Separability, Locality, and Higher Dimensions in Quantum Mechanics

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Alyssa Ney
aney@ucdavis.edu

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Abstract: This paper describes the case that can be made for a high-dimensional ontology in quantum mechanics based on the virtues of avoiding both nonseparability and nonlocality.

1. Introduction

In his paper, "On the Einstein Podolsky Rosen paradox," John Bell derived a result according to which a theory capturing the statistical predictions of quantum mechanics cannot be one that avoids situations in which the result of one measurement correlates with the result of another space-like separated from it such that no prior determination could suffice to explain the correlation. He used this result to argue that:

> 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)

As we know, it has since been observed that settings of a measuring device in one location may exhibit an instantaneous, thus superluminal dependence on outcomes in distant locations (Aspect et. al. 1981), thus confirming Bell's predictions. And so such nonlocal dependence seems to be a feature of our world, not merely for a quantum theory with "added parameters." Both quantum theories and our world thus seem to exhibit the kind of nonlocality Bell argued for. But is this a necessary consequence of his proof and the experimental tests that we should include in our best metaphysical interpretation of quantum systems?

Although some may be happy or at least resigned to accept nonlocality as a consequence of quantum theories, others seek ways to avoid the implication that nonlocality is a fundamental feature of our world. One strategy is to reject a key assumption on which Bell's derivation of his theorem is thought to rely: the separability of quantum systems.

The goal of this paper is to discuss what is perhaps a more promising alternative. This is to avoid both nonlocality and nonseparability by adopting a higher-dimensional interpretation of quantum systems. This higher-dimensional interpretational framework is now commonly referred to in the literature as *wave function realism* (Albert 2013). It provides an interesting way to achieve a kind of local and separable metaphysics, however, as we will see, not all considerations in favor of locality and separability may apply to generate support for this interpretation.

2. Entanglement, Nonseparability, and Nonlocality

Bohm's illustration of the kind of case with which Einstein, Podolsky, and Rosen (and thus Bell) were concerned considers an extremely simple entangled state (Bohm 1951).

> Suppose that we have a molecule containing two atoms in a state in which the total spin is zero and that the spin of each atom is $\hbar/2$. Roughly speaking, this means that the spin of each particle points in a direction exactly opposite to that of the other, insofar as the spin may be said to have any definite direction at all. Now suppose that the molecule is disintegrated by some process that does not change the total angular momentum. The two atoms will begin to separate and will soon cease to interact appreciably… When the atoms separated, each atom would continue to have every component of its spin angular momentum opposite to that of the other. The two spin-angular-momentum vectors would

therefore be correlated… Suppose now that one measures the spin angular momentum of any one of the particles, say No. 1. Because of the existence of correlations, one can immediately conclude that the angular-momentum vector of the other particle (No. 2) is equal and opposite to that of No. 1. (1951, p. 614)

In this scenario, our atoms are in an entangled state, the singlet state, in which two particles are entangled with respect to their spin along some particular axis. Particles in such a state may be represented by the following wave function:

$$\psi_{singlet} = \frac{1}{\sqrt{2}}|x - up\rangle_A |x - down\rangle_B - \frac{1}{\sqrt{2}}|x{-}down\rangle_A |x - up\rangle_B$$

The Born rule, the rule of quantum mechanics that allows us to infer probabilities for measurement results from such representations, will then tell us that were we to measure the spin states of these atoms, we would have a 50% chance of finding the first x-spin-up and the second x-spin down, and a 50% chance of finding the first x-spin-down and the second x-spin up.

To say that the wave function of these atoms describes an entangled state is simply to say that they are in a state where due to some previous process or interaction, the expectation values of measurement results with respect to a particular variable are modally correlated. We are able to correctly describe a system as in an entangled state without yet getting into the metaphysics of the situation, in particular before asking whether the atoms are in a state that is either (a) nonseparable or (b) nonlocal, in the senses to be described.[1] Let's disentangle these notions now.

A. Nonseparability

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[1] But don't we need to know at least that e_1 and e_2 are numerically distinct, that they are two things, to know $\psi_{singlet}$ is an entangled state? No, different variables of a single entity can be entangled as well (cf. Quian and Eberly 2013).

Separability is a feature of physical systems in which the systems' constituents individually occupy distinct regions of space-time. A system located at a space-time region R is separable when it contains subsystems located at nonoverlapping proper subregions of R and all states of the system at space-time region R are wholly determined or grounded by the states of those subsystems. A state of such a system is a separable state when it is wholly determined by states of these subsystems. Similarly, Howard writes:

> [Separability] is a fundamental ontological principle governing the individuation of physical systems and their associated states, a principle implicit in many classical physical theories. It asserts that the contents of any two regions of space-time separated by a nonvanishing spatiotemporal interval constitute separable physical systems, in the sense that (1) each possesses its own, distinct physical state, and (2) the joint state of the two systems is wholly determined by these separate states. (1989, pp. 225-226)

The key difference here is Howard's addition of the constraint that the relevant subsystems are those separated by some "nonvanishing spatiotemporal interval." I don't think this is required to discuss separability or its failure.

We may illustrate this notion using nonscientific examples. For example, that a pair of tennis balls is orange and yellow is a separable state of the pair, for that they together have these colors is determined by the colors of the individual balls, one being orange and one being yellow. On the other hand, a couple's being married is a nonseparable feature of a pair of individuals, technically, since it is not determined by the states of the individuals taken separately. A couple's being married is not a particularly interesting nonseparable feature since although it is true that it is not determined by features of the individuals taken separately, it is determined by the state of the individuals plus the features of some other things in the couple's environment. The kind of nonseparability suggested by quantum entanglement is rather more interesting because it is often thought not to be reducible to individual states of subsystems combined with states of the system's environment, or anything else.

Systems in quantum mechanically entangled states, like Bohm's pair of atoms, are often thought to exhibit fundamental nonseparability. The singlet state is thought to be an example of a nonseparable state because the atoms' being in such a spin state is not determined by any individual facts about them, including facts about their individual x-spins. For in such a state, it appears there is no definite fact about the atoms' individual x-spins. For each one, we know that if we conduct an x-spin measurement, there is a 50% chance of finding an x-up result and a 50% chance of finding an x-down result. There is nothing more definite we may say about their individual x-spins. And yet it is also a fact about the pair that if their x-spin state is to be measured, it is absolutely certain that they will be found to have opposite spins. This joint fact about the system as a whole is not determined by any fact about the atoms' individual x-spins. Schrödinger emphasized this seeming consequence of quantum mechanics explicitly in 1935:

> *Maximal knowledge of a total system does not necessarily include total knowledge of all of its parts, not even when these are fully separated from each other and at the moment are not influencing each other at all.* (1935, p. 160)

This consequence is significant enough for Schrödinger that he places the entire sentence in italics.

