Book Review

The World in the Wave Function: A Metaphysics for Quantum Physics, by Alyssa Ney, Oxford: Oxford University Press, 2021. Pp. xiv + 269.

Alyssa Ney's book, *The World in the Wave Function*, defends 'wave function realism' (WFR), which

> is a way of interpreting quantum theories so that the central object they describe is the quantum wave function, an object they view as a field on an extremely high-dimensional space. According to wave function realism, we and all of the objects around us are ultimately constituted out of the wave function and although we may seem to occupy a three-dimensional space of the kind described by classical physics, the more fundamental spatial framework of quantum worlds like ours is instead quite different, one of very many dimensions, with no three of these dimensions corresponding to the heights, widths, and depths of our ordinary experience. (pp. ix–x)

This is a fantastical thesis—albeit not currently a popular one. As Ney notes, 'wave function realism is a position whose advocates … can be counted on a single hand' (pp. xi–xii). Ney's goal is to 'present what I regard as the best case that can be made for wave function realism' (p. xii), and thereby to rectify this situation.

Ney's book is a remarkably clear piece, which anyone interested in the metaphysics of quantum mechanics (QM) would be well advised to read; indeed, whatever one makes of WFR, there is much to learn here regarding central issues in the foundations of QM. That said, ultimately the book fails to convince that WFR is *the*—or even a *viable*—approach to the ontology of QM; at the very least, there remains much to be done to render the position compelling. (In fairness to Ney, she acknowledges this latter point throughout the book.)

Before I discuss the content of Ney's book any further, I should define WFR. Consider Euclidean three-space; the position of any particle in this space is given by three numbers; thus the positions of N such particles are specified by $3N$ numbers. For such a system of N particles, 'configuration space' is a $3N$-dimensional space, each point of which encodes the instantaneous positions of all N particles. More generally, a configuration space is the space of possible instantaneous positions of some system. Classically, a trajectory through configuration space represents a history of that system; given some dynamics, only certain histories are dynamically allowed.

Recall now that the basic objects of QM are vectors $|\psi\rangle$ in some Hilbert space. Projecting onto the position basis, one obtains a wave function $\psi(x) := \langle x|\psi\rangle$ which is a function from configuration space to the complex numbers. The wave function is thus a complex-valued field on configuration space. While classically, dynamically allowed trajectories are given by paths through configuration space, in QM dynamical possibilities are given by the correct evolution of the wave function on configuration space—where 'correct' means in accordance with the time-dependent Schrödinger equation.

The empirical significance of the wave function is this: for N particles, the probability of their $3N$ position coordinates lying in a small volume δV around a point $(q_1, \ldots, q_{3N})$ is given by the Born rule, that is, by $|\psi(q_1, \ldots, q_{3N})|^2 \delta V$. Regardless of this phenomenological connection, however, there remains a challenge to account for the ontology of the wave function. WFR proposes to take the above field-on-configuration space picture literally: fundamentally, the world *just is* $3N$-dimensional, and the fundamental field defined thereon is the wave function; our familiar three-dimensional spatial world is (somehow) *emergent* therefrom.

With WFR stated, I'll turn now to a chapter-by-chapter assessment of Ney's book. In Chapter 1, Ney reviews some of the essential formalism of QM, the measurement problem, traditional collapse-based responses to this problem, and the three best known realist approaches which seek to resolve this problem—namely, Bohmian mechanics, dynamical collapse theories, and the Everett interpretation. Ney's survey of these matters is admirably clear and to the point. Ney next proceeds to distinguish the question of what the correct solution of the measurement problem is from the *ontological* question of 'what kinds of worlds we should take these versions of quantum mechanics to be describing' (p. 33). I fully agree that these are distinct questions—although not completely unrelated, for if a certain approach to QM admits of no coherent metaphysical interpretation, then it surely cannot be taken to offer a completely satisfactory solution to the measurement problem (this is related to 'interpretationalism' and 'motivationalism', discussed below). In any case, Ney's point is that in so far as we must make sense of the ontology of the wave function on any of these approaches, the possibility of WFR arises in any such approach.

In Chapter 2, Ney considers an argument which traditionally has been proffered in favour of WFR: the 'argument from entanglement'. Ney characterizes entanglement thus:

> One common way of understanding entangled states takes them to be states of two or more systems where, due to some interaction in their past, there now exists a correlation between the values they are predicted to take on upon measurement. (p. 50)

The argument from entanglement then maintains that only WFR has the resources to distinguish certain distinct entangled quantum states (pp. 53–4).

