Wave Function Realism in a Relativistic Setting

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## 1. Introduction

Over the past several years, I have been interested to defend a revisionary view about the interpretation of quantum theories. This is a view David Albert and Barry Loewer have proposed and labeled *wave function realism* (Loewer 1996, Albert 1996, 2013, 2015). It is a view that was early considered yet quickly discarded by Schrödinger (Schrödinger 1934). According to the wave function realist, we should take quantum theories to reveal to us that contrary to what perceptual appearances suggest, the world we inhabit is not fundamentally a world of discrete objects located in a three-dimensional space or even of matter fields in a four-dimensional space-time. Instead, the world is fundamentally constituted by a more peculiar field, the quantum wave function, which inhabits a much different and higher-dimensional space, one adequate to capturing the full range of pure quantum states.

For my part, I don't know if wave function realism is correct or even if I believe that it is correct. It is, like all proposals for how to interpret our quantum theories and what they reveal to us about the fundamental structure of reality, a piece of speculative metaphysics. And as a piece of speculative metaphysics, it is, when contrasted with some other proposals, those falling under the classification of primitive ontology theories (Dürr et. al. 1992, Allori et. al. 2008, 2014), much stranger and more revisionary to our ordinary way of thinking. But the frequently startling lessons of quantum theories certainly present us with the suggestion that the world may be, fundamentally, as strange as the wave function realist says it is. And since at this stage of inquiry, no one interpretation has yet captured the common imagination, it is worth following these suggestions out and seeing whether they can be made tenable, what they would imply, and whether they may bear fruit.

The purpose of the present paper is to respond to recent criticism about wave function realism based on the fact that it has until now been formulated and defended solely within the context of nonrelativistic quantum theories. Although nonrelativistic quantum theories are useful as approximations, teaching us important lessons about a range of real world phenomena, it seems if we are going to learn things about our world from a consideration of quantum theories, these are going to have to be lessons that remain even when we move beyond the nonrelativistic to the relativistic domain. After all, we know our world to be a relativistic world. With this in mind, Wayne Myrvold, Chris Timpson, and David Wallace have all argued (Wallace and Timpson 2010, Myrvold 2015, Wallace forthcoming) that wave function realism is an interpretation reliant on features of quantum theories that do not carry over into a relativistic setting. Therefore, wave function realism does not adequately capture aspects of the fundamental nature of our world according to quantum theories.

It is an interesting question whether wave function realism must, to be viable as an interpretation of quantum theories, have application beyond the domain of nonrelativistic quantum theories. Must an interpretation of a quantum theory be workable as an interpretation for all quantum theories? For the purposes of the present paper, I'll bracket this question and address the issue of what good wave function realism may be as an interpretation of relativistic quantum theories. Myrvold, Wallace, and Timpson raise several specific concerns based on issues that come into play when we move to a relativistic setting. After a brief primer on how wave function realism looks in the nonrelativistic context, I'll recap these objections. I'll argue that none of these objections give conclusive reason to reject wave function realism, however some do present a challenge to the wave function realist to be clearer about what the view looks like when extended especially to quantum field theories. And thus I provide a sketch of what the view looks like in relativistic contexts, one that is straightforwardly extendable from the simple case I describe in detail to more complicated ones. This will establish the main point of this paper, namely that the primary motivation for wave function realism is one that rests in no way on details peculiar to nonrelativistic theories and so there is a prima facie case for a suitable extension to the relativistic domain whatever that may in the future look like.

## 2. Wave Function Realism for Nonrelativistic Quantum Mechanics

Wave function realists explore the possibility that what quantum mechanics is trying to tell us about the world is that what appear to be numerically distinct objects located in separate regions of space are in fact manifestations of a more fundamental field, the quantum wave function, living on a less familiar space, one quite different from that presented in ordinary perceptual experience. Practically all discussions of wave function realism have until now been carried out in the context of nonrelativistic quantum mechanics, where one starts the project of interpretation from data suggesting the world is constituted by a determinate number of particles that may be in more or less determinate states (superpositions) of momentum, position, and so on, states which may be correlated with one another by entanglement relations. The wave function realist then argues, appealing to the virtues of metaphysical frameworks that are separable and local, arguments that will be fleshed out in more detail below, that the more fundamental reality underlying the appearance of a world of many particles in three-dimensional space is one of a single entity, the wave function, characterized by an assignment of numbers (amplitude and phase values) to a space with the structure of a classical configuration space, one for which every point in the space corresponds to a state in which all particles have determinate positions. Since particles in the quantum description do not all have determinate positions, the wave function at any given time will be a field smeared out over many locations in its space. This field is then said to be the fundamental reality with the initial particle description ontically derivative.

