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Three arguments for wave function realism

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Abstract
Wave function realism is an interpretative framework for quantum theories which recommends taking the central ontology of these theories to consist of the quantum wave function, understood as a field on a high-dimensional space. This paper presents and evaluates three standard arguments for wave function realism, and clarifies the sort of ontological framework these arguments support.

Keywords Quantum mechanics · Wave function · Wave function realism

1 Introduction

In nonrelativistic quantum mechanics, the state of a system is given by its wave function. The wave function is often captured by a vector on Hilbert space, where the dimensions of this space correspond to the number of eigenstates associated with a given observable. For example, to describe the z-spin state of a particle, the wave function is given by a state vector on a two-dimensional Hilbert space, with one axis corresponding to an eigenvalue of z-spin = +1 and the other to an eigenvalue of z-spin = -1. In contexts in which the variable of interest is position, the wave function will be captured by a state vector in a Hilbert space with dimensions corresponding to definite position states. Alternatively, it may be given by a function on configuration space. For a system consisting of a single particle system in three-dimensional space, the wave function is a function that takes in locations in this space and yields complex numbers. In general, to represent the position states of N-particle systems, the wave function is a function that takes in locations in a 3N-dimensional configuration space.

According to wave function realist interpretations of quantum theories, a or the central object in the fundamental ontology of quantum theories is the "wave function," an object corresponding to the function used to specify the quantum state. This wave function is taken to be a field (an object defined by an assignment of

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values to points), but not a field on ordinary three-dimensional space, nor on Hilbert space. Rather, for wave function realists, the fundamental ontology of quantum theories consists at least partly of a field on a space with the structure of a configuration space. This interpretative framework yields different ontologies when applied to different quantum theories. For nonrelativistic quantum theories, the configuration space, as noted above, will be a 3N-dimensional space. Adding spin degrees of freedom, the values the wave function will assign to points in configuration space will be structured in order to accommodate the spin of each particle. In quantum theories in which particle number is not determinate, such as quantum field theories, the configuration space will be a space defined by the number of classical, i.e. determinate, field configurations.[1]

Wave function realism is intended to be a versatile framework that is capable of providing an ontological interpretation of any quantum theory. As we will see, it is motivated by the argument that it is the best way to make ontological sense of quantum entanglement, the characteristic phenomenon of quantum theories (cf. Schrödinger, 1935). Nonetheless, wave function realists are especially interested in providing ontological interpretations for quantum theories that provide solutions to the quantum measurement problem (Albert, 1992). After all, it is only those quantum theories capable of solving the measurement problem that allow us to connect the predictions of the theory with what we observe. And so, I will focus in what follows on theories that can clearly solve the measurement problem, in particularly Everettian quantum mechanics with decoherence (Wallace, 2012) and the GRW theory (Ghirardi et al., 1986).[2]

The goals of the present paper are twofold: first, to provide a compact and accessible account of the three primary arguments that have been used to motivate wave function realist interpretations of quantum theories; and second, to clarify the conclusions we are licensed to draw from these arguments. A longer development of each argument may be found in Ney (2021). As I will explain, only the third argument, the argument from separability and locality, is capable of motivating the wave function ontology over rival ontological frameworks. The other two arguments are at best incomplete, if not simply unsound. Each would require supplementation with premises about the virtues of having a separable and local metaphysics in order to make any case for the fundamentality of a wave function in a high-dimensional space, given the ability of rival metaphysical frameworks to accommodate the phenomenon of entanglement.

Once it is seen that the case for wave function realism over rival interpretations needs an appeal to the attractiveness of separable and local metaphysics, this raises the question of whether such metaphysics are indeed attractive, and how far the "attractiveness" of a metaphysics may take us. In this paper, I hope to make it clearer than I did previously that this only takes us so far, but it does not undermine

[1] For further discussion, see Ney (2021), pp. 138-150.

[2] The De Broglie-Bohm theory also provides a solution to the measurement problem, however, for reasons explained in Ney (2021), pp. 42-47, it is not a particularly good fit for wave function realism.

the ability of the framework to be compatible with a scientifically realist approach to the interpretation of quantum theories.

A perhaps surprising conclusion I reach toward the end of this paper is that actually not even the argument from separability and locality gets us all of the way to a genuine wave function *realism*. I will clarify this point below. The upshot is that the argument from separability and locality gives one some practical reasons to work with the wave function ontology, but it overreaches to take this all of the way to adopting full belief in the wave function as a field on a high-dimensional space.

The final section of this paper uses the results of the previous sections to show why wave function realists prefer to see the wave function as a field on a space with the structure of a configuration space, as opposed to a vector or ray on Hilbert space, as in the Hilbert space realist approach of Carroll and Singh (2020) and Carroll (2022).[3] A view like Hilbert space realism needs a different argument to motivate it, and so far, the arguments that have been proposed do not appear stronger than the case for standard (configuration space) wave function realism.