Contrary to previous writings (Ney 2012), Ney now concedes that a range of alternative approaches can meet this challenge—in particular, primitive ontology approaches, holisms, relational approaches (including 'ontic structural realism'), a view due to Wallace and Timpson (2010) known as 'spacetime state realism', and 'multi-field approaches'. I won't go into the details of these—suffice it to say that Ney is, again, admirably clear in her presentation. The only point which I would raise is that Ney's categorization might be taken to imply that these approaches are mutually exclusive. This, however, is not the case—for example, Wallace self-identifies as a structural realist (see, for example, Wallace 2021b); he would therefore presumably expect spacetime state realism to be compatible with ontic structural realism. In any case, in the final section of this chapter, Ney registers that, from considerations of entanglement alone, WFR is not *forced* upon us.

Chapter 3 articulates the reasons to favour WFR over rival approaches—these centre upon the idea that WFR yields an ontology which is both 'separable' and 'local'. Here is how Ney defines separability:

> A system located at a region *R* is separable when it consists of subsystems located at non-overlapping proper subregions of *R* each possessing their own individual states, and all states of the system at *R* are wholly determined by or grounded in the states of those subsystems. (p. 81)

One might naturally take entanglement to imply a violation of separability. WFR, however, is not so implicated:

> It [the wave function, according to WFR] is separable because all states of the wave function, including the entangled states we have been considering, are completely determined by localized assignments of amplitude and phase to each point in the higher-dimensional space of the wave function. (p. 87)

Having discussed separability, Ney turns next to locality. Here's how she puts the difference between the two notions:

> [U]nlike separability, which concerns the notion of *metaphysical* determination of the features of a total system by the features of the subsystems located at that system's subregions, locality, in the sense to be discussed here, is a causal notion tracking facts about the *causal* determination of events. (p. 96, emphasis in original)

At its core, locality demands that there be 'no action at a distance' (Bell 1981, p. 46). For authors such as Maudlin (2014), Bell's theorem is taken to demonstrate—via its demonstration that local hidden variable theories would be empirically distinct from QM—that quantum theory (whether supplemented with hidden variables or not) is *necessarily* non-local. Not all agree with Maudlin's take on Bell, however—notably, Everettians maintain that an assumption of this analysis is that measurements have single outcomes. In fact, Everettian spacetime state realists such as Wallace endorse a local but non-separable ontology (Wallace 2012, p. 295). I needn't go into the details here; rather, let me turn to what Ney says on the bearing of WFR on locality. That WFR affords an ontology satisfying the principle of locality again appears to be immediate, since there indeed appears to be 'no action at a distance' *on configuration space*. (Though note that the situation is delicate in the case of GRW: see Wallace 2021a, p. 10 and p. 105 of Ney's book.)

But, as Ney goes on to ask, why care about separability and locality? In brief, her answer is that a metaphysics with these properties is simpler (p. 128) and more congenial to intuitions (p. 129). Since so much of the credibility of WFR hinges on these points, this struck me as a weak point in the book, and indeed I was left unconvinced. In particular, I would like to have read more on (a) different notions of simplicity and their associated virtues, and (b) the significance of intuitions in physical theorizing (particularly in the context of discovery versus context of justification).

In Chapter 4, Ney considers how WFR fares in a relativistic setting; her central goal is to rebut five critiques which have been raised in this context. Before turning to these, I should register some discontent with how Ney frames the chapter:

> It is an interesting question whether wave function realism must, to be viable as a framework for interpreting quantum theories, have application beyond the domain of nonrelativistic quantum mechanics. Must a framework for the ontological interpretation of a quantum theory be workable as an interpretation for all quantum theories? I do not see why it must. (p. 134)

It's certainly true that we often restrict ourselves to one particular theory, and ask: what is the most appropriate metaphysics for this theory, considered unto itself? Understood in that spirit, there's nothing wrong with what Ney writes above: WFR could constitute a perfectly viable—perhaps even the best—understanding of the ontology of non-relativistic QM. However, if the five problems to be considered in this chapter do indeed find their mark, then it's incorrect to maintain that WFR is 'a particular framework for understanding the world' (according to the book's blurb), for it is not adequate to the relativistic quantum field theories (QFTs) which we know to be the best descriptions of the world. Ney goes on to suggest that, even granting this, WFR may nonetheless be helpful in expanding our understanding of the limits of the possible in the development of a quantum theory of gravity—and while I concur that anything goes in the context of discovery, to suggest that a defunct metaphysics might be revived at some later stage of scientific enquiry seems to be clutching at straws. In any case, Ney continues:

