Next Best Thing

—What Can Quantum Mechanics Tell Us About the Fundamental Ontology of the World?

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Abstract

Many discussions in the metaphysics and philosophy of physics literature aim to use physics as a guide to elucidate what the world *really*, *fundamentally* is like. However, we don't yet have a confirmed fundamental theory of physics—what's the next best thing we can possibly say about the fundamental that is properly informed by our best theories of physics? This paper offers a starting point to address this question. It focuses on the literature on the ontology of quantum mechanics, where the problem is especially salient: Many proposals aim at drawing the fundamental ontology of the world from quantum mechanics, even though they often focus on a non-fundamental theory such as nonrelativistic quantum particle mechanics. I argue that quantum mechanics can plausibly be informative about the fundamental if it is taken as a general *framework* theory, which covers a range of specific *concrete* theories, including nonrelativistic quantum particle mechanics, the Standard Model of particle physics, and string theory. I use Wavefunction Realism as an example to demonstrate what kind of ontological lessons about the world at the fundamental level the quantum framework may teach us.

1 Introduction

Physicists have long aspired to develop the fundamental theory of physics, the final theory, or the theory of everything. It is intended to give a unified and comprehensive account of the physical world, especially at the smallest scale. Weinberg (1994, 7), one of these physicists, traces the search for explaining all natural phenomena in terms of fundamental constituents of matter back to ancient Greeks. The modern aspiration for a final theory became a real possibility and gained widespread consideration after the work of Newton and Maxwell.

Meanwhile, science has produced all sorts of successful theories, across various areas such as chemistry, astrophysics, and condensed matter physics. Almost none of these theories, though, are proposed as candidates for a fundamental theory. Rather, they describe the world only at larger length scales or higher, emergent levels, and are applicable only within limited domains. The closest to a fundamental theory of physics we currently have that is confirmed by experiments is the Standard Model of particle physics plus general relativity. However, it has limited validity and is not a universal theory: it breaks down at the Planck scale and does not account for dark matter. The status of the Standard Model as an emergent, approximate theory "is built into its characterization as an effective field theory" (Wallace 2020b, 96). Our best theoretical candidates for a fundamental theory are string theory and loop quantum gravity, but they are relatively speculative and far from being confirmed by experiments. Thus at the moment we do not have the fundamental theory yet, and are not likely to find it soon (Weinberg 1994, 6; Rovelli 2005, 259).

Anyone with a naturalistic tendency, believing that our understanding of the natural world should be informed by our best scientific theories and wanting to read off metaphysics from physics, would look at the fundamental theory of physics to learn what the world *really*, *fundamentally* is like—the fundamental ontology, the fundamental laws, or the fundamental structure of the world, and so on. However, even in the absence of a confirmed fundamental theory, it is common in the metaphysics and philosophy of physics literature to see discussions on what is fundamental.[1] Few of these discussions engage with any of current candidates for a fundamental theory of physics.[2] Some of them work under the fiction that classical mechanics is a fundamental theory.[3] There is thus a prima facie problem of how to make sense of such discussions from a naturalistic point of view: What can they tell us about the *actual* world? Will their conclusions carry over to whatever turns out to be the fundamental theory of physics?

The problem is especially salient in the literature on the ontology of quantum mechanics. Although quantum mechanics is very powerful at predicting experimental results, it is unclear what exactly happens during those experiments and how we should understand them. Various interpretations of quantum mechanics have been proposed, and many of them promise a realistic description of the quantum world. However, it is still unclear what ontology each interpretation of the quantum formalism implies, or what quantum mechanics is a theory *of*. There are a number of competing *proposals for the ontology of quantum mechanics* based on different interpretations on the table. To name a few, Wavefunction Realism (Albert 1996, 2013, 2015; Ney 2021), Spacetime State Realism (Wallace and Timpson 2010), the Primitive Ontology views (Maudlin 2013; Allori 2013; Goldstein and Zanghì 2013; Esfeld et al. 2013; Egg and Esfeld 2015), and Mad-dog Everettianism (Carroll 2022). These proposals are often construed as drawing the *fundamental* ontology of the world from quantum mechanics,[4] or addressing what the *fundamental* structure of the world is according to quantum mechanics (Arntzenius 2012, 79). The prima facie problem is: how is quantum mechanics relevant

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[1] See, for example, Sider (2011), Paul (2012), and Ismael and Schaffer (2020).

[2] With exceptions in the literature on philosophy of quantum gravity.

[3] For example, Lewis (1986, 1994), Hicks and Schaffer (2017), and Schroeren (2020). Schroeren (2021) further develops his proposal for quantum theory. Hicks and Schaffer claim that their point is applicable to quantum mechanics. Lewis (1986, xi) specifically said that he was not ready to take ontological lessons from quantum mechanics until it's purified; he (1994, 474) does think the tenability of Humean Supervenience can be adapted to better physics.

[4] Wallace (2020a) disagrees with this way of construing the project and points out that we don't yet have a theory that gives us the fundamental ontology.

Egg (2022) calls the view that "quantum mechanics should inform us about fundamental ontology" 'quantum fundamentalism'. He ascribes this view specifically to the Primitive Ontology views and criticizes it.

to the fundamental theory of physics (which is unknown)? In what sense can quantum mechanics tell us anything about the world at the fundamental level?