A variety of questions are typically raised about this proposal. For example, if the fundamental reality is really a field on a space with the structure of a configuration space (which would mean the fundamental space is extremely-high dimensional, given the number ($\sim 10^{80}$) of particles that appear in the observable universe), then why does it seem we inhabit a world of discrete objects in a much lower-dimensional space. Wave function realists have addressed this question, often by arguing that the contingent dynamical behavior of the wave function is such as to generate the existence of what may accurately be described as (non-fundamental) three-dimensional objects that may have at least moderately precise three-dimensional locations. Wave function realists and their supporters debate the best way to fill in this account David Albert, Barry Loewer (Albert and Loewer 1996, Albert 2015), Jill North (2013), and myself (forthcoming) have all made proposals. The critics with whom I engage in this paper do not question whether this project may be successfully carried through in the nonrelativistic case.

## 3. Critiques

I count six different critiques of wave function realism in the literature citing the difficulties of extending wave function realism to a relativistic setting. I will describe them in chronological order of publication.

A. The first critique (Wallace and Timpson 2010) is that there is no good account of the sort of space the wave function is meant to be defined on when wave function realism is considered as an interpretation of relativistic quantum field theories. In the nonrelativistic case, as has already been mentioned, the wave function is defined on a space that has the structure of a classical configuration space. This is a space with 3×N dimensions, where N is the number of particles in the universe, particles which are claimed to be ontically derivative. For the wave function realist, this provides a "top-down" description of the fundamental space, since particles are not fundamental; but one that nonetheless singles out a primitive structure. For a nonrelativistic quantum theory, the character of the configuration space is straightforward, since particle number is assumed to be conserved. However, in quantum field theories, particle number is not conserved; moreover, systems may evolve into states describable as superpositions of particle number. This undermines the possibility of understanding the world as simply constituted by a relativistic wave function as a field on some unique, determinate configuration space. Wallace and Timpson consider an alternative possibility, that for relativistic quantum theories, the wave function realist will instead postulate an infinite number of (non-normalized) wave functions: a single-particle wave function living on a three-dimensional space, a two-particle wave function living on a six-dimensional space, and so on. However, they (rightly) assume the wave function realist will not prefer to adopt such an ontologically profligate metaphysics.

B. A second objection (Wallace and Timpson 2010) is that wave function realism "obscures the role of spacetime in quantum theories" (2010, p. 707). Here Wallace and Timpson are especially concerned with quantum field theories. Standard presentations of quantum field theories work by assigning field operators to localized space-time regions. (This is true as well in algebraic quantum field theories, where algebras are associated with space-time regions.) Systems are not described as in the Schrödinger wave-dynamical representation of nonrelativistic quantum theories in terms of the evolution of a wave function in configuration space. And so the representations on which wave function realism is based simply are not standard representations in relativistic quantum theories.

C. A third critique relates to the demand of relativistic covariance. To get a theory of the evolution of the wave function that is relativistically covariant, one sacrifices what David Albert has called 'narratability' (Albert 2015). That is, there will be no unique account of how the wave function evolves from one time to the next. Wallace and Timpson (2010) press this failure of narratability not as leading to a decisive refutation of wave function realism. Rather they argue that this failure of narratability is obscure and surprising in the context of wave function realism where one is supposed to be achieving a separable metaphysics. It is, by contrast, unsurprising in the context of rival interpretations of quantum theories, including the one they prefer, space-time state realism.

D. A fourth critique (Myrvold 2015) aims to show that in the context of relativistic theories especially, the existence of a wave function is derivative on the antecedent existence of structures defined on ordinary spacetime. Myrvold shows how wave functions, to the extent that they may be constructed in quantum field theories, may be defined in terms of the global quantum state, vacuum state, and field operators associated with points of spacetime. So, he concludes, the wave function cannot be more fundamental than a spatiotemporal ontology, as the wave function realist believes.

E. Myrvold (2015) also argues that in the case of relativistic quantum theories, the wave function cannot be thought of as a field in the way the wave function realist presupposes. This would require its specification by an assignment of local values to points or subregions of the space it occupies. Myrvold argues that facts about the state of the wave function at arbitrary subregions of the wave function's space are not local to those regions.