> [O]ne might argue that solutions to the measurement problem have actually only been worked out clearly and adequately in the context of nonrelativistic quantum mechanics. … [T]he project of the ontological interpretation of physical theories begins with those that make contact with the world of our experience; therefore, it is not clear whether it is appropriate to be interpreting theories without a clear solution to the measurement problem. (p. 134)

This seems too glib—for Everettians would contend that their approach is perfectly reconcilable with relativistic QM (Wallace 2012); moreover, there are in development various proposals for relativistic versions of Bohmian mechanics (Dürr et al. 2004, 2014; Struyve 2010). Finally, Ney suggests that the domain of application of relativistic QFTs is actually rather scant, and that she is thereby justified in focusing attention on the non-relativistic case:

> It can be questioned whether quantum field theories are more general than nonrelativistic quantum mechanics. This comes down to which kinds of theories are applicable to the most phenomena in nature. It may be argued that actually in physics, nonrelativistic quantum mechanics gets applied to more phenomena; however, I won't engage in this bean-counting exercise. (p. 134)

Ney is correct that no bean-counting exercise is necessary, but for the wrong reasons: *overwhelmingly* more empirical results require recourse to QFT for their explanation than to non-relativistic QM alone (see Wallace 2022a). Overall, in these passages one has the impression that Ney is floundering to justify focusing her attention on the non-relativistic case.

In any case, I turn now to the five critiques of WFR in the relativistic context:

(A) Since in relativistic QFT particle number is not conserved, 'the wave function realist should instead postulate an infinite number of (non-normalized) wave functions: a single-particle wave function living on a three-dimensional space; a two-particle wave function living on a six-dimensional space, and so on. However, … the wave function realist will not prefer to adopt such an ontologically profligate metaphysics' (pp. 135–6). (See Wallace and Timpson 2010.)

(B) WFR 'obscures the role of spacetime in quantum theories' (p. 136). (See Wallace and Timpson 2010.)

(C) WFR in the relativistic context leads to a failure of what Albert (2015) dubs 'narratability'—'there will be no unique and correct account of how the wave function evolves from one time to the next'. (See Wallace and Timpson 2010.)

(D) '[I]n the context of relativistic theories especially, the existence of a wave function is derivative on the antecedent existence of structures defined on ordinary spacetime' (p. 137). (See Myrvold 2015.)

(E) '[P]rivileging of the position basis is problematic in the context of quantum field theories, for which quantum states and observables are more typically defined in terms of a momentum basis' (p. 137). (See Wallace 2021a.)

Before I discuss these objections, two more points. First, a discussion of the problem of fermions is conspicuously absent from the above. Here's how Wallace puts this problem:

> [O]nly bosonic field theories can be represented as wavefunctions on configuration space. Others—the 'fermionic' field theories that represent electrons and quarks (and so are central to our quantum-mechanical descriptions of ordinary matter)—possess no such representation. (Wallace 2021a, p. 6)

For me, this alone would suffice to place WFR in hot water, so I was disappointed that Ney does not engage with it with any vigour. (In fairness, Ney later writes, 'The consideration of quantum field theories for fermionic particles, or those with charge or spin, would not affect the general ontological points that follow' (p. 144)—but in the absence of further details it's hard to take that seriously when fermions don't have configuration spaces.)

The second point is this: Ney goes on to point out that the relevant notion of configuration space will be different in the case of quantum fields than in the case of *N*-particle non-relativistic systems:

> [A]ssuming that the spacetime representation from which we began is continuous, the higher-dimensional space will be continuously infinite-dimensional with each point corresponding to an assignment of field operators to all spacetime points or, assuming discreteness, to the smallest regions in the low-dimensional representation …
>
> At this stage, we may note that we are no longer considering wave functions on a space with the structure of a classical configuration space as the central elements in the wave function realist's basic ontology. What we have instead is a field defined on another kind of high-dimensional space, one for which locations are correlated with assignments of field operators to regions in a four-dimensional ontology. (p. 149)

(Perhaps making this move to a more general framework can help Ney with the problem of fermions—but again, I would like to have seen Ney join the dots explicitly, since much of the interesting action seems to be situated just here.) There is something puzzling about the structure of this presentation. Why focus so much attention on the case in which the wave function lives on an *N*-particle configuration space, when it is the above case which is closer to reality—and, moreover, when the ontological consequences in the latter case are yet more severe than those of WFR? Here, I concur with Wallace:

> My immediate feeling about this move is: if what is really intended is a wavefunction on field configuration space, shouldn't we be discussing that metaphysics rather than being distracted by the red herring of wavefunctions on *N*-particle configuration space? Granted, the latter has the virtue of being simpler to talk about, but it has the vice of being inconsistent with our current best quantum theories, which seems more serious. (Wallace 2021a, pp. 4–5)

