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The One Magic Wave: Quantum Monism Meets Wavefunction Realism

Claudio Calosi

The paper provides a systematic assessment of wavefunction mereological priority monism, the combination of priority mereological monism and wavefunction realism. Such a combination has been recently discussed and defended both in philosophy of physics and metaphysics. I argue that such a combination threatens to undermine the master arguments in favour of its components. Furthermore, wavefunction mereological priority monism entails controversial consequences for both mereology and location. In the light of the above, I explore different ways to resist the arguments and different combinations of monism and realism about the wavefunction.

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Doesn't your monism bore you? [...] All monism is boring.
—T. Mann, *The Magic Mountain*

1. Introduction

According to what I shall label wavefunction mereological priority monism, there is only one fundamental entity, the universal quantum wavefunction,[1] and non-fundamental—that is, derivative—entities are mereological parts of it. The view is a peculiar combination of monism on the one hand, more precisely of priority mereological monism, and realism about the wavefunction on the other, more precisely wavefunction realism. Recently, this view has attracted considerable attention in both philosophy of physics and metaphysics.[2] Most notably, the view

[1] I will abuse terminology and will not distinguish between the mathematical object and what it represents. Such abuse is common in the literature and mostly harmless. Also, I will use 'wavefunction' and 'wave' interchangeably.

[2] See, for example, (Calosi [2018]; Ney [2020], [2021]), and to a different extent (more on this later on), (Schaffer and Ismael [2020]).

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has been defended by Ney in her new insightful defence of wavefunction realism, one of the most widely discussed ontological proposals for quantum theories. This paper provides the first thorough assessment of wavefunction mereological priority monism. I will argue that this combination actually threatens to undermine the master arguments in favour of its components (section 4). That is, the endorsement of wavefunction realism threatens to undermine the main quantum argument in favour of mereological priority monism, the 'determinatation' argument (section 2). Conversely, the endorsement of mereological priority monism threatens to undermine the main argument for wavefunction realism, the 'separability' argument (section 3). There are indeed interesting ways to avoid such conclusion, but they all come at significant cost (section 5). On top of that, wavefunction mereological priority monism has radical consequences when it comes to both mereology and location (section 6). Perhaps different combinations of monism and realism ought to be explored (section 7).[3]

2. Varieties of Monism and Realism

Monism comes in different varieties. In its weakest form, which I will simply call monism (M), it holds that

(1) Monism: There is only one fundamental entity.

As of now, I simply take 'fundamentality' as a primitive piece of ideology—but I will come back to this in section 5. (1) does not say whether there are derivative—that is, non-fundamental—entities. If there are not, one gets existence monism (EM):

(2) Existence monism: There is only one fundamental and there are no derivative ones.

By contrast, if one adds to (1) that there are derivative entities, one gets priority monism (PM):

(3) Priority monism: There is one fundamental entity and there are derivative ones.

(3) is silent about possible relations *R* that hold between the fundamental entity and the derivative ones—beside the relation of 'being more fundamental than'. Adding the claim that the fundamental entity and the derivative ones are related by *R*, one gets different versions of priority monism, *R*-priority monism (RPM)[4]:

[3] One may be surprised that there is no mention of quantum interpretations, such as Bohmian mechanics, GRW, or many worlds. Both Ismael and Schaffer ([2020]) and Ney ([2021]) are explicit in claiming that their arguments apply to many different interpretations of quantum mechanics. It is not the aim of the paper to address such issue. For a discussion of monism in different quantum interpretations, see (Calosi [2018]).

[4] The attentive reader probably realized that my 'monism chart' departs from other ones in the literature, for example, from the one in (Schaffer [2010], [2018]). The latter actually offers a more fine-grained distinction of different versions of monism that differ with respect to what they target and how they count. These details do not matter for the purpose of the paper.