He argues as follows. Consider two states. S1 is a state in which a single-particle wave function takes on a nonzero value at some point x. S2 is a state just like the first near x, but differs in that there is with certainty a particle confined to a spacetime region R, far from x. It follows by construction that in S2, the probability that an array of detectors spread through space will report a particle detection at x and nowhere else is zero. This means that the single-particle wave function for S2 must take the value zero at

x. And from this, it follows that a nonzero value of a single-particle wave function at x is incompatible with there being a particle definitely located in region R, no matter how far away R is. Myvold's conclusion is that the assignment of the nonzero value to some point near x in S1 is not a local fact about that point. This, he then claims, means that wave functions are not like traditional fields, contra the wave function realist.[1]

F. Finally, David Wallace (forthcoming) argues that the privileging of the position basis is problematic in the context of quantum field theories, for which quantum states and observables are more typically defined in terms of a momentum basis. We can see that at least in the nonrelativistic case, the wave function realist does privilege the position basis as she defines the wave function as an assignment of values to points in a space with the structure of a classical configuration space as opposed to some other kind of state space. One might think it is unproblematic that quantum field theories generally characterize states in terms of a momentum basis, as one can simply Fourier transform to achieve a position representation. But this is not straightforward in the case of quantum field theories. There it turns out that even if representations of exact states of position can be achieved, these have the consequence of violating Lorentz covariance (cf. Teller 1995, pp.

[1] Simon Saunders (p.c.) has questioned whether this argument of Myrvold's ought to be classified as an objection to wave function realism that concerns its extension to relativistic quantum theories, claiming there is nothing particularly relativistic about this example, and though the other examples Myvold provides to illustrate the premises of the argument are relativistic, the arguments based on them use the same basic reasoning as that presented above. In my view, the argument turns on a situation in which particle number is not conserved, a feature characteristic of relativistic as opposed to nonrelativistic quantum theories. Whether one wants to think of the failure of particle conservation as essentially a relativistic phenomenon or not, Myrvold's argument at least offers a concern for the extension of wave function realism to examples of more realistic quantum theories than those in which particle number must be conserved.

85-90). And so if the privileging of position is an essential feature of wave function realism, not merely confined to the interpretation of nonrelativistic quantum mechanics, wave function realism cannot be generalized into an interpretation of relativistic quantum theories.

So these are the objections. What all of these critics prefer is an interpretation according to which quantum theories describe an assignment of values (operators, algebras) to space-time regions rather than to the high-dimensional space preferred by the wave function realist. This is a view that Wallace and Timpson (2010) label *spacetime state realism*. Adopting this interpretation avoids the privileging of the position basis and the dependence on a fixed number of particles that the framing of an ontology in terms of a configuration space representation requires. However, before giving up the high-dimensional metaphysics favored by the wave function realist and moving to spacetime state realism, it is worth considering why the wave function realist favored such a picture in the first place. I will argue that the wave function realist has the same reason to reject spacetime state realism as she had for rejecting the picture of fundamental particles arranged in three-dimensional space. The motivations for the high-dimensional picture carry over to the relativistic case, even if the applicability of a high-dimensional configuration space representation do not. Shrugging off the constraints of the wave-function-in-configuration-space view, we can begin to see what a more plausible relativistic extension of wave function realism may look like and how one may respond to the six criticisms above.

## 4. Why Higher Dimensions?

At the inception of quantum mechanics, in the 1920s and 30s, the preference for something like a wave metaphysics for quantum mechanics arose from the desire to avoid the dynamical and ontic discontinuities and consequent perplexities rampant in the more dominant interpretations of Bohr and Heisenberg (Schrödinger 1935, Jammer 1966). However, in the interim, alternative interpretations of quantum theories have been developed in some detail that lack the problems of those of Bohr and Heisenberg. One prominent example is the De Broglie-Bohm theory, which as frequently interpreted, proposes an ontology for quantum mechanics consisting of a determinate number of particles with determinate positions evolving in three-dimensional space in a way determined by the state of the wave function, now interpreted as something with a nomic status guiding the matter in the theory (Goldstein and Zanghì 2013).[2] Given a distinct set of interpretative rivals, the primary motivation for wave function realism becomes somewhat different. In brief, the advantage wave function realism has over rival interpretations of quantum theories one finds today, keeping in mind these discussions are generally held in the context of nonrelativistic quantum mechanics, is that only wave function realism provide a metaphysics that is fundamentally both separable and local.

Both separability and locality are features that may apply to physical systems bearing constituents that individually occupy distinct regions of space-time (or distinct features of their respective background frameworks). A system located at a region R is

[2] Albert (1996, 2015) proposes an alternative wave function realist interpretation of the De Broglie-Bohm formalism in which the metaphysics is set in a high-dimensional space with the structure of classical configuration space. However, the more common way of developing the De Broglie-Bohm theory is as a three-dimensional ontology with the particles the central, "primitive" ontology.

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 individual states of its subsystems, all states at the system's subregions are determined by states at their respective subregions, and so on. A state of a system is a separable state when it is wholly determined by states of the systems located at its subregions.

