Locality and Wave Function Realism[1]

Alyssa Ney

For the volume *Identity, Indiscernibility, and Locality in Quantum Mechanics*,

edited by Olimpia Lombardi to be published by Cambridge University Press

Draft of October 11, 2017

Abstract: Wave function realism is an interpretational framework for quantum theories that has been defended for its ability to provide a clear and natural metaphysics for quantum theories, one that is fundamentally both separable and local. This is in contrast to competitor primitive ontology frameworks that while they could be separable, are not local, and holist or structuralist approaches that while they could be local, are not separable. The claim that wave function realist metaphysics is local, however, is not as straightforward as it has sometimes been assumed to be (nor as straightforward as the sense in which wave function realist metaphysics are separable). This paper distinguishes different senses in which a metaphysics for physics may be local, what may be the virtues of a metaphysics local in these senses, and the capacity of wave function realism to deliver such a metaphysics.

1. Introduction

Wave function realism is a framework for interpreting quantum theories. Applied to nonrelativistic versions of quantum mechanics, wave function realism yields metaphysics according to which the central, fundamental object is the quantum wave function, understood as a field on a high-dimensional space with the structure of a classical

[1] I am grateful to Wayne Myrvold, Alison Peterman, and participants at conferences in Buenos Aires and Lake Arrowhead for conversations that greatly improved this paper.

configuration space, perhaps supplemented with additional degrees of freedom to capture spin and other variables. Particles and other low-dimensional objects are understood by the wave function realist to be ontically derivative objects, constituted ultimately out of wave function stuff. For more sophisticated relativistic quantum theories and quantum field theories, the framework recommends a suitable relativistic extension of this metaphysics, a field in whatever high dimensional space is capable of capturing the full range of pure quantum states.

The case for such high-dimensional field interpretations varies from one framework proponent to another, but a recurrent theme is wave function realism's ability to provide ontologies for quantum theories that have some intuitively nice metaphysical features. For example, one may note the fact that quantum entanglement threatens to force a fundamentally nonseparable metaphysics on the interpreter or what is to some (Howard 1985, and, he argues, Einstein) worse, a fundamentally nonlocal metaphysics. However, these defects may be seen to drop away in the higher-dimensional interpretations preferred by the wave function realist. For her, what initially appear to be distinct entities possessing primitive relations and communicating instantaneously across distant regions of space are revealed to be manifestations of a single object fundamentally possessing only intrinsic features and acting locally on a high-dimensional space. This motivation for wave function realism is, as I shall explain below, more compelling than that suggested by other authors who have argued that one should adopt such a framework simply because it is the sort of thing that is most naturally read off of the physics.

Although some have challenged the wave function realist's claim to provide a separable metaphysics for quantum theories (e.g. Myrvold (2015), Lewis (2016)), I would say it is the claim that wave function realism provides a local metaphysics that is more difficult and less straightforward.[2] And so this is what I wish to examine in the present paper. I'll introduce and distinguish several senses in which a metaphysics for physics may be local, starting with two notions made use of by Bell (1964, 1976). From there we may evaluate in which sense(s) if any, the wave function realist's metaphysics are local and what, after all, is the virtue of having interpretations for quantum theories that are local in that (those) sense(s). I'll focus on the nonrelativistic case. Ney (manuscript) examines the extension to relativistic theories.

2. Wave Function Realism and its Competitors

It is worth noting at the outset that the interpretational question to which wave function realism is intended to provide an answer is to a large extent orthogonal to other interpretational questions, for example, that of what is the most promising approach to addressing the measurement problem for quantum theories. The measurement problem is the problem of how systems that are indeterminate with respect to one or another variable may evolve into states of what appear to be determinate values of such variables upon measurement. How can indeterminacy appear to evolve into determinacy, given a dynamics which seems to make such evolution impossible?

There are many approaches available to solving the measurement problem, ranging from collapse theories to the postulation of hidden variables to the appeal to relative states (or many worlds).[3] Here, the question is: should the quantum dynamics be

[2] I rebut the concerns about separability in Ney (manuscript).

[3] In this paper I focus on what are termed psi-ontic or objectivist approaches to solving the measurement problem since my interest is in what might be the mind-independent

supplemented, modified, or left alone? By contrast, wave function realism and its competitor frameworks are addressed at the question of what such dynamics describe – what is the ontology of a theory with a dynamics like that? In principle, each rival metaphysical framework may be applied to any of the dynamical proposals aimed at solving the measurement problem, although some combinations are more natural than others. I will not address all of the possibilities here, though I will provide brief overviews of wave function realism and its competitors.[4]

As mentioned, wave function realism is a framework for the interpretation of quantum theories in which the wave function is the central ontological item and is interpreted as a field on a high-dimensional space that (for the nonrelativistic case) is assumed to have at least the structure of a classical configuration space. For hidden variable theories, this wave function is supplemented with additional ontology, e.g. for Bohmian mechanics, a single particle evolving in a way determined by the motion of the wave function. Wave function realists thus take wave function representations literally and straightforwardly. As Albert has written:

> The sorts of physical objects that wave functions *are*, on this way of thinking, are (plainly) *fields* – which is to say that they are the sorts of objects whose states one specifies by specifying the values of some set of numbers at every point in the space where they live, the sorts of objects whose states one specifies (in *this* case) by specifying the values of *two* numbers (one of which is usually referred to as an

---

metaphysics of quantum theories. This isn't to reject the existence or interest of psi-epistemic or subjectivist approaches which deny that the role of the quantum state is to represent some mind-independent reality.