Ney dubs the more general position 'Localism': this is the view that physical theories should be interpreted in terms of local and separable ontologies on higher dimensional spaces. Fair enough—but then I do not understand why Localism is not front and centre in this book. Why not discuss the general case, rather than focusing on a(n unrealistic) special case, while leaving the general case as an afterthought? There is so much action—both technical and metaphysical—to be had with Localism, that to focus on WFR seems to me to be an unduly narrow approach. In fairness to Ney, I think she would agree with this assessment, but take her explorations of WFR in the context of relativity to constitute but the initial skirmishes of a broader campaign. That notwithstanding, I would have preferred a presentation emphasizing from the outset both this point and the significance of the more general thesis of Localism.

In any case, in light of the possibility of Localism, in response to (A), Ney writes, 'The wave function realist need not and should not offer the wave-function-in-configuration-space picture as an interpretation of relativistic quantum theories' (p. 150). Noted—but then (again) I want to see more details on the technical and metaphysical details of the Localist picture.

That said, I endorse Ney's responses to (B), (C), and (D). To (B), she replies that the 'claim is not that [spacetime] representations should be rejected, but rather that they should be seen as metaphysically explained or grounded in terms of a more fundamental representation of a field in high-dimensional space' (p. 152). On (C), Ney argues that WFR can, in fact, explain the observed failure of narritability (pp. 155–7). On (D), Ney writes that 'the fact that wave function representations may be mathematically derived from spacetime directions does not show anything about the direction of ontological priority' (p. 157). Just so.

On (E)—the charge of basis-relativity—Ney writes, 'In the absence of a Lorentz covariant position representation for a quantum field theory, the wave function realist will construct her higher-dimensional representation using a different kind of basis. The example above used a momentum basis' (p. 159). But even granting this, Ney must contend with the apparent basis-dependence of WFR more generally. Fortunately, Ney does just this. In response to the apparent basis-dependence of WFR, one suggestion would be to 'represent the world by a state vector in Hilbert space, and have this representation guide one's fundamental ontology' (p. 161) (this view Carroll and Singh dub 'Mad-Dog Everettianism': Carroll 2019; Carroll and Singh 2019). While granting that such a picture would avoid the charge of coordinate-dependence, Ney objects to it, for two reasons:

- 'The ray-in-Hilbert space view fails to be separable because it lacks in the first place an ontology of distinct objects occupying nonoverlapping regions' (p. 164). My response: (a) The claim appears incorrect, for whether there is 'an ontology of distinct objects' should surely not depend upon the basis which one chooses. (b) In any case, perhaps separability is, in the end, not the be-all and end-all of physical interpretation.
- 'If we are going to take seriously a fundamental ontology for quantum theories, we must find some way of demonstrating how that ontology may ultimately constitute the macroscopic objects that we already know exist'

> (p. 164). My response: All of the structure encoded in the wave function is still present in the ray-in-Hilbert-space approach: indeed, it *must* be, since one can move from the latter to the former by simply choosing a basis. (Cf. (a) above; also Wallace 2021a, p. 8.)

Ney's thought, given her rejection of the ray-in-Hilbert-space approach, is that basis-relativity is acceptable. In light of the foregoing, this is perhaps to throw in the towel too early, for an alternative approach which does not manifest such problems remains viable (notwithstanding objections to all such approaches—see Wallace 2021a, p. 8).

In Chapter 5, Ney addresses the question: must an ontology for quantum theories contain local beables? The central idea of proponents of local beables is that 'an ontology for quantum theories should include a class of fundamental local beables, that is, entities assigned to definite locations in three-dimensional space or spacetime' (p. 167); WFR, however, seems to violate this requirement. Here, I agree with Ney, in so far as I would also reject the premiss that 'providing a plausible account of the constitution of macroscopic objects demands the postulation of fundamental local beables' (p. 168). Even granting that our empirical evidence consists of macroscopic local beables (see Maudlin 2007, p. 3159), why require that these be *fundamental* (p. 176)? And even granting this, I concur with Ney when she writes that '[e]mpirical confirmation per se does not need to proceed through our observations of objects at distinct three-dimensional spatial locations rather than (what is more general) our observations of different sorts of states in whatever is the correct ontology' (p. 177).