Systems in quantum mechanically entangled states such as a pair of atoms or photons are often thought to exhibit fundamental nonseparability (e.g. Teller 1985). There obtain relational facts about correlations or anti-correlations among their features that are not grounded in any intrinsic features of the constituent spatially-separated atoms or photons. On this view, such relational features are brute, bearing no more fundamental constitutive explanation. Wave function realism provides an explanation for correlations among entangled systems that seeks to avoid fundamental nonseparability: although the explanation for correlations among entangled pairs cannot lie in any intrinsic features of the relata, the intrinsic state of the system's wave function provides a more fundamental fact capable of explaining observed correlations. And since there are no relational facts about the wave function that are not reducible to intrinsic facts about the values assigned to it at each point in its space, the wave function metaphysics is fundamentally separable.

The issue of locality/nonlocality is frequently conflated with that of separability/nonseparability in the scientific and philosophical literature. But unlike separability which concerns (noncausal) metaphysical determination or grounding of the features of systems in terms of features of subsystems, in the sense to be discussed here, locality is a causal notion. The rough idea is that a system is local if there is no action at a spatiotemporal distance in that system that is not mediated by a chain of causes at intermediate distances.

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 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. Subsequently, nonlocality appears to have been demonstrated in many experimental settings. However, just as the wave function realist's fundamental metaphysics avoids nonseparability, so does it avoid nonlocality. What appears in the derivative three-dimensional metaphysics as nonlocal influence is explained by the evolution of the wave function in its space where there are no nonlocal influences. How exactly this behavior works depends on the dynamical laws associated with the wave function – both collapse and no-collapse dynamics are possible. But in no situation does an event in one region of the high-dimensional space trigger an instantaneous or unmediated response in some other such region.[3] In a collapse dynamics, such collapses may be instantaneous and even spontaneous, but no nonlocal influence is involved.

Now there is a question about whether there is nonseparability or nonlocality simpliciter on the wave function realist's picture, even if fundamentally everything is separable and local. First one must ask, can the wave function realist accept in addition to what is given in the high-dimensional fundamental picture, a three-dimensional metaphysics as some kind of derivative reality. If wave function realism is compatible with a derivative (but real) three-dimensional world, then there will be nonseparability in

[3] See Ney (forthcoming) for explanation.

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. (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 spatially distant measurement events. According to the wave function realist, it is not an interaction between the two wings of an experiment that explains any correlations, but instead the dynamical evolution of the wave function. So although there may be observed correlations in three-dimensional space, there fails to be even derivative nonlocal influence.

So we see that the motivation for wave function realism comes from the sense that quantum phenomena, in particular the observed correlations that are a consequence of entanglement, may simply be manifestations of a separable and local metaphysics inhabiting a higher-dimensional space. In the nonrelativistic case, this discussion begins by considering what appear to be spatially separated particles of a determinate number. However at least prima facie, the case for wave function realism may be extended to consider any type of events occurring at distinct spacetime locations for which there appear to be correlations induced by entanglement. The wave function realist will take these correlations to suggest that what appear to be distinct events occurring at distant spacetime locations are manifestations of a more fundamental ontology in a higher-dimensional framework.

## 5. Wave Function Realism in Relativistic Quantum Theories

The question of how to extend wave function realism to a relativistic context is complicated by the fact that the basic mathematical structure of relativistic quantum theories and quantum field theories, especially when interactions are factored in, is not entirely clear. Disputants seem to agree however that whatever the best way to express the mathematical structure of these theories, they ultimately involve an assignment of values of some kind (operators or algebras) to regions of spacetime. From this, the critics of wave function realism infer that the ontology of these theories must involve features instantiated at spacetime regions. This is the inference that the wave function realist wishes to call into question.

For example, consider Wallace and Timpson's spacetime state realism. They argue:

> Suppose one were to assume that the universe could be divided into subsystems. Assign to each subsystem a density operator. We then have a large number of bearers of properties – the subsystems [they take these to be spacetime regions] – and the density operator assigned to each [spacetime region] represents the intrinsic properties that each subsystem instantiates, just as the field value assigned to each spacetime point in electromagnetism, or the complex number assigned to each point in wave-function realism, represented intrinsic properties. (2010, p. 709)

For those with concerns about, for example, unitarily inequivalent representations (Ruetsche 2011), Wallace and Timpson allow that one can also think of the ontology in terms of an assignment of algebras of operators to each spacetime region rather than operators of some kind (2010, p. 712).

Wallace and Timpson both acknowledge and embrace the fact that although relativistic quantum systems can be characterized in terms of an assignment of algebras or density operators to spacetime regions, interpreting this literally leads to a nonseparable metaphysics. Facts about the assignment of such features to the subregions of a spacetime region R does not determine the assignment of features to R.