[4] Wave function realism is more natural as an interpretation of collapse theories like GRW and many worlds. The competitor primitive ontology approach is more naturally combined with hidden variables theories like Bohmian mechanics.

> amplitude, and the other as a *phase*) at every point in the universe's so-called *configuration* space. (1996, p. 278)

As has been mentioned and will be discussed in more detail below, this simple interpretation of the wave function has the advantage of providing a metaphysics for quantum theories that is fundamentally separable and local. However, other interpreters challenge this reading.

The primitive ontology approach of Dürr, Goldstein, Zanghì, Allori, and Tumulka (Dürr et. al. 1992, Allori et. al. 2008, Goldstein and Zanghì 2013) insists that the ontology of quantum theories consists primarily of entities in ordinary space or space-time. For example, particles for Bohmian mechanics, matter density fields for collapse theories or many worlds approaches. On the primitive ontology approach, the wave function is interpreted as real, but not an element of a quantum theory's primitive ontology: it is not what any physical theory is primarily about, not what constitutes the matter in the theory.[5] Instead, the wave function plays some other role, to guide the behavior of the matter, and so it is something more like a law broadly speaking. Those adopting the primitive ontology framework (and some of the other approaches I describe below) complain about the use of the name 'wave function realism' to apply solely to views according to which the wave function is a physical field on a higher-dimensional space, claiming they too are realists about the wave function, taking it to be a real, mind-independent element of quantum ontology. In a sense, this complaint is fair, but by now the terminology has become so entrenched, I will continue to use it. And anyway, in defense of the terminology, one thing that distinguishes the status of the wave function on

[5] See Ney and Phillips (2013) for a detailed examination and critique of the notion of a primitive ontology.

the wave function realist view from how it is viewed in primitive ontology or other psi-ontic approaches to interpretation is that for the wave function realist, the wave function is real in the classical sense of being *res*- or thing-like; it is a substance, *re*-al. This contrasts with its status on other interpretational approaches in which it occupies one or another distinct ontological category; rather than being *res*, it viewed as law, property, or a pattern of relations.

To many, the primitive ontology framework has appeal over wave function realism in providing metaphysics for quantum theories that are intuitive in certain respects – according to most applications of the approach, the fundamental entities of the theory inhabit our familiar space or space-time, and the macroscopic objects we observe may be built out of these basic constituents (particles or matter fields) in straightforward ways.[6][7] Moreover, these approaches hold out the promise of a separable metaphysics. The features of composite objects are determined by the features of their smaller constituent particles or field values at individual space-time points. For example, for Bohmian mechanics, one may argue that there are no facts about joint states of the particles that fail to be determined by the states of individual particles. Facts about quantum entanglement do fail to be determined by facts about the states of particles taken individually or together, but on a primitive ontology approach to Bohmian mechanics, entanglement is a feature of the wave function, not the particles. And so one could say the matter ontology of Bohmian mechanics is perfectly separable. The same may be said for the matter density ontology the primitive ontology view attaches to collapse theories.

---

[6] An exception is the flash ontology offered as a primitive ontology interpretation of some collapse approaches. This ontology is surprisingly sparse and unfamiliar.
[7] *May* be so built: for critique, see Ney and Phillips (2013).

Nonetheless, such metaphysics are not local. As Bell showed:

> In a theory in which parameters are added to quantum mechanics to determine the results of individual measurements, without changing the statistical predictions, there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote. Moreover, the signal involved must propagate instantaneously, so that such a theory could not be Lorentz invariant. (1964/1987, p. 20)

In situations characterized by the presence of quantum entanglement, measurements made on one entity at one location can have immediate influence on that entity's entangled partner at a spatially distant region. This is so in situations evolving according to both collapse and no-collapse dynamics. Even for many worlds versions of the primitive ontology approach, although locality is often claimed, as Lewis (2016) notes, this locality is only available in the higher-dimensional space the wave function inhabits. Once the wave function is relegated to some other non-primitive status, as something un-field- and un-matter-like, this advantage is lost.

A distinct class of approaches to the interpretation of quantum theories seeks to obtain a local metaphysics, but at the cost of rejecting separability. This is characteristic of the approaches of Howard and Teller from the 1980s. Howard (1985) argues that what seem to be entangled pairs of objects in distant regions of space should not be viewed after all as numerically distinct entities. In the extreme case in which every putative entity is entangled with any other, the view becomes a version of monism. There is only one thing. According to Howard, there is no instantaneous action between spatially separated entities because there aren't multiple entities after all. He argues that if faced with the choice of preserving separability or locality, Einstein too would have chosen to reject separability in order to maintain locality (Howard 1985, p. 197). Teller (1985) offers a distinct nonseparable approach, allowing that entangled pairs are fundamentally distinct entities while claiming that entanglement forces us to admit the existence of irreducible relations between pairs that do not reduce to any intrinsic features of the individuals constituting those pairs. He argues (1989) this allows one to avoid nonlocality since the view rejects the general claim that correlations between objects must ever be explained in terms of more fundamental features of these objects such as the causal relations between them.

