Does an Adequate Physical Theory Demand a Primitive Ontology?

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Configuration space representations have utility in physics but are not generally taken to have ontological significance. We examine one salient reason to think configuration space representations fail to be relevant in determining the fundamental ontology of a physical theory. This is based on a claim due to several authors (Allori, Dürr, Goldstein, Tumulka, and Zanghì) that fundamental theories must have primitive ontologies. This claim would, if correct, have broad ramifications for how to read metaphysics from physical theory. We survey ways of understanding the argument for a primitive ontology in order to assess the case against configuration space realism.

1. Configuration Space Representations and Ontology. Configuration and phase space representations are ubiquitous in physics. Yet despite their prevalence, they are very commonly not taken seriously when philosophers look to physical theories to draw ontological conclusions. Philosophers may concede that physicists use such representations to describe systems and their evolution over time. For example, in classical physics one uses a six-dimensional configuration space to describe a two-particle system's movement over time or a 12-dimensional phase space to describe its total dynamical state. But the philosopher interested in issues of interpretation often keeps this abstract description of the system at arm's length when assessing the theory's ontological implications. Just because one can model a system this way, this does not mean that it really is in any sense a point in a six- or 12-dimensional space.

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As metaphysicians interested in recovering an ontology from fundamental physics, we find this state of affairs perplexing. We are taught to look to the formulation of our physical theories that are simplest, that have the most informational strength, unifying power, and so on, and read our ontology off from there. But in the case of configuration and phase space formulations of a theory, we seem to be asked to set these principles aside. Let's focus on the case of configuration space representations. Configuration space representations are in a good sense simpler than space-time representations of many-particle systems. This is their appeal. The physicist need not represent a system in terms of the movement of many points; instead, she can represent the whole system's evolution as a simple line. One may say, "Not so fast, although there may be simplicity in a configuration space representation, there is a corresponding deficit in accuracy." For there is a systematic divergence between what a theory formulated using configuration space says there is and what our evidence supports. Although there might be an easy mapping between how we observe things to be (many particles in three-dimensional space) and what the description says (one particle in a higher-dimensional space), there is a gap in reality. And so one might argue that we should not read our ontology off of configuration space formulations since what these representations gain in simplicity, they lose in accuracy. This is how things may seem to stand in classical physics.[1] However, more pressure in favor of the ontological relevance of configuration space representations comes when we consider quantum mechanics.[2] In this case, some have argued, it is three-dimensional representations themselves that would suffer with respect to accuracy were one to try and understand quantum mechanics that way. After all, there are states that we know to be empirically distinct that are not distinguished in three-dimensional coordinate representations—certain entangled states. And this seems to tip the balance toward the configuration space representation of quantum systems.[3] Some have argued that in quantum mechanics, the best (all things considered) representation the physicist has is a configuration space representation. And so if we are going to draw metaphysical conclusions from quantum mechanics, we should believe that the fundamental space of our world is configuration space and that the fundamental entities are those that are defined on or exist in configuration

1. Although perhaps the naturalness of the mapping between the configuration space and three-dimensional representations suggests that there is no major deficit in accuracy. Still, let's take this point on board for now.

2. We will confine the current discussion to nonrelativistic quantum mechanics.

3. Or it may support a Hilbert space representation. Here we will focus only on the status of configuration space representations, although one could also raise questions about Hilbert space representations and their metaphysical status.

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space.[4] For most formal versions of quantum mechanics, there is just one such entity: the quantum wave function, which is typically understood as a field on configuration space, represented using an assignment of amplitudes and phase to each point in configuration space (see Albert 1996). When one interprets such theories realistically, what results is a metaphysical view called *wave function monism*. This is related to a more general position that takes a realist attitude toward the wave function as a field on a physical configuration space without claiming that it is the only fundamental entity. This view is alternatively called *wave function realism* or, as in North (2013), *configuration space realism*.

The purpose of the current article is to engage a particularly salient and prima facie compelling form of response to these views, one that centers around the notion of a primitive ontology. In rough form, this response is a critique of the above methodology for scientifically informed metaphysics, arguing that this method has things the wrong way around. We should not choose between formulations of a physical theory from an abstract standpoint, finding the best one through a weighing of the rival formulations' theoretical virtues, and reading off an ontology from there. Rather, when considering the best formulation of a scientific theory (in particular one that is supposed to tell us what our world is fundamentally like), certain basic constraints are in place about what the fundamental ontology of that theory should be. These constraints are derived from the sort of evidence and historical circumstances that motivated the scientific inquiry in the first place. Theories have *primitive ontologies*: those they are fundamentally aimed at or about. In the case of physical theories like quantum mechanics, this is a primitive ontology of matter in three-dimensional space or four-dimensional space-time. It follows from this line of reasoning that wave function monism (discussed in secs. 4 and 5) and realism (discussed in sec. 6) fail as interpretations of nonrelativistic quantum mechanics. The preceding sections of this article will provide more background on the context of this debate (sec. 2) and aim to make precise the central notion of a physical theory's primitive ontology (sec. 3).

The notion of a primitive ontology was first introduced in Dürr, Goldstein, and Zanghì (1992). Since then, the notion has been employed in several more papers by these authors and their more recent collaborators, Valia Allori and Roderich Tumulka (e.g., Allori et al. 2008, 2011). Although we will focus like they do on quantum mechanics, we would like to emphasize that the ramifications of their argument and the application of its core notion of

4. Additionally, the fundamental ontology might include, if substantivalism is true, the points or regions of configuration space themselves. We will leave this qualification tacit in what follows.