We may debate the importance of having a metaphysics that is separable. Wallace and Timpson (2010) question its importance; Ney (forthcoming) attempts to lay out the case for separability and locality in some detail. But like it or not, wave function realists are motivated by the desire to have a separable metaphysics, and there does not seem to be any prima facie argument that the desire for a relativistic theory conflicts with the desire for a theory that is separable and local. And so spacetime state realism, although it may have the virtue of producing a metaphysics that is close to the mathematical structure of quantum field theories (insofar as that is a virtue), will only be a stopping point for the wave function realist on the way to a fundamentally separable metaphysics.

The simplest way for the wave function realist to proceed in developing an interpretation of relativistic quantum theories then would be in many respects analogous to the way she achieved the high-dimensional representation in the nonrelativistic case. Starting from an apparent ontology of localized subsystems in three-dimensional space with nonseparable features, the wave function realist posited a more fundamental, higher-dimensional space in which each point corresponded to an entire three-dimensional configuration of subsystems. In the relativistic case, for simplicity, let's consider the Hilbert space version of spacetime state realism in which operators are assigned to subregions of the total spacetime manifold. As mentioned, for a total region R, the features of two nonoverlapping but together exhaustive subregions of R, R1 and R2, do not determine the features of R. So, for example, let's start by considering a Fock space representation in which $\hat{a}^\dagger(\mathbf{k})$, $\hat{a}(\mathbf{k})$, and $N(\mathbf{k})$[4] denote raising, lowering, and number operators for quanta (here, we'll consider bosons) of momentum **k** and their assignments to regions of spacetime. Suppose there is an assignment of $N(\mathbf{k})$ to a total spacetime region R with expectation values that would lead us to predict a total of either two or three quanta with determinate momentum **k** in R. The system is in a superposition of a state with three quanta in R1 and zero quanta in R2 and a state with zero quanta in R1 and two quanta in R2. This may be described in terms of the total number of quanta of momentum **k**:

$$|3>_{R1} \otimes |0>_{R2} + |0>_{R1} \otimes |2>_{R2},$$

or it may be described in terms of raising operators applied to the vacuum state:

$$a_{\mathbf{k}}^\dagger a_{\mathbf{k}}^\dagger a_{\mathbf{k}}^\dagger|0>_{R1} \otimes |0>_{R2} + |0>_{R1} \otimes a_{\mathbf{k}}^\dagger a_{\mathbf{k}}^\dagger|0>_{R2}.$$ [5]

Confined to the low-dimensional image, there is nonseparability. The facts about the quantum state at R are not wholly determined by the states at its subregions. What things are like at R1 is inextricably correlated with the situation at R2, but this fact is left out if one just looks at what things are like at R1 and R2 individually. To achieve a separable metaphysics, the wave function realist can postulate a higher-dimensional space in which each point corresponds to an assignment of operators to the subregions of R. In this case, she will postulate a field with nonzero amplitude at a point corresponding to three quanta at R1 and zero at R2, and another point corresponding to zero quanta at R1 and two at R2.

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[4] The number operator's hat must remain invisible for reasons known only to the developers of Microsoft Word.

[5] Note that normalization constants have been elided for presentation.

Generalizing from this simple case in which we are just considering two regions R1 and R2, and assuming the spacetime representation from which we begin is continuous, the higher-dimensional space will be continuously-infinite-dimensional with each point corresponding to an assignment of operators to all spacetime points or smallest regions in the low-dimensional representation. This recipe further generalizes to the more abstract algebraic approach in which algebras of operators are assigned to spacetime regions. This is straightforward in the case of unitarily equivalent representations. In the case of unitary inequivalence, further degrees of freedom may be needed to represent the possibilities of states lying outside an one Hilbert space representation. But, either way, one recovers a separable and local fundamental metaphysics.

## 6. Interpretations and Interpretational Frameworks

At this stage, we may note that we are no longer considering wave functions on a space with the structure of a configuration space as the central elements in the wave function realist's fundamental ontology. What we have instead is a field, one defined in another kind of high-dimensional space that is correlated with assignments of values to regions in a four-dimensional ontology. This is a simple consequence of the fact that the low-dimensional, nonseparable representations from which the separability and locality arguments depart are different in the relativistic case than they were in the nonrelativistic case.

The point I want to make here – and this is the central point of the present paper – is that there is a deeper interpretative ideology underlying wave function realism: that which guides one to a metaphysics for quantum theories lacking fundamental nonseparability and nonlocality. This ideology or interpretative framework – *call it Localism* if you like – leads one to adopt a picture of a wave function on a space with the structure of a classical configuration space in the context of nonrelativistic quantum theories. But it will lead one to adopt a different metaphysical interpretation for relativistic quantum mechanics and quantum field theories.

7. Response to Objections

Once we see that the wave function in configuration space view is only an instance of a broader strategy of interpretation applied to the special case of nonrelativistic quantum mechanics, and that relativistic implementations of this strategy will not rely on the configuration space framework, some of the objections to wave function realism canvased in Section 3 may be quickly dispensed with.