This becomes particularly problematic for some of these proposals that focus on nonrelativistic quantum particle mechanics (instead of, say, relativistic quantum field theory). Notable examples includes Wavefunction Realism and the Primitive Ontology views. Since we know that nonrelativistic quantum particle mechanics is only valid in a limited regime and thus not a fundamental theory, these proposals inevitably raise the question: How can a non-fundamental theory such as nonrelativistic quantum particle mechanics tell us anything about the fundamental ontology of the world? At least, it is a problematic to take the ontology of nonrelativistic quantum particle mechanics to be the fundamental ontology of the world. Along similar lines, Wallace (2020a, 14-15) asks metaphysicians who treat the ontology of nonrelativistic quantum particle mechanics as a candidate for fundamental metaphysics to tell a methodological story as to "what they are doing and why it is worthwhile".

This paper supplies such a methodological story, focusing on Wavefunction Realism as an example. (I choose Wavefunction Realism because it offers a sharp and straightforward case.) The motivation is not to defend Wavefunction Realism or any other proposal for the ontology of quantum mechanics *per se*. Rather, the point is to make sense of proposals like these that aim to figure out what the world is like at the fundamental level in the absence of the fundamental theory of physics. More generally, this paper is meant to offer a starting point to address the question: given that we do not have a confirmed fundamental theory of physics, yet remain interested in knowing what the world is like at the fundamental level, what can we possibly say about the fundamental that is not merely philosophical speculation but is properly informed by our best theories of physics? In particular, which parts of those discussions on the fundamental will carry over to the fundamental theory, and which parts will not?

This paper works with two basic assumptions. First, there is a fundamental level of the world. Second, acquiring the fundamental theory of physics is possible, or at least we're getting closer and closer to it. A skeptic may question their validity, and consequently the value of any project operating under these two assumptions. They might argue: we don't have conclusive evidence to believe that the world has a fundamental level.[5] Even if such a level does exist, we may never have access to it, or succeed in developing a unified and complete theory for it. Even if we do eventually develop such a theory, how can we ascertain that it is indeed the final theory, one that will not fail in some new domain as classical mechanics once did? If we want to avoid the pitfall of unwarranted speculation or armchair philosophy, isn't quietism the best approach, at least until we actually figure out what the fundamental theory of physics is?

Nevertheless, we also lack conclusive evidence to believe that the world does not have a fundamental level, or that it is impossible for us to know about the fundamental. While it is true that whatever we say about the fundamental now may turn out to be false later, the risk of fallibility is not unique to investigations on the fundamental. We're always in danger of being potentially mistaken, but this should not deter us from trying. It can still be philosophically valuable to carefully tease out what we have said about the fundamental that is clearly false, given our best scientific theories, and explore what we can say about the fundamental, until further evidence shows our current theories fail.

Another way to dismiss the value of carrying out such a project is to argue that the problem of drawing the fundamental ontology from nonrelativistic quantum particle mechanics can be quickly resolved along either one of the following two lines. (1) Nonrelativistic quantum particle mechanics is used only as a toy model and its ontological lessons will carry over to the relativistic domain[6] and eventually to the fundamental theory. However, it is unclear whether the ontological lessons will carry over, and why. In fact, it has been argued that Wavefunction Realism does not carry over to the relativistic domain (e.g., Wallace 2021a). Much more needs to be said to justify (1). (2) Proposals like Wavefunction Realism can be understood as giving the ontology of nonrelativistic quantum particle

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[5] See, e.g., Schaffer (2003) and McKenzie (2011). For a literature review, see Morganti (2020a, 2020b).

[6] One effort to extend Wavefunction Realism to relativistic quantum field theories is in Ney (2021, Chapter 4). I'll discuss her position in Section 2.

mechanics, which is not fundamental but emergent like atoms or fluids.[7] This is to drop the goal of drawing the fundamental ontology.

In Section 2, I argue that (2) is not really viable for Wavefunction Realism, because it is essential to the proposal and its arguments to assume that *quantum mechanics is a fundamental theory*; call this assumption *Quantum Fundamentality*. In Section 3, I propose a different solution to the problem of how quantum mechanics can tell us anything about the fundamental ontology of the world: If quantum mechanics is taken to be a general *framework theory* (which covers a range of specific *concrete* quantum theories), it can plausibly be informative about the fundamental in the sense that the *concrete* fundamental theory of physics will likely fall within the quantum framework, from which we can draw ontological lessons about the world at the fundamental level.[8] I first illustrate the distinction between a framework theory and a concrete theory, and then explain in what sense quantum mechanics as a framework theory can tell us something about the world at the fundamental level. To address the objection that it is a category error to ask what *the* ontology of a framework theory is, I argue: even though the quantum framework does not specify what exactly the fundamental ontology is, it can still inform us about ontological features of the world at the fundamental level. In Section 4, I employ Wavefunction Realism as an example to demonstrate what ontological lessons quantum mechanics as a framework theory can teach us. It requires modifying the current formulation of Wavefunction Realism.

2 Assumption of Quantum Fundamentality: A Case Study from Wavefunction Realism

Wavefunction Realism consists of two main claims:

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[7] Myrvold (2015), though not a defender of Wavefunction Realism, discusses how to think about wavefunctions by taking into consideration that "the nonrelativistic quantum theory of systems of a fixed, finite number of degrees of freedom" is not fundamental.

[8] One can view this solution as providing a justification for (1): It highlights a connection between nonrelativistic quantum particle mechanics and the fundamental theory so that studying the former could be of heuristic value for the latter. It also identifies what kind of lessons from the former will carry over to the latter and what kind of lessons will not.

> WFR (I): the wavefunction represents a concrete physical object, a field, in the same sense that particles are concrete physical objects in Newtonian mechanics and electromagnetic fields in Maxwell's theory of electromagnetism.
>
> WFR (II): the fundamental physical space of the world is isomorphic to the high-dimensional configuration space in which the wavefunction is mathematically defined.