2 The prima facie case for wave function realism

The first argument for wave function realism can be found most explicitly in Lewis's (2004) paper, "Life in Configuration Space." The argument is that every quantum theory that solves the measurement problem makes central use of wave function representations. Although in classical mechanics, to specify a state of a system is to list the definite positions and momenta of all particles in the system, in quantum mechanics, states are given by specifying a wave function. In addition, the central law or laws of quantum theories describe the evolution of the wave function over time. Thus, it seems that if we want to interpret quantum theories realistically, we should take them to be about wave functions as real entities, and how these wave functions evolve.

Here is Lewis:

> The wavefunction figures in quantum mechanics in much the same way that particle configurations figure in classical mechanics; its evolution over time successfully explains our observations. So absent some compelling argument to the contrary, the prima facie conclusion is that the wavefunction should be accorded the same status that we used to accord to particle configurations. Realists, then, should regard the wavefunction as part of the basic furniture of the world… This conclusion is independent of the theoretical choices one might make in response to the measurement problem… it is the wavefunction that plays the central explanatory and predictive role. (2004, p. 714)

In classical mechanics, since states are specified by providing the positions and momenta of all particles in the system, it is reasonable to take particles (with determinate locations and momenta) as the fundamental ontology of the theory. Wave

3 Carroll and Singh call the view 'Mad-Dog Everettianism."

functions play the role in quantum mechanics that were played by particles in classical mechanics, so we should take the fundamental ontology of quantum mechanics to be the wave function.

Note that Lewis takes realism about the wave function to be only a "prima facie conclusion" that one might infer from the role wave functions play in quantum mechanics. If we just look at the formal structure of quantum theories, they seem to be about wave functions. They don't seem, at least from the formal apparatus these theories use to specify states and their dynamical evolution, to be (fundamentally) about particles or other material objects inhabiting three-dimensional space.[4] By calling this a prima facie conclusion, Lewis is indicating that the appearances may be deceiving. In general, we shouldn't think that we can reliably read the ontology of a theory off of a mathematical description of that theory in such a superficial way.[5]

So far as I can tell, no wave function realist has claimed that the prima facie argument is their reason for endorsing the framework, although opponents of wave function realism (e.g. Emery, 2017) sometimes present them as doing so.

Even if we could read the fundamental ontology of a theory directly off of its mathematical structure in the way Lewis entertained, this still wouldn't support wave function realism in its official form, the view that the fundamental ontology of quantum theories includes a field (the wave function) on a space with the structure of a configuration space. The prima facie argument may tell us that quantum theories that solve the measurement problem are about wave functions. But why think they are about wave functions construed as fields on a high-dimensional space? We need more of an argument to get us all of the way to the wave function realist's distinctive metaphysical proposal.

3 The argument from entanglement

The argument from entanglement aspires to be such an argument, and it is one that has actually been used by wave function realists to argue for their position. I find this argument most explicitly in the work of North (2013):

> In quantum mechanics… we must formulate the dynamics on a high-dimensional space. This is because quantum mechanical systems can be in entangled states, for which the wave function is nonseparable. Such a wave function cannot be broken down into individual three-dimensional wave functions, corresponding to what we think of as particles in three-dimensional space. That would leave out information about correlations among different parts of the system, correlations that have experimentally observed effects. Only the entire wave function, defined over the entire high-dimensional space, contains all the

[4] We can already see here why wave function realism is a poor fit for the De Broglie-Bohm theory. That theory does look to be about particles in three-dimensional space. But see also the discussion in Ney (2021), pp. 42-47.

[5] A particularly compelling argument for this point was given by Maddy in her 1992 paper "Indispensability and Practice," but this is a common view in post-Quinean metaphysics of science.

> information that factors in the future evolution of quantum mechanical systems.
> Following the principle to infer, at the fundamental level of the world, just that structure and ontology that is presupposed by the dynamics, we are led to conclude that the fundamental space of a world governed by this dynamics is the high-dimensional one. The fundamental ontology, which includes the wave function, then lives in it. (2013, pp. 190-191)

It is plausible, I think, to also interpret David Albert as having something like the argument from entanglement in mind when he says that "in the quantum-mechanical case, the reason for taking these high-dimensional pictures seriously are, on the face of it, very powerful" (2013, p. 56).