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a primitive ontology is much broader. What we are considering is the correct methodology for reading metaphysics from physics, and the ontological status of configuration or phase space representations in physics more generally.

2. The Context of the Debate. Dürr, Goldstein, and Zanghì's (1992) paper, in which the concept of a primitive ontology was introduced, argued in defense of a particular approach to quantum mechanics differing significantly from the orthodox model: Bohmian mechanics. Part of the benefit these authors ascribe to Bohmian mechanics is that it provides a clear solution to the measurement problem, and this is because of its choice of ontology.[5] Bohmian mechanics, it is argued, avoids the apparent consequence of other approaches to quantum mechanics that objects may be in superpositions of variables like position, which are never directly observed. It avoids this conclusion by positing (by way of a new law, the guidance equation) a primitive ontology of particles possessing determinate positions at all times. This, it is claimed, makes for a more satisfactory solution to the measurement problem than is provided by frameworks that only specify the evolution of a wave function. Bohmian mechanics is preferred for its less abstract ontology that is more straightforwardly capable of explaining our observations (see Dürr et al. 1992, 56–57).

In addition to the measurement problem, there is another problem some versions of quantum mechanics face: how to ground the macroscopic world in a fundamental ontology as esoteric as a wave function in configuration space. This is what is usually referred to as the 'macro-object problem'. This is another problem that may be avoided if the fundamental ontology of quantum mechanics is not a wave function in configuration space but includes some kind of primitive ontology in a three-dimensional space (e.g., the particles of Bohmian mechanics). If the fundamental ontology includes particles in three-dimensional space, then an explanation of the existence of macroscopic objects with familiar properties like locations, sizes, and so on, may be provided that shares much in common with the explanations one was able to provide using the framework of classical mechanics (see Allori, forthcoming).

Dürr, Goldstein, and Zanghì (1992) aimed to defend Bohmian mechanics against not only orthodox quantum mechanics (that of, e.g., Von Neumann 1932) but also other alternative approaches to quantum mechanics (spontaneous collapse models like Ghirardi-Rimini-Weber [GRW], Everettian many-

5. This is the problem that the dynamical law of quantum mechanics (Schrödinger's equation) permits the evolution of systems into states that are superpositions of variables like position, and the linearity of this dynamics fails to allow them to evolve out of such states into the sort of determinate states that we observe.

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worlds theories, etc.), all of which appear wave function monist.[6] They appear wave function monist because their dynamical laws solely describe the evolution of one thing, the wave function in configuration space. Dürr, Goldstein, and Zanghì favored Bohmian mechanics as an alternative approach because Bohmian mechanics (mainly due to its having an additional law about the way the wave function constrains the movement of particles, the guidance equation) was clearly a theory about something other than the wave function, particle configurations. In more recent work (e.g., Allori et al. 2008, 2011; Allori 2013), the target is no longer exactly alternative approaches to quantum mechanics like Everettian quantum mechanics, GRW, and so on. To see what they are criticizing in the more recent work, we will distinguish an *approach to* quantum mechanics (e.g., Bohmian mechanics, GRW, Everettian quantum mechanics) from a *version of* quantum mechanics: a specific set of axioms, dynamical laws, and so on, that constitute a way of formulating that approach. What these authors in the more recent papers target are not alternative approaches to quantum mechanics to Bohmian mechanics but rather different ways of formulating these approaches (different versions). In Allori et al. (2008), for example, two alternative versions of GRW are proposed, each with its own additional laws, which make it not solely about a wave function. These versions of GRW, called GRW_m and GRW_f, describe the behavior of a matter density field and localized events called 'flashes', respectively. These versions are like the original wave function monist version of GRW (distinguished as GRW_0), except that they add mathematical structure to the theory that describes the occurrence of the flashes or changes in the matter density field. In Allori et al. (2011), an alternative to the more traditional wave function monist version of Everettian quantum mechanics is proposed. This version, called S_m, where the 'S' stands for the Schrödinger equation, is about a matter

6. It may be helpful to give just a quick summary of what is different about these approaches. These differences will not matter for the discussion in this article, as our question is orthogonal to the question of which of these approaches is best motivated; however, it may help fix the ideas of the reader. Bohmian mechanics, GRW, and Everettian quantum mechanics all deploy different strategies to solve the measurement problem. What is special about Bohmian mechanics is that it does so by positing additional variables (particle positions) that can explain why our measurements have determinate results even though the wave function itself never collapses out of a superposition of position states. GRW postulates a collapse of the wave function to explain why our measurements have determinate results. (This makes it like the approach of Von Neumann, except that in GRW, the collapses occur spontaneously, not due to an act of measurement.) The Everettian posits neither wave function collapse nor the existence of additional variables beyond the state of the wave function. Everettian quantum mechanics explains our belief that measurements have determinate results by allowing that all states of the superposition are equally real, and we see determinate results because we are only seeing one part of the overall total state. Because the Everettian allows that all parts of the superposition persist and are real, it is often called the "many-worlds" approach to quantum mechanics.