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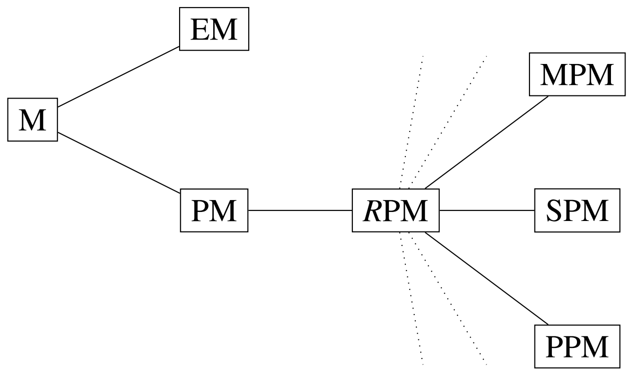

Figure 1. The monism chart.

(4) *R*-priority monism: There is one fundamental entity and there are derivative ones, and the fundamental entity and the derivative ones are related by *R*.

If *R* is part–whole, the result is what I shall call mereological priority monism (MPM):

(4.1) Mereological priority monism: There is one fundamental entity, and there are derivative ones, and the derivative entities are (proper) parts of the fundamental whole.

If *R* is substance-mode, substance priority monism (SPM) ensues:

(4.2) Substance priority monism: There is one fundamental entity, and there are derivative ones, and the derivative entities are modes of the fundamental substance.

To conclude the discussion about different varieties of monism, let me mention yet another possibility—the reason will be obvious in due course. If *R* is pattern-structure one gets pattern priority monism (PPM):

(4.3) Pattern priority monism: There is one fundamental entity, and there are derivative ones, and the derivative entities are patterns in the fundamental structure.

Figure 1 sums up the relations between different varieties of monism.[5] I formulated them in such a way that every right-to-left entailment along the lines holds by logic alone, whereas no left-to-right entailment holds.

Quantum mechanics is often said to favour monism, and it is a substantive question which variant of monism it favours, if any.[6] It is agreed that one needs a somewhat realist understanding of the wavefunction in order to get quantum monism. Now, like monism, realism about the wavefunction comes in many varieties.[7]

[5] For the most part, I do not discuss varieties of monism in which only some of the derivative entities are related by *R*—and the rest of the derivative entities are related to these *R*-related derivative entities by yet another relation R^*—but see section 7. This is indeed a logical possibility, but one that delivers an account that is clearly unsystematic. All else being equal, I take we should prefer systematic accounts. Furthermore, many of the arguments in the paper—for example, the mereology and location arguments in section 6—apply also in the cases in which only some derivative entities are *R*-related to the fundamental one.

[6] For an introduction to the debate, see (Calosi [2018]).

[7] For an introduction, see (Chen [2019]).

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Let me suppose, for the sake of simplicity, that we are dealing with an n-particle world. Then one realist approach has it that the wavefunction represents a multi-field that specifies a field-value for each n-tuple of points in three-dimensional space.[8] According to another it represents a property-like entity—say a disposition—of the mereological sum of the n-particles.[9] Yet another one has it that it is a highly structured object-like entity.[10] One can even go as far as claiming that it does not fit in any of our classical ontological categories.[11] According to the realist variant that I am interested on here—and for which I will reserve the label wavefunction realism—it represents a field in $3n$-dimensional configuration space.

Recently, wavefunction mereological priority monism, that is, the combination of mereological priority monism and wavefunction realism, has been thoroughly discussed and defended, most notably in (Ney [2020], [2021]). Here is Ney:

> For according to the wave function realist, only the wave function is fundamental, and so for the particles to be real but not fundamental, they must somehow be constituted out of the wave function. A natural place to start in explicating this constitution relation, [. . .] is with the hypothesis that the metaphysical relation obtaining between these many particles and the wave function is a mereological relation. This picture would thus be a version of Jonathan Schaffer's priority monism [mereological priority monism]; priority monism is the view according to which wholes are ontologically prior to their parts. ([2020], p. 4244)

> The wave function is the fundamental whole; the particles its derivative parts. This picture recalls Schaffer's priority monism [mereological priority monism] described in Chapter 2. Recall priority monism is the view according to which wholes are ontologically prior to their parts. ([2021], p. 240)

Ismael and Schaffer ([2020], p. 4154) discuss wavefunction realism at length and conclude that 'Wave Function Realism does provide a common ground explanation in terms of the shape of the wave'. The connection between 'common ground explanations' and mereological priority monism is made explicit by Ismael and Schaffer ([2020], p. 4150) themselves:

> There is interpretive pressure to regard the separated components of entangled systems as grounded in the whole integrated entangled system [the alleged common ground], and thus to regard quantum mechanics as a theory that portrays entangled wholes as more fundamental than their parts [. . .] The idea of the whole being prior to its parts is reminiscent of the classical monistic idea in metaphysics.