A. Recall the first objection (from Wallace and Timpson 2010) was that wave function realism, as applied to relativistic quantum theories in which particle number is not conserved, led to an ontologically profligate picture of an infinite sequence of configuration spaces. Viewing the wave function in configuration space picture as an implementation of an interpretative strategy that applies only to nonrelativistic theories, this objection does not get off the ground. The wave function realist need not and should not offer the wave function in configuration space picture as an interpretation of relativistic quantum theories.

Now, there would nonetheless be something to this objection were the wave function realist not able to suggest an alternative picture applicable in the case of relativistic quantum theories. But, as we saw in Section 5, these concerns are unfounded. In the case of relativistic theories, the wave function realist can start from the same place as the spacetime state realist, with a nonseparable metaphysics of operator or algebra assignments to spacetime regions, and infer from there a more fundamental, separable metaphysics in a high-dimensional space in which each point corresponds to a total assignment of operators or algebras to local spacetime points or regions. Wallace (forthcoming) argues that:

> [W]avefunction realism seems to rely on features of toy NRQM which, far from being universal features of any realistic quantum theory, drop away as soon as we generalise.

The response is that wave function realism applied to toy NRQM relies on features of toy NRQM. However, the wave function realist achieves an interpretation of more realistic quantum theories by relying on the features of these more realistic theories, those same features on which the spacetime state realist bases his interpretation.

B. The second objection Wallace and Timpson (2010) raised for wave function realism is that the theory "obscures the role of spacetime in quantum theories." What seems to be underlying this objection is a kind of normative constraint that metaphysical interpretations of physical theories should themselves remain close to the mathematical structure of those theories. Wallace and Timpson defend their own spacetime state realism for the fact that "it adds no additional interpretational structure (given that the compositional structure of the system is, *ex hypothesi*, already contained within the formalism); and it gives an appropriately central role to spacetime" (2010, p. 712).

Myrvold (2015) presents similar concerns as well noting that characterizing the ontology of quantum field theories in terms other than an assignment of values to spacetime regions "is not what is done in the usual presentations" (2015, 3271). He also notes that "the empirical content of [QFTs] remains tied to observables that are associated with regions of spacetime" (ibid.)

The first thing to note is that the wave function realist does not reject the truth or empirical adequacy of the spacetime representations that are characteristic of usual presentations of both conventional and algebraic quantum field theory. Her claim is not that these representations should be rejected, but rather that they should be seen as metaphysically explained or grounded in terms of a more fundamental representation of a field in a high-dimensional space. This is a metaphysical claim motivated, as we have seen, by a commitment to fundamental separability and the thought that nonlocal correlations should be explained in terms of a more fundamental picture lacking them.[6] Because the wave function realist takes as a given the truth of spacetime representations, only questioning their fundamentality, there is no problem with her using them to understand the empirical content of quantum field theories or even their role in standard expositions of quantum field theories.

How closely a metaphysical interpretation of a physical theory should adhere to the picture immediately suggested by the formalism is a vexed issue. Insofar as this is a desideratum, then we can see that wave function realism when applied to nonrelativistic quantum mechanics does better at achieving it than does the strategy when applied to

[6] Although it is worth noting that the Everettian quantum mechanics at least Wallace prefers avoids nonlocality as well. The wave function realist appeals to locality rather to distinguish her metaphysics from the Bohmian's.

relativistic quantum theories, since textbook discussions of nonrelativistic quantum mechanics often rely on the wave function in configuration space picture. However, in the relativistic case, the wave function realist does have a justification for moving beyond the sort of picture suggested by the relativistic quantum formalism. And this is that what she is trying to do is seek out what the strange observations constituting our evidence for quantum theories are telling us about the fundamental structure of our world. Of course it makes sense, when we construct quantum theories that do justice to our evidence and are relativistically covariant, that we will start with spacetime representations. However, persistent correlations that we observe between spatiotemporally distant events suggest that there is something more basic underneath the spacetime picture. Or maybe not, at this stage at least, it is not possible to know whether there is or isn't. But the aim of wave function realism is to spell out what this more basic picture looks like if nonlocal correlations do possess a more fundamental explanation. And it does not seem possible to achieve a simple explanation of them without moving beyond a spacetime framework.

C. The third critique Wallace and Timpson (2010) raised for wave function realism, recall, was that relativistically covariant quantum theories violate narratability – the history of events cannot be told as a single story evolving over time, but will vary depending on the way one slices up the manifold into times – and this violation is surprising from the point of view of a separable theory like wave function realism but not a nonseparable theory like spacetime state realism. To see how narratability fails, consider one of the simple cases presented by Albert (2015).