For its proponents, e.g., Albert (2013) and Ney (2021, 47), WFR (II) follows from WFR (I).

One central argument for Wavefunction Realism is that it provides a quantum ontology that is separable in the fundamental physical space. The state of a system is separable in a physical space if it supervenes on or is fully determined or specifiable by the local properties at each point in that space. Phenomena of quantum entanglement indicate that, say, the state of a pair of entangled particles is not fully determined by the local properties of each particle located at separate point in three-dimensional space, and thus not separable in that space. For example, a pair is in the state such that the two particles are correlated in the following way: when one particle is measured as having spin-up along a certain direction, a measurement on the other particle will have a result of spin-down along the same direction, regardless of how far away one particle is located from the other. This correlation encoded in the total state of the particles is not specifiable or determined by the properties or state of each individual particle. (Put more generally, the pure state of a system is not determined by the mixed states of its subsystems.)

The wavefunction, which corresponds to the state of the two entangled particles, is however separable in a high-dimensional space. To understand this idea, consider a toy example: two points in three-dimensional space (x_1, y_1, z_1) and (x_2, y_2, z_2). They can also be represented as one point in the six-dimensional configuration space $(x_1, y_1, z_1, x_2, y_2, z_2)$. This allows us to represent the state of any two-particle system, whether it is entangled or not, in terms of a single (wave) function which takes on a definite value at each point in the six-dimensional configuration space. This wavefunction is fully determined by the local properties at each point in the six-dimensional space, that is, the amplitude and phase of each point. Accordingly, one way to enforce separability of the state of an N-particle system is to take its wavefunction to represent a physical field and the $3N$-dimensional configuration space of such a system—or, rather, something isomorphic to it—to represent a real physical space. In this way, even though N particles are not separable in three-dimensional space, the wavefunction of the N particles is separable in the space that is isomorphic to the $3N$-dimensional configuration space.

One may question why we even want or need separability, or what the compelling reasons are for insisting our world is indeed separable. As Wallace and Timpson (2010, 713–714) point out,

> It is tempting to regard separability as part of our ordinary conception of space: arguably, if some putative spacetime has essentially non-local properties, or perhaps better, if the things in it (e.g., fields) have to end up being attributed non-separable properties, we ought not to call the arena 'spacetime'. But there is nothing *mathematically* improper about these non-local properties.

One argument for separability to which Albert alludes is: separability is required of what it is to be the *fundamental* physical space of the world. For Albert (1996, 282), the fundamental space is the arena in which the entire history of the world unfolds itself, the "arena within which the dynamics does its work". More specifically, it is

> the space in which one can *represent* everything that's going on, in which one can *keep track* of everything that's going on, merely by saying what it is that's going on at every individual one of its points—the space (you might say) of *the totality of atomic opportunities for things, at any particular temporal instant, to be one way or another*. (Albert 2019)

This is the space, that is to say, in which a specification of all the local properties at every individual space point at a particular time “amounts to a complete specification of the physical situation of the world” at that time (ibid.). This characterization of space is not new or unique to Albert. It is reminiscent of Lewis’s thesis of Humean Supervenience (1986, ix-x): All there is to the world is the spatiotemporal distribution of local properties “which need nothing bigger than a point at which to be instantiated”; everything else supervenes on that.

If there is indeed a fundamental space, one that is separate from ordinary three-dimensional space, and Albert’s conception rightly captures what it is to be the fundamental physical space of the world, then it follows that the world is indeed separable in the fundamental space so that its state is determined or specifiable by the local properties at each space point. To those who take nonseparability as a brute fact of the world and are not compelled by having an ontology that is separable in the fundamental space, a defender of Wavefunction Realism would argue: an alternative conception of what it is to be the fundamental space is needed, or why Albert’s conception is inadequate to characterize the physical space of our world needs to be spelled out.

My point here, however, is not to justify separability or Albert’s conception of fundamental space, or to defend Wavefunction Realism. Rather, the point is to show that this argument for separability (and accordingly for Wavefunction Realism) hinges critically on the assumption of Quantum Fundamentality. In this argument, quantum mechanics is taken to be fundamental, and its ontology is the fundamental ontology that is located in the fundamental space and thus is the one that is subject to the requirement of being separable. If quantum mechanics were not taken to be fundamental and its ontology were recognized as emergent at a higher-level, it is unclear how that ontology has anything to do with the fundamental space, or why it cannot be nonseparable in three-dimensional space just like other higher-level, emergent objects.

After all, Albert does not mean to deny the existence of nonseparable objects in three-dimensional space or to simply take the fundamental space to be the only physical space for the world. He distinguishes the fundamental space from the emergent, phenomenal space, in which the non-fundamental, emergent objects reside. He calls the latter *the space of possible interactive distances* or *the space of dynamics*. It is the set of possible distances that material objects could have from one and another. (For example, the set of possible distances the objects could have in the one-dimensional space of dynamics would be different from the set of possible distances the same objects could have in the two-dimensional space.) This space is produced by the dynamics of the material objects; its dimensionality is determined by the structure of dynamical equations. Both in classical mechanics and in quantum mechanics, it is the dynamical phenomena through which the world emerges as three-dimensional (this is the reason why our world appears to be three-dimensional). In classical mechanics, the fundamental space and the space of dynamics happen to coincide. But it just happens in quantum mechanics that they come apart. The ontology of quantum mechanics resides in the high-dimensional fundamental space, while any higher-level ontology resides in the three-dimensional emergent space. It is hard to make sense of the relation between these two spaces, if Wavefunction Realism is understood as a proposal for the ontology of nonrelativistic particle quantum mechanics, which only emerges at a higher-level. (I'll say more about this later.)

