so in order to be empirically adequate. She goes on, though, to note that a satisfactory quantum metaphysics had better recover the existence of ordinary 3-dimensional objects, on Moorean grounds: we are really confident that those objects exist!

Chapter 6 is largely critical: an extended exegesis of the functionalist strategy for recovering higher-order ontology developed by David Albert, myself, and others. She raises two main criticisms of the functionalist strategy: it fails to distinguish between the wavefunction *simulating* three-dimensional objects and *constituting* those objects; it is restricted to recovering *classical* three-dimensional ontology, whereas we want to recover quantum-mechanical phenomena in three dimensions too. (The former objection is a development of criticisms by Monton, Maudlin and others; the latter is novel so far as I know.) For reasons of space I won't attempt to reply on behalf of the functionalist, but Ney certainly puts the challenge with admirable clarity.

The final chapter of the book presents Ney's positive account of emergent ontology, based not on functionalism but on considerations of symmetry (though she concedes that the separation is not completely sharp). Simplifying Ney's subtle position: the permutation symmetries of quantum mechanics give a clear *dynamical* reason to regard certain decompositions of 3N-dimensional space (intuitively: those that decompose it into the N-fold product of Euclidean space) as preferred; that then licenses the metaphysical hypothesis that a localized wavefunction in 3N-dimensional space has, as its parts, particles in 3-dimensional space. If the wavefunction is *not* localized (as will be the case generically, at least for the Everett interpretation) then we can think of those particles as being partially localized in various different regions of space.

I have to say that I am not convinced this works, at least without a dynamical collapse mechanism: in the Everett interpretation, it will yield an ontology where *all* the particles are *completely* delocalized. We only see a somewhat-localized description of matter in three dimensions when we restrict to an Everett branch, and that restriction is normally motivated on functionalist grounds. But this may simply reflect subtleties of Ney's intriguing proposal that I am not fully grasping at present.

In summary, I congratulate Ney for a rich, subtle, and provocative account of wavefunction realism. Her edited collection of papers (co-edited with Albert), *The Wave Function*, set the agenda for much of the metaphysics of quantum mechanics in the 2010s; *The World in the Wave Function* has a good chance of doing the same for the 2020s.

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