A more recent development of the idea that quantum entanglement should be interpreted as characterizing a world with fundamental relations not reducible to features of their relata is ontic structural realism, which has been advocated in a variety of forms (Ladyman 1998, Esfeld 2004, Ladyman and Ross 2007, French 2014). Such a framework for interpretation provides a metaphysics that is manifestly nonseparable. However ontic structural realists typically resist the claim of Teller that the existence of irreducible relations allows one to avoid the consequence of nonlocality.[8]

Similarly, another interpretative framework, the spacetime state realism advocated by Wallace and Timpson (2010) and Myrvold (2015), aims neither at providing metaphysics for quantum theories that are either separable or local. On this view, even in nonrelativistic quantum mechanics, the wave function characterizes highly abstract features of space-time regions, where the features of composite regions do not generally reduce to features of their constituents. What happens at one region can instantaneously

[8] Thanks to Michael Esfeld here.

affect what happens at another. In both cases, that of the ontic structural realist and of the spacetime state realist, the view is motivated not by the fact that it provides an intuitive metaphysics with various attractive and natural features such as separability or locality, but instead by the fact, inter alia, that it stays truer to the way physics represents the world rather than our expectations about what an ontology for physics should look like.

3. Entanglement and Separability

So far I've said that wave function realism is a framework aimed at providing metaphysics for quantum theories that are separable, but it would be good to have a straightforward definition of separability with which to work. We may initially consider the following:

> A metaphysics is *separable* if and only if (i) it includes an ontology of objects or properties instantiated at distinct regions and (ii) when any objects or properties are instantiated at distinct regions R1 and R2, all facts about the composite region R1 ∪ R2 are determined by the facts about the objects and properties instantiated at its subregions.

The first clause is needed in order to rule out monistic metaphysics in which there is only one thing or one spatial location. Separability implies that there are distinct objects or at the very least (if one prefers a field metaphysics) distinct field values instantiated at distinct locations in space.

One drawback to this definition is that, as it stands, it requires a separable metaphysics to be a Humean metaphysics. Since it speaks of *all* facts being determined by facts about what occurs at individual spatial regions, this makes separability require that all facts about dispositions, counterfactuals, causation, and laws are determined by what occurs at individual spatial regions.[9] One might avoid this implication by modifying the second clause of the definition to state only that the categorical or nondispositional or non-nomic facts are determined by the facts about individuals at subregions. We then have the following.

> A metaphysics is *separable* if and only if (i) it includes an ontology of objects or properties instantiated at distinct regions and (ii) when any objects or properties are instantiated at distinct regions R1 and R2, all categorical facts about the composite region R1 ∪ R2 are determined by the facts about the objects and properties instantiated at its subregions.

Some might object that the matters of concern when we discuss entanglement relations are dispositional – *this electron would be measured spin up were its z-spin to be measured*. And so we really want a definition of separability that requires dispositional features too to reduce to localized facts about individual spatial regions. But although these are some of the features of interest, entanglement can appear to force on us as well the violation of even this weaker account of separability. For, unless one adopts the Copenhagen-ish view that we can only talk sensibly about the results of measurements or the features of systems when they are in eigenstates, it is the occurrent and categorical spin states of entangled pairs as well, not merely how they would behave upon measurement, that appears to be determined only jointly, not individually by objects at distinct spatial regions.

---

[9] Loewer (1996) defends wave function realism explicitly for its ability to provide an interpretation of quantum theories compatible with Humean supervenience.

With this definition of separability in hand, we may see how the wave function realist may claim to provide interpretations of quantum theories that recognize the phenomenon of quantum entanglement without committing herself to fundamental nonseparability. To illustrate, consider the EPRB state, in which a pair of atoms is entangled with respect to their z-spin. Suppose our atoms are created in the singlet state:

$$\psi_S = 1/\sqrt{2}\ |\text{z-up}\rangle_A|\text{z-down}\rangle_B - 1/\sqrt{2}|\text{z-down}\rangle_A|\text{z-up}\rangle_B$$

and then sent in opposite directions toward two Stern-Gerlach magnets which will bend them up or down in accordance with their z-spin toward a measurement screen. Consider four locations between the magnets and screen with the following labels:

R1: where atom A goes at time t should it get deflected up

R2: where atom A goes at t should it get deflected down

R3: where atom B goes at t should it get deflected up

R4: where atom B goes at t should it get deflected down

At time t, the atoms will be an entangled state of position:

$$\psi_x = 1/\sqrt{2}|R1\rangle_A|R4\rangle_B - 1/\sqrt{2}|R2\rangle_A|R3\rangle_B$$

And so there are facts at t about properties instantiated at the joint regions $R1 \cup R4$ and $R2 \cup R3$ that are not determined by any facts local to their subregions, e.g. there is an atom at R1 iff there is one at R4. There is an atom at R2 iff there is one at R3. We thus have a violation of separability.