Another promoter for Wavefunction Realism, Ney, gives a different set of arguments for separability in terms of conceptual clarity and intuitions. She claims: "There is something intuitively compelling . . . about the idea of separability, that . . . what things are like at any composite region is *ultimately* determined by the features of these more basic objects", which one should endorse "as a matter of clarity" (Ney 2021, 127; my emphasis). Separability is "at least intuitive in the respect of being simple" (ibid., 128). In particular, Ney points out that an ontological interpretation (of quantum mechanics) that is compatible with our intuitions may be useful for physics students who want to "learn about the *fundamental* nature of reality" (ibid., 131; my emphasis). Setting aside the question of whether these arguments for separability are convincing, what matters for our purpose is: whether or not they rely on the assumption of Quantum Fundamentality. The word 'ultimately' or 'fundamental' suggests, at least *prima facie*, fundamentality plays some role. I suspect that Ney would not find it intuitive if the world were separable only at a non-fundamental level but turned out to be nonseparable at a more fundamental level. Put another way, given that our world is already nonseparable at a non-fundamental level, in what sense is it more intuitive if the world is separable only at some other non-fundamental level, but may not be separable *ultimately*, *fundamentally*? This leads to my next point.

There is one argument for separability (and Wavefunction Realism) I can think of that does not *directly* rely on the assumption of Quantum Fundamentality: A quantum theory with a separable ontology is more explanatory than without. Recall the earlier discussion on the state of a pair of entangled particles being nonseparable in three-dimensional space: the state of one particle is correlated with the result of a certain measurement on the other particle, no matter how far apart they are. As Bell (2004, 152) points out, "the scientific attitude is that correlations cry out for explanation". Wavefunction Realism contributes to an explanation for the correlations between a pair of entangled particles: they are not mysterious, but are in fact grounded by the dynamics and local properties of the wavefunction at a more fundamental level. In contrast, accepting nonseparability as a brute fact of the world is to say that such correlations have no further explanation. [9]

This argument does not require that quantum mechanics be the fundamental theory and the wavefunction be the fundamental object in the fundamental space, but only that the wavefunction be *more* fundamental than the particles. This argument allows proponents of Wavefunction Realism to restrict their goal to giving the ontology of nonrelativistic quantum particle mechanics, instead of the fundamental ontology of the world (as introduced in Section 1). They can argue that separability provides a compelling reason to take the ontology of nonrelativistic quantum particle mechanics with N particles to be, at a *more* fundamental level, a wavefunction in the $3N$-dimensional space. But it doesn't mean this high-dimensional space is the fundamental space or the fundamental ontology is

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[9] This argument could be what Albert and Ney have in mind, but they haven't put it this way.

I take it to be an open question of how to understand such explanation—whether it is reductive explanation, grounding explanation, constitutive explanation (which is suggested by Ney), or causal explanation (which is hinted by Albert (2023) in his analogy with how the weirdness of shadows on a wall can be explained).

the wavefunction.

Although this argument seems reasonable by itself, conceptual difficulties arise when we consider its broader implication. Nonseparabillity of physical systems in three-dimensional space is not unique to nonrelativistic particles, but a feature common to any quantum system. If correlations between entangled particles cry out for explanation in terms of a separable ontology at a more fundamental level, shouldn't we apply the same reasoning to other quantum theories (such as relativistic quantum field theories) as well? If we shouldn't, why not? If we should, we will end up with a picture of the world in which there is a wavefunction in the $3N$-dimensional space for nonrelativistic quantum particle mechanics, and another wavefunction in a space with possibly infinitely many dimensions for a relativistic quantum field theory, and some other wavefunction for some other quantum theory. In such a picture, how are these wavefunctions related to one another? What about all these various high-dimensional spaces?

Moreover, applying Wavefunction Realism to multiple quantum theories beyond the most fundamental one seems redundant. Suppose we already apply Wavefunction Realism to, say, relativistic quantum field theory and explain nonseparability and correlations in its domain in terms of a separable ontology in a high-dimensional space. Since relativistic quantum field theory is more fundamental than nonrelativistic quantum particle mechanics and the latter can be explained by the former, whatever nonseparability and correlations between nonrelativistic particles can already be explained by the separable ontology underlying quantum fields. What additional explanatory power can we gain by also applying Wavefunction Realism to nonrelativistic quantum particle mechanics and adding another separable ontology at a higher-level? At the end of the day, as long as the ontology of the most fundamental quantum theory is separable, nonseparability and correlations at any higher-level can be accounted for. Why do we need additional explanations for the same correlations provided by a separable ontology at each higher-level?

Ney (2021) offers a different way to make sense of Wavefunction Realism and its focus on nonrelativistic quantum particle mechanics. She takes Wavefunction Realism to be an *interpretative framework* that "guides one to a metaphysics for quantum theories lacking fundamental nonseparability and nonlocality" (ibid., 149). In other words, Wavefunction Realism provides a framework, or a general strategy, for interpreting quantum theories ontologically. Interpreting nonrelativistic quantum particle mechanics is only an instance of the broader strategy (ibid., 150). Ney's account, however, faces the same problems discussed above: What's the need to apply Wavefunction Realism to different quantum theories? How should we understand the relations between various wavefunctions and high-dimensional spaces? Most importantly, her account falls short in giving a justification as to why Wavefunction Realism, originally developed within the context of nonrelativistic quantum particle mechanics, can be generalized as an interpretative framework, or (in other words) why we should expect Wavefunction Realism to be applicable to any other quantum theories[10]—this is exactly what opponents of Wavefunction Realism like Wallace (2021a) call into question.[11]