One may take this as an indication that they endorse wavefunction mereological priority monism, or something in its vicinity. The case of (Ismael and Schaffer [2020]) is more nuanced than it might first appear, and I will return to this in section 7. In any case, my interest in

[8] See, for example, (Hubert and Romano [2019]; Romano [2021]).
[9] See, for example, (Monton [2006]; Esfeld et al. [2014]; Suarez [2015]). The proposals differ, even significantly, in the details.
[10] See, for example, (Wilson [2011]).
[11] See, for example, (Maudlin [2019]). The list of different varieties of realism is by no means exhaustive.

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this paper is on wavefunction mereological priority monism itself, rather than in the exegesis of its (alleged) defenders. Indeed, my discussion of wavefunction mereological priority monism goes (sometimes) beyond what its (alleged) defenders explicitly endorse—and I will flag out explicitly when it does so. Regardless of my interest here in the position itself rather than the exegesis of its defenders, this serves a further important dialectical role: I will discuss what I take to be the overall best, more detailed formulation of the view. Crucial details of its articulation are currently lacking in the extant literature. I will provide them on behalf of the defender of wavefunction mereological priority monism.

3. The Determination Argument

The main quantum argument for mereological priority monism is the 'determination argument', as I shall call it. The argument was first given in (Schaffer [2010]), and is developed in (Schaffer [2018]; Ismael and Schaffer [2020]). It has attracted considerable attention since its very first formulation.[12] Morganti ([2009], p. 274) sums it up nicely:

> [...] entangled quantum systems are such that facts about them as wholes [...] are not reducible to facts about the separate particles. These systems are fundamentally holistic because the total physical state in which they are found is not 'factorizable' (that is, decomposable) into separate states of the component particles. This, according to Schaffer, bears witness to the priority of the whole over its parts [...] The whole cosmos is in a non-factorizable state. Schaffer concludes that the cosmos is a fundamental whole.

It is not my intention to either criticize or defend the argument. Therefore, a little more precision in its formulation will be enough for the present purposes. The argument rests upon a principle that I will call whole–part determination:

(5) Whole–part determination: For any quantum whole w with parts $p_1, p_2, ..., p_n$, the state of the whole w always determine that of the parts $p_1, p_2, ..., p_n$, whereas the converse does not hold. In particular it does not hold for entangled states.

According to Schaffer, the metaphysical lesson to draw from (5) is:

(6) Entangled systems are fundamental wholes—their parts being derivative.[13]

Schaffer goes on to argue:

(7) The cosmos—the mereological fusion of all concrete objects—is an entangled system.

[12] The interested reader is referred to (Morganti [2009]; Bohn [2012]) for discussion.
[13] See (Schaffer [2010], p. 54).

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Therefore, the cosmos is fundamental. Mereological priority monism now follows from (6) and (7) together with the so-called tiling constraint. According to such a constraint the fusion of all fundamental objects is the cosmos and no two fundamental objects overlap. The tiling constraint entails that if the cosmos is fundamental nothing else is, because every other object overlaps it. That is, mereological priority monism follows.

4. The Separability Argument

In her new book-length development and defence of wavefunction realism, Ney ([2021], pp. 80–132) takes the master argument in its favour to be the separability (and locality) argument. Even in this case, it is not my intention to either criticize or defend the argument. Thus, the following formulation will suffice:

(8) Separability and locality are desirable features of a (fundamental) metaphysics.