To see this, consider two particles that are prepared in the spin singlet state. The particles are then sent in opposite directions toward two Stern-Gerlach devices that will deflect them up or down, according to their z-spins. If particle 1 is z-spin up, it will be deflected up to location A; if it is z-spin down, it will be deflected down to location B. If particle 2 is z-spin up, it will be deflected up to location C; if it is z-spin down, it will be deflected down to location D. As the particles become entangled with the measuring devices, they come to be in a state that is entangled not only with respect to their spins, but also their positions as follows:

$$\psi = \frac{1}{\sqrt{2}}\left[\left|\uparrow_z, A\right\rangle_1\left|\downarrow_z, D\right\rangle_2 + \left|\downarrow_z, B\right\rangle_1\left|\uparrow_z, C\right\rangle_2\right]$$

The question is: how should realists about quantum theories understand states like ψ?

If we are to take a realist attitude toward states like this, then this means somehow understanding them as describing an objective reality. But what kind of objective reality? If we want to understand this quantum state as describing a three-dimensional system, such as a pair of particles, this is tricky. Ordinarily, particles are taken to be objects with definite locations and yet, the particles in quantum state ψ do not have definite locations. Instead, we might try to understand the state as describing not what are strictly speaking two *particles* in three dimensions, but instead two fields. These fields have different components associated with different locations in the three-dimensional space given by the mod-squared amplitudes in their shared quantum state.

The difficulty with this approach is that, as North emphasizes, it cannot capture the correspondences between the two particles. It doesn't capture their entanglement. To see this, we may consider an alternative quantum state, one that results after we measure the z-spin of two particles that were not prepared in the singlet state, but rather were prepared in a product state and both x-spin up:

$$\psi' = \frac{1}{2}\left[\left|\uparrow_z, A\right\rangle_1\left|\uparrow_z, C\right\rangle_2 + \left|\uparrow_z, A\right\rangle_1\left|\downarrow_z, D\right\rangle_2 + \left|\downarrow_z, B\right\rangle_1\left|\uparrow_z, C\right\rangle_2 + \left|\downarrow_z, B\right\rangle_1\left|\downarrow_z, D\right\rangle_2\right]$$

If we try to take a realist attitude to this quantum state, and interpret it as the state of a system in three-dimensional space, we will assign the state the same ontic interpretation as we assigned state ψ. We will conclude there are two fields with the same components assigned to regions A, B, C, and D. A realist wanting to understand the quantum ontology simply as fields living in three dimensions cannot distinguish these distinct quantum states. And it is for the reason North noted, because this three-dimensional interpretation misses the correspondences between the two particles given by their entanglement in state ψ.

On the other hand, if we interpret these states not as describing two fields in three-dimensional space, but instead one field (a wave function) in a 3N=6-dimensional space with the structure of a configuration space, we do capture the correspondences between the particles in state ψ, and hence, the distinction between states ψ and ψ'. For let us consider 4 points in this six-dimensional space that we may suggestively label AC, AD, BC, and BD. The first point AC in the six-dimensional configuration space corresponds to the situation in three-dimensional space in which particle 1 is at location A and particle 2 is at location C, and so on. In the 3N-dimensional field ontology, state ψ depicts a field with components only at locations AD and BC. By contrast, ψ' depicts a field with components at each of the four locations AC, AD, BC, and BD. Thus, if a realist wants to distinguish between distinct quantum states, they can do so by interpreting quantum systems not as many particles (or fields) in three-dimensional space, but instead as a single wave function field on a space with the higher-dimensional structure of a configuration space.

This argument from entanglement improves on the prima facie case in that it allows us to see why wave function realists think the ontology of quantum theories should be a field in a space with the structure of a configuration space. It is in order to capture the correspondences between subsystems in entangled states. That said, the argument is defective. Although it is correct that a simple low-dimensional field ontology does not adequately capture the distinctions between quantum states like ψ and ψ', there are more sophisticated proposals for a quantum ontology that do. There are many such alternatives that do not take quantum states to describe the state of a wave function in a high-dimensional space, and yet are tailored specifically to capture entanglement relations. These include the primitive ontology view (Dürr et al., 1992; Allori et al., 2008), relational holism (Teller, 1986), priority monism (Schaffer & Ismael, 2020), ontic structural realism (Ladyman, 1998), spacetime state realism (Wallace & Timpson, 2010), and the multi-field view (Belot, 2012, Hubert & Romano, 2018). All of these approaches take quantum states like ψ and ψ' to correspond to distinct ontologies in (three-dimensional) space or spacetime.

For example, Paul Teller's view, relational holism, takes ψ and ψ' to both describe a system of two particles. In ψ however, there are relations between particles 1 and 2 that do not reduce to properties of the particles taken individually. To cite one such relation, particle 1 will be found at location A if and only if particle 2 is found at location D. This is not the case for the particles in state ψ'. Teller's irreducible relations capture the entanglement between the particles.