Developers of Wavefunction Realism often use the word 'fundamental' to articulate their proposal (e.g., 'fundamental law' and 'fundamental stuff' for Albert; 'fundamental objects', 'fundamentally separable', and 'the fundamental nature of our world' for Ney). This appeal to 'fundamental' goes beyond mere invocation of the term, nor does it simply reflect a personal interest in the world at the fundamental level. Rather, Wavefunction Realism needs the assumption of Quantum Fundamentality to be defensible and compelling.[12] Although I only focus on Wavefunction Realism as an example, I don't think it is unique among proposals for the ontology of quantum mechanics to assume that quantum mechanics is fundamental. Similar arguments apply to the Primitive Ontology views and Mad-dog Everettianism. Provided that such proposals can't simply drop their goal of drawing the

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[10] In fact, Ney (2021, 134) doesn't see why Wavefunction Realism as "a framework for the ontological interpretation of a quantum theory" must be workable for all quantum theories.

[11] We will see in the next section that my proposal does not suffer from these problems, because what it takes to be the framework is quantum mechanics, the physical theory.

[12] Nina Emery and Gabrielle Kerbel try to develop a version of Wavefunction Realism explicitly without aiming at the fundamental ontology and the fundamental space in a talk called "Configuration Space Realism and Fundamentality". However, they only mean to explore this possibility without offering arguments why this version is actually true.

fundamental ontology, I will outline an alternative way to reconcile the potential tension within proposals that aim to draw the fundamental ontology from quantum mechanics.

3 Quantum Mechanics as a Framework Theory

It can often be ambiguous what one means by 'quantum mechanics', especially when it is described as fundamental. One might have in mind a particular quantum theory (such as nonrelativistic quantum particle mechanics or the Standard Model), working under the fiction that it is a fundamental theory. One might use quantum mechanics to refer to a collection of quantum theories and suppose one of them is fundamental. Or one might use quantum mechanics in a rather generalized sense, contrasting it with classical mechanics (for instance, the world is fundamentally quantum mechanical, whereas we used to think that the world is classical). In this section, I first employ the distinction between an abstract *framework* theory and a specific *concrete* theory to specify a sense in which quantum mechanics can be thought of as fundamental.

To explain this distinction, let's first consider classical mechanics as an example of a framework theory. Its dynamical equation, stated in the form of Newton's second law, is

$$\vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt}. \tag{1}$$

It describes the relation between force $\vec{F}$ and acceleration $\vec{a}$. This is rather general as it doesn't specify what kind of systems are subject to this equation. To apply it to concrete systems, we can specify the kind of forces under consideration, such as gravitational forces or electromagnetic forces. Eq. (1) thus is not an equation specific to concrete systems, but rather a general framework within which equations for concrete systems can be stated. For example, the Newtonian equations for point particles interacting under some potential

$$-\sum_{j:j\neq i}\vec{\nabla}V(|\vec{x_i}-\vec{x_j}|)=m_i\frac{d^2\vec{x_i}}{dt^2}. \tag{2}$$

are a specification of Eq. (1), where $\vec{F}$ is characterized in terms of the potential of pairs of interacting particles that depends only on the distance between particles. Eq. (2) thus applies to systems with gravitational forces, but not with magnetic forces on moving charges. To calculate Eq. (2), we need to further specify what exactly the potential V is, how many particles are involved, and so on. The more details we provide, the more concrete the theory is.

Consider the Hamiltonian formulation of classical mechanics, which in some contexts is more useful than the Newtonian formulation. Its dynamical equations,

$$\dot{q}^i=\frac{\partial H}{\partial p_i}\qquad \dot{p}_i=-\frac{\partial H}{\partial q^i}, \tag{3}$$

are also a schema that contains blanks to be filled in: to obtain equations for a concrete system, we need to fill in specific information about the system, such as its Hamiltonians, the initial conditions, and the physical constraints. Different choices of filling in give us equations that characterize different physical systems (Wallace 2021b): for example, the simple harmonic oscillator equations for springs and other vibrating systems, Euler's equations for the rotations of rigid bodies and for fluids with zero viscosity, the field equations of classical electromagnetism, and general relativity. Accordingly, we have a collection of different theories with different ontologies that all fall within the framework of classical mechanics, such as classical particle mechanics, fluid dynamics, and electromagnetism.

Similarly, quantum mechanics is also a framework theory. Its dynamical equation, the Schrödinger equation written as follows,

$$i\hbar\frac{d}{dt}\left|\psi\right\rangle=\hat{H}\left|\psi\right\rangle, \tag{4}$$

is not an equation for concrete systems. We can fill in the Hamiltonian and specify the Hilbert space on which the system is defined to obtain the Schrödinger equation in a more concrete form. For example,

$$i\hbar\frac{d}{dt}\left|\psi\right\rangle=\left[\frac{\hat{p}^2}{2m}+\hat{V}\right]\left|\psi\right\rangle, \tag{5}$$

where the Hamiltonian of the system is specified by its kinetic and potential energies. To be more concrete, we can further specify $\hat{p}$ and $\hat{V}$; for instance,

$$i\hbar\frac{\partial}{\partial t}\psi(\vec{x},t)=-\sum_{i=1}^{N}\frac{\hbar^2}{2m_i}\nabla_i^2\psi(\vec{x},t)+\sum_{1\leq i<j\leq n}V_{ij}\left(\left|\vec{x}_i-\vec{x}_j\right|\right)\psi(\vec{x},t), \tag{6}$$

where $\hat{V}$ only depends on the distances between particles. Eq. (6) characterizes nonrelativistic point particles interacting under some potential (in position basis). It is more concrete than Eq. (5), also because (6) does not apply to systems with spins whereas (5) can. Similarly to the case of classical mechanics, different choices of filling in the blanks lead to equations that characterize different physical systems (Wallace 2021b): for instance, the quantum version of the harmonic oscillator equations, the quantum field theories of solid-state physics for systems such as superconductors and vibrating crystals, and the quantum field theories of particle physics.

