Next Best Thing

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

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Abstract

What is the world *ultimately*, *fundamentally* like? Naturalistic metaphysicians and philosophers of physics aim to use physics as a guide to what is fundamental. However, we don't have a confirmed fundamental theory of physics yet. What, then, can we responsibly say about the fundamental that is properly informed by our best theories of physics? This paper offers a starting point to address this issue by focusing on the literature on the ontology of quantum mechanics, where the problem is especially salient: Many proposals aim to draw 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. We reconcile this tension by treating quantum mechanics as a general *framework* theory, which covers a range of specific *concrete* theories (such as nonrelativistic quantum particle mechanics, the Standard Model of particle physics, and string theory). The quantum framework can, plausibly, be informative about the fundamental. We use Wavefunction Realism as an example to sketch what kind of ontological lessons the quantum framework may provide, while flagging further challenges this approach poses for Wavefunction Realism.

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 the 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 specific length scales or emergent levels, and are applicable only within limited domains. The closest to the fundamental theory of physics we currently have that is confirmed by experiments is the Standard Model of particle physics. However, it has limited validity and is not a universal theory: The Standard Model breaks down at the Planck scale and does not account for dark matter; its status as an approximate, emergent 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; Hooft et al. 2005, 259).

And yet, it is common in philosophy—particularly metaphysics and philosophy of physics—to see discussions on what is fundamental.[1] According to Sider (2011, 5), for instance, "The heart of metaphysics is the question: what is the world ultimately, or fundamentally, like? . . . The truly central question of metaphysics is that of what is most fundamental." 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 turn to the fundamental theory of physics to learn what the world is like at the fundamental level and to inquire about the fundamental ontology, the fundamental laws, or the fundamental structure of the world.[2] However, few of these discussions engage with any

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1. See, e.g., Paul (2012) and Ismael and Schaffer (2020).

2. See McKenzie (2021) for an argument that the fundamental theory of physics is crucial to success of the metaphysical

current candidates for a fundamental theory of physics.[3] Some of them even work under the *fiction* that classical mechanics is fundamental.[4] From a naturalistic point of view, this raises the problem of how to make sense of such discussions: What can they tell us about the *actual* world? Will their conclusions carry over to whatever turns out to be the fundamental theory?

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 (such as the many-world interpretation and Bohmian mechanics), and many of them promise a realistic description of the quantum world. However, it still leaves open 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), and Mad-dog Everettianism (Carroll 2022). Many of these proposals are often construed as drawing the *fundamental* ontology of the world from quantum mechanics,[5] 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 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, the Standard Model). Notable examples includes Wavefunction Realism and some Primitive Ontology views. Since we know that nonrelativistic quantum particle me-

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project if we take a naturalistic approach.

3. With exceptions from the literature on philosophy of quantum gravity.

4. For example, Lewis (1994, 1986), 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 of its conceptual issues; he (1994, 474) does think Humean Supervenience can be adapted to better physics.

5. 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.

chanics 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 like nonrelativistic quantum particle mechanics tell us anything about the fundamental ontology of the world? At least, it is problematic to take the ontology of nonrelativistic quantum particle mechanics to be the fundamental ontology. 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 offers such a methodological story. Its aim, however, is not to defend Wavefunction Realism or any other proposal for the ontology of quantum mechanics. Rather, the point is to examine 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. In doing so, the paper also explicates how quantum mechanics bears on the fundamental theory. More generally, this paper aims to offer a starting point for addressing the question: Given that we are interested in what the world is like at the fundamental level, but do not yet have a confirmed fundamental theory of physics, what's the next best thing we can possibly say about the fundamental that is not merely philosophical speculation but properly informed by our best theories of physics?

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 critic 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.[6] 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 anything we

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6. See, e.g., Schaffer (2003) and McKenzie (2011). For a literature review, see Morganti (2020).

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 at risk of being mistaken, but this should not deter us from trying. It can still be philosophically valuable, given our best scientific theories, to carefully tease out what we have said about the fundamental that is clearly false and to explore what we can say about the fundamental, unless and until further evidence shows that our current theories fail.