Systems can be and often are in entangled states of many variables, such as spin, position, momentum, and energy. For this reason, nonseparability appears to be a pervasive feature of quantum mechanics. Below I will consider ontological interpretations of quantum systems that reveal this apparent nonseparability to be a consequence of a more fundamental metaphysics that is separable in higher dimensions. It is worth mentioning beforehand however that there is a way of ensuring separability, if one wants to adopt the Bohmian approach to quantum theories. Bohmian mechanics is an alternative approach to quantum mechanics. It contains a dual ontology of (a) particles that always possess determinate individual values of position and momentum and (b) a wave function, which is interpreted in various ways, sometimes as a physical wave in three-space, a so-called guiding wave that pushes the particles around (Bohm 1952), other times as something with more of a nomological status, determining like a law how the particles will behave over time (Goldstein and Zanghì 2013).

In Bohmian mechanics, one may argue that there are no facts about joint states of the atoms that fail to be determined by the states of the individual atoms. There is a fact about something else, the wave function, that is not determined by the states of the atoms (taken individually or together). Bohmian mechanics interprets entanglement as a feature of states of the wave function. However, one could say the matter ontology of Bohmian mechanics is perfectly separable. Perhaps because Bohmian mechanics has this feature, it is also manifestly nonlocal.

B. Nonlocality

The issue of locality/nonlocality has frequently been conflated with that of separability/nonseparability in the scientific and philosophical literature. This is not really so surprising given the multiplicity of meanings our language assigns to 'local.' In one such usage, we may think of nonlocality as a matter of a system's features not being determined by features of its “local” (i.e. spatially more localized) parts. However, we already have a name for that feature, ‘nonseparability.’[2]

Unlike separability which concerns (noncausal) metaphysical determination or grounding of the features of systems, in the sense to be discussed here, locality is a causal notion. Lange has defined locality in the following way:

> *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)

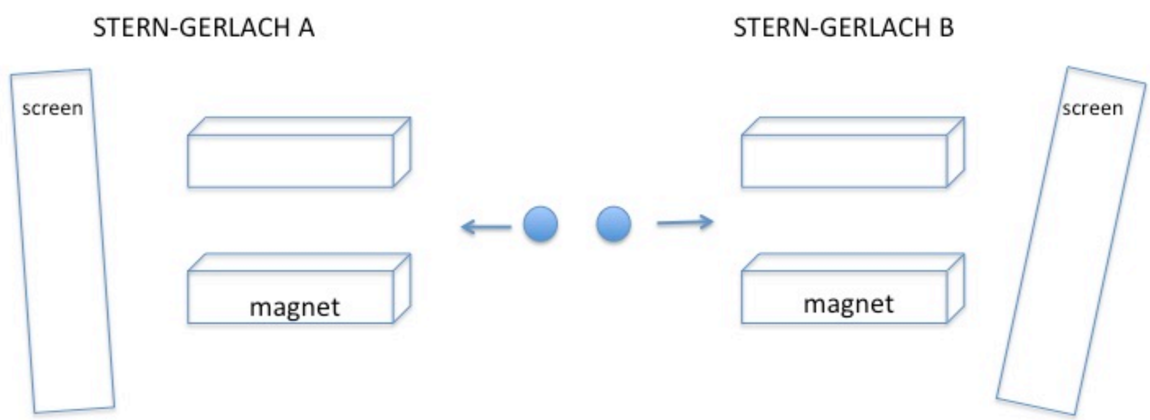
This account captures the idea that a system is nonlocal if it manifests direct instantaneous action at a spatiotemporal distance. Thus nonlocal systems exhibit superluminal influence in violation of the special theory of relativity. As is standard in the literature then, we can understand locality as a principle that there is no superluminal influence, including instantaneous action across spatial distances. However, it is also worth noting as it will be important below that Lange’s more precise and general definition does not assume what spatial background the distances δ appear in. We may ask about the preservation of locality in any spatial framework, even those less familiar than the three-dimensional spatial framework of the manifest image.

Just as entangled systems are often thought to instantiate fundamental nonseparability, so they are thought to manifest fundamental nonlocality. This was famously argued to be a

[2] Howard (1985) is especially direct that we should avoid this conflation of concepts: “Most importantly, it should be understood that the separability of two systems is not the same thing as the absence of an interaction between them, nor is the presence of an interaction the mark of their non-separability” (p. 173).

consequence of quantum entanglement in the Einstein, Podolsky, and Rosen (EPR) paper of 1935, assuming quantum mechanics is able to give a complete description of reality. To make this more vivid, let's again consider the EPRB setup and imagine the atoms' spins are measured by sending them through a Stern-Gerlach apparatus, a simple device involving a pair of magnets that deflects particles in one spatial direction or another based on their spin.

Figure 1



Let's imagine $atom_A$ is sent through its apparatus slightly before $atom_B$ is sent through its. The measurement on $atom_A$ will then instantaneously affect whether $atom_B$ is deflected up or down by the magnets. And this is so no matter how far apart the two Stern-Gerlach apparatuses are.

Nonlocality is widely believed to be a genuine feature of quantum systems. After the EPR paper, as we noted, Bell argued that nonlocality cannot be avoided by granting the ontological incompleteness of quantum mechanics and postulating additional variables, so even Bohmian mechanics is a nonlocal theory. Subsequently, nonlocality appears to have been demonstrated in many experimental settings. The experiments by Alain Aspect in the 1980s are perhaps the most famous (Aspect et. al. 1981). However, some believe it is possible to avoid nonlocality by appealing to the nonseparability of quantum systems or by providing an even more revisionary metaphysical interpretation.

3. Avoiding Nonlocality

In a later section we will explore what exactly is supposed to be so problematic about nonlocality. Presently, we will address some ways of avoiding at least fundamental nonlocality in quantum mechanics. The first involves an appeal to the failure of separability and has been defended by Howard and Teller. The second allows for a recovery of separability while simultaneously ensuring locality by way of a move to a higher-dimensional metaphysics.

A. Fundamental Nonseparability

Howard argues that we can ensure a local metaphysics for quantum mechanics by rejecting the separability of quantum states. He writes:

> The separability principle operates on a more basic level as, in effect, a principle of individuation for physical systems, a principle whereby we determine whether in a given situation we have only one system or two. If two systems are not separable, then there can be no interaction between them, because they are not really *two* systems at all. (1985, p. 173)

And, in light of the experimental confirmation of Bell's results:

> We must give up either separability or locality… But if these are our only alternatives, then most of us would likely prefer the former alternative, on the grounds that special relativistic locality constraints are too much a part of our physics to be sacrificed to the cause of saving separability, all the more so because we have ready at hand a highly successful non-separable quantum mechanics… In fact, I believe that Einstein himself would have followed us in this choice had he been forced to choose between these two alternatives. (1985, p. 197)

Howard's view is that when one accepts nonseparability, one thereby rejects the numerical distinctness of the individuals in entangled states. In Bohm's set-up, the proposal is we reject the belief that the atoms are distinct entities and instead view them as one. Then we can explain the observed correlations without requiring nonlocality. There is no instantaneous superluminal influence of $atom_A$ on $atom_B$ because there is no distinction between $atom_A$ and $atom_B$.