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TABLE 1. Versions of Quantum Mechanics

Approach	Dynamical Law	Fundamental Ontology
Many-worlds quantum mechanics:		
I (S_0)	Schrödinger equation	Wave function (a field on configuration space)
II (S_m)*	Schrödinger equation + matter guidance equation	Wave function (nomological or quasi-nomological) + matter density field (in ordinary space)
Spontaneous collapse theory (GRW):		
I (GRW_0)	Modified Schrödinger dynamics with collapse	Wave function (a field on configuration space)
II (GRW_m)*	Modified Schrödinger dynamics with collapse + matter guidance equation	Wave function (nomological or quasi-nomological) + matter density field (in ordinary space)
III (GRW_f)*	Modified Schrödinger dynamics with collapse + flash determination equation	Wave function (nomological or quasi-nomological) + flashes (in ordinary space-time)
Bohmian mechanics:		
I*	Schrödinger equation + particle guidance equation	Wave function (nomological or quasi-nomological) + particles (in ordinary space)
II	Schrödinger equation + world particle guidance equation	Wave function (a field on configuration space) + world particle (in configuration space)

Note.—GRW = Ghirardi-Rimini-Weber.
* Theories preferred by Goldstein, Zanghì, and their collaborators.

density field. Table 1 summarizes these versions of quantum mechanics, all of which offer solutions to the measurement problem, as well as their fundamental ontologies. An asterisk (*) marks the theories preferred by these authors.

Our sense is that as Goldstein, Zanghì, and their collaborators came to see the possibility of formulating other approaches to quantum mechanics in a way that, like their favored Bohmian mechanics, had a clear primitive ontology; they came to see their case not so much being against these other approaches but rather against ways of developing and interpreting such approaches so that they were only about something in configuration space.[7] We must emphasize that these authors are not opposed to the view that the wave function is an element of the fundamental ontology of any adequate formula-

7. Indeed, as one can see in table 1, even the ontology of Bohmian mechanics may vary. Albert (1996) proposes a version of Bohmian mechanics ('Bohmian mechanics II') that describes only objects in configuration space.

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tion of quantum mechanics. They believe there is such a thing as a wave function and have views about the kind of entity the wave function is. As we will see, the wave function for them has a nomological or quasi-nomological status. But wave function realism is not merely the view that there *is* something, the wave function. It is usually understood as a stronger view, that the wave function exists as a real field on a physical configuration space (see Albert 1996; Lewis 2004).[8] Wave function realists take it to be a concrete thing, a substance. Those who advocate the primitive ontology view tend to argue not only that there is not such a thing as a wave function that is a physical field on configuration space but also that there is not such a thing simpliciter.[9] So the view may have more general metaphysical implications about the status of configuration space representations.

3. The Notion of a Primitive Ontology. Let's begin by introducing some of the key passages in which the concept of a primitive ontology is explicated. These passages make use of the concept of a local beable drawn from the physicist John Bell (1987). By 'beable', Bell means an entity, an element of one's ontology. Bell introduces the notion to contrast it with that of an observable so central in canonical formulations of quantum mechanics following Bohr and Heisenberg. As Bell says, "The concept of 'observable' lends itself to very precise *mathematics* when identified with 'self-adjoint operator'. But physically, it is a rather wooly concept. . . . So it could be hoped that some increase in precision might be possible by concentration on the *be*ables, which can be described in 'classical terms', because they are there" (52). Bell characterizes *local* beables as those that "can be assigned to some bounded space-time region" (53). Better, since one may always propose a mapping or assignment of objects in configuration space to locations in space-time without implying that these objects really exist in space-time, we may define local beables as those entities that exist in or at some bounded space-time region. Examples of local beables are particles and fields confined to a certain space-time region. Bell's example of what is not a local beable is the total energy of a system. Anything that exists in or on configuration space, like the wave function, and thus does not exist in ordinary space-time, will fail to be a local beable.

8. One could use the phrase 'wave function realism' to denote the weaker view that the wave function is real (although it may be a field or something of another ontological category). We will stick with the way the phrase is used in the papers mentioned above as well as throughout the essays in Ney and Albert (2013).

9. Throughout this article, we will use 'primitive ontology view' to refer to the view that an adequate version of quantum mechanics (and perhaps any adequate version of a physical theory more generally) should have a primitive ontology, where this notion is characterized by the four criteria in sec. 3.

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Here are some of the key passages from Dürr et al. (1992) in which the notion of a theory's primitive ontology is introduced:[10]

> According to (pre-quantum-mechanical) scientific precedent, when new mathematically abstract theoretical entities are introduced into a theory, the physical significance of these entities, their meaning insofar as physics is concerned, arises from their dynamical role, from the role they play in (governing) the evolution of the more primitive—more familiar and less abstract—entities or dynamical variables. For example, in classical electrodynamics the *meaning* of the electromagnetic field derives solely from the Lorentz force equation, i.e., from the field's role in governing the evolution of the positions of charged particles. . . . That this should be so is rather obvious: Why would these abstractions be introduced in the first place, if not for their relevance to the behavior of *something else*, which somehow already has physical significance?
>
> Indeed, it should perhaps be thought astonishing that the wave function was not also introduced in this way—insofar as it is a field on configuration space rather than on physical space, the wave function is an abstraction of even higher order than the electromagnetic field.
>
> But, in fact, it was! . . .
>
> What we regard as the obvious choice of primitive ontology—the basic kinds of entities that are to be the building blocks of everything else [footnote: Except, of course, the wave function.]—should by now be clear: Particles, described by their positions in space, changing with time—some of which, owing to the dynamical laws governing their evolution, perhaps combine to form the familiar macroscopic objects of daily experience. (7, 9)