One dismiss the value of carrying out such a project by arguing: the problem of drawing the fundamental ontology from nonrelativistic quantum particle mechanics can be easily resolved along one of the following two lines. (1) Nonrelativistic quantum particle mechanics is used only as a simple example, and its ontological lessons will eventually carry over to the fundamental theory. However, it is unclear whether they will carry over, and why. As a matter of fact, it has been argued that Wavefunction Realism relies on specific features of nonrelativistic quantum particle mechanics that do not generalize to the relativistic domain; e.g., Wallace (2021). Much more needs to be said to explicate and justify (1).

(2) Proposals like Wavefunction Realism can be understood as offering only an ontology of nonrelativistic quantum particle mechanics, which is not fundamental but emergent like atoms or fluids.[7] This amounts to dropping the goal of drawing the fundamental ontology. In Section 2, we argue that (2) is not 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, we propose a different solution to the problem of how quantum mechanics can tell us anything about the fundamental ontology. We begin by showing that the abstract *framework* of quantum mechanics can be distinguished from specific *concrete* quantum theories, and explaining how the two are related. Although we do not yet know what the *concrete* fundamental theory of physics is, the working assumption in physics is that it falls within the quantum framework. This assumption is the next best thing we can work with for now.[8] To address the objection that it is a category error to ask what *the* ontology of a framework theory is, we argue: although the quantum framework does not have a unique ontology, it can still inform us about ontological features of the world at the fundamental level.

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7. Myrvold (2015), though not a defender of Wavefunction Realism, argues that the wavefunctions of nonrelativistic quantum particle mechanics "are not part of the fundamental ontology of the world" and "are constructed from a relativistic quantum field theory".

8. Our solution can be seen as providing a systematic justification for (1). It explicates the relationship between nonrelativistic quantum particle mechanics, the quantum framework, and the fundamental theory.

In Section 4, to demonstrate what *kind* of ontological lessons quantum mechanics as a framework theory can teach us, we again turn to Wavefunction Realism as a case study. (We have chosen it not because we intend to defend Wavefunction Realism, but because it offers a sharp and straightforward case.) We extract what might be seen as its core idea, and explain in what sense that idea is transferable to the fundamental ontology (modulo the technical issues). This 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:

> 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 represented by 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 points in three-dimensional space and thus not separable in that space. More specifically, the state of the pair is such that a measurement on each individual particle can result in, say, either spin-up or spin-down along a certain direction with given probabilities, but if one particle is measured to have a certain spin, the other particle will have a measurement result of the opposite spin along the same direction, regardless of how far away the two particles are. This correlation between entangled particles encoded in their total state 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 of the two entangled particles is however separable in the 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), 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 a 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 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 $3N$-dimensional space.

One may question why we even want or need separability, or what the compelling reasons are for insisting our world is 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 and 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 see no need for a separable ontology in the fundamental space, a defender of Wavefunction Realism would argue: they need to provide an alternative conception of what it is to be the fundamental space, or spell out why Albert's conception is inadequate to characterize the physical space of our world.

Our 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 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 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 one-dimensional space would be different from the set of possible distances the same objects could have in 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. In classical mechanics, the fundamental space and the space of dynamics happen to coincide. But it just so happens in quantum mechanics that they come apart. The ontology of quantum mechanics resides in the high-dimensional fundamental space, while a non-fundamental ontology resides in the three-dimensional emergent space. It is hard to make sense of the relation between these two spaces, if Wavefunction Realism were understood as a proposal for the clearly *non-fundamental* ontology of nonrelativistic particle quantum mechanics. (More on this later.)

Another promoter of Wavefunction Realism, Ney, gives different 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; our 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 compatible with our intuitions may be useful for physics students who want to "learn about the *fundamental* nature of reality" (ibid., 131; our emphasis). Setting aside the question of whether these arguments for separability are convincing, what matters for our purpose is whether they rely on the Assumption of Quantum Fundamentality. The word 'ultimately' or 'fundamental' suggests, at least *prima facie*, fundamentality plays some role. We 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*?