The wave function realist argues that what appears as nonseparability arises because what we are seeing is a three-dimensional manifestation of a more fundamental and higher-dimensional metaphysics that is entirely separable. The individual atoms A and B are ultimately constituted out of a field, the quantum wave function. This field is spread not over our familiar three-dimensional space in which there are the four locations R1, R2, R3, and R4, but instead over a space with the structure of a classical configuration space. This space instead contains (for example) regions we may suggestively label R13, R14, R23, R24. The wave function has amplitudes at these regions corresponding to the Born rule probabilities for the quantum state. So, in the present case, given the quantum state ψ_x, the wave function will have nonzero amplitude only at the two locations R14 and R23 and it will have an amplitude of ½ at each of these locations. Spin states will correspond to additional degrees of freedom. For a system initially appearing to have N particles then, the dimensionality of the wave function's space is posited to be at least 3N.

The wave function realist's proposed higher-dimensional metaphysics then may be entirely separable. All categorical features are determined by features of the wave function instantiated at individual regions in its space.[10] That the wave function takes a particular shape across the joint region R14∪R23, for example, is entirely determined by its features at the individual regions R14 and R23.

So far, what we have been discussing is wave function realism as applied to a nonrelativistic quantum mechanics without hidden variables. But as has been mentioned, wave function realism is only a framework for interpretation: the metaphysics it entails will vary in details depending on the details of the theory it is applied to be an interpretation of. If we are interested in the interpretation of a hidden variables theory, then in addition to the wave function, there will also exist some entity in the high-dimensional space corresponding to these variables. In quantum field theories in which

[10] The wave function has phase values in addition to the amplitude values highlighted in this discussion.

particle number fails to be conserved, the dimensionality of the space will instead be determined by the number of basis states of the quantum field. In summary, the wave function realist's metaphysics depends on the quantum theory one wants an interpretation of. It will consist (at least) of:

- a background space with (at least) the structure of a classical configuration space,
- the wave function, a field on that space, characterizable in terms of an assignment of amplitude and phase values and evolving according to the dynamics of the theory, e.g. the Schrödinger equation, perhaps supplemented with a collapse mechanism.

This metaphysics is postulated to be separable. There are properties instantiated at distinct spatial regions. But there are no facts about the wave function's categorical features at composite regions that are not determined by facts local to these regions' respective subregions.

The question I now want to raise is whether this metaphysics is also local.

4. Concepts of Locality

The concepts of locality most frequently invoked when the purported violations of locality brought about by quantum entanglement are under discussion are those highlighted by Bell. Wiseman (2014) has argued that Bell really had two different accounts of what locality may come to in physics. The first is the notion of locality invoked in his 1964 paper "On the Einstein-Podolsky-Rosen paradox":

> … the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past.

This is equivalent to what Shimony called 'parameter independence.'-Applied to the situation described in the previous section, it is the principle that the probabilities for the results of a measurement on atom B are independent of what we choose to do to what is at time t the spacelike separated atom A, including what measurements we choose to perform on it.

In his 1976 paper, "The theory of local beables," however, following Wiseman, we may see Bell invoking a distinct principle that he calls 'local causality':

> Let A be localized in a space-time region 1. Let B be a second beable in a second region 2 separated from 1 in a spacelike way… Now my intuitive notion of local causality is that events in 2 should not be 'causes' of events in 1, and vice versa.

By 'beable', Bell simply means entity, something that is real. This is a stronger principle than the early "locality" principle from 1964. It states not only that the probabilities for the results of a measurement on one system are independent of how we may manipulate another system at a spacelike separation from it, but also that these probabilities are independent of the actual measurement results we find when we measure that other system. Wiseman argues that it is local causality that Bell took to be the primary locality principle of interest from at least 1976 on. And it is what he argued must be violated if quantum theory is correct.

Arguably, neither of these interpretations of 'locality' suffices to explicate the sense in which the metaphysics of the wave function realist is claimed to be local. For the principles invoked by Bell both concern the existence of causal relations in spacetime, the second one especially explicitly by invoking facts about certain events exhibiting spacelike separation. Yet there is no spacetime interval defined on the space the wave function is said to inhabit, nor is the space of the wave function the space in which light propagates, and so there is no sensible notion of spacelike separation in the wave function realist's fundamental metaphysics to let us settle the issue of whether these senses of 'locality' obtain. To explain the way in which wave function realism may be claimed to involve a local metaphysics, we must move to a concept of locality that makes sense in the context of the high-dimensional space of the wave function realist.

Sometimes, when Bell discusses his principle of local causality, he states it in broader terms than we just saw:

> What is held sacred is the principle of 'local causality' – or 'no action at a distance'. (Bell 1981).

This principle is generalizable so as to be of use by the wave function realist. And so we may say

> A metaphysics is local if and only if it contains no instantaneous action across spatial distances.

Or perhaps:

> A metaphysics is local if and only if it contains no instantaneous and unmediated action across spatial distances,

where 'spatial' refers to whatever is the spatial background of the metaphysics. It may be our familiar three-dimensional space or space-time. But it may also be the high-dimensional spatial background of the wave function realist.