The notion is discussed again in Allori et al. (2008):

> The matter density field in GRW_m, the flashes in GRW_f, and the particle trajectories in [Bohmian mechanics] have something in common: they form (what we have called) the primitive ontology [PO] of these theories. The PO of a theory—and its behavior—is what the theory is fundamentally about. It is closely connected with what Bell called the 'local beables'. . . . The elements of the primitive ontology are the stuff that things are made of. The wave function also belongs to the ontology of GRW_m, GRW_f, and [Bohmian mechanics], but not to the PO: according to these theories, physical objects are not made of wave functions. . . .
>
> In each of these theories, the only reason the wave function is of any interest at all is that it is relevant to the behavior of the PO. Roughly speaking, the wave function tells the matter how to move. . . .

10. This is a bit unorthodox, but because they may be unfamiliar to some philosophers, we think it will be useful to reproduce the relevant passages nearly completely.

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> Each of these theories is about matter in space-time, what might be called a decoration of space-time. Each involves a dual structure . . . : the PO . . . providing the decoration, and the wave function . . . governing the PO. The wave function in each of these theories, which has the role of generating the dynamics for the PO, has a nomological character utterly absent in the PO. (362–63)

And finally, in Allori et al. (2011):

> To introduce a PO for a theory means to be explicit about what space-time entities the theory is fundamentally about. There are various possibilities for what type of mathematical objects could represent the elements of the PO, including particle worlds lines as in classical or Bohmian mechanics, world sheets as maybe suggested by string theory, world points as in the GRW theory with the flash ontology. . . . The wave function also belongs to the ontology of S_m, but not to the PO: physical objects in S_m are made of [the matter density field], not of [the wave function]. (4)

In these passages, we find several claims about what it is for a certain kind of thing to be an element of a theory's primitive ontology. We find it useful to cluster these components under four headings:

> *Familiarity*: Antecedent familiarity/physical significance (from other physical theories or prior experience)
>
> *Relevance (with respect to the theory)*: Being the target of the theory/what the theory is fundamentally about
>
> *Constitution*: Being what makes up things in the world of our experience, including other elements of the ontology of the theory
>
> *Space-time location*: Possessing location in ordinary space or space-time, being a local beable.

We should emphasize that the notion of a primitive ontology is not the same as that of a fundamental ontology. There is a live dispute today in metaphysics about what is meant by 'fundamental', but it is certainly something different from what our authors mean by 'primitive'. One common position is that the fundamental entities are those that suffice to give rise to all other facts.[11] To see that the concepts of a fundamental ontology and primitive ontology are not the same, we may note that our authors do not want to deny that the wave function should be an element of the fundamental ontology of any adequate formulation of quantum mechanics. Indeed they imply that the wave function should be an element of a quantum theory's fundamental

11. This is roughly what Theodore Sider (2012, chap. 7) calls the "completeness" of the fundamental.

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ontology when they note the dual structure of their preferred versions of quantum mechanics. Recall from above: "Each involves a dual structure . . . : the PO . . . providing the decoration, and the wave function . . . governing the PO." The wave function cannot exhaust the fundamental ontology: "Thus it seems that for a fundamental physical theory to be satisfactory, it must involve, and fundamentally be about, 'local beables', and not just a beable such as the wave function, which is nonlocal" (Allori et al. 2011, 10).

To capture all of the facts in the domain of quantum mechanics, it is necessary to include both facts about the primitive ontology and facts about the wave function. But, the wave function should be part of the fundamental ontology. So, it is not necessarily the case that all of the fundamental ontology of a physical theory be primitive ontology, even though all of the primitive ontology is fundamental.

There is a complication we should note. The authors also say: "In S_m, the right way to understand the theory is to regard the m [matter density] function as the basic reality and not ψ [the wave function]" (Allori et al. 2011, 9). If one takes 'basic' and 'fundamental' to have the same meaning, it might seem that they are denying that the wave function is part of the fundamental ontology of (in this case) S_m. But Allori et al. go on to clarify what is meant here by 'basic'. The next sentence is: "The way S_m connects with the world of our experiences is analogous to the way that Bohmian mechanics does. The connection is made through the particles, not through the wave function" (9–10). This implies a difference between what these authors mean by 'basic' and what is standardly meant by 'fundamental'. The primitive ontology is basic in the sense that it is what makes up the macroscopic objects of our experience. By contrast, although the wave function is part of the fundamental ontology of S_m, it is not basic. It is not what explains the connection between the theory and our experience by constituting the objects of the macroscopic world. Still, it is fundamental because it is not constituted out of nor does it supervene on anything else contained in the theory, including the primitive ontology.[12]

4. Arguing against Wave Function Monism. There are several reasons why one might think that the wave function is not a candidate for the primitive ontology of quantum mechanics. Most clearly, the wave function fails *space-time location*.[13] The wave function is defined on configuration space, not ordinary space or space-time. And so, if it is a physical object, it exists in (or better, on) configuration space, not ordinary space. Second, the wave function fails *familiarity*. It is a theoretical entity introduced by Schrödinger

12. We discuss the status of the wave function more in sec. 5.

13. Although, see Lewis (2004, 2013), who argues for a nonstandard interpretation according to which the wave function is located in ordinary space.