Another approach is the spacetime state realism of David Wallace and Chris Timpson. Here, spacetime regions are the fundamental bearers of properties. Reduced density matrices capture these properties, which are taken to be intrinsic to their corresponding regions. In this view, since the reduced density matrices associated with the spatial region A∪B∪C∪D differ in the case of ψ and ψ', again we arrive at a low-dimensional quantum ontology that is able to capture the distinction between these distinct quantum states.

So, the argument from entanglement is not sound if it relies on the premise that one cannot capture the correspondences between the subsystems of entangled states without moving to a high-dimensional ontology. Nonetheless, a defender of wave function realism might ask us here to notice a difference between the wave function ontology and those favored by the relational holists and spacetime state realists, (a difference that also demarcates wave function realism from ontic structural realism and the multi-field approach). This is that, unlike wave function realism, relational holism, spacetime state realism, and the others yield nonseparable metaphysics. A metaphysics is *separable* iff (i) it includes an ontology of objects or other entities instantiated at distinct regions, each possessing their own distinct states and (ii) when any such objects or entities are instantiated at distinct regions R1 and R2, all categorical facts about the composite region R1∪R2 are determined by the facts about objects and properties instantiated at R1 and R2 individually. Relational holism, spacetime state realism, ontic structural realism, and the multi-field approach all violate separability in that each takes there to be facts about regions that are not determined by facts about their subregions.

This is again most straightforward in the case of relational holism. In the case of relational holism, there are relations between the particles at three-dimensional regions A∪B and C∪D that do not supervene on what is happening locally at A∪B and C∪D. For spacetime state realism, if we consider the reduced density matrices associated with regions A∪B and C∪D individually, these will not determine the reduced density matrix associated with the larger region A∪B∪C∪D. This is not a hidden bug within these frameworks for interpreting quantum states. It is a feature that Teller, Timpson, and Wallace take to be one of the interesting metaphysical lessons we should draw from the fact of quantum entanglement – a quantum ontology should be nonseparable.

Of the alternatives to wave function realism already mentioned, there is only one framework that is (arguably) separable. This is the primitive ontology view defended by Valia Allori, Detlef Dürr, Sheldon Goldstein, Roderich Tumulka, and Nino Zanghì (Dürr et al., 1992; Allori et al., 2008).[6] According to the primitive ontology view, physical theories come with primitive ontologies. The primitive ontology of a physical theory is the set of entities the theory is about, and these are always entities with locations in three-dimensional space or spacetime (what Bell (1976) called 'local beables'). They are the kinds of entities that can straightforwardly be taken to make up more familiar macroscopic entities (Allori, 2013). According to the primitive ontology view, quantum theories are not about wave functions, as wave functions are not local beables. This isn't to deny that wave functions shouldn't be considered parts of a quantum ontology. They must, Allori et al. argue, if the framework is going to capture all of the distinctions between quantum states. But primitive ontologists will often argue that wave functions have something more like the

[6] See also the very similar appeal to "primary ontology" in Maudlin (2013).

status of law, guiding the primitive ontology in how to evolve, rather than making up the matter of a quantum theory (Goldstein & Zanghì, 2013).

The primitive ontology view is separable because all facts about composite spacetime regions are completely determined by facts about their subregions. There are additional facts about wave functions – and this is what allows the primitive ontologist a way to distinguish between ψ and ψ' above. But facts about wave functions aren't for them facts about spatiotemporal regions, and so they don't imply any failure of separability.

Now, interestingly, although the primitive ontologist's metaphysics is separable, it does in most incarnations entail the violation of another principle: locality, or the principle of local action. When systems are in entangled states like ψ, a measurement of particle 1 at its location can produce an instantaneous change in the facts about particle 2 at its location, which might be quite distant. For wave function realists, the appearance of nonlocality in low dimensions is explained in terms of a more fundamental ontology that is local.[7] However, for primitive ontologists, nonlocality is accepted as real and basic. Again, this isn't a hidden bug in the primitive ontology view; it is something they make plain. However, it is a feature that distinguishes the way the primitive ontologist makes ontological sense of quantum entanglement from the way the wave function realist does.

We may conclude then that if the wave function realist is only interested in quantum ontologies that are separable and local, then they may argue that wave function realism is the only quantum ontology that can accommodate the distinctions between quantum states that arise due to quantum entanglement. However, this raises the question why one should insist on a metaphysics that is fundamentally separable and local. This takes us to the third argument for wave function realism, the argument from separability and locality.

4 The argument from separability and locality

The argument from separability and locality may be summarized as follows: wave function realism is unique in yielding quantum ontologies that not only distinguish quantum states, but do so by retaining two intuitively nice metaphysical features: separability and locality. Although the pictures of the world yielded by the primitive ontology view, relational holism, ontic structural realism, spacetime state realism, and the multi-field view may capture the distinctions between quantum states, they fail to provide pictures of the quantum world that are fundamentally both separable and local. For this reason, they fail to interpret quantum theories in a metaphysically attractive way. This is a reason to favor wave function realism against these other quantum ontologies.