We can think of one argument for separability defenders of Wavefunction Realism may offer that does not *directly* rely on the Assumption of Quantum Fundamentality: A quantum theory is more explanatory with a separable ontology than without.[9] Recall the earlier discussion on the state of a pair of entangled particles being nonseparable in three-dimensional space. It is mysterious that the outcome of a spin measurement on one particle is somehow correlated with the outcome of a spin measurement on the other particle, no matter how far apart they are. As Bell (2004, 152) points out, "the scientific attitude

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

is that correlations cry out for explanation". Wavefunction Realism contributes to an explanation for the correlations between a pair of entangled particles: their behaviors are grounded in the dynamics and local properties of the wavefunction at a more fundamental level; there is nothing mysterious about the correlations because the two particles at separate locations are just aspects of a single wavefunction.[10] In contrast, accepting nonseparability as a brute fact of the world is to say that such correlations have no further explanation.

This argument does not require that quantum mechanics be the fundamental theory or the wavefunction be the fundamental object in the fundamental space, but only that the wavefunction be *more* fundamental than particles. It allows proponents of Wavefunction Realism to restrict their goal (as introduced in Section 1) to providing an ontology for nonrelativistic quantum particle mechanics, instead of the fundamental ontology of the world. 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 wavefunction is the fundamental ontology.

Although this argument seems reasonable by itself, conceptual difficulties arise when we take into account the relations between various quantum theories. 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 yet another wavefunction for some other quantum theory. In such a picture, how are these different wavefunctions related to one another? And how are these various high-dimensional spaces related? All these questions need to be addressed.

More importantly, applying Wavefunction Realism to multiple quantum theories beyond the most

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10. The quote from Bell only suggests the need to explain correlations, not that he would accept separability in a high-dimensional space as an explanation for the correlations.

We take it to be an open question of how to understand such explanation—whether it is reductive explanation, grounding explanation, constitutive explanation (as suggested by Ney (2021, §7)), or causal explanation (as hinted by Albert (2023, 60)).

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, nonseparability and correlations between nonrelativistic particles can 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, so long as the ontology of the most fundamental quantum theory is separable, nonseparability and correlations in all higher-level quantum systems can be accounted for. Why would we need additional explanations for the same correlations provided by a separable ontology at each higher-level?

Ney (2021) interprets Wavefunction Realism and its focus on nonrelativistic quantum particle mechanics differently. 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). That is to say, Wavefunction Realism provides a framework, or a general strategy, for interpreting quantum theories ontologically. Interpreting nonrelativistic quantum particle mechanics is only an instance of this 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 relationships between the 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.[11]

Developers of Wavefunction Realism often use the word 'fundamental' to articulate their proposal (e.g., 'fundamental law', 'fundamental stuff', 'fundamental space', and 'fundamental physical theory' for Albert (2023, 2015); 'fundamental objects', 'fundamentally separable', and 'the fundamental nature

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11. In response to the criticism that Wavefunction realism does not carry over to the relativistic setting, Ney (2021, 134) claims that she doesn't see why Wavefunction Realism as "a framework for the ontological interpretation of a quantum theory" must be workable for all quantum theories. We will see in the next section that our proposal does not suffer from these problems, because what it takes to be the framework is quantum mechanics, the physical theory.

of our world' for Ney (2021)). This appeal to 'fundamental' goes beyond mere personal interest in the fundamental. Nor can it simply be understood as 'relatively fundamental' either. Rather, Wavefunction Realism needs the Assumption of Quantum Fundamentality to be defensible and compelling.

Although we only focus on Wavefunction Realism as an example, we don't think this assumption is unique among proposals for the ontology of quantum mechanics. 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 fundamental ontology, we outline an alternative way to reconcile the tension within proposals that aim to draw the fundamental ontology from quantum mechanics.

3   Quantum Mechanics as a Framework Theory

The idea that quantum mechanics is (in some sense) fundamental is not uncommon, especially in physics.[12] It however can be ambiguous what exactly is meant by "quantum mechanics", and, accordingly, in what sense it is fundamental.

Traditionally, quantum mechanics refers to the quantum theory of particles, or even more specifically, of nonrelativistic particles—a usage still somewhat common in philosophy of physics (Wallace 2023). One might consider what the world is like under the fiction that this specific theory were fundamental. Or "quantum mechanics" might be used more broadly to refer to a collection of quantum theories, including but not limited to the Standard Model of Particle Physics, nonrelativistic quantum particle mechanics, and theories as simple as those of harmonic oscillators or qubits, and one might suppose one of these is fundamental.