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into his formal system of quantum mechanics. Our authors would also argue that the wave function in at least one sense fails *relevance (to quantum mechanics)* and also *constitution*. We will question these points. But given that the wave function fails at least *space-time location* and *familiarity*, it is disqualified as an element of primitive ontology.[14] And noting this, our authors argue that we should adopt a formulation of quantum mechanics that is about something more than a wave function, which includes terms referring to some primitive ontology.

We would like to clarify how one might establish the claim that any adequate formulation of quantum mechanics should possess a primitive ontology. A natural thought given some of what is said in the above passages (especially those from Dürr et al. 1992) is that the motivation for a primitive ontology comes from the fact that there is something already familiar to us, some domain of local beables that constitute the macroscopic objects of our experience, that any adequate formulation of quantum mechanics aims to be about, and this is not the wave function.

This point is in some ways compelling. Of course physicists did not initiate quantum mechanics as an investigation into the nature of the wave function. Rather, the wave function was posited to explain the behavior of something else, something with which we were already familiar and wanted a comprehensive theory. As a matter of historical fact, this was the behavior of subatomic matter and radiation (a class of familiar entities located in space-time that constitute the macroscopic objects of our experience). So, to return to the criteria displayed in the previous section, it would seem there is something quantum mechanics is about—something satisfying *relevance (to quantum mechanics)*—and this is something that also satisfies *familiarity*, *constitution*, and *space-time location*.[15] So, an adequate formulation of quantum mechanics should contain a primitive ontology. And so, wave function monism is false. But, we would like to argue, even if one concedes that there is a real sense in which any adequate formulation of quantum mechanics should be about subatomic matter and radiation, this does not show that any adequate formulation of quantum mechanics must involve a fundamental ontology of antecedently familiar objects that are local beables, a primitive ontology.

There is one sense of 'what quantum mechanics is about' for which certainly this is determined by the historical conditions in which the theory was developed: in this sense, quantum mechanics is about whatever its founders were interested in explaining. Call this 'the explanatory sense of *relevance*'.

14. 'Primitive ontology' is a technical term. We do not dispute the meaning provided by those who introduced it.

15. When we say 'what quantum mechanics is about' we intend this to be shorthand for 'what any adequate version of quantum mechanics is about'.

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But there is another way one might interpret the phrase 'what quantum mechanics is about', that is, what the central terms in any formulation of the theory represent. Call this 'the ontological sense of *relevance*' because, as we will argue, this is the only sense that has direct implications for the fundamental ontology of the theory.[16] What we want to point out is that what quantum mechanics is about in the explanatory sense (what the founders were most interested in explaining) need not overlap with what it is about in the ontological sense. And so even if it is true that a physical theory's ultimate explanatory target must be something with antecedent familiarity and significance to us, this thing need not occur as part of the fundamental ontology of the theory.

Consider, for example, a theory of the chemical properties of molecules. If this theory is successful, one must get out of it an explanation of why molecules of the kind we observe exist and behave in the way they do. But a theory of the chemical properties of molecules might be a reductive theory, one whose fundamental ontology is limited to nucleons, electrons, and their electromagnetic features. It can still be true, even though the theory does not involve a fundamental ontology of molecules (and so is not about molecules, in the ontological sense), that it is straightforwardly about molecules in the explanatory sense. This is because through describing the behavior of nucleons and electrons, it is able to capture all of the features of molecules we were interested in explaining. It is because of the reduction of molecules to nucleons and electrons that this is possible. So, what a theory is about in the ontological sense and what a theory is about in the explanatory sense may be distinct. And even if the latter must satisfy *familiarity*, this does not entail that the former must as well.

Now one might argue that a reductive theory will not provide a genuine explanation of its target unless it includes an explicit statement of the reductive relationships tying the target of explanation to the fundamental ontology of the theory. In the above case, one might insist that the reductive theory itself include claims like:

> (**C**) Molecules are identical to configurations of protons, neutrons, and electrons.

If so, then even in the case of a reductive theory, the explanatory sense of 'what a theory is about' would impose a direct constraint on the ontology. If

16. This is not to say that the explanatory sense of *relevance* does not also have ontological implications. For example, if a theory is to explain (say) superconductivity, it cannot have just any fundamental ontology. It is going to have to posit something that is explanatorily relevant to the target phenomenon. We are saying only that the fact that the theory is about (in the explanatory sense) superconductivity does not have the direct implication that the theory must posit (as part of its fundamental ontology) superconductivity.

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x is something the theory is aimed at explaining, then *x* would have to be at least part of the ontology of the theory, if not in the fundamental dynamical equations, then in the statements describing the reductive relationships between *x* and the terms in the equations. Our own view is that C is a metaphysical statement that better belongs to what Bell would call "the surrounding talk" of the theory (1987, 52). However, even if we include it in the theory, this would still not make the target entities part of the theory's *fundamental* ontology. In the above case, even if our chemical theory is targeted at explaining molecules and we concede reference to molecules must occur as part of the theory at least in claims like C, this will still not require that molecules be part of the theory's fundamental ontology. Since molecules are constituted by the nucleons and electrons according to clause C, they are derivative ontology.