[7] This requires a fuller discussion, including an analysis of how the wave function ontology avoids action at a distance no matter how one solves the measurement problem. It has been especially controversial how this is supposed to work in the GRW theory. This is explained in Ney (2021), pp. 105-113.

David Albert, in his most recent 2023 book, advocates wave function realism for the way it is capable of capturing the facts of quantum entanglement while not ultimately sacrificing separability and locality.[8] Albert makes a distinction between the way we might represent quantum systems in a lower-dimensional (three-dimensional) "space of ordinary material bodies" and a higher-dimensional, perhaps 3N-dimensional, "space of elementary physical determinables." This latter space, is of course, the space deemed fundamental by the wave function realist.

Albert argues that:

> A qualitative description of the physical situation of this world, at some particular time, in the [low-dimensional space of ordinary material bodies] (that is: a complete specification of which …points… are occupied by particles, together with a specification of the *velocities* of the particles at each of those points, together with a specification of the *intrinsic properties* of the particles at each of those points) is *not* going to give us enough information to predict, even in principle, the qualitative situation of this world at other times. (2023, p. 20)

And yet:

> A complete specification of the qualitative situation, at any particular instant, in the [high-dimensional space of elementary physical determinables] *is* going to give us enough information to predict, in principle, how that situation is going to evolve into the future. And from *that* (of course) we are going to be able to read off all of the future qualitative situations in the [space of ordinary material bodies] as well. (2023, p. 21)

What is being noted here is that one cannot obtain a *separable* representation of the world in three dimensions. In a later passage, he makes explicit that the low-dimensional representation fails to be local as well (p. 48). To get a specification of the world that reduces ultimately to facts about objects and their features at points (is separable), one that avoids non-locality, we require the high-dimensional space. And for this reason, Albert argues that it is the wave function and its high-dimensional space that are fundamental.

Now in making this point, Albert draws a conclusion that is too strong[9], namely:

> And so the *history* of the universe we are dealing with here… can simply not be *presented* in the form of a history of the motions of familiar bodies, and the *dynamical laws* of a universe like the one we are dealing with here can simply

[8] As one sympathetic to both the deBroglie-Bohm theory and GRW as solutions to the measurement problem, but not Everettian quantum mechanics, Albert allows that there is both nonseparability and nonlocality in the less fundamental, three-dimensional space. But what he is after is a metaphysics that is separable and local in the fundamental space.

[9] This follows other overly strong claims in Albert's earlier work, for example in (1996) that "it has been essential… to the project of quantum-mechanical *realism* … to learn to think of wave functions as physical objects *in and of themselves*" (1996, p. 277). My point here is that it is *an option* to think of wave functions as independent physical objects if one cares about separability and locality; it is not *essential*.

> not be *written down* in the form of *laws* of the motions of every day material bodies… the reason everything looks so odd as viewed from the perspective of the [low-dimensional space of ordinary material bodies] is that [it] *isn't where things are really going on*, and that the *material particles* that *move around* in that space are really just "shadows" (as it were) of the actual, fundamental, physical items. (2023, p. 21)

This is too strong because it's just not true that you *can't* present the world in the form of a history of material bodies in low-dimensional space. The primitive ontologists do so, as do the relational holists, and so on. What Albert is entitled to is only the much weaker claim that if one wants to represent the world in a way that is separable and local, one needs to work with the higher-dimensional ontology.

In Albert's work, we don't find an argument for why we should prefer separable and local metaphysics for quantum theories, especially when the violation of Bell's inequalities seems to be screaming out that the world is fundamentally nonseparable and nonlocal. But I think there is something to say here.[10]

It is helpful to think back to Loewer's (1996) article, "Humean Supervenience." A central issue Loewer discussed in that paper was the challenge that entangled states make for David Lewis's famous metaphysical framework, according to which all facts about the world ultimately supervene on the facts about intrinsic properties instantiated at spacetime points, and the only fundamental external relations are spatiotemporal relations. The issue, of course, is that quantum entanglement seems to involve objects bearing non-spatiotemporal relations to each other that do not supervene on properties of their relata. It also seems to involve events that are causally related in a way that does not supervene on features of the relata. Lewis was aware of this, but didn't seem to think it was much of a problem. His stated reason for not thinking it was a problem was his belief that quantum mechanics was formulated as an instrumentalist theory and so shouldn't be interpreted in a realist way. Loewer, knowing that there are several ways to interpret quantum theories realistically (i.e. there are several realist solutions to the measurement problem) doesn't sidestep the issue in this way. But he argues that quantum entanglement isn't a problem for Humeans if we think that fundamentally the ontology of quantum mechanics is a wave function, a field in a high-dimensional space with the structure of a classical configuration space. Then everything will supervene on the values of the wave function at points in its space.