Can we be more precise? In his philosophy of physics textbook, Marc Lange provides an account which seems aimed at capturing such a notion:

> Spatiotemporal locality: For any event E, any finite temporal interval $\tau > 0$, and any finite distance $\delta > 0$, there is a complete set of causes of E such that for each event C in this set, there is a location at which it occurs that is separated by a distance no greater than δ from a location at which E occurs, *and* there is a moment at which C occurs *at the former location* that is separated by an interval no greater than τ from a moment at which E occurs *at the latter location*. (2002, p. 15)

But as Myrvold has noted (p.c.), without a metric, it is not clear how the wave function realist can make use of this account. Perhaps no more precision can be achieved for the sense of locality claimed by the wave function realist than with the intuitive definition of no instantaneous (unmediated) action across spatial distances.

To see how the wave function realist's metaphysics generally satisfy this form of locality, one should be careful about distinguishing the situation for the interpretation of different quantum theories, including those with and without collapse. In the case of Everettian quantum theories without collapse, the wave function simply evolves unitarily in accordance with the Schrödinger equation or its relativistic variant. The wave function spreads out and may interfere with itself as waves do. But at no point does an action at one point in the space influence an action somewhere else.

For collapse theories like GRW, the wave function may evolve unitarily, but from time to time there is a spontaneous collapse. This involves the entire wave function undergoing a hit, which may be represented mathematically by the multiplication of the quantum state by a Gaussian function localized on a particular region of the space. In this case, it is not correct to say that what happens in one region of the wave function's space acts immediately to influence what happens in another. Rather, in these models, collapses are not caused by anything about the state of the wave function at the previous time, but occur spontaneously. One could say that there are facts about the wave function at the time prior to collapse that determine how likely it is that the hit is localized at one point rather than another. The probability of the collapse being localized at one point rather than another is given by the Born rule probabilities which are associated with the amplitude squared of the wave function at the different points in its space. But there is still no reason to say that the amplitude of the wave function at one distant region R causes a collapse to be localized at another region R' of the space instantaneously. Even if the wave function later becomes more peaked around R', the collapse isn't something that takes place at R', but is rather something that happens across the entire space. So there isn't really a localized effect that may be influenced by some distant cause. The evolution of the wave function through collapse may be jerky and discontinuous, but it does not result in nonlocal action.

Finally, in the case we are interpreting no-collapse theories with hidden variables such as Bohmian mechanics, the wave function behaves identically to how it does in the nonrelativistic Everettian model. However, in this case, there will be some additional ontology, such as a particle (the so-called marvelous point) that moves around the wave function's space in a way described by the theory's guidance equation[11], that is, as determined by the state at a time of the wave function:

[11] For discussion, see Albert (1996).

$$\frac{d\boldsymbol{Q}_k}{dt} = \frac{\hbar}{m_k} Im \frac{\psi * \partial_k \psi}{\psi * \psi}(\boldsymbol{Q}_1, \dots, \boldsymbol{Q}_N)$$

In this case, the behavior of this additional ontology, the particle, is determined by the state of the wave function in the neighborhood of the place in the high-dimensional space it occupies. And so there is no threat of nonlocal action. Despite this fact, Bohmian mechanics is a quantum theory (or solution to the measurement problem) that combines rather poorly with the interpretational framework of wave function realism. After all, the very motivation for adopting Bohmian mechanics (at least as presented in Dürr, et. al. 1992) depends on an argument that wave function realists should not accept, namely that quantum theories are not theories about the behavior of the wave function but rather of something else, matter in three-dimensional space or space-time.[12] But if one was worried about nonlocal action, a wave function realist interpretation of Bohmian mechanics could be of help.

5. Fundamental and Derivative

So we have seen that wave function realism is a framework most naturally combined with Everettian and collapse versions of quantum mechanics, theories in which the wave function ontology is not supplemented with additional variables. When applied as an interpretation of these theories, wave function realism may yield a metaphysics that is local in its distinctive, (relatively) fundamental high-dimensional framework. But we may also ask what becomes of the nonlocality that appeared in the lower-dimensional space-time framework. Is there still not an issue of nonlocality there according to the wave function realist?

[12] See Ney and Phillips (2013), especially Section 5.

The answer to this question turns first on whether the wave function realist accepts the existence of three-dimensional space and space-time or of such low-dimensional facts. As has been mentioned, she typically does, although she will also claim that the low-dimensional facts require no addition to being beyond the high-dimensional framework she posits. The low-dimensional facts are derivative, i.e. metaphysically explained (grounded) by the behavior of the wave function.

One response the wave function realist may give to the question of whether there is nonlocal action in the derivative low-dimensional framework is that no, in that framework, there are correlations between spacelike separated events, but no genuine causal interaction because all such correlations have a deeper explanation in terms of the behavior of the wave function. The dynamical explanation for these correlations thus undercuts any causal explanation that may be provided by the existence of spatially distant events such as measurements on one half of an entangled pair.

I tried out such a line of reasoning in an earlier paper (Ney forthcoming) as do Ismael and Schaffer (forthcoming). However, I now find such a position unsatisfactory.[13] The reason is that if one wants to argue in this way that there is no immediate causation across spatial distances because such causal relations are undercut or screened off by the behavior of the wave function, then one must similarly do so for all other causal relations in the low-dimensional framework. For there will always be a wave function dynamical explanation available at the more fundamental level. So, unless we are to be causal nihilists about what happens in ordinary space-time, the behavior of the wave function does not undercut the reality of nonlocal action in space-time. What the wave function

[13] Thanks to Jessica Wilson for pressing me on this issue.

realist can offer is a more fundamental explanation of in virtue of what that derivative nonlocal action obtains, one that may give a more satisfying picture of what makes things happen in our world than one that contains unexplained nonlocal action. But it does not remove low-dimensional facts about nonlocal action.