Alternatively, one might use quantum mechanics in a rather general sense, as opposed to classical mechanics. On this usage, the world is fundamentally quantum-mechanical, whereas we used to think that the world is classical. A general, abstract framework of quantum mechanics can be identified, and distinguished from specific, concrete quantum theories. In this section, we employ the distinction between a *framework* theory and a *concrete* theory to clarify the sense in which quantum mechanics bears on the

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12. See, for example, Deutsch (1997, 24), Rovelli (2004, 164), and Tong (2025, Chapter 3.5, 89).

fundamental.[13]

To explain this distinction, let's first consider a more familiar example: classical mechanics as 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 a concrete system, 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 to systems 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 specified, the more concrete the theory is.

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

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

can be thought of as 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 Hamiltonian H, the initial conditions, and the physical constraints. Different choices of filling in give us equations that characterize

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13. The framework/concrete distinction is developed from Wallace (2016, 2020b). Similar terminology has been used by Flores (1999) and Benitez (2023)—they draw a distinction between framework and interaction theories based on Einstein's distinction between principle and constructive theories. Although these two uses of 'framework theory' bear interesting connections, in this paper we adopt Wallace's usage and defer its connection to Flores's and Benitez's to future work.

different kinds of physical systems: 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, there is also a framework of quantum mechanics. Its dynamical equation, the Schrödinger equation written as follows,

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

is quite abstract. 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,

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

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 $\hat{V}$ (while expressing the equation in a particular basis); for instance,

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

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), because not only is it an equation explicitly for an N-particle system with specific $\hat{p}$ and $\hat{V}$, but also it 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: 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. In particular, whether the Schrödinger equation characterizes a relativistic or nonrelativisitic system has nothing to do with the equation itself, but depends on the Hamiltonian of the system.

The dynamical equations in quantum field theories may look different from the Schrödinger equation as expressed by Eq. (4). $|\psi\rangle$ in quantum field theory is a functional (that is, a function of a function): e.g.,

$\Psi[\phi, t]$ (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, nonetheless, are effectively equivalent. The basic idea remains the same: specify the quantum state of the system and its Hamiltonian, plug them into the Schrödinger equation, and see how the state evolves in time.

The quantum framework refers to the formal scaffolding or general structure shared by all quantum theories. It can be formulated in a number of more or less equivalent ways. Usually it includes:

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. *Composition rule*: Given systems A and B, the Hilbert space for the combined system A and B is the tensor product of the Hilbert spaces of A and B.

3. *Linear Dynamics*: The evolution of a closed quantum system is a unitary transformation such that $|\psi(t)\rangle = U(t, t_0) |\psi(t_0)\rangle$. It is often given by the Schrödinger equation, Eq. (4).

4. *Measurement*: The Born rule gives probabilities of possible outcomes in a measurement.

I don't intend this list to be definitive or exhaustive. Traditionally, the collapse postulate and the so-called eigenvalue–eigenstate link are also included (Barrett 2019, §4). It has been argued in more recent work, notably by Wallace (2019) and in the physics literature (e.g., Weinberg 2013), that these should not be included as part of the quantum formalism but rather viewed as possible interpretive additions to it. Moreover, depending on one's preferred solution to the measurement problem, the guiding equation for particles (in Bohmian mechanics) may be included as well.[14] Since it's not the purpose of this paper to settle these debates and they do not affect the general point that there is a common framework underlying all quantum theories (see Rovelli 2004, 164–165; Nielsen and Chuang 2010, §2.2; Wallace 2020b), we leave it to the reader's discretion to decide what elements should be added.

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 that covers a range of *concrete*

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14. The GRW theory, on the other hand, would be understood as a distinct theory, since its dynamics is not unitary.

quantum field theories. The Standard Model of particle physics is one example. 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 whether its number of degrees of freedom is infinite or finite. Moreover, since neither the framework of quantum field theory nor the quantum framework is necessarily relativistic, relativistic quantum field theory is more concrete than both.