It is worth noting that Humean supervenience does not require locality. The sort of counterfactual interpretations of causation that Humeans tend to prefer do not entail any ban on action at a distance (see e.g. Lewis, 1973 and the essays in Collins et al., 2004). But, Humean supervenience is a metaphysics that is unquestionably separable. According to this framework, all facts are determined by facts about local properties instantiated at points and the basic spatiotemporal relations. And so, one

[10] I say a lot more in my book (2021), pp. 120-132. I present the story somewhat differently here to emphasize some key points that have been missed by critics, particularly the discussion on the last pages of that chapter.

might trace the desire for separability the wave function realist has to a desire for a Humean metaphysics. Not surprising, as the two pioneers of wave function realism, Albert and Loewer, are staunch Humeans.[11]

But, why be Humean? Typically, Humeans are motivated by the simplicity of their metaphysics. Nolan, in his book on Lewis, is probably most explicit about this (Nolan, 2005, p. 31). But it comes across already rather clearly in Lewis's work, that an ontology where everything supervenes on the local arrangement of intrinsic properties in spacetime is a clean and simple one:

> For short: we have an arrangement of qualities. And that is all… I concede Humean supervenience is a contingent truth… Perhaps there might be extra, irreducible external relations, besides the spatiotemporal ones; there might be emergent natural properties of more-than-point-sized things… It is not, alas, unintelligible that there might be suchlike rubbish. (Lewis, 1986, p. x)

There *might* be. But that would be a world that is less ontologically parsimonious, and so if we could accommodate the phenomena without appealing to such "rubbish," then we should. It's simpler.

Let's be explicit about what is going on here. Lewis doesn't adopt Humean supervenience because he knows it is the one true metaphysics:

> Really, what I uphold is not so much the truth of Humean supervenience as the *tenability* of it. If physics itself were to teach me that it is false, I wouldn't grieve. (Lewis, 1986, p. xi)

Rather, as Humean supervenience provides a simple, clean, parsimonious ontology, this makes it a reasonable place to start in addressing metaphysical questions.[12] If it turns out we need something more complicated, "rubbish" like fundamental non-spatiotemporal external relations, density matrices that apply fundamentally to whole regions, fields that take values not at individual points, but sets of points, then fine, but it is simpler and thus more reasonable to start by thinking we do not.

So far, by arguing that the case for a separable metaphysics can be traced back to the same points about cleanliness and simplicity that motivated Lewis to adopt Humean supervenience, I hope to have shown one reason why someone might be drawn to argue for wave function realism by the argument from separability and locality. But this isn't the only reason. I also believe there are certain propositions in support of separable and local metaphysics that can seem to many of us to be analytic or true by definition. This doesn't mean they are incorrigible. As Quine (1951) showed us, even those propositions that are held up at one time as analytic can be given up, if enough evidence requires it. In favor of separability, there is the proposition that the basic facts about one entity don't depend on facts about any other entity. In favor of locality, there is the proposition that an object cannot act where it is not. In my 2021 book, I argued that it is for these reasons that the wave function

[11] On the other hand, the other wave function realist I've discussed here, North, reports to be undecided on the question of Humeanism (p.c.).

[12] Ockham's razor is a central virtue of metaphysical theories, for a Quinean like Lewis.

ontology is not just simple, but also intuitive. By this, I simply mean that it is supported by our rational faculties (intuition), not by observation. I mean that it is supported by claims that are analytic and so closer to the center of my (but I think not just my) Quinean web of belief.

In that book, I also noted that "the basic facts about one entity don't depend on facts about any other entity" is very similar to a point made by Einstein (1948) in his discussion of separability, and that "an object cannot act where it is not" was a proposition appealed to by Samuel Clarke in his correspondence with Leibniz. This led Maudlin (2022) to reply that one shouldn't draw lessons about quantum ontology from the claims physicists made before the discovery of the violation of Bell's inequalities. I would agree if these claims were intended to be descriptions of scientific results. But they are not. Rather, I take them to be analytic claims made on the basis of reflection about what it is for something to be an entity or what it is for something to act. Again, this doesn't mean these claims are incorrigible, only that our rational intuition supports them. And so this is another virtue of wave function realism over its rivals, that it does not require the rejection of analytic truths.[13]