One may ask why we are entitled to conclude just by the assumption that $atom_A$ and $atom_B$ are numerically identical that there cannot be causal influence between distant wings of the experiment. Surely a state of one object can cause another state of that self-same object. My being thirsty can cause my getting up to get a glass of water. What is more plausible, however, is that causal relations are irreflexive, that one state of an individual cannot cause that very state of the self-same individual. My being thirsty at a certain time t cannot cause my being thirsty at that same time t.[3] And so what Howard seems to be assuming is not or not merely that the atoms are numerically identical, but that the relevant states are identical ($atom_A$'s being found x-spin up and $atom_B$ x-spin down).

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[3] That causal relations are irreflexive is a standard assumption in the causation and causal modeling literature, e.g. Pearl (2000).

Strictly speaking, this rejection of numerical distinctness of states goes beyond what nonseparability requires. We can see this by considering an alternative nonseparable approach advocated by Teller. Teller also argues that nonseparability can help us avoid nonlocality, elaborating a view he calls 'relational holism.' Teller defines this as the view that "collections of objects have physical relations which do not supervene on the non-relational physical properties of the parts" (1986, p. 73). Given skepticism in contemporary metaphysics that supervenience is adequate to representing metaphysical positions like this (e.g. Kim 1984, Fine 2001), it is probably better to construe relational holism as the view that collections of objects have fundamental physical relations which are not grounded in (i.e. metaphysically determined by) the non-relational physical properties of the parts.[4] Teller argues that cases of quantum entanglement like the EPRB setup we have been considering provide genuine cases in which collections of objects have what he calls "inherent relations," relations whose instantiation are not determined by intrinsic features of the relata. They are thus genuine examples of nonseparable states.

It may not be immediately clear how Teller's view avoids non-locality. According to relational holism, Bohm's atoms are numerically distinct, as are the states into which they enter on the two wings of the experiment. Thus it seems measurement on one atom does instantaneously affect the other (and the relevant expectation values) some distance away. In a later paper (1989), Teller argues how it is supposed to be that relational holism avoids nonlocality. Teller grants that there will be stable correlations between the states of the two atoms in Bohm's set-up, but argues that because of the inherent relations linking them, there is no reason to infer from these correlations to a causal mechanism linking the two wings. Because of the entanglement, the correlation may be brute:

[4] Below, I will use the language of 'determination' to be neutral between Teller's supervenience formulation of relational holism and a more contemporary grounding formulation.

> To say that causal locality has been violated most plausibly should be taken to mean that there are nonrelational properties of space-time points which are related in some other way – by action (lawlike dependencies) at a distance or through superluminal causal chains. On the other hand, when we are concerned with nonsupervening [or ungrounded] relations, this circle of ideas has no grip. There is no question of superluminal or distant action between nonrelational, definite values. (1989, p. 215)

and later:

> The correlation – as an objective property of the pair of objects taken together – is simply a fact about the pair. This fact will arise from and give rise to other facts. But it need not itself be decomposable in terms of or supervenient upon some more basic, nonrelational facts. There need be no mechanism into which the correlation can be analysed. (1989, p. 222)

Thus, Teller argues relational holism allows the Bell correlations to be brute, not requiring further explanation as the consequence of a causal relation between the distant events.

It is worth noting that today, a more common nonseparable interpretation of quantum mechanics postulating irreducible relations is not framed in terms of Teller's relational holism, but rather ontic structural realism.[5] Some versions are very much like Teller's in terms of positing objects bearing primitive relations not explainable in terms of intrinsic features of the relata (Esfeld). Others differ in that they aim to eliminate objects altogether (Ladyman and Ross 2007, French 2014). I will not discuss such approaches here however since advocates of such views do not typically use structural realism in order to avoid nonlocality.

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[5] Thanks to Michael Esfeld.

Returning to Teller, it is not clear to me why he thinks that the pull to explain correlations is removed once we allow there are relations that are not determined by intrinsic features of their relata. The idea seems to be that once one gives up the assumption that *all* relational features are determined by intrinsic features of their relata (that is, in other words, once one adopts relational holism), one will thereby give up the general assumption that correlations must have explanations. Indeed he states that the adoption of relational holism frees us generally from all common cause reasoning. But even if relational holism makes it reasonable to allow *some* brute relations, it is not clear why it should remove the general presumption that correlations not be brute. To do so would seem to throw the baby out with the bathwater, giving up one of the most basic assumptions of scientific reasoning. Thus, at least for now, I would argue that prima facie, Howard's nonseparable metaphysics provides a more successful metaphysical motivation for the avoidance of nonlocality. Though, as I have noted, it is involves more than a mere rejection of separability.

B. Wave Function Realism

A metaphysics for quantum mechanics that was considered and rejected early on by Schrödinger but more recently advocated by David Albert (1996, 2013, 2015) has the virtue of avoiding both nonseparability and nonlocality at least at the fundamental level and perhaps simpliciter. Like Howard's interpretation, this involves the view that what appear to be distinct particles are instead manifestations of one fundamental entity. This for Albert is a single field, which he labels, following the name for the mathematical object used to represent it, the quantum wave function. It is a field in the sense that it is an object whose nature is specified by an assignment of numbers (complex values of amplitude and phase) to each point in the space it inhabits. The view is thus called 'wave function realism.' The key innovation of wave function realism is to allow that this field is not spread out in the three-dimensional space of our ordinary experience, but instead is spread out in the space in which wave functions are typically represented, a higher-dimensional state space. So unlike in standard versions of Bohmian mechanics, where we recognize both ordinary three-dimensional matter and a wave function, in this picture, there is only what inhabits the high-dimensional space of the wavefunction.[6] The matter is itself constituted by the wave function.

The nature of the space the wave function inhabits is based on configuration space representations in classical mechanics. In classical mechanics, we use a configuration space of 3N dimensions to represent the possible three-dimensional locations of a system of N particles. Since classical particles always have definite locations, the locations of an entire system of N particles can be represented by a single particle at one point in configuration space.