By introducing the distinction between a framework and a concrete theory, we can articulate more precisely what we do and do not know about the fundamental theory. What we currently lack is an experimentally tested, *concrete* fundamental theory of physics. However, we do know that our best theoretical contenders for such a theory (i.e., string theory and loop quantum gravity), as well as the closest to a fundamental theory that is confirmed by experiments (i.e., the Standard Model), all fall within the quantum framework. In fact, it is a widely held working assumption in physics that the concrete fundamental theory falls within the quantum framework.[15]

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 generally conceived of as developing a quantum theory of gravity that unifies quantum mechanics and general relativity, rather than as proposing a radically new framework that replaces quantum mechanics (in the way that quantum mechanics replaced classical mechanics). 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. If this was the problem, we would have plenty of complete, predictive and coherent theories of quantum gravity. . . . The fact is that we do have plenty of information about quantum gravity, because we have QM [quantum mechanics] and we

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15. This is noted by, e.g., Penrose (2004, 817).
   This is more subtle than simply saying that quantum mechanics is fundamental, i.e., the Assumption of Quantum Fundamentality. As the quantum framework covers both fundamental and non-fundamental theories, calling the framework itself "fundamental" would be misleading confusing.

have GR [general relativity]. 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.

We want to be clear that we are not arguing here that the fundamental theory of physics is, or must be, quantum. Nor do we suggest that the key ingredients of the quantum framework are equally secure. There are reasons one might think that the quantum framework requires revisions or fails ultimately. The technical challenges we encounter while developing a unified theory of quantum gravity might suggest that we need a new theory—perhaps a nonlinear one—to replace standard quantum mechanics (which is unitary and linear). Penrose (2004, §30.1) proposes that "a completely radical change" in the structure of quantum mechanics is needed in order to be reconciled with general relativity. (He suggests that taking gravitation into account can also solve the measurement problem.) Additionally, Goldstein and Teufel (2001) identify several conceptual problems with canonical approaches to quantum gravity and claim that these problems, and the attempts to solve them, have led to the technical difficulties. They believe these conceptual problems are inherited from orthodox quantum mechanics and may disappear if one adopts a Bohmian approach to quantum gravity. If Bohmian mechanics is seen as an alternative to the standard quantum framework—in the sense that a Bohmian version of, say, quantum field theory needs to be developed separately[16] and Bohmian mechanics diverges from the framework underlying our best quantum field theories, string theory, and loop quantum gravity—and if it is successful, then the fundamental theory would not fall within the standard quantum framework. While these two proposals present stimulating possibilities, they are only suggestive and remain minority views in physics.[17] Lastly, it is always possible that new empirical data will emerge that quantum mechanics fails to accommodate or explain, and we will find ourselves just like the optimistic physicists in the nineteenth century who prematurely believed classical mechanics to be the final theory of physics. We don't intend to argue against any of these possibilities.

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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. 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), this does not undermine our general point: namely, that the fundamental theory falls within quantum mechanics; in this case, the Bohmian version of quantum mechanics.

Rather, our point is simply to recognize the working assumption that is widely by the current physics community and to make sense of claims like "the fundamental theory is quantum" or "the world is (fundamentally) quantum", and proposals that rely on such claims. There is a clear sense in which quantum mechanics is taken to be fundamental, and this is the best thing we can work with for fundamental metaphysics next to having a confirmed fundamental theory. Anyone who thinks that the fundamental theory 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 they should provide some other naturalistic basis for fundamental metaphysics, or adopt quietism.

Granted that the concrete fundamental theory falls within the quantum framework, one may still question how the framework can say 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. This is not unique to the quantum framework. Classical mechanics, as a framework theory, similarly applies to point particles, fluids, classical electromagnetic fields, and so on—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.

We agree that a framework theory does not specify a unique ontology. But does it mean that a framework theory cannot tell us anything ontological about the world? We argue not. Our 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 is really like: 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 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 kinds of 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

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18. Also see Wilson (2013).