To be clear, I am not arguing that we should not be cautious about trusting intuitions in metaphysics. Of course, we have to recognize that what we find intuitive has its source in historical facts about us and our ancestors (Ladyman et al., 2007). Again, when I say something is analytic and so intuitive, I am not also saying it is incorrigible. But I am skeptical that we should move from "we must be cautious about trusting our intuitions" to "we should throw all claims we take to be analytic by the wayside." We know from the history of physics that having intuitive metaphysical frameworks available for physical theories, indeed for quantum theories (think of the transition from matrix mechanics to wave mechanics (Jammer, 1966), is practically useful for scientists when carrying out their work. This isn't even to mention how useful it is for those who want to have an understanding of the world described by these theories.[14]

I want to make it clear then, if it is not already, that in my view Albert reaches beyond what is motivated when he claims that it is essential to think of quantum ontology in terms of wave functions, or that one can't present the world of quantum mechanics completely in terms of material bodies in a low-dimensional space. Rather, I would say, the high-dimensional wave function ontology is a reasonable framework to work with because its separability and locality make it simple and intuitive, and when one can attach a simple and intuitive metaphysics to a physical theory, this yields practical benefits. Perhaps my disagreement with Albert was not as clear as it could have been, as Maudlin recently suggested that my book claims that we need to adopt separability and locality "at any price" (2022, p. 4), noting "what seems simple and 'intuitive' to us need not be the way the world is" (2022, p. 5).

[13] In a recent paper, Calosi (n.d.) argues that separability can be derived from some distinct, analytic facts about fundamentality.

[14] Ney (2021), pp. 129-132 goes into more detail about the practical benefits of supplementing a physical theory with an intuitive metaphysical framework. An analogy is drawn with the case of special relativity.

This point is a bit misplaced, however. Unlike Albert, my conclusion (Ney, 2021, pp. x, 129-132) wasn't that wave function realism was the one true quantum metaphysics, but that the framework's practical benefits made it worth keeping on the table and developing. I even cited Carnap to make explicit that I was in favor of keeping rival frameworks on the table at the same time:

> To decree dogmatic prohibitions of certain linguistic forms [ontological frameworks] instead of testing them by their success or failure in practical use, is worse than futile; it is positively harmful because it may obstruct scientific progress. (Carnap, 1950, p. 221)

The fact is, we don't know what is the ultimate metaphysical truth underlying the data we have in tests of quantum entanglement. The world is weird in some way. But we don't know which weird way it is. If the other metaphysical frameworks for interpreting quantum theories have something to argue for them, then they should be kept on the table as well. It wasn't my business to argue for them in my book on wave function realism, but I would certainly acknowledge that the primitive ontologists, especially Allori (2013), and spacetime state realists, especially Chris Timpson and Wallace (2010), have made really strong cases that their frameworks are worth development as well. I have no idea what is the one true quantum metaphysics.

One of my main aims in discussing the arguments for wave function realism is to show that they really do not, as Albert and others have suggested, show us that realism about quantum mechanics forces the framework on us. The prima facie argument does not get us to wave function realism, since the mathematical formalism of quantum theories don't entail that the wave function be a field in high-dimensional space. The argument from entanglement does not support wave function realism over its competitors, since all of the rival frameworks are at least equally capable of capturing the facts of entanglement. And the argument from separability and locality is at best only able to show us that a wave function ontology provides a simple and intuitive framework for interpreting quantum theories, and so one that can be practically useful. But the wave function ontology is only one among many reasonable frameworks one can adopt to make sense of the world presented to us by quantum mechanics, one that (as continues to be pressed by Wallace (2020) and more recently, Read (2022) needs a more thorough development for it to be clear what metaphysics it assigns to quantum field theories.[15]

[15] I attempted to make progress on this question in Chapter 5 of Ney (2021). My view is that there are no good arguments to the effect that the wave function ontology *can't* be applied to quantum field theories. The arguments to that effect in Wallace and Timpson (2010), Myrvold (2015), and Wallace (2020) are all unsound. But this doesn't mean there isn't a lot of work to do in spelling out what wave function metaphysics for quantum theories ought to look like.

5 Is this realism?

At this point, a natural question to ask is whether wave function realism then turns out to be a version of (scientific) realism.[16] I and others often describe wave function realism as the view that the world is fundamentally a wave function (field) on a high-dimensional space with the structure of a configuration space. This suggests the wave function realist thinks:

1. Some quantum theories are (or will be) true, fundamental representations of our world.
2. Quantum theories are fundamentally about wave functions.
3. These wave functions are fields on high-dimensional spaces with configuration space structure.
4. And so, the world fundamentally consists of a wave function, a field on a high-dimensional space with the structure of a configuration space.

It is reasonable to infer from their work that Albert, Loewer, and North accept all of these claims, and so for them, wave function realism is straightforwardly a version of scientific realism.