(9) Wavefunction realism is the only metaphysics of quantum mechanics that is both separable and local.

Given (8) and (9), all else being equal,[14] we should indeed prefer wavefunction realism over its rivals. The crucial notion I will focus on here is that of 'separability'. Ney provides slightly different phrasings of separability—for example, in (Ney [2021], pp. 81, 85, 127)—and quotes the classic formulation of Howard ([1989], pp. 225–26). These different phrasings might differ in the letter but they do not differ in the spirit. We can capture such a spirit as follows, in the terminology I used so far:

(10) Separability: A metaphysics is separable if and only if (i) it admits of composite wholes, and (ii) for any admissible composite whole w with parts $p_1, p_2, ..., p_n$, the states of the parts p_1, p_2, ..., p_n determine the state of the whole w.[15]

Everything is ready for an assessment of wavefunction mereological priority monism.

[14] The proviso is clearly important, but its discussion goes beyond the scope of the paper.
[15] Here is (one of) Ney's ([2021], p. 83) own formulation:

> A metaphysics is separable if and only if (i) it includes an ontology of objects or other entities instantiated at distinct regions, each possessing their own, distinct states, and (ii) when any such objects or entities are instantiated at distinct regions $R1$ and $R2$, all categorical facts about the composite region $R1 \cup R2$ are determined by the facts about objects and properties instantiated at $R1$ and $R2$ individually.

I did not use such a formulation because it brings in some subtleties, for example, the distinction between categorical versus non-categorical facts that are not important for the purposes of the paper. Note also that Ney uses regions and objects located (or entities instantiated) at these regions. I take that my formulation can be simply re-worked in those terms. As far as I can see, the crucial details are the existence of composite wholes, and the determination claim about their states. And it is clear upon inspection that my formulation retains such crucial details. This is indeed the traditional formulation of separability, as given, for example, in Howard (1989). I will look for alternative formulations in section 5.

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5. Separating Waves and Parts

Let me first give an 'official formulation' of the view. A little dramatically:

(11) Wavefunction mereological priority monism: The wave is the only fundamental entity and the derivative ones—comprising, for example, the concrete objects of our three-dimensional ontology—are parts of the wave.

I aim to show that, as it stands, the endorsement of wavefunction mereological priority monism threaten to undermine both the determination argument for mereological priority monism and the separability argument for wavefunction realism.[16] Ultimately the argument boils down to a tension, in fact an outright inconsistency, between the two principles that are crucial for the arguments, namely, whole–part determination and separability, at least in their present formulations—more on this in the following section.

The argument here is that there is no separable ontology that obeys whole–part determination. Conversely, there is no ontology that obeys whole–part determination that is also separable. Unsurprisingly, the problem is easily appreciated considering entangled systems. By way of illustration, consider the simplest such system, a whole w that only has two (atomic) proper parts p_1 and p_2. According to wavefunction mereological priority monism w is part of the fundamental entity, the wave. As it stands, Separability applies to w. This dictates that the state of w is determined by the states of p_1 and p_2. This contradicts whole–part determination.

Insofar as whole–part determination and separability, in their present formulations, are crucial ingredients of the Determination and the separability argument respectively, we get to the desired conclusion. The endorsement of wavefunction mereological priority monism undermines the master arguments for each of its components.[17] Admittedly, this argument is preliminary in that it depends upon a somewhat strict understanding of the relevant principles, namely, whole–part determination and separability. However, the argument is important in that

[16] One might have different immediate reservations. First, the two arguments above rely on a very different understanding of the wavefunction. In the determination argument, it is best interpreted as a property-like entity. In effect, it is a property-like entity of a specific kind, namely, an emergent property. Schaffer ([2010], p. 55) is explicit: 'I have argued that quantum entanglement is a case of emergence, in the specific sense of a property of an object that has proper parts, which property is not fixed by the intrinsic properties of its proper parts and the fundamental relations between its proper parts'. Clearly, this is not the same interpretation of the wavefunction that wavefunction realism delivers. Perhaps one may argue that a distinction can be drawn between entanglement and the corresponding entangled wavefunction. And then go on to claim that only the former represents a property of the composite quantum system. I will not discuss this argument here, for I think there is a more substantive argument to be made. Second, one might note that according to the wavefunction variant of mereological priority monism the fundamental entity is the wavefunction. By contrast, in the original argument for mereological priority monism the fundamental entity was supposed to be the cosmos. And the cosmos is not the wavefunction—as I go on to argue myself later on in the paper. I will not press this here, for I will return to this in section 7. Relatedly, the difference between the wavefunction and the cosmos runs afoul of the tiling constraint.