These equations may look different from Eq. (4). Unlike in Eq. (6), $|\psi\rangle$ in quantum field theory is a functional (that is, a function of a function): e.g., $\Psi[\phi]$ (for a relativistic scalar field ϕ). Moreover, quantum field theories often use the Heisenberg picture or the path-integral formulation, and we do not always see the dynamical equations explicitly stated in the form of Eq. (4); these formulations, nevertheless, are effectively equivalent. To put it more precisely, every quantum system is subject to a version of the Schrödinger equation, Eq. (4).

Generally speaking, the quantum framework consists of the following:

1. *Representation*: A quantum system is associated with a Hilbert space $\mathcal{H}$. Its states are represented

by normalized vectors $|\psi\rangle$ in that Hilbert space, called state vectors. A physical quantity (such as position, momentum, and energy), called an *observable*, is associated with a Hermitian operator on $\mathcal{H}$.

2. *Dynamics*: The evolution of a quantum system is unitary, given by the Schrödinger equation, Eq. (4).
3. *Measurement*: The Born rule gives probabilities of outcomes in a measurement.
4. *Composition rule*: Given systems A and B, the state space for the combined system A and B is the tensor product of the Hilbert spaces of A and B.

I intend to present the quantum framework in a way that is neutral to various interpretations; some interpretations may add further content;[13] for example, the dynamics in Bohmian mechanics includes additionally the guiding equation. There are further subtleties that I won't address here; for instance, whether or not the so-called eigenvalue–eigenstate link should be included.[14] But this is more or less the standard way to present the quantum framework.[15] All concrete quantum theories fall within this general framework of quantum mechanics.

The distinction between a framework theory and a concrete theory is not absolute, but a matter of degree. On the one hand, quantum field theory, for instance, is a framework theory which covers a range of *concrete* quantum field theories. The Standard Model of particle physics is one such concrete quantum field theory. The framework also applies to systems studied in condensed matter physics such as superfluids and superconductors. On the other hand, quantum field theory as a framework is more concrete than the quantum framework. The former works specifically with fields, which have an infinite number of degrees of freedom, whereas the latter deals with any quantum system, regardless of how many degrees of freedom. Furthermore, relativistic quantum field theory is more

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[13] The GRW theory, however, modifies the Schrödinger equation; one might rather think of it as a distinct theory.

[14] See, e.g., Barrett (2019, §4) and Wallace (2019).

[15] For closed systems. One can extend this to open systems.

concrete than the framework of quantum field theory as well as the quantum framework, neither of which is necessarily relativistic.

Although we do not know yet what the *concrete* fundamental theory of physics is, the closest one we currently have that is confirmed by experiments (i.e., the Standard Model of particle physics), as well as our best theoretical contenders for a fundamental theory (i.e., string theory and loop quantum gravity) are all quantum theories. In other words, they all fall within the quantum framework. It is thus reasonable to presume that quantum mechanics is likely to be the framework theory under which the fundamental theory falls, or what one might like to call the *fundamental* framework theory. Besides, we don't have any strong reasons to suspect that the concrete fundamental theory of physics will not be quantum mechanical. It is true that quantum mechanics appears to be in tension with another pillar of modern physics, general relativity. Nonetheless, the research program of fundamental physics is usually conceived as developing a theory of quantum gravity that unifies quantum mechanics (QM) and general relativity (GR), rather than introducing a radically new theory to replace QM (in the way that classical mechanics was replaced by QM). As explained by Rovelli (2004, 5-6),

> Since quantum gravity is a theory expected to describe regimes that are so far inaccessible, one might worry that anything could happen in these regimes, at scales far removed from our experience. Maybe the search is impossible because the range of the possible theories is too large. This worry is unjustified. . . . The fact is that we do have plenty of information about quantum gravity, because we have QM and we have GR. Consistency with QM and GR is an extremely strict constraint.
>
> A view is sometime expressed that some totally new, radical and wild hypothesis is needed for quantum gravity. I do not think that this is the case. Wild ideas pulled out of the blue sky have never made science advance. . . . Generally, arbitrary novel hypotheses lead nowhere.

Accordingly, the research program is envisioned as pursuing a *quantum* theory that accounts for gravity. That is to say, it is a working assumption in physics that the concrete fundamental theory, whatever it turns out to be, will fall within the quantum framework.

This in no way suggests that the fundamental theory of physics *must* be quantum, or that the physics community is being dogmatic and unwilling to accept any candidate for a fundamental theory simply because it is not quantum. There are some reasons one might think that the quantum framework fails to apply to a more fundamental theory. The technical challenges we encounter while developing a unified theory of quantum gravity might suggest that we need a new theory, say, a nonlinear theory, to replace the unitarity of quantum mechanics. Penrose (2004, Chapter 3) proposes that the structure of quantum mechanics needs to be modified in order to be reconciled with general relativity. (He argues that taking gravitation into account can also solve the measurement problem.) Moreover, Goldstein and Teufel (2001) identify several conceptual problems of canonical approaches to quantum gravity, and claim that these problems and the attempts to solve them had led to the technical difficulties. They believe that these conceptual problems are inherited from orthodox quantum mechanics and may disappear if one adopts a Bohmian approach to quantum gravity. One may see Bohmian mechanics as an alternative to the standard quantum framework, because it diverges from the framework underlying our best quantum field theories, string theory, or loop quantum gravity (to the extent that a Bohmian version of, say, quantum field theory needs to be developed separately[16]). While these two proposals present stimulating possibilities, they are only suggestive and remain minority views in physics.[17]

It is also possible that new empirical data could emerge that quantum mechanics fails to accommodate or explain, and we are just like optimistic physicists in the nineteenth century who prematurely

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[16] For attempts, see, e.g., Duerr et al. (2004) and Struyve (2010). See Wallace (2022) on whether such attempts can reproduce the empirical success of our best quantum field theories.