Since quantum mechanics allows individual particles to have locations that are indefinite, quantum systems will generally be represented as fields smeared out over this 3N-dimensional space. For example, in Bohm's set-up, at the start of the measurement process, the atoms will have indeterminate locations, i.e. it is indefinite whether each atom is deflected up or down by the magnetic field in its respective Stern-Gerlach apparatus. According to wave function realism, the field (the wave function) will possess nonzero amplitude at points in configuration space corresponding to each of these possibilities. For the nonrelativistic case, the ontology of quantum mechanics is a wave function spread over a high-dimensional space with the structure of a classical configuration space evolving according to the Schrödinger dynamics, supplemented

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[6] The qualification "standard versions of Bohmian mechanics" is needed because Albert (1996) has also proposed a wave function realist interpretation of Bohmian mechanics, where both the matter and the wave function live in the high-dimensional space required to capture the allowable states of the wave function.

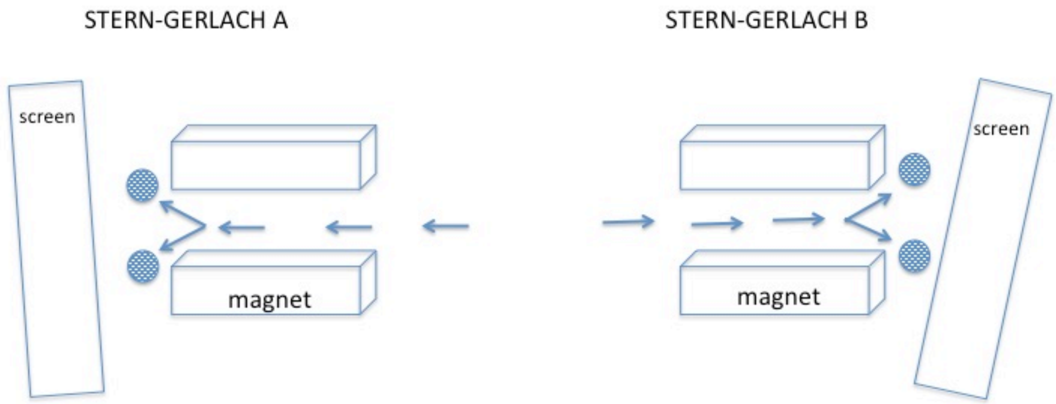
perhaps with a collapse dynamics, depending on one's favored approach to the measurement problem.[7] It should be noted it would be incorrect strictly speaking to call the space the wave function inhabits a configuration space since in this picture it is the wave function that is fundamental, not particle configurations. However, we can capture the features of the wave function and its space in a "top-down" manner by considering what sort of fundamental metaphysics would be capable of recovering the nonfundamental appearances of a system of multiple particles in three-dimensional space, and this is how the configuration space representation is useful.

To visualize the wave function realist's proposal, we may consider first an image of how things would appear in a three-dimensional representation, when the locations of the atoms are indeterminate after they pass through their respective Stern-Gerlach devices but before wave function collapse (should there be collapse). The position state of the atoms is represented by the circles.[8]

Figure 2

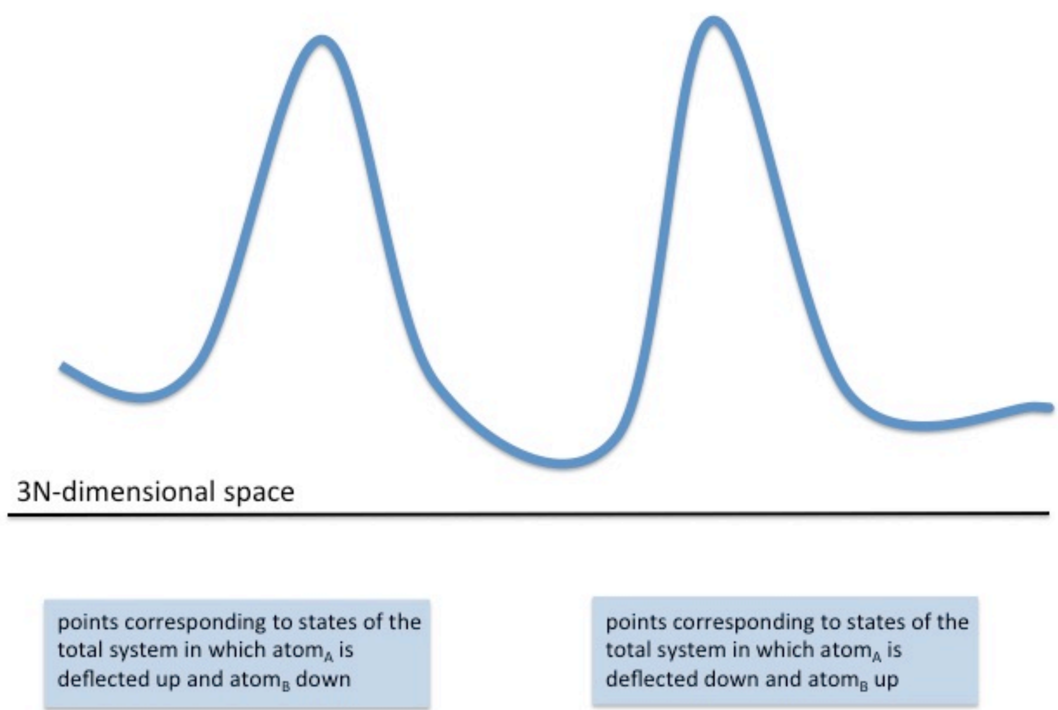
[7] The total space of the wave function must actually have a more complex structure. One reason is we must include additional dimensions as well corresponding to the degrees of freedom for the spin states of the particles.

[8] Note I am setting to one side Bohmian mechanics, which provides an alternative strategy for ensuring separability.



Note that in this three-dimensional image, we do not immediately see the correlation between the first atom's being deflected upward (or downward) and the second atom's being deflected downward (or upward). We only see that each individual atom has its state spread over the two possible deflection locations. This contrasts with the image of what is found according to the higher-dimensional interpretation. Here each point in the higher-dimensional space corresponds to a total three-dimensional state of the entire system (states which include the positions of the atoms and the whole of the apparatus). The wave function in the case of the EPRB setup before measurement will be spread over multiple points. In particular, there are clusters of high amplitude at two regions in the higher-dimensional space, one corresponding to situations in which atom_A is deflected upwards and atom_B is deflected downwards, and the other corresponding to situations which atom_A is deflected downwards and atom_B upwards. Facts about the entanglement of the system are thus captured directly in the 3N-dimensional interpretation.[9]

Figure 3



The resulting wave function metaphysics is completely separable. It is separable because all states of the wave function, including the entangled states we have been considering, are completely determined by localized assignments of amplitude and phase to each point in the space of the wave function. This is not so if we want to get facts about entanglement into the three-dimensional interpretation. This requires adopting some form of nonseparability, either by

[9] For much more detail on the nature of the wave function according to the wave function realist, see Ney (2013).

denying the distinctness of atoms A and B, or as in Teller's picture, adding fundamental facts about the correlations between the atoms.[10]

Howard cites a late discussion of the EPR thought experiment in which Einstein appears to argue that if one wishes to avoid the incompleteness of quantum mechanics, one's only options are to embrace nonseparability or nonlocality (Einstein 1949, quoted in Howard 1985). The way Howard sees it, one can deny that objects at spatial distances have separate existences, or one must accept superluminal influence. Of course, he chooses to reject separability. What we are seeing here is that by shifting our conception of what the fundamental space is, one can avoid having to make this choice. Wave function realism provides a metaphysical interpretation of quantum mechanics that is compatible with EPR, Bell's theorem, and the laboratory experiments that followed while being both separable and local. The state of the total field is determined by its state at each point and there is no action at a distance.