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,[19] 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. (We 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 objects *per se*.[20])

One might object, arguing that it is only the success of concrete theories, not framework theories, that can be invoked 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 treats a framework theory as merely mathematical instead of physical, that is, not as a theory that carries physical significance. 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. Accordingly, it does not address how these mathematical structures are related to the physical world, or why these mathematical axioms are physically significant and relevant for certain systems and not others. If one denies that the reason why different systems share certain mathematical structures is that they reflect physical similarities, one needs to provide an alternative reason. Moreover, what all quantum systems share in common, such as being able to be in superposition, be entangled, or be nonseparable in three-dimensional space, are in fact physical properties. Hence, 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. Although the framework of quantum field theory does not specify a unique ontology, the systems to which it applies all share structural features characteristic of a quantum field:

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19. This paper works under the assumption of scientific realism and the success of its major arguments, which we don't intend to defend here. Skeptics of scientific realism are likely to outright dismiss the specific realist project addressed in this paper, namely, reading the fundamental ontology off quantum mechanics. I'm grateful to an anonymous referee for helping me clarify this.

20. Structural realism (see, e.g., Ladyman 2023) is aligned with, but not required by, this talk of structure features.

for instance, being defined at every point in spacetime and being able to be in superposition. We can, and in fact do, engage in a meaningful discussion regarding the ontology of quantum field theory: for example, whether particles are prior to fields or the other way around.[21] The talk of quantum field involved is rather general. 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. For instance, quantum electrodynamics is a concrete relativistic quantum field theory that characterizes electromagnetic fields interacting with electron and positron fields. But this does not mean that taking all quantum fields together is somehow not physical, or that they do not share any physical properties in common. Nor does claiming that the idea of quantum fields carries physical significance require one to believe in universals. It's just that 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.

To summarize, quantum mechanics understood as a framework theory can plausibly be informative about the fundamental, provided that the concrete fundamental theory of physics falls within the quantum framework. Although a framework theory does not specify a unique ontology and thus we can't infer what *the* ontology of quantum mechanics is or what *the* fundamental ontology of the world is, this does not preclude us from drawing ontological implications from quantum mechanics. It does, however, impose a constraint on what proposals aiming to draw the fundamental ontology from quantum mechanics could be like.

4 Modifying Wavefunction Realism

By treating quantum mechanics as a framework theory that can be informative about the fundamental, Wavefunction Realism can preserve its assumption of Quantum Fundamentality. Recall that WFR (I) takes the wavefunction to be a concrete physical object (i.e., a particular kind of field). This however violates the constraint that the quantum framework does not have a unique ontology. Hence, Wavefunction Realism needs to be reformulated.

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21. See, for example, Fraser (2022).

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

Following the core argument for Wavefunction Realism that the fundamental ontology is separable in the fundamental space (noted in Section 2), the fundamental space is not the ordinary three-dimensional space but a high-dimensional space isomorphic to the configuration space. This does not say 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, and nonseparability provides the reason to take the space that is isomorphic to the configuration space to be the fundamental physical space.

What else can we say about the fundamental ontology? Let it be represented by a function whose evolution is characterized by unitary dynamics, possibly in the form of the Schrödinger equation Eq. (4). Call this the wavefunction*. This does not characterize the fundamental ontology of the world as a specific, concrete physical object, as original Wavefunction Realism does. Rather, the wavefunction* stands for a kind of physical object (i.e., quantum objects): it encodes the structural features shared by all quantum ontologies. In other words, the fundamental ontology has structural features that are captured by the wavefunction*.

As for what exactly the wavefunction for the fundamental quantum theory—or any concrete quantum theory—is like beyond its structural features, it 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. While the position basis is privileged for the former, the latter, and the wavefunction of the fundamental quantum theory, might be stated in some other basis or have no preferred basis at all. (This does not commit Wavefunction Realism to the existence of these various wavefunctions for each concrete quantum theory. We

may write down wavefunctions for non-fundamental quantum theories, but they need not exist in the way that the fundamental ontology does.[22])

In sum, Wavefunction Realism is modified in two ways. (a) In the original formulation, WFR (II) follows from WFR (I). That is, we first take the wavefunction to represent a physical object, and then it follows that the high-dimensional space in which the wavefunction lives is also physical. In contrast, the modified formulation proceeds in reverse. 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. (b) Unlike the original, the modified formulation does not specify what exactly the fundamental ontology is. It only tells us that the fundamental ontology has the structural features characteristic of a wavefunction. As for what exactly the fundamental ontology is like, and how many dimensions or what other properties the fundamental space has, it is determined by the concrete fundamental theory.