[17] On the other hand, even if Bohmian mechanics proves to be correct, insofar as one thinks that it is the framework under which a theory of quantum gravity falls (as Goldstein and Teufel do), it does not undermine my general point. Namely, the fundamental theory will fall within quantum mechanics; in this case, the Bohmian version.

believed classical mechanics to be the final theory of physics. I don't intend to argue against any of these possibilities. The point rather is: the working assumption is that quantum mechanics is the framework under which the concrete fundamental theory falls, until new theoretic developments or empirical evidence suggests otherwise. Insofar as we have reasons to work with this assumption, we can get a glimpse of what the world is like at the fundamental level according to quantum mechanics, if only limited and tentative. Anyone who thinks that the fundamental theory of physics won't be quantum mechanical needs to suggest what else we can justifiably say about the fundamental theory that is better supported by our best scientific theories or provide some other naturalistic basis for fundamental metaphysics, or adopt queitism.

Granted that the concrete fundamental theory falls within the quantum framework, one may question how the framework theory can tell anything about the fundamental ontology of the world. After all, as suggested earlier, the quantum framework covers a wide range of different kinds of systems and does not have a unique ontology. Similarly, classical mechanics as a framework theory covers point particles, fluids, classical electromagnetic fields, and so on, but these are quite different ontologies.[18] As Wallace (2020a, 2020b) puts it, it is a category error to ask what the ontology of a framework theory is.

I agree that a framework theory does not specify a unique ontology. But does it mean that a framework theory cannot tell us anything ontological[19] about the world? I argue not. My argument employs the No Miracles Argument for scientific realism. Science has been very successful at making novel predictions, generating technological applications, and providing unifying explanations for diverse phenomena. The best explanation for the success of science is that scientific theories actually latch onto what the world really is: These theories are true (or at least approximately true), and the unobservable objects postulated by scientific theories do exist in the world (instead of being mere human

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[18] See Wilson (2013).

[19] I use the term 'ontological' in a broad sense: there is *something* a framework theory can tell us about a class of physical systems, such as their structural properties, dynamics, or what kind of space they live in; it doesn't have to be about the ontology *per se*. (Structural realism is not required but can be friendly in this context.)

constructs). If scientific theories are far from the truth, it would be miraculous that our best scientific theories are so successful. Following this line of reasoning, we may ask: Insofar as a framework theory is a scientific theory, why is it successful? Why can different physical systems be characterized by the same framework theory? What similarities do these systems share? A scientific realist answer would be: the best explanation for the success of a framework theory is that it is true (or at least approximately true) and it captures some genuine features of the world. There are structural features shared by a range of various kinds of physical objects such that they can be collectively characterized by the framework theory. If scientific realism is right and the No Miracles Argument provides compelling reasons for why it is right, there are similar compelling reasons to believe that a framework theory can tell us something ontological about the world, even though it does not specify a unique ontology.

One might object, arguing that it is only the success of concrete theories, not framework theories, that can be explained by the No Miracles Argument. What various concrete theories share in common such that they can be characterized by the same framework theory are instead some basic axioms or mathematical structures. That is to say, what a framework theory captures is not ontological features of the world, but only mathematical features. It is thus only successful in the sense that mathematics is successful. This understanding of a framework theory, however, is unsatisfying. It does not explain why it is this specific collection of concrete theories that share certain mathematical structures instead of some other collection of theories. Put another way, it does not address how these mathematical structures are related to the physical world, or why these mathematical axioms are physically significant. Insofar as a framework theory is a physical theory, it falls under the purview of the No Miracles Argument, and can tell us something about the physical world.

Consider an example. The framework of quantum field theory does not specify a unique ontology. Nonetheless, the systems to which it applies all share structural features characteristic of a quantum field; for instance, being defined at every point in spacetime and able to be in superposition. We can engage in a meaningful debate regarding the ontology of quantum field theory—whether it takes particles to be prior to fields or the other way around.[20] The notion of quantum field involved is rather general and in some sense abstract. It doesn't concern a specific kind of quantum field (and its specific properties), but pertains to any quantum field. Once we get to a more *concrete* quantum field theory, it specifies in more detail what kinds of quantum fields there are—such as the electron field, the electromagnetic field, and the Higgs field—and what properties they have. Quantum electrodynamics, for instance, is a *concrete* relativistic quantum field theory that characterizes electromagnetic fields interacting with charged matter. The more concrete a theory is, the more specifics it can tell us about the system. Conversely, the more general the framework theory, the fewer ontological features it can provide.

In sum, quantum mechanics understood as a framework theory can plausibly be informative about the fundamental, providing that the *concrete* fundamental theory of physics falls within the quantum framework. Since a framework theory does not specify a unique ontology, we can't infer what *the* ontology of quantum mechanics is or what *the* fundamental ontology of the world is. Nonetheless, we can still draw ontological implications from quantum mechanics. This imposes a constraint on what proposals aiming to draw the fundamental ontology from quantum mechanics could be like.