However, as I have argued, I believe this position overreaches. I don't think the evidence on balances licenses us to infer (2) or (3), even if working with (2) and (3) are practically reasonable for these propositions' simplicity and intuitiveness. I don't see this as being incompatible with scientific realism. Anjan Chakravartty, in his influential exposition of scientific realism (2017) notes that although scientific realism is often defined in terms of the truth or approximate truth of scientific theories and the successful reference of theoretical terms in these theories to things in the world,

> adopting a realist attitude toward the content of scientific theories does not entail that one believes all such content, but rather that one believes those aspects, including observable aspects, regarding which one takes such belief to be warranted, thus indicating a realism about those things most specifically. (2017)

In my view, there is no empirical evidence at this time that favors realism about wave functions (as fields in a high-dimensional space) nor a primitive ontology nor a metaphysics of multi-fields nor… But this is compatible with the truth of some (perhaps future) quantum theories, and the successful reference of many if not most of these theories' distinctive theoretical terms, e.g. 'spin,' 'entangled state,' 'Higgs boson,' and so on.

But is my position a realism about the wave function? Well, no. We are overreaching if we take the attitude of belief towards wave functions as fields in a space with the high-dimensional structure of a configuration space. So here is where I

[16] This is a question Hubert asks in a recent review (Hubert, 2022). It was also pressed to me by North.

land. Of course, we should be realists about quantum theories. Quantum theories, like the quantum field theories that make up the Standard Model of particle physics, have been extremely well-confirmed. And we should be realists about quite a lot of the phenomena quantum theories reveal. But whether we should think that these phenomena are ultimately traceable to a field in a high-dimensional space is another question. At this point, the best we can do is say there are good practical reasons in favor of thinking in these terms, those described above, and that is all. So, no, I would not say any of the three arguments for wave function realism really motivate a genuine wave function realism. But the space between the two positions (mine and Albert's), I think, is narrow. I don't think we should be wave function realists, but I do think it is reasonable to think in terms of and develop a wave function ontology. I don't think the view's main critics would accept even the latter.

6 Why not Hilbert space realism?

Finally, I am often asked why wave function realists think that the fundamental quantum ontology is a field in a high-dimensional space with the structure of a configuration space, and not a ray in Hilbert space. After all, Hilbert space representations, one might say, are the more fundamental representations in quantum theories. They are certainly more general and capable of subsuming configuration space representations. Indeed, Carroll and Singh (2020, Carroll, 2022) argue that we should take the ontology of quantum theories (Everettian quantum theories, in particular) to fundamentally consist of a ray in Hilbert space. So why isn't this a more plausible interpretation of wave function realism?

If the argument that made wave function realism compelling was what I have called the prima facie argument or even the argument from entanglement, then we might have a case for the ray-in-Hilbert-space view. However, as I have tried to make plain, these two arguments do not succeed in supporting the wave function ontology over rival frameworks. Only the argument from separability and locality does. But the argument from separability and locality cannot support the ray-in-Hilbert-space view, because it is not a separable metaphysics. Recall the definition of separability:

> A metaphysics is *separable* iff if (i) it includes an ontology of objects or other entities instantiated at distinct regions, each possessing their own distinct states and (ii) when any such objects or entities are instantiated at distinct regions R1 and R2, all categorical facts about the composite region R1∪R2 are determined by the facts about objects and properties instantiated at R1 and R2 individually.

The ray-in-Hilbert-space view does not include an ontology of objects or other entities instantiated at distinct regions of space and so it violates clause (i). This is why wave function realists like Albert and Loewer do not hold the ray-in-Hilbert-space view, as intriguing as it is. If one wants to argue that this is the correct way to be a wave function realist, they will need a distinct argument for their position.

Actually, there is an argument I find supporters use to motivate the ray-in-Hilbert-space view, and it is distinct from any point about separability or locality. The point is interestingly similar in spirit to the simplicity point used to motivate the separable wave function ontology. Carroll describes the ray-in-Hilbert-space view as "our simplest construal of the rules of quantum theory," and argues that if we could understand in detail how the three-dimensional world of our experience is emergent from a more fundamental Hilbert space ontology, then "this project would represent a triumph of unification and simplification, and is worth taking seriously for that reason alone" (2022, p. 12).

The ray-in-Hilbert-space view is certainly even simpler than the wave function as field-in-configuration-space view. And for that, I agree with Carroll that it is worth keeping on the table and developing. A concern the wave function realist will raise is that it is much less clear how to recover all that is emergent from a single vector in Hilbert space, as opposed to a wave function field on a space with the structure of configuration space. But again, my purpose here is not to rule out other views. I only want to be clear about the arguments in favor of the wave function realist framework and the sort of conclusions they entail.

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