Albert describes a system S consisting of four spin-1/2 particles. From the perspective of a frame of reference K, particles 1 and 2 are permanently located at their respective spatial positions, and particles 3 and 4 move with uniform velocity along parallel trajectories intersecting the paths of particles 1 and 2 at spacetime locations P and Q respectively. P and Q are simultaneous from the perspective of K. The spin states of the particles may be described as $|\varphi\rangle_{12}|\varphi\rangle_{34}$, where:

$$|\varphi\rangle_{AB} = 1/\sqrt{2}\ |\uparrow\rangle_A|\downarrow\rangle_B - 1/\sqrt{2}\ |\downarrow\rangle_A|\uparrow\rangle_B$$

Albert notes that from the perspective of K, there is no difference between the following two Hamiltonian descriptions of S's evolution. The effect of the two Hamiltonians may be summarized simply as:

$H_1$: S evolves freely

$H_2$: Particles exchange spins upon contact.

Interestingly, although reference frame K recognizes no difference between evolution according to $H_1$ and $H_2$, since from the perspective of K, the state of S is always $|\varphi\rangle_{12}|\varphi\rangle_{34,}$ this is not so in any other frame of reference K'.

And so the story or "narrative" of the evolution of S over time is dependent on one's reference frame. Nor can one transform between the description of K and other frames by a Lorentz transformation. No such transformation is possible since it would require mapping identical states in K to distinct states in K'. And so specifying a system's state at all times in any one frame of reference is not sufficient to specify all facts about that system.

Wallace and Timpson argue that on spacetime state realism, narratability failure is natural given the interpretation's postulation of nonseparability:

> [S]uppose that we have *any* spacetime theory which (i) is non-separable, so that there can be simultaneous spacetime regions A and B such that the state of A∪B is not determined by the states of A and B separately, and (ii) is also covariant. Covariance entails that there can also be *non*-simultaneous spacetime regions whose joint state is not fixed by their separate states. This opens up the possibility of failure of narratability: specification of global states on elements of one foliation on their own will not in general fix the joint states of non-simultaneous regions. (2010, p. 721)

The key issue though, if narratability failure is to provide a case for spacetime state realism over wave function realism, is whether the implication works in the other direction. The failure of separability suggests a failure of narratability, Wallace and Timpson point out. But does the failure of narratability suggest a failure of separability? It is not clear why it should. Nor must the explanation of the failure of narratability arise from within wave function realism specifically as opposed to what Albert's case shows, that it arises from physical facts about entanglement and Lorentz covariance.

D. As we've seen, Myrvold (2015) objected to wave function realism that in quantum field theories wave functions are constructed from structures defined on spacetime and so they cannot be more fundamental than spacetime structures. He demonstrates the derivation of wave functions in the context of both nonrelativistic and relativistic quantum field theories. We need not get into the details of these derivations though to see that this criticism of wave function realism is misplaced. The fact that wave function representations may be mathematically derived from spacetime representations does not show anything about the direction of ontic priority. And the wave function realist (at least in the nonrelativistic context) only argues that wave functions are ontically prior to spacetime structures. Myrvold's demonstrations do not show that spacetime representations cannot be similarly derived from wave function representations, or the kinds of representations I have argued the wave function realist should take to be tracking fundamental structure in the case of relativistic quantum theories.

E. Myrvold's other criticism relates to the wave function realist's claim that her fundamental metaphysics consists of a field in a high-dimensional space. As we saw above, Myrvold presents an example intended to show that the central object in the wave function realist's fundamental metaphysics is not a field, as it isn't something defined by local assignments of values to regions of the space the object occupies.

There are several issues with Myrvold's argument, the first being its reliance on an interpretation of relativistic quantum theories I have already noted the wave function realist should reject – one according to which what fundamentally exists is a plurality of wave functions of increasing dimension. But set that issue aside. Myrvold's argument can be summarized in the following way:

1. In S1, the single-particle wave function takes on a nonzero value at x.

2. In S2, a state just like S1 except with a particle confined to a region R far from x, the single-particle wave function will take on a zero value at x.

3. So, a nonzero value of a single-particle wave function at x is incompatible with there being a particle located in region R, no matter how far R is from x.

4. So, facts about the assignment of values of wave functions to regions of wave function space depend on circumstances in distant regions.

5. So, wave functions are not defined by an assignment of local quantities to regions of the space they inhabit.

6. So, wave functions are not fields in the usual sense.

I wish to argue that depending on what one means by ‘assignment of local quantities’, the wave function realist has good reason to reject the inference either from (4) to (5) or from (5) to (6). Before getting to this, it is worth noting why Myrvold thinks this critique is so powerful against the wave function realist. This is because, as Myrvold recognizes, one of the central motivations for wave function realism is to provide a separable metaphysics for quantum theories. But if the state of wave functions do not depend on the assignment of local features, then the wave function realist’s metaphysics will not be separable. So, really the key point is what I have stated as subconclusion (5) above.