To help visualize this consequence, consider the following diagram which depicts the evolution of the quantum state from a situation in which the location of the atoms (in three-space) are indefinite to one in which atom_A is measured. For concreteness, we assume a spontaneous collapse dynamics and the three-dimensional interpretation of quantum systems as grounded in a mass-density field as articulated by Ghirardi and Bassi (2003).

<u>Figure 4</u>

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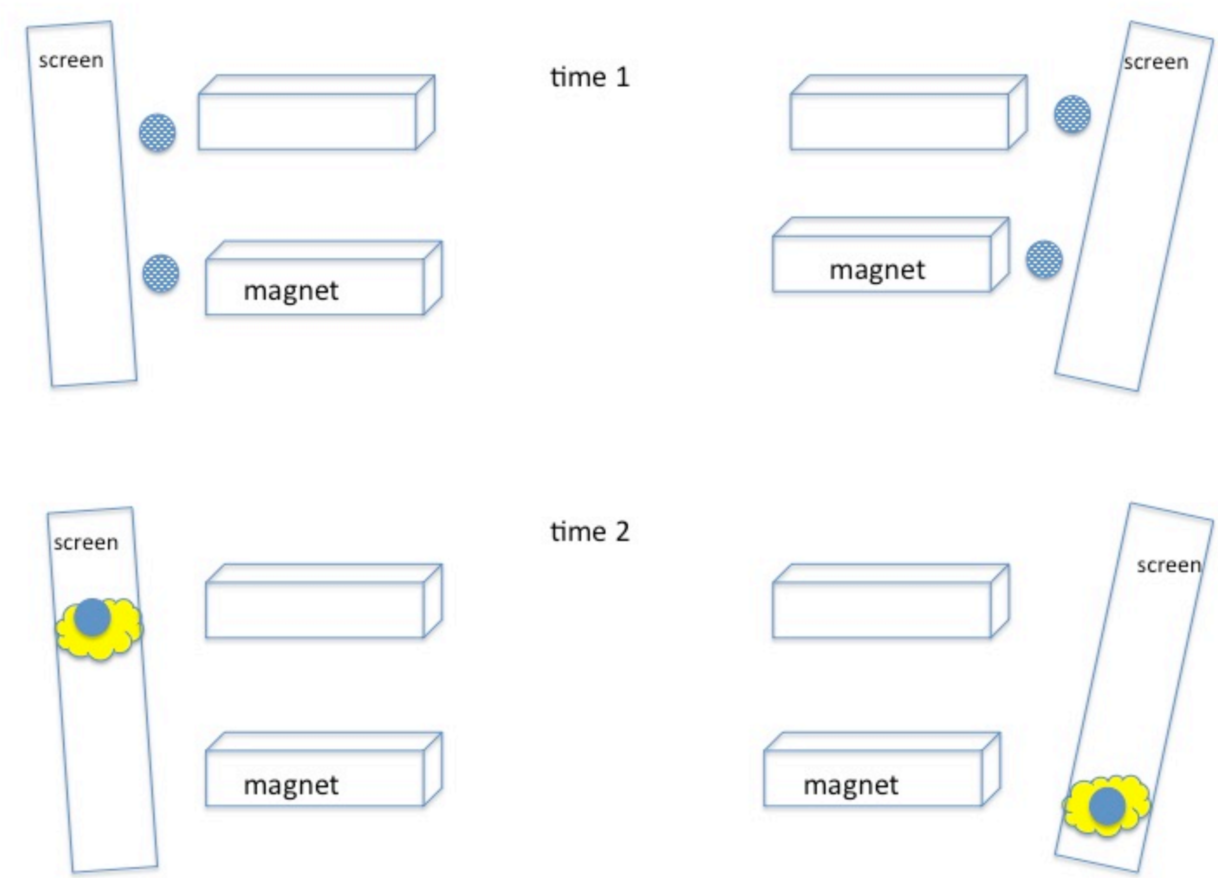
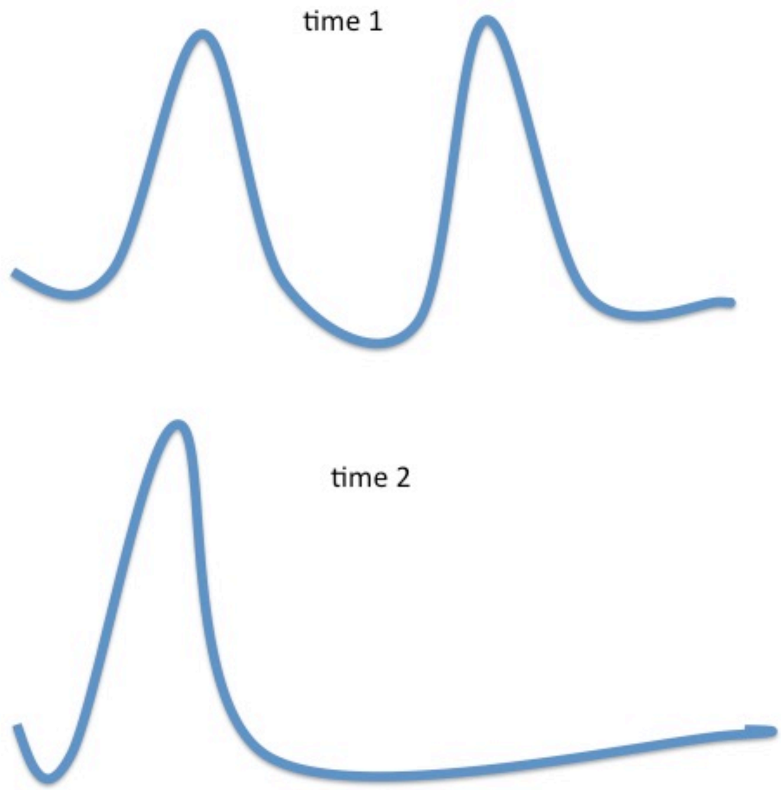
[10] Barry Loewer (1996) also argues that a move to a higher-dimensional ontology is needed to preserve separability for quantum systems.