There is a question about whether this analogy with chemistry is appropriate when we are considering the case of wave function monism. One main point of contention between those holding the primitive ontology view and wave function monists is whether we can plausibly see the explanatory targets of quantum mechanics as reducible to the wave function. Wave function monists (and their sometimes allies like Wallace and Timpson [2010]) do typically insist that there could be a constitutive relationship between the wave function and entities such as subatomic particles. More work must be devoted to spelling out the nature of this relation, for it is clear that the relation will not be the same intuitive one that the Bohmian appeals to, of particles making up other objects like bricks make up a house. Nonetheless, work on spelling out this metaphysical relation is under way. Typically, an appeal is made to functionalism. Wave function monists then argue that what is needed is just a compelling story about how a particular wave function may have what it takes to play the functional role of subatomic matter and radiation.[17]

If this project succeeds, we may see how a version of quantum mechanics may explain the behavior of what is familiar (and so be about what is familiar in the explanatory sense), while not containing what is familiar in its fundamental ontology. At the same time, note that even if particles and particle trajectories may be familiar to those of us who have been raised on classical physics, matter density fields and especially GRW flashes hardly seem familiar entities. And yet these are the types of things that are being proposed by our authors as elements of a primitive ontology for versions of GRW and Everettian quantum mechanics. Ultimately, it seems that the advocates of the primitive ontology view do not really want to insist that the primitive ontology of a theory be familiar to us in any ordinary sense of the word. Instead what is most important is that there be a fundamental

17. For a distinct proposal about how this project should proceed, see Ney (2013).

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ontology containing some kind of entity that can plausibly constitute the things with which we are familiar. The thought is that while this is promising for particles, matter density fields, and even the flashes of GRW_f, this is much less plausible for the wave function. If so, then the primitive ontology view is not motivated as a way of keeping the fundamental ontology of quantum mechanics faithful to its historical explanatory targets. The point is just that local beables such as particles, flashes, and the like are capable of constituting matter, while the wave function is not. This is a distinct argument against wave function monism.

The issue comes down to whether it is possible to reductively explain the existence and behavior of subatomic matter and radiation without a fundamental ontology of local beables. Most wave function monists concede that things like electrons and photons do possess space-time locations and so are local beables, but since they deny that space-time is fundamental, they must motivate the claim that objects with space-time locations can be reduced to more fundamental objects that lack them. Just as ordinary objects may be functionally reduced to a more fundamental ontology, they argue, so may space-time locations be functionally reduced (Albert 2013). It is a challenge to show how this may be done, but not one unique to wave function monism. The lack of a fundamental spatiotemporal framework is common to many if not most of the current theories of quantum gravity. These theories, too, must recover local beables from a fundamental ontology that lacks them. This is work in progress (see Huggett and Wüthrich, forthcoming).

Some have suggested that the *fundamental* ontology of any adequate formulation of quantum mechanics must be in space-time, not configuration space, because a configuration space ontology would be too revisionary (Monton 2013). We are doubtful of this claim. Of course, at the end of the day we must explain those familiar phenomena for which we sought an explanation. It is not clear why, though, (a priori) low-dimensional space-time is not just one more feature that can be recovered as part of the derivative metaphysics of a theory.

5. An Inference to the Best Explanation. In recent work by Allori, we find a distinct way of arguing for the primitive ontology view and against wave function monism. Allori offers an inference to the best explanation: we do not necessarily have to think that physical theories have primitive ontologies. Perhaps, for example, a formulation with a primitive ontology is not available. Indeed, perhaps before Bohm, a primitive ontology was not available for quantum mechanics. But other things being equal, if we have a version of a theory with a primitive ontology, we should prefer it. Here is Allori: "The common problem to theories in which the wave function is taken as describing matter is that they are incredibly radical in an unnecessary way: if less farfetched alternatives work, why go radical? Even if we grant that

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there are reasons to go that way, still the theory does not seem to provide (at least at the moment) something to be compared to the explanatory [power] we just described which is available to theories with a primitive ontology" (forthcoming, 16). The explanatory power Allori is referring to is the ability to explain the macroscopic features of matter in a way analogous to what we can do using classical physics. It is just so much easier to see how macroscopic objects may be constituted by a microscopic ontology in ordinary three-dimensional space (or four-dimensional space-time) rather than by a wave function in configuration space. At best for the wave function monist, this explanatory task is work in progress.

We find this method of arguing against wave function monism much more compelling than the strategy we described above. It is not that physical theories must have primitive ontologies. It is that, when given the choice, we should prefer those that have them.

What we would like to do here is go on the defensive and try to argue that there may be reasons yet to prefer wave function monist versions of quantum mechanics. There are some ways in which wave function monist versions of quantum mechanics are superior to those with a primitive ontology.[18]

First, as is demonstrated by table 1, wave function monist versions of quantum mechanics are ontologically more parsimonious than those with a primitive ontology. The wave function monist need only believe fundamentally in a wave function, while one subscribing to the primitive ontology view must believe fundamentally in a wave function plus a primitive ontology of particles, a matter density field, or flashes. Allori and her camp may defend their view on parsimony grounds by saying that although the wave function is an element of their preferred theories' fundamental ontologies, it is not an element of their primitive ontologies. Indeed, Allori suggests (forthcoming, sec. 5.3) that if the wave function is not taken to be a concrete entity like a field, then the wave function's status as abstract will not contribute to surplus ontology. However, confining the wave function to this status does not eliminate it; it only shows that the wave function is not part of what constitutes matter on these theories. It still exists and so is relevant for considerations of parsimony.