Later, Ney contends with the view that QM requires an interpretation in terms of a 'primitive ontology' of particles in a classical spacetime, as such an ontology is 'less radical', and (supposedly) superior in terms of the explanations it can offer (see Dürr et al. 1992; Allori et al. 2011; Allori 2013). In response, Ney cites Ladyman (2010, p. 155): 'Science is not under obligation to recover familiar truths from the manifest image, only approximations of them, the reasonableness of asserting them even though they are false, or their persistence as illusions.' Again, I agree completely—although I would like to take this opportunity to connect the remarks here with another literature. In the philosophy of symmetries, there is a debate between 'interpretationalism' and 'motivationalism' (Møller-Nielsen 2017). According to the former, one need not wait upon a 'metaphysically perspicuous characterization' (MPC) of the common ontology of symmetry-related models before adjudicating that they are physically equivalent (that is, represent the same physical states of affairs); according to the latter, one must secure an MPC in advance of such adjudications. Of course, this leaves open what an MPC really consists in—arguably, such a characterization really amounts to a *psychologically satisfying* characterization. On this understanding, interpretationalists are simply the limiting case in which the mathematical structure of the models of one's theories *already suffices* to yield an MPC (Wallace is a self-declared interpretationalist—see Wallace 2022b); others, all motivationalists, will have more or less stringent standards as to the additional philosophical and technical work that must be done before an MPC is secured. At one extreme of this spectrum are primitive ontologists, who maintain that all theories should be interpreted by *beginning* with a perspicuous ontology, which *they* find psychologically satisfying. O.K., but here I would side with Ney and Ladyman in finding other ontologies—admittedly potentially with some extra philosophical/technical work, so I would still identify as a motivationalist rather than an interpretationalist—perfectly satisfying.

In Chapter 6, Ney turns to the relationship between the high-dimensional reality of WFR and our more parochial three-dimensional world. Ney gives particular attention to Albert's proposal (see Albert 2013) to invoke functionalism:

> [I]f we can characterize *what it is for there to be* a three-dimensional object in terms of the playing of some functional role, and the wave function plays that role, then the wave function will ipso facto be capable of constituting three-dimensional objects. (p. 211, emphasis in original)

Assuming that functionalism is a viable means of securing this link (see below), one issue is this. Knox (2011)—a well-known 'spacetime functionalist'—proposes that functionalism allows one to judge that there is no real ontological difference between general relativity and certain alternative—but empirically equivalent—theories. If so, one might worry that the ontological priority of configuration space in WFR cannot be maintained. I would like to know whether Ney thinks that the suggested analogy with the kinds of case which Knox considers holds up.

In any case, Ney in fact does not favour functionalism, and in Chapter 7 articulates her alternative proposal. Ney begins by noting that North (2013) 'proposes that we see macroscopic, three-dimensional objects as related to the wave function by grounding relations' (p. 226); however, as Wilson (2014) notes, in Ney's words, 'to simply say that that one fact grounds another leaves completely open what the relationship between these facts is, and indeed even whether the derivative facts describe any realm of genuine objects' (p. 228). Ney proposes that the relation is mereological: 'three-dimensional particles are related mereologically to the whole that is the wave function. Although these particles usually do not have determinate locations, they may instantiate multiple locations to various degrees' (p. 242). Ney summarizes thus:

> [I]n this account, functionalism plays no role in recovering the three-dimensional ontology from the higher-dimensional one. It only serves to recover material objects, once their lower-dimensional, microscopic counterparts are already recovered. The relationship between the wave function and particles is one of whole to part, but no part of the wave function in its space plays the role on its own of a three-dimensional object. Three-dimensionality arises due to the behaviour over time of the wave function as a whole. (p. 249)

Ney's point is that functionalism will not serve for establishing the connection between the two spaces under consideration, for there is no particular part of the wave function which realizes the functional role of an object in three-dimensional space. I agree that this would mean that functionalism *à la* Knox is a non-starter; however, it's not obvious that the kind of functional reduction advocated by Lewis (1970) cannot succeed (cf. Butterfield and Gomes 2020). Recall that in the latter case, there need not be a *particular* element of one's ontology which plays a certain functional role—rather, the issue is whether something which plays that role can be (implicitly) *defined*. I would have found it helpful and illuminating if Ney could have engaged with these different versions of functionalism.

There ends Ney's book. As should by now be evident, I regard it as an immensely clear, highly valuable contribution to the literature on the metaphysics of QM. While there are places where the book could have been enriched by engagement with further philosophical debates, my central concern is that Ney's defence of WFR falters at key moments—in particular, at least as things now stand, it's not obvious to me how the view can survive in the relativistic context; moreover, the more general view of Localism to which Ney appeals is insufficiently articulated and assessed. The appeal of a separable and local metaphysics is also something which I think one can take or leave. In any case, though, and to close, I would implore authors interested in these matters to push their investigations in these directions—for what the book certainly does reveal is that there remains much interesting work on WFR to be done.*

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