What happens is that the measurement process (and resulting collapse) on the left-hand-side immediately causes a change in the state of the system on the right-hand-side.[11] By contrast, consider an image of the measurement process in the higher-dimensional space of wave function realism. Again, we consider the evolution of the wave function according to spontaneous collapse dynamics.

<u>Figure 5</u>

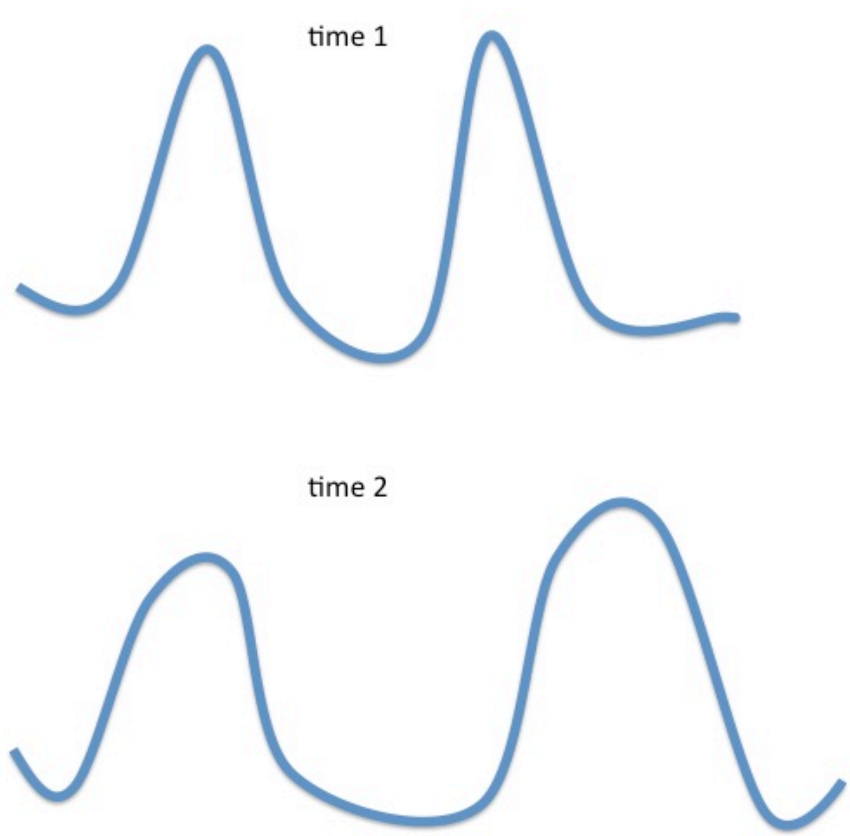
[11] In the Ghirardi and Bassi framework, collapses are spontaneous, they are not caused by measurements. In situations describable as measurements, in which we are dealing with the interactive entanglement of a very high number of fundamental particles, the probabilities of such a spontaneous collapse event becomes extremely high.



In this case, we again see a change starting from a field that is initially spread out to one that is subsequently less spread out. However what has happened in this case is not that something on the left has caused a change in the part of the field on the right, has caused it to become more localized. Recall that each point in the wave function's space corresponds to a total configuration of a three-dimensional system. So if you want to ask where in this picture is the measurement that took place on the left wing of the experiment, the answer is: it is located all over the configuration space. So it is the state of the wave function at each point at the first time that then causes the state of the wave function to be what it is at each point at the second time. What we have is simply a smooth process in which the whole wave becomes more bunched up over time in one region of its space.[12]

The evasion of nonlocality is maintained even more clearly on a dynamics for the wave function that does not involve collapse. For example, on an Everettian picture, the evolution of the wave function over time could instead be pictured as:

Figure 6



[12] Some might balk at the use of causal language here because they believe that causation has to (by definition) always involve the action of small/localized things on other small/localized things (see e.g. Field 2003), and what is happening here instead is the global state of a wave function at all points at a time determining the global state of the wave function at a later time. If so, fine, whether this is described as global causation or only determination, there is still no action at a spatial distance.

Again, the global state of the wave function at one time influences the global state of the wave function at all later times. What we have is simply a wave that becomes a bit more spread out over time. Again, there is no action at a spatial distance in the fundamental metaphysics.

Now there is a question about whether there is nonseparability or nonlocality simpliciter on this picture, even if fundamentally everything is separable and local. First one must ask, can the wave function realist accept in addition to what is described by Figure 5, the situation depicted in Figure 4 as some kind of derivative reality. This depends on whether it is correct to say that the wave function is capable of grounding the derivative existence of three-dimensional objects. This is a contentious issue we will not get into here.[13] However, if wave function realism is compatible with a derivative (but real) three-dimensional world, then there will be nonseparability in that derivative three-dimensional space, since there will be states of systems that are not determined by states of what is happening at the subregions occupied by those systems' constituents.[14] (These states will only be determined by states of the wave function.) What about derivative nonlocality? This is a question about what explains the correlations between the spatially distant measurement events. On this view, it is not an interaction between the two wings of the experiment that explains the correlations, but instead the dynamical evolution of the wave function. So although there are certainly the observed correlations in three-dimensional space, there fails to be nonlocal influence. One might think there is no obvious reason why one would care to avoid such derivative nonlocality. After all, what appears in the three-dimensional metaphysics as nonlocality is only a nonfundamental manifestation of a more fundamental local process. We will return to this issue in the penultimate section. But I take it to

[13] But see Albert (2013, 2015) and Ney (in progress).
[14] Note again, I am putting Bohmian mechanics to one side here.

be a virtue of the wave function realist interpretation that it may explain the Bell correlations without having to violate relativity by postulating nonlocal, superluminal influence.

4. Objection: Nonseparability Does not Ensure Locality

I now want to consider arguments that the nonseparable metaphysics of Howard is not itself sufficient to avoid the nonlocality that appears to arise in the case of EPRB setups. If it is not, then wave function realism would be an even more attractive option for those hoping to avoid nonlocality.

In his paper "Nonseparability does not relieve the problem of Bell's Theorem," Joe Henson argues that Howard is mistaken that one can avoid nonlocality by rejecting separability. Howard had argued that it is generally assumed that the systems on the two wings of an EPRB setup are separable, numerically distinct systems. In a formal reconstruction of Bell's argument, one that I will not reproduce here, Henson argues that Bell's argument requires only a weaker principle, that the systems on either wing of the experiment may be localized at distinct spatial regions, a principle he calls Localized Events:

> All events can be associated to regions of spacetime in a consistent manner. (2013, p. 1012)

Since the argument doesn't require the stronger separability principle, one cannot avoid the conclusion (nonlocality) by rejecting it. As Henson puts it:

> If one wants to rely on one's favourite derivation of Bell's theorem for the purposes of this discussion, one needs to show that the assumptions one makes are equivalent to, or weaker than, what is used (explicitly or implicitly) in the standard versions. After all, if I added the assumption that I live in London to a derivation of Bell's theorem, that would

not make it reasonable for a group of angry realists to drive me out of town in the hope of saving locality. (2013, p. 1009)

But does Howard's argument rest on this mistake?