Second, Allori highlights the fact that theories with a primitive ontology are more conservative in that their ontology is closer to that of both the manifest image and earlier physical theories. As she puts it, "in contrast to the case of wave function ontology, the primitive ontology approach reflects the desire to keep the scientific image closer to the classical way of understanding things" (Allori 2013, 62). Now some might think that conservatism has no place in the evaluation of rival physical theories. For example, James Ladyman has argued: "Science is not under any obligation to recover

18. This is to develop the line of argument sketched in our introduction.

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familiar truths from the manifest image, only approximations of them, the reasonableness of asserting them even though they are false, or their persistence as illusions. . . . Conserving common sense is not a desideratum for physical theory or its interpretation and it may well be that 'most of our ordinary beliefs about the physical world are false', . . . or at least only approximately and partially true and in other ways systematically wrong" (2010, 155). Ladyman suggests that we do not at all need our ontology to be conservative in Allori's sense; we only need to recover why we thought earlier (perhaps mistaken) ontologies were correct.

We are sympathetic to Ladyman's point. But let's for the sake of argument allow that Allori is correct and that it would be a virtue of a scientific theory if it came with a fundamental ontology closer to that of earlier (classical) theories or the manifest image. Still, there is another sense of conservatism in which the primitive ontology approach does poorly. This is not in being faithful to earlier scientific or quasi-scientific theories but in being faithful to the scientific theory under consideration. All of the versions of quantum theory with a primitive ontology are revisionary in this latter respect. They add new laws and new ontology to earlier versions of quantum mechanics. Bohmian mechanics was a revision to orthodox quantum mechanics: GRW_m and GRW_f are revisions to the wave function monist GRW_0, and S_m was a revision to the wave function monist S_0. We are not convinced that conservatism is an intrinsic virtue of scientific theories. However, if it is, it is not clear why we should prefer conservation of the ontology of classical mechanics, as opposed to conservation of the ontology of earlier versions of quantum mechanics itself.

Finally, we would like to suggest that the advantage Allori claims for the primitive ontology view, that of having a relatively simple way of explaining the macroscopic features of matter, ends up a wash. Theories with a primitive ontology do have an easier time explaining the macroscopic features of matter. This is not to concede that things are as straightforward as Allori makes out. For the primitive ontology that Allori and her collaborators take to constitute macroscopic objects does not on its own have all that is needed to ground most familiar properties (colors, textures, etc.) of matter. Bohmian particles and GRW flashes may have spatiotemporal locations; the matter density field, variations in intensity. But to ground the existence and behavior of macroscopic objects as we know them requires more than what is contained in the primitive ontology. Additional information is needed that is contained in the state of the wave function.[19] We may concede that the existence of a primitive ontology of matter in space-time makes the constitution of macroscopic objects at least more straightforward. But this should not be viewed as a decisive reason to reject wave function

19. Thanks to David Albert here.

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monism. As it stands, the primitive ontology view also requires more philosophical work, not merely to give a full account of the emergence of macroscopic objects but also to explain the metaphysical status of the nonprimitive fundamental ontology, in particular, the wave function.

One option is to reject the existence of the wave function altogether. This is compatible with the primitive ontology view, but it is a position that Allori et al. reject for the reason just mentioned. What then is the ontological status of the wave function? We have seen these authors suggest it is abstract, something with a nomological character, something that governs the primitive ontology. However, several authors before us have pointed out issues with this characterization of the wave function.[20] For example, can the wave function really be nomological, that is, a law, if it itself evolves according to a dynamical equation, the Schrödinger equation? Goldstein, Zanghì, and their collaborators give a response to these worries, but again this is at this time work in progress. These authors often point to the possibility that a final theory, a quantum cosmology, may replace the Schrödinger equation with something looking more like the Wheeler-DeWitt equation of canonical quantum gravity. Here, the time variable drops out, and we may see the wave function as static and unchanging, thus more like a law. This goes some way toward answering the worry but holds the very coherence of the view hostage to one speculative proposal about quantum gravity. What is more, one wants to know what is to be said for viewing the wave function as nomological on current versions of quantum mechanics, which after all, is the subject of the present discussion.

Another feature that makes the wave function seem less like a law is the physical contingency of its initial state. It is natural to think there could be different physically possible worlds with different initial wave functions. However, if the wave function has nomological status, then this is ruled out.[21] To say that a contingent fact about the initial state of the universe has the status of a law is not completely unheard of today. David Albert, for example, argues that the fact that the universe started in a low-entropy state, what he calls the Past Hypothesis, should be understood as a law (2000). This classification of the Past Hypothesis is motivated by his preferred theory of laws, the Humean best system analysis, in which laws are those statements that appear in the description of our world that best maximizes simplicity and informational strength. However, it is not clear that Albert's strategy may be applied to the case of the initial state of the wave function. The initial state of the wave function of our universe is extremely complex. This makes it less plausible that a statement about it would likely appear in the Humean's best system. Goldstein and Zanghì acknowledge this point

20. See esp. Brown and Wallace (2005) and Belot (2012).

21. Thanks to an anonymous reviewer for pressing this.

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and claim as a result that "we should expect somehow to arrive at physics in which the universal wave function involved in that physics is in some sense simple—while presumably having a variety of other nice features as well" (2013, 103). This raises an interesting issue of how one might characterize the initial wave function so that it is simple enough to occur in our best system. But we cannot tell now whether this expectation will be met.