6. Motivating a Local Metaphysics

So assuming the wave function realist can provide a local interpretation of at least some versions of quantum theories, in at least some sense of 'local', we may ask, why should one care?

I will start with some empirical considerations and move toward some that are more a priori. I have already noted that wave function realism is not successful at securing the conceptions of locality used by Bell. And yet these are the senses of locality that some would say are mainly at issue when one worries about the incompatibility of relativity and quantum mechanics. But perhaps there is more one can say and the fact that wave function realism provides a metaphysics local in its own space may help alleviate some of the concerns arising about nonlocality in space-time.

In his recent book *Quantum Ontology*, Peter Lewis states the reason why nonlocal action is in tension with relativity in the following way. Suppose one allows that there exists at least some instantaneous action at a distance. Then there is some one time at which one event influences another at a spatial distance from it. For example, something happening right here right now depends on the simultaneous mass of a distant star. But according to special relativity, there are no absolute facts about which spatially distant events are instantaneous with which others. So, in Lewis's example, there is no fact about the mass of the star right now. So what this action at a distance is is ill-defined according to relativity. Thus, it would seem, according to relativity, there cannot be action at a distance.

However, what looks puzzling, ill-defined, or brute from the perspective of a nonfundamental metaphysics may be revealed as expected and explained in terms of a more fundamental metaphysics. To the extent that wave function realism supports a derivative ontology, it will yield an account of which space-time configurations exist and are causally related in that derivative ontology. So, at least *Lewis's* concern about the conflict between special relativity and quantum mechanics seems avoided if one adopts wave function realism. This is not to say that other issues, which I would concede are more basic, are not avoided, namely a conflict with Lorentz covariance.

Another important feature of local theories is articulated by Einstein, who in a famous paper from 1948 argued that local metaphysics seem to be required for the possibility of physical theories:

> For the relative independence of spatially distant things (A and B), this idea is characteristic: an external influence on A has no *immediate* effect on B; this is known as the 'principle of local action', which is applied consistently only in field theory. The complete suspension of this basic principle would make impossible the idea of the existence of (quasi-)closed systems and, thereby, the establishment of empirically testable laws in the sense familiar to us.

The point seems straightforward enough. If what is nearby and observable may be affected by objects that are spatially distant, then without full knowledge of the occupants of the total space-time manifold, how are we to make predictions about how the objects we observe will behave? Locality appears required to allow us to formulate testable empirical theories.

Now this point of Einstein's is itself contestable. In conversation, Myrvold has questioned it, claiming that even in classical physics we are very comfortable writing down and testing laws knowing full well that there are spatially distant objects affecting the behavior of local objects. His example is the astrophysicist's description of the motion of Jupiter's moons. The Sun being 480 million miles away, Einstein's reasoning would lead one to believe that the physicist would need to reject its influence, modeling the behavior of the moon solely in terms of nearby factors. But this would produce wildly wrong results. This is a clear case in which the assumption of spatially distant influences is essential, not an obstacle to the formulation and testing of physical laws. Now of course what Einstein rejects is that an external influence on A has *immediate* effect on B, and one might respond to Myrvold by arguing that relativistic modeling will reject that the Sun's influence is immediate. But, astronomical phenomena are modeled quite well by Newtonian physics according to which gravitational influence is unmediated and instantaneous. Einstein seems wrong that physics simply cannot be done when we assume there are nonlocal influences and build these into our models.

Myrvold is right to object to hyperbole in Einstein's defense of locality in physics, but I don't believe this undermines a weaker defense of locality as an assumption guiding the formulation of tractable and testable physical theories. For in the case of the Sun and Jupiter's moons, the physics works because we are considering the influence of just a few large bodies at a distance away. Things would devolve quite quickly if the modeling of Jupiter's moons needed to take into account immediate and significant influences from many or all distant bodies. So perhaps this is what Einstein is concerned about, thinking of widespread effects from quantum entanglement that would massively complicate physics, perhaps leading to intractability. And so, for physics "in the sense familiar to us" to work, we discount immediate influence *in general and for the most part* where this is justified. Note that with advances in computational modeling, physics can take into account a much larger number of distant bodies successfully. However this doesn't undermine Einstein's point, as in the age of big data, we are moving away from physics in the sense familiar to Einstein circa 1948.

So I propose we can make use of the weak point that we have good inductive reason to believe that physics of the kind that is already familiar to us, which involves modeling systems based on the assumption of (mostly) local influence is a way of developing inductively successful theories. But can this justification for a local metaphysics be used to generate any support for wave function realism? I am afraid it cannot – the point is, after all, that the testing of laws depends on our ability to manipulate and observe what is happening at a confined, region of space, isolating objects from outside influences. But of course the space in which human beings' manipulations and observations take place is not the high-dimensional space of the wave function. Thus, it seems, Einstein's defense of locality justifies a local metaphysics in three-dimensional space or space-time, the framework in which we interact with objects, but not a local wave function metaphysics.