As we have seen, Howard's main point is that the metaphysical conclusion we should draw from experimental confirmations of the quantum predictions is that the systems A and B are not numerically distinct. "If two systems are not separable, then there can be no interaction between them, because they are not really *two* systems at all." And so although standard derivations of Bell's theorem may not assume a separability assumption explicitly, in describing the measurement results as distinct events that may be localized at distinct locations, we are thus assuming the negation of what Howard wants us to consider. So Howard could plausibly reject even Henson's weaker principle of Localized Events.

But it seems to me that separability is a red herring here. By denying the distinctness of $atom_A$ and $atom_B$ and indeed the corresponding measurement events, Howard is denying that there even are such two subsystems localized at distinct regions. Rather, there is just one system that isn't (at least straightforwardly) localized to one or the other region. So there is no issue of whether the facts about A and B determine the facts of the system contained at the union of the space-time regions at which they are located. But whether what is at issue is nonseparability or not, there is a question about whether Howard's strategy is successful.

Henson argues that his claim of numerical identity is unwarranted. He says:

The suggestion … is that one could say to the worried experimenter "don't worry, when you saw the flashing light, that actually corresponded to an event in the whole experimental region, not an event in your lab. So you see, it's all local… Actually your reaction to the flashing light didn't happen in your head either, but in the larger

> region."… It is in no way more unreasonable to apply this kind of reasoning to a hypothetical case of superluminal signaling than it is to apply it to outcomes in the EPRB experiment. (2013, p. 1020)

Henson's objection is essentially that Howard's rejection of numerical distinctness is ad hoc. I interpret him in this last sentence as pointing out that we could make a similar move in any hypothetical case of superluminal signaling and thus avoid nonlocality. But, he says, "if we rely on this, we may as well have avoided analysis of Bell's theorem by rejecting all locality assumptions except no-signaling in the first place" (2013, p. 1021).

I do not agree that the move Howard makes would be "no more unreasonable" to apply in any case of superluminal signaling. And this is because the denial of numerical distinctness in situations of quantum entanglement like the EPRB setup is motivated independently of the desire to avoid nonlocality (or superluminal signaling). It is motivated also by the fact that in a three-dimensional metaphysics, it is simply not possible to give a complete account of what measurement results we should expect for $atom_A$ without considering the entangled system of which $atom_A$ appears to be only a part (and similarly for $atom_B$). The atoms thus do not appear to have distinct realities.[15] This supports Howard's interpretative strategy.

But ultimately I am sympathetic to Henson's skepticism. Although Howard may avoid what is strictly speaking nonlocal interaction between distinct objects or events, I don't think his strategy to avoid nonlocality is as satisfactory as the wave function realist's. For recall that according to the wave function realist, the entire three-dimensional framework is derivative. Influence only appears to be transmitted instantaneously across a spatial distance, but the source of these correlations is really a local influence in a higher-dimensional space. On the other hand,

[15] Arguments to this effect, not in any way relying on a desire to evade superluminal influence are presented in other work. See, for example, Ney (2013, in progress).

Howard wants us to view reality as three-dimensional. We may say that what appear to be two distinct measurement events are not fundamentally distinct, but Howard will not deny that the single object and event is indeed spread out somehow in the three-dimensional space. And so although we might not have be a causal interaction between two things, but only a state? or a process? involving only one, what we are committed to is still something that will involve a mysterious coordination across two distant parts of space at a time.

5. Why Prefer a Metaphysics for Quantum Physics that is Separable and Local?

It is possible to paint the demand for both separability and locality as the results of an unreasonable demand to make our interpretations of physical theories conform to our intuitions. For it can seem to us only natural that the properties of a whole all be traceable to, determined by properties of its parts, and also that actions do not have immediate effects across spatial distances. But, as Ladyman and Ross (2007) have rightly argued, there is no reason to believe that we would have been hardwired as a result of evolution to be good at reasoning about topics of fundamental physics or metaphysics. Our question here is what a quantum world would be like, and there is no good reason to think our intuitions are good guides to the nature of a world like this.

Some would press back on this last point. For example, Valia Allori (2013) defends a view she finds in Einstein, that "the whole of science is nothing more than a refinement of our everyday thinking." In her view, the best physical theorizing departs as minimally as possible from the manifest image of ordinary experience, and only where it has to. However, first, it is not clear what the argument for this claim is. If theory and experiment allow for a radical departure from the manifest image that yet possesses many other theoretical virtues including fertility for the development of further physics, then why would it not be worthwhile to explore what this unfamiliar metaphysics looks like? Second, because the interpretation we have seen that recovers both separability and locality 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* separable, local metaphysics is closer to the manifest image than one that would jettison one or both of separability and locality, but retain the low-dimensional spatial background of our experience.[16]

One might argue that it is not merely our intuitions and background assumptions that support separability and locality, but inductive reasoning. One could thus appeal to our past observations in day-to-day life. However, this sort of strategy seems hopeless, since what we are evaluating here are the conclusions we should draw from more refined experiments that do suggest the world is nonlocal or at least nonseparable.

A more promising type of argument considers the sort of interpretational assumptions that will allow us to formulate inductively successful empirical theories. Howard considers several passages from Einstein that make this kind of case for separable and local theories. On separability, Einstein proposes:

> [I]t appears to be essential for this arrangement of the things introduced in physics that, at a specific time, these things claim an existence independent of one another, insofar as these things 'lie in different parts of space'. Without such an assumption of the mutually independent existence (the 'being-thus') of spatially distant things, an assumption which originates in everyday thought, physical thought in the sense familiar to us would not be

[16] To be clear, Allori herself doesn't argue for wave function realism. She is just advocating for the methodological principle stated above.

possible. Nor does one see how physical laws could be formulated and tested without such a clean separation. (quoted in Howard 1985, pp. 187-188)

Howard claims he doesn't know what to make of this passage; how it is to be supported. But he speculates that what makes separability useful in the construction of successful physical theories is that it gives us a sufficient condition for the individuation of physical systems: spatial separation (Howard 1985, p. 192). Without this, it is difficult to imagine what could provide an objective basis for individuating objects.[17]

But this doesn't seem correct. First, separability does not seem sufficient to allow for the individuation of physical systems by spatial separation. Even if we grant that all states of systems are metaphysically determined by the states of subsystems located at subregions of the region the system occupies, these subsystems (and the systems they constituent) may nonetheless fail to be clearly individuated because they possess gappy or otherwise deviant spatial trajectories. But anyway there is a more natural way to interpret Einstein's concern.