Sometimes Goldstein, Zanghì, and their collaborators conjecture that perhaps instead the wave function is quasi-nomological: not quite a law but at least more like a law than a concrete, physical object (Goldstein and Zanghì 2013, sec. 4). The wave function is at least quasi-nomological because its role is to govern the primitive ontology of the theory, and, as they note, there is no "back action" in the other direction. This distinguishes it from, for example, the electromagnetic field, for which although we may also view its role as governing other objects, the matter of the theory (see the passage from Dürr et al. [1992] above), there is also reciprocal influence of the matter back on the field.

We do not want to dismiss this proposal, that the wave function might have a status that is not quite nomological but still like a law in certain ways. However, we note only that this raises philosophical questions. One immediate question is, if it is not a law but still able to affect the behavior of objects in the primitive ontology like a law, then does this mean it lacks a spacetime location? If so, then how does it affect the primitive ontology? Also, is this intended to be a general principle that if an object affects but in turn is not affected by matter that it thereby fails to qualify as a physical field? These are questions that do not arise for the wave function monist.

6. Wave Function Realism? The arguments we have considered in this article take as their target wave function monism, the view that the fundamental ontology of quantum mechanics is the wave function alone. But what are the implications for the more general position of wave function realism, the view that the wave function, understood as a field on a physical configuration space, is at least one (but not necessarily the only) element of the fundamental ontology of quantum mechanics? This view seems at least intelligible, even if we assume that any adequate formulation of quantum mechanics must include a primitive ontology, although our authors appear to reject it. Why?

One reason we have just outlined: in versions of quantum mechanics with a primitive ontology, the wave function constrains the behavior of the primitive ontology (via the various guidance equations), without an effect of the primitive ontology back on the wave function. This suggests that the wave function has a different status than that of a physical field. In addition, Goldstein and Zanghì note: "For a multi-particle system the wave function . . . is not a weird field on physical space, it's a weird field on config-

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uration space, the set of all hypothetical configurations of the system. For a system of more than one particle that space is not physical space. . . . What it suggests to us is that you should think of the wave function as describing a law and not as some sort of concrete physical reality" (2013, 97). So it is also the fact that the wave function is not defined on a real, physical space that leads these authors to reject its status as a physical field.

If one accepts the existence of fundamental local beables, it does seem strange to view configuration space as physical and, so, grant the wave function the status the wave function realist wants. There are metaphysical problems that arise. For example, how can the wave function as a physical field in one space (configuration space) have causal efficacy on the behavior of a primitive ontology inhabiting a distinct space altogether? But we suspect our authors are less concerned with this type of metaphysical problem than an interpretative one: the configuration space is defined as a space of configurations (of the primitive ontology). It is simply misunderstood if it is interpreted as a real physical space.

Not everyone who is interested in the notion of a primitive ontology is so skeptical of supplementing the primitive ontology with a concrete wave function. Gordon Belot (2012, 13) suggests there are at least the following four options for how a primitive ontologist can treat the wave function: as a generalized field (assigning properties to n-tuples of points of space) on ordinary three-dimensional physical space, as a physical field on configuration space, as a law, and as a property (encoding abstract features of the primitive ontology). We are here focusing on the second option.[22] We have noted that the existence of the primitive ontology threatens this option, as there is pressure to view the configuration space not as physical but as a space of configurations of the primitive ontology. If so, it is hard not to see it as our authors do, as abstract and not a genuine physical space. But this is not decisive. The indispensable role of the wave function in all candidate versions of quantum mechanics combined with the fact that, like the electromagnetic field, it is defined by an assignment of numbers to points, as well as the conceptual difficulties involved in understanding it as a law, gives pressure in the opposite direction, providing reason to reconceptualize the space the wave function lives on not literally as a space of configurations but rather as a genuine physical space. We conclude that we have not been provided with definitive reason to reject the wave function as a physical field even on primitive ontology views. Wave function realism remains a tenable option even for those who argue that any adequate version of quantum mechanics needs a primitive ontology.

22. The remaining options have been defended by Wallace and Timpson (2010) and Monton (2013).

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7. Conclusion. The debate between Goldstein, Zanghì, et al. and wave function monists makes clear a divide that exists among those who are interested in the connection between metaphysics and physics. How does one decide the correct form and ontology of our fundamental physical theories? Do we take scientific theory as far as we can go and attempt to read an ontology off of those theories, no matter how foreign it may seem? Or are scientific theories and their interpretations somehow bounded by metaphysical presuppositions, certain criteria we must meet to get at the right story of what our world is like? We have extracted some conditions that a primitive ontology is supposed to meet and argued that the claim that physical theories should have a primitive ontology is contentious.

At the end of the day, one might simply insist that the wave function ontology is too radical and the configuration space's role is only as a convenience in the representation of systems. However, we would like to ask just as so many have asked about mathematics generally, why does this representation work so well, and why can its virtues not provide some pressure toward taking it with ontological seriousness? For those who agree with the points we have made here, the next step is to tackle the metaphysical task of understanding the reductive relationship between this scientific image and the familiar objects we were interested in explaining in the first place.

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