4 Modified Wavefunction Realism

In order to keep its assumption of Quantum Fundamentality, Wavefunction Realism needs to take quantum mechanics as a framework theory so that it can be informative about the fundamental. Recall that WFR (I) takes the wavefunction to be a *concrete* physical object, a particular kind of field. This however defies the constraint that the quantum framework does not specify a unique, concrete ontology. Hence, Wavefunction Realism needs to be reformulated.

To do that, we need to first consider: what ontological features are shared by all quantum systems?

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[20] See, for example, Fraser (2022).

What structural features does quantum mechanics have that are shared by all concrete quantum theories? One structural feature that is pertinent to our discussion on Wavefunction Realism stands out: nonseparability in ordinary three-dimensional space. In sharp contrast to classical mechanics, quantum systems are *not* always separable; the quantum state of a composite system can be entangled, and thus *not* fully determined by the states of its component systems (see, e.g., Wallace 2020a). This feature applies to any concrete theory that falls within the quantum framework.

As noted in Section 2, one of the central arguments for Wavefunction Realism is that its fundamental ontology is separable in the fundamental space of the world. This is usually demonstrated under the fiction that nonrelativistic quantum particle mechanics is a fundamental theory. How can it be generalized to the quantum framework, where there may not be a well-defined configuration space of particles? Analogously to nonrelativistic quantum particle mechanics, we can try to define, more generally, a space in which each point corresponds to a possible configuration of variables associated with some complete set of commuting observables. Once we pick a complete set of commuting operators whose common eigenvectors form a basis of Hilbert space, the associated configuration space is just the space of all tuples of eigenvalues that uniquely correspond to the eigenvectors. One set of observables is preferable over some other some set if it has a clearer connection with tables, chairs, and pointers of experimental apparatus. The dimension of this configuration space will be much much higher than three; maybe even infinite. Although quantum states are *not* separable in three-dimensional space, they will be separable in this high-dimensional space.

In order to have a fundamental ontology that is separable in the fundamental space as stated by Wavefunction Realism, the fundamental space cannot be the ordinary three-dimensional space but a high-dimensional space represented by the configuration space. Note that so far I have not said anything about what exactly the fundamental ontology is or what features the fundamental space has (such as exactly how many dimensions it has), but only the general structural feature that the fundamental ontology is separable in the fundamental space, which is represented by the high-dimensional configuration space.

What else can we say about the fundamental ontology? Its evolution is characterized by the dynamical equation of motion, the Schrödinger equation in the form of Eq. (4). The kind of wavefunction defined on the high-dimensional configuration space represents at least partially the structural features of the fundamental ontology. This does not mean that *the* fundamental ontology just is the wavefunction, a specific, concrete physical object. Rather, being a wavefunction stands for being a kind of physical object: its structural features are shared by any specific quantum ontology. As for what exactly the wavefunction for a concrete quantum theory is like, beyond its structural features, this depends on the details of the concrete quantum theory and can vary from one theory to another. For instance, the wavefunction of nonrelativistic quantum particle mechanics would be different from the wavefunction of relativistic quantum field theory. The wavefunction of nonrelativistic quantum particle mechanics is preferentially stated in the position basis; the wavefunction of the concrete fundamental quantum theory might be stated in some other basis, or have no preferred basis at all. This does not mean that the modified formulation of Wavefunction Realism necessarily commits to the existence of all these various wavefunctions for each concrete quantum theory. We may be able to write down a wavefunction for nonrelativistic quantum particle mechanics or for any other non-fundamental quantum theory, but they may not exist in the way that particles or the fundamental ontology exists. For reasons discussed in Section 2, separability does not provide a sufficient reason to take all the high-dimensional spaces on which these wavefunctions are defined to be physical.

To summarize, there are two main differences between the original and the modified formulation of Wavefunction Realism. (a) Unlike the original formulation, the modified formulation does not specify what exactly *the* fundamental ontology is. It only tells us that the fundamental ontology has the structural features of a wavefunction. As for what exactly the fundamental ontology is like, it is determined by the *concrete* fundamental theory. Neither does the modified formulation tell us exactly how many dimensions, or what other properties, the fundamental space has. Again, it is determined by the *concrete* fundamental theory. (b) In the original formulation, WFR (II) follows from

WFR (I). That is, we first take the wavefunction to represent a physical object; it then follows that the high-dimensional space in which the wavefunction lives is also physical. In contrast, the modified formulation goes the other way around. Nonseparability provides the reason to first take the fundamental space to be high-dimensional. It then follows that the fundamental ontology has the structural features of a wavefunction.

5 Conclusion

Ideally, our understanding of the physical world at the fundamental level should be informed by the fundamental theory of physics. Unfortunately, we don't have that theory yet. This significantly constrains what we can read off from physics about the fundamental ontology, fundamental laws, and fundamental structure of the world. Attempts that ignore this, working under the fiction that some non-fundamental theory (such as nonrelativistic quantum particle mechanics) is fundamental, face a naturalistic challenge: What and how can they be informative about the *actual* world? Will anything carry over to whatever turns out to be the fundamental theory of physics?

Given that we don't yet have a confirmed fundamental theory of physics, what's the next best thing we can say? I proposed: quantum mechanics can plausibly be informative about the fundamental if understood as the framework theory under which the *concrete* fundamental theory falls. The modified version of Wavefunction Realism proposed in this paper demonstrates one way in which we can draw metaphysical content from the quantum framework. The metaphysical content might be thinner than one would like, but that seems unavoidable until we reach a confirmed fundamental theory. A naturalistic methodology would require us to recognize and adapt to this constraint rather than ignore it.

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