As we've seen, there are at least two ways to develop a nonseparable metaphysics for quantum mechanics. The weaker version is Teller's which would have us say that entangled systems may involve distinct entities, but that these entities instantiate inherent, i.e. irreducible relations. What this entails is that if we want to have a complete description of one of these objects that will allow us to know how it will behave over time in its environment, one must bring in facts about the other entity with which it is entangled. The facts about it and how it will behave in its environment necessarily bring in facts about the other object, which may be a significant distance away. In the absence of full knowledge of entanglement relations, this makes

[17] Since Howard himself rejects separability, he cannot use spatial separation then as a principle for individuating physical systems. He proposes (1985, p. 198) we instead use facts about the nonexistence of quantum correlations to individuate physical systems.

it challenging to predict what something in a given spatially localized set of circumstances is going to do, how it will behave. In the stronger version, Howard's, we don't know how the object will behave, for we don't even have the full object in front of us.

What can be said for locality? There does not seem to be anything conceptually incoherent in the idea of a nonlocal metaphysics. However, here again we may bring in considerations about prediction and control. Indeed this is how Einstein appears to defend locality:

> 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. (quoted in Howard 1985, p. 188)

Although clearly distinct from the first concern about developing successful theories without a separable metaphysics, the motivation for a local metaphysics is similar. 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 is required to allow us to formulate testable empirical theories.

As an additional empirical point, nonlocality implies a violation of special relativity. So to support locality, we may appeal to all of the considerations supporting special relativity. Although the wave function realist interpretation supports nonlocal correlations in the derivative three-dimensional space of objects, it does not support nonlocality, since these correlations are not explained in terms of superluminal influence. This by itself does not mean it is compatible with special relativity, which ultimately depends on whether the theory wave function realism is an interpretation of is Lorentz covariant. Versions of quantum theory with collapse of the wave function will still include frame-dependent facts about probabilities that don't crop up for, e.g., Everettian quantum mechanics. This is an issue that runs orthogonal to the metaphysical question of wave function realism. Nonetheless, the issue of frame-dependent facts about causal influence is a metaphysical issue, and it is a virtue of wave function realism that it can avoid such facts.

In addition to the empirical considerations that speak in favor of interpretations of quantum mechanics that are separable and local, there are also pure metaphysical considerations. Returning to separability, the nonseparable metaphysics we have seen seem both of them in a respect to be conceptually unstable. According to Teller's relational holism, the fundamental facts about any object A in an entangled state cannot be grasped without considering what is a distinct object B. But this suggests that these objects are not actually distinct, since one cannot really understand one apart from the other. It thus raises the question of why one should think there really are two things, not one. Thus, I would argue that relational holism isn't just problematic for the construction of empirically testable physical theories, the position threatens to collapse into some more traditional form of holism, like Howard's.

Now Teller rejects a form of holism according to which the entangled objects are numerically identical, because he finds such views obscure:

> Holism has always seemed incoherent, for it seems to say that two distinct things can somehow be entangled or intermeshed so that they are not two distinct things after all. Yet apparent unintelligibility does not prevent holism from recurring, not only in the

work of philosophers of East and West, but also in what quantum mechanics seems to many of us to be saying about the world. (1986, p. 73)

Relational holism is the solution that allows us an intelligible form of holism. But why is it unintelligible to say that what appear to be two things are really one? One problem may be that we know there are two of something. The data we have for the Bell correlations are numerically distinct. We observe this state here and at one time, and we observe a distinct state there at some other time.[18] So how can we consistently maintain that what we know to be two states are in fact one? One answer would be to interpret holism as a fundamentality thesis: a thesis about what fundamentally exists, not what exists simpliciter. Jonathan Schaffer in his work has helpfully articulated a distinction between existence monism and priority monism (Schaffer 2010). In the former, the claim is that there is only one entity full stop. Priority monism by contrast asserts that fundamentally there is only one entity. The multiple entities (particles, states, etc.) we encounter in our experience are nonfundamental or derivative entities that are grounded in what is fundamentally just one thing. In recent work with Jenann Ismael (Ismael and Schaffer forthcoming), they argue for this priority monism as a reasonable interpretation of quantum mechanics.

Howard himself clearly has in mind a more traditional kind of holism (the form that says there is just one thing simpliciter).[19] However, I want to suggest that either form of monism is unstable for it is obscure on these proposals how objects (in the case of priority monism, how the fundamental objects) get assigned locations. We have seen Howard must reject Henson's Principle of Localized Events. Neither atom gets assigned to one location or the other, but rather

[18] This is similar to a principle Henson takes to be essential to the derivation of Bell's theorem. He call it the Operational Consistency of Localization (2013, p. 1016).
[19] Schaffer distinguishes this, what he calls 'existence monism,' from priority monism.

to the total region. But then it appears that there is nothing assigned to either subregion. And this would seem to indicate the region is empty. Yet it is not. I would suggest that a view that embraces holism while capturing a coherent account of locations would only be the wave function realist framework. We say there is one thing, but it is located in the higher-dimensional space of the wave function.

Now unfortunately while the wave function realist proposal does provide a coherent, conceptually stable metaphysics, it cannot reap the consequences of all of the good arguments for separability and locality considered above. Since our observations represent objects in the low dimensional space, to have a successful physical theory, we will want to be able to make reliable predictions about what will happen when we observe or manipulate objects localized to three- or four-dimensional regions. But to the extent that wave function realism allows for the existence of a three-dimensional metaphysics, it will not be separable, and although it will strictly speaking be local, it will possess nonlocal correlations. The full separability and locality reside in the higher-dimensional picture which is unfortunately not the picture we use when we do experiments and manipulate objects.

The case for a separable and local metaphysics for quantum mechanics then comes from more broadly philosophical considerations, special relativity, perhaps brute intuition, and additionally considerations of what provides a more coherent and stable picture.

6. Conclusion

In this paper, we have seen how the higher-dimensional, wave function realist interpretation of quantum theories provides a metaphysics that is fundamentally both separable and local. If one favors separability and locality for the reasons described, then one will thereby have reason to prefer wave function realism and its attendant higher dimensions over rival interpretations of quantum theories such as standard Bohmian mechanics (which may be separable but is certainly not local) or the various holist approaches (which may be local – though I am skeptical – but are certainly not separable). It is worth emphasizing however that although the fundamental metaphysics offered by the wave function realist is both separable and local, the more pragmatic, inductive arguments favoring separability and locality are unable to provide support for this position. This is because it is only the fundamental metaphysics on this picture that is separable and local.

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