In light of these modifications, Wavefunction Realism faces further challenges. The ontological implications of the quantum framework (that is, structural features common to all quantum systems) may strike some as too thin, especially if the quantum framework is to appropriately cover quantum gravity theories without a fundamental spatiotemporal structure. One may find this thinness unsatisfying and ask whether more can safely be said beyond separability of the fundamental ontology.

Moreover, Wavefunction Realism demonstrates that the fundamental ontology is separable in the fundamental space (a space that is isomorphic to the configuration space) only under the fiction that non-relativistic quantum particle mechanics is fundamental, relying on its specific feature that there is a well-defined configuration space. Can it be generalized to the broader quantum framework, where there isn't necessarily a well-defined notion of particles and, accordingly, no well-defined configuration space?[23]

It is not obvious how to do so. Here are some preliminary ideas. Analogous to the configuration space of particles, we can try to define a space in which each point corresponds to a possible configuration of, more generally, *variables* associated with some complete set of commuting observables. To do that, we

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22. For reasons discussed in Section 2, separability does not provide a sufficient reason to take all the high-dimensional spaces, and accordingly all those wavefunctions defined on them, to be physical.

23. At best, efforts have been made to extend Wavefunction Realism to relativistic quantum theories (Ney 2021, §4), yet they fall short of a fully general quantum framework.

need to pick a complete set of commuting operators $\hat{X}_i$. Their common eigenvectors form a basis of Hilbert space which can be used to express any quantum state. A set of commuting operators is complete if their joint eigenvectors are uniquely labeled by their eigenvalues. The associated configuration space is just the space of all tuples of eigenvalues.

This definition needs to be applicable not only to, say, quantum field theories, but to any quantum theory, especially the fundamental one. The configuration space in nonrelativistic quantum particle mechanics, for example, is just a special case of this generalized configuration space: given N particles in three-dimensional space, if we pick the complete set of commuting observables to be the $3N$ position operators $\hat{X}_1^1, \hat{X}_2^1, ..., \hat{X}_N^1, \hat{X}_1^2, \hat{X}_2^2, ..., \hat{X}_N^2, \hat{X}_1^3, \hat{X}_2^3, ..., \hat{X}_N^3$, their joint eigenvectors form a basis of Hilbert space and are uniquely labeled by their eigenvalues,

$$\hat{X}_i^j \left| x_1^1, x_2^1, ..., x_N^1, x_1^2, x_2^2, ..., x_N^2, x_1^3, x_2^3, ..., x_N^3 \right\rangle = x_i^j \left| x_1^1, x_2^1, ..., x_N^1, x_1^2, x_2^2, ..., x_N^2, x_1^3, x_2^3, ..., x_N^3 \right\rangle.$$

The space of all tuples of eigenvalues is the configuration space of particles. In the case of quantum field theory or string theory, the dimension of the configuration space will be vastly higher than three; maybe even infinite. Crucially, quantum states are separable in this high-dimensional space, even though they are not in three-dimensional space.

Much more needs to be said to develop the technical details and implications of generalizing the notion of configuration space building on this preliminary sketch. For instance, how should we pick out the complete set of commuting observables and justify the choice of a particular set over others? Moreover, if the dimension of the configuration space in the fundamental theory turns out to be infinite, is there any conceptual issue with the fundamental physical space of our world being infinite-dimensional? There is also the question of how configuration space functions in a timeless setting (given that this might be the case for the fundamental theory). The viability of Wavefunction Realism depends on whether these details can be worked out properly. We will not pursue them here, since it is not the purpose of this paper to perfect and defend Wavefunction Realism (or its modified formulation). Rather, the point is to show that it needs to be generalizable to the quantum framework if it is even to be pertinent to the fundamental. Some of the above questions may not be new, but they have become more urgent, as Wavefunction Realism cannot rest content with nonrelativistic quantum particle mechanics as a toy model—it might

well be the case that Wavefunction Realism eventually fails because the technical details of generalizing it to the fundamental theory prove intractable.

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, be it ontology, laws, or structure. 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 said 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? We proposed: quantum mechanics can plausibly be informative about the fundamental if understood as the framework theory under which the concrete fundamental theory falls. We modified Wavefunction Realism as an example to sketch 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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