Perhaps another case to be made for local interpretations of physical theories may be found in the work of Allori. Allori (2013) defends another view she finds in Einstein, that "the whole of science is nothing more than a refinement of our everyday thinking." She elaborates:

> The scientific image typically starts close to the manifest image, gradually departing from it if not successful to adequately reproduce the experimental findings. The scientific image is not necessarily close to the manifest image, because with gradual departure after gradual departure we can get pretty far away…. The point, though, is that the scientist will typically tend to make minimal and not very radical changes to a previously accepted theoretical framework. (2013, p. 61)

One might then say since our pre-scientific thinking and subsequent physical theories postulated local and separable metaphysics, our quantum theories should, if possible do so as well.

To be clear Allori is herself not making this point to argue for the local metaphysics of wave function realism, she is using the point to argue for her preferred primitive ontology view since she believes that all previous (i.e. nonquantum) physical theories also possessed a primitive ontology. But one might hope that her point extends to make a case for a local wave function metaphysics as well.

But unfortunately, I don't think it does. Because wave function realism also rejects as fundamental a three-dimensional spatial background, replacing it with an unfamiliar, high-dimensional background, it is not really so plausible to argue that *this* local metaphysics is closer to the manifest image and classical theories than one that would jettison one or both of separability and locality, but retain the low-dimensional spatial background of our experience. If we agree with Allori that minimal departures should, where possible, be preferred, the move to higher dimensions is very far from a minimal departure.

Finally we may move to consider more purely a priori reasons in support of a local metaphysics.[14] Some of these were brought to bear in the eighteenth century as natural philosophers struggled with Newton's characterization of gravitational forces as acting immediately across spatial distances in Newtonian physics. Newton himself sometimes claimed that action at a distance is impossible, e.g.:

> The cause of gravity is what I do not pretend to know and therefore would take more time to consider of it… That gravity should be innate, inherent, and essential to matter, so that one body may act upon another at a distance through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it. (Letter to Bentley)

To claim nonlocality is absurd is not thereby to offer an argument against it. Nor to my knowledge did Newton ever offer a clear argument for why action at a distance is absurd, however we do find something in the work of Clarke in his correspondence with Leibniz:

> That one body should attract another without any intermediate means, is not a miracle, but a contradiction: for 'tis supposing something to act where it is not. But the means by which two bodies attract each other, may be invisible and intangible, and of a different nature from mechanism; and yet, acting regularly and constantly, may well be called natural… (fourth letter to Leibniz)

Clarke, like Newton, supposes that gravity must act locally even if the means by which it does so may be invisible. And the reason why this must be so is for something to act, it

[14] A greater exploration of the a priori considerations may be found in Ney (in progress).

must be located where it acts. Otherwise, it wouldn't be it itself that is so acting, but something else, or nothing at all. There is something, I believe, that is sensible about this point and it explains at least one reason why nonlocal action strikes us as deeply unintuitive and worse, incoherent. And it is, finally, a consideration that may be brought to be bear in support of wave function realism's local metaphysics.

7. Intuitions

It is my view that the best case the wave function realist has for developing her distinctive local metaphysics comes from such conceptual considerations and intuitions. But one might question whether it is at all desirable to have an interpretation of quantum theories that conforms to our intuitions. Ladyman and Ross et. al. (2007) criticize such interpretational projects, calling them domestications of science. My project is openly one of the domestication of a large part of physics. It is my attitude that quantum theories stand very much in need of domestication to the scientific community and greater public.[15] Following out interpretations that are compatible with our intuitions may be useful for a number of reasons. I will just now mention three benefits that such an interpretation may bring. All are unabashedly pragmatic.

First, an interpretation of a physical theory, by providing one with a clear account of what the world is like according to the theory benefits students and scientists in allowing them a clearer handle on the theory they are working with. Although it is not possible to understand our best scientific theories without having a handle on the mathematics used to state it, a clear metaphysics to supplement the mathematics can be

[15] This is not to deny that the project of domestication has already been carried out to a large extent by the work of those providing clear solutions to the measurement problem.

instrumental in seeing more clearly what the theory says, allowing one to more easily learn and use it. As an example, the special theory of relativity before it was supplemented with the clear interpretation of a four-dimensional Minkowski space-time seemed to lead to paradoxes in measurements that were difficult to comprehend like the paradox of the train and the tunnel or the twins paradox. These were not genuine paradoxes; there was no such inconsistency in the theory, but this was much easier to comprehend when one grasped the theory not purely through the predictions the mathematics produced, but supplemented it with a picture of entities spread out in four-dimensional space-time, for which facts about elapsed time or spatial distance failed to be absolute. I believe something similar can come to pass for quantum theories. Once supplemented with a clear metaphysics, what looks paradoxical or surprising becomes clear and natural and easier to use. And there is no reason distinct interpretations cannot produce alternative accounts useful in this respect.

Second, an interpretation says things that go beyond what the theory on its own says and in this respect, interpretations can be fruitful in generating new speculations or predictions that can then extend the theoretical power of the theory. Should one adopt the wave function metaphysics and its attendant higher dimensions, one can begin to ask more questions about the structure and contents of this higher-dimensional space and learn more things about it that would simply not be discussed without attention to this question of interpretation.