Assuming that by ‘assignment of local features’, one means an assignment of features not determined by what takes place at distant locations, it is easy to see that (5) does not follow from Myrvold’s earlier claims. What we find in S1 and S2 are two distinct wave functions, where the state of each wave function is determined by the assignment of amplitudes (and phase, though this is ignored in the example) to each point in its space. The amplitude of the single-particle wave function at x in S1 is not equal to the amplitude of the single-particle wave function at x in S2 and this is what determines the fact that these are distinct wave functions. Now Myrvold notes that we can infer that the single-particle wave function for S2 differs from that of S1 simply by knowing in S2 there is a particle definitely located at a distant region R. This is due to a modal dependence between the fact about the particle and the fact about the wave function. But, that there is a particle definitely located at R is not what ontically determines the amplitude of the single-particle wave function at x for S2. That fact is brute (at least according to the kind of wave function realist interpretation Myrvold wants us to consider here). According to the wave function realist, facts about the locations of particles are ontically derived from facts about the wave function (or wave functions). The fact about dependence stated in (4) obtains due to this fact of ontic priority. So, (5) simply does not follow from (4). This part of Myrvold's argument simply begs the question against the wave function realist. It assumes facts about the locations of particles determine facts about the wave function rather than vice versa.

That the case for (5) begs the question is already enough to show that Myrvold's argument does not undermine the case for wave function realism in the way he thinks it does. But there is another point that is interesting about Myrvold's argument that is perhaps worth bringing out in more detail. What is going on in this case, we can see, is that in S2, since we are told that a particle is definitely located at R, we know that the single-particle wave function must take on value 1 at location R. If single-particle wave functions were normalized, this would mean that it must take on a value of 0 at every other location. As a rule, these individual (single-particle, two-particle, etc.) wave functions won't be normalized. Nonetheless, we can still infer that the amplitude of the single-particle wave function at x is 0, since it is still reasonable to require that the amplitude-squared of all of the wave functions at all of the points in their respective spaces must add exactly to 1. Now one might read Myrvold as saying that it is this fact that makes these wave functions un-field-like: that the amplitude the wave function takes on at one point depends on (this isn't to say is determined by) what it takes on at another point. Surely, one might think, for waves in an ocean, one can have peaks at some point and this doesn't determine how they are at some other point.

If this is Myrvold's concern, and what might be motivating a move from (5) to (6) in my formulation of the argument, then it seems misplaced. Since actual water waves or waves on a string, etc. are always made of a finite amount of material, there necessarily will be a dependence of what amplitude the wave takes on at one location and what it takes on at others. So if one likes, in a sense one can say that waves of these kinds are not defined by an assignment of local features because there are dependence relations obtaining between the values the wave takes on at distinct locations. But noting that the wave function too has this feature does not make it in any way un-field-like unless all of these things are un-field-like as well.

F. The final objection one finds in the literature, in Wallace (forthcoming), challenges the wave function realist's privileging of the position representation, noting that such representations fail to be straightforward in relativistic quantum theories. My response to this objection is similar to the response I have argued the wave function realist should make to the first objection. This is that the objection mistakenly assumes that all features of the interpretation the wave function realist gives for nonrelativistic quantum mechanics will carry over to interpretations of relativistic theories. As illustrated in Section 5, just as the wave function realist bases her interpretation of NRQM on standard presentations of NRQM, the wave function realist will base her interpretation of QFTs on standard presentations of QFTs. In the absence of a Lorentz covariant position representation of a QFT, the wave function realist will construct her higher-dimensional representation using a different kind of basis. The example in this paper used the momentum basis. Importantly, the wave function realist may start from the same formal framework as the spacetime state realist.

## 8. Conclusion

We may see that at least some of the main objections raised to wave function realism from the putative difficulties of extending the view to relativistic quantum theories rest on the false assumption that the resulting interpretation of relativistic quantum theories must postulate a field in configuration space. Others rest on the failure to see that the wave function realist allows the truth and/or legitimacy of spacetime representations, and claims these are determined by the higher-dimensional facts she posits. So, it seems to me there are no clear barriers to extending wave function realism to the relativistic domain.

Wave function realism should still be on the table as one among many interpretations of quantum theories. Although the wave function in configuration space view is really only plausible as an interpretation of nonrelativistic quantum mechanics, it is a particular case of a broader framework for interpretation applicable to relativistic quantum theories as well. Insofar as it provides the interpreter with a separable and local fundamental metaphysics, it may benefit from an air of comprehensibility that does not similarly apply to alternative approaches. This itself makes it worth keeping on the table.

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