Finally, for myself and many other former physics students, the reason we chose physics as a focus of study in college was to learn about the fundamental nature of reality. Without an interpretation, physics doesn't provide this. Under the influence of

Copenhagen, Mermin's "Shut up and calculate!", and Feynman's "I think I can safely say no one understands quantum mechanics," students often come to quantum theories puzzled about what they say about the world, but then are told not to ask such questions because the theory is impossible to understand. This is disappointing and drives students out of the field. Not all physics students care about questions of interpretation and the deep issue of the nature of reality, but for those that do, it is worth having serious work on interpretation that can give them what they are looking for. We need more, not fewer students of physics.

I don't want to leave the reader with the sense that anything I am saying challenges the idea that we should not at the same time work on interpretations that challenge our thinking. In fact, all of the interpretations of quantum theories that are available have aspects of unintuitiveness – this is simply unavoidable in the interpretation of quantum theories. And it is what is so exhilarating about the study of these theories, how they challenge what we previously thought was obvious. What is being suggested in this last section however is that there is nothing problematic about trying to fit these startling aspects of the world into a picture we can understand.

8. Conclusion

The wave function realist need not deny that there is a clear sense of locality in which our world contains nonlocal influences. This is the sense of local causality taken up by Bell from 1976 onwards. The question is whether one should take this to be a brute fact about our world or attempt to provide explanations in terms of an underlying metaphysics. Wave function realism is such an attempt at explanation. The virtues of having interpretative options that provide such an explanation justify the exploration and development of this framework which should be pursued alongside others.

Work Cited

Albert, David Z. 1996. Elementary Quantum Metaphysics. In *Bohmian Mechanics and Quantum Theory: An Appraisal*. J.T. Cushing, A. Fine, and S. Goldstein, eds. Dordrecht: Kluwer.

Allori, Valia. 2013. Primitive Ontology and the Structure of Fundamental Physical Theories. In *The Wave Function*. A. Ney and D. Albert, eds. Oxford: Oxford University Press.

Allori, Valia, Sheldon Goldstein, Roderick Tumulka, and Nino Zanghì. 2008. On the Common Structure.

Bell, John. 1964. On the Einstein-Podolsky-Rosen Paradox. *Physics*. 1: 195.

Bell, John. 1976. A Theory of Local Beables. *Epistemological Letters*. 9: 11-24.

Bell, John. 1981. Bertlmann's Socks and the Nature of Reality. *Journal de Physique Colloques*. 42: 41-62.

Dürr, Detlef, Sheldon Goldstein and Nino Zanghì. 1992. Quantum Equilibrium and the Origin of Absolute Uncertainty. *Journal of Statistical Physics*. 67:1-75.

Esfeld, Michael. 2004. Quantum Entanglement and a Metaphysics of Relations. *Studies in History and Philosophy of Science Part B*. 35(4): 601-617.

French, Steven. 2014. *The Structure of the World*. Oxford: Oxford University Press.

Goldstein, Sheldon and Nino Zanghì. 2013. Reality and the Role of the Wave Function in Quantum Theory. In *The Wave Function: Essays in the Metaphysics of Quantum Mechanics*. A. Ney and D. Albert, eds. Oxford: Oxford University Press.

Howard, Don. 1985. Einstein on Locality and Separability. *Studies in History and Philosophy of Science*. 16(3): 171-201.

Ismael, Jenann and Jonathan Schaffer. forthcoming. Quantum Holism: Nonseparability as Common Ground. *Synthese*.

Ladyman, James. 1998. What is Structural Realism? *Studies in History and Philosophy of Science Part A*. 29(3): 409-424.

Ladyman, James and Don Ross. 2007. *Every Thing Must Go*. Oxford: Oxford University Press.

Lewis, Peter. 2016. *Quantum Ontology*. New York: Oxford University Press.

Loewer, Barry. 1996. Humean Supervenience. *Philosophical Topics*. 24: 101-27.

Myrvold, Wayne. 2015. What is a Wave Function? *Synthese*. 192(10): 3247-3274.

Ney, Alyssa. forthcoming. Separability, Locality, and Higher Dimensions in Quantum Mechanics. *Current Controversies in Philosophy of Science*. London: Routledge.

Ney, Alyssa. manuscript. Wave Function Realism in a Relativistic Setting. Available online at: https://philpapers.org/rec/ALYWFR

Ney, Alyssa. in progress. *Finding the World in the Wave Function*.

Ney, Alyssa and Kathryn Phillips. 2013. Does an Adequate Physical Theory Demand a Primitive Ontology? *Philosophy of Science*. 80: 454-474.

Teller, Paul. 1986. Relational Holism and Quantum Mechanics. *British Journal for the Philosophy of Science*. 37(1): 71-81.

Teller, Paul. 1989. Relativity, Relational Holism, and the Bell Inequalities. *Philosophical Consequences of Quantum Theory: Reflections on Bell's Theorem*. J.T. Cushing and E. McMullin, eds. Notre Dame: University of Notre Dame Press, 208-223.

Wallace, David and Christopher Timpson. 2010. Quantum Mechanics on Spacetime I: Spacetime State Realism. *British Journal for the Philosophy of Science*. 61(4): 697-727.

Wiseman, Howard. 2014. Two Bell's Theorems of John Bell. *Journal of Physics A*. 47: 424001.