[17] Naturally one can simply argue for (quantum) mereological priority monism and for wavefunction realism on different grounds. But these arguments are the 'master arguments' for a reason.

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it uncovers a general and genuine tension between mereological priority monism on the one hand and wavefunction realism on the other. This is a genuine tension that, as we shall see, resurfaces over and over, even in the presence of less strict understanding of said principles. Monism in general is a metaphysics that points to 'Top-Down determination', from wholes to parts. By contrast, separability is one paradigmatic example of 'Bottom-Up determination', from parts to wholes. This is the general tension the argument in this section uncovers.

6. Varieties of Separability

The argument in section 4 crucially relies on the formulations of whole–part determination and separability I provided. These formulations should not be discarded light-heartedly.[18] That being said, perhaps one should be a little less strict, and allow for minor tweaks and reformulations. In this section I will indeed discuss some such tweaks and reformulations. These are the ones I could came up with, and I don't lay claim that they provide an exhaustive list. I will focus on separability for the simple reason that I don't see any viable—or plausible—reformulation of whole–part determination that is able to (i) do the job the principle is supposed to do in the determination argument, and (ii) undermine the argument in section 4 at the same time. By contrast, I think Ney herself in some passages moves to a different understanding of separability that can be of help. Consider the following: 'Thus, the wave function metaphysics is fundamentally separable, in the sense that there are no categorical facts about spatially separated objects that are not determined by local facts about the wave function and its parts' (Ney [2021], p. 89).

Ney mentions here 'fundamental separability' rather than simple separability. This is, I think, insightful. One of the things to learn from the argument in section 4 is that separability cannot hold for every admissible composite object. For there are composite objects that are surely derivative—entangled three-dimensional systems—for which it fails. Perhaps the thought is that we should restrict the quantifiers in the formulation of separability so as to have them range only over either admissible fundamental composites, or admissible composite objects with fundamental parts. These restricted versions would give us fundamental separability rather than simple separability, in line with Ney's passage above. A little more precisely[19]:

(12.1) Fundamental separability$_1$: A metaphysics is fundamentally separable$_1$ if and only if (i) it admits of composite fundamental wholes, and (ii) for any admissible composite fundamental whole w with parts $p_1, p_2, ..., p_n$, the states of the parts p_1, p_2, ..., p_n determine the state of the whole w.

[18] To be fair, the discussion on the proper formulation of separability involves many subtleties I gloss over. For a review, see (Ramírez [2020]).

[19] One can restrict both quantifiers and have them both range only over fundamental wholes with fundamental parts. The consequence for monism will be exactly the same as the consequences of fundamental separability$_2$ in the main text, so I will not consider this formulation here.

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(12.2) Fundamental separability$_2$: A metaphysics is fundamentally separable$_2$ if and only if (i) it admits of composite wholes with fundamental parts, and (ii) for any admissible composite whole w with fundamental parts $p_1, p_2, ..., p_n$, the states of the parts p_1, p_2, ..., p_n determine the state of the whole w.

It should be clear that neither fundamental separability$_1$ nor fundamental separability$_2$ can be of help in this context. Upon inspection, fundamental separability$_2$ is simply inconsistent with monism, and *a fortiori* with mereological priority monism. It clearly entails the fundamentality of more than one thing, namely, the (proper) parts of the relevant whole.[20] Fundamental separability$_1$ might not be in direct contrast with monism but it is still in serious tension with the determination argument in general. For, according to that argument, fundamental wholes are the ones such that the states of their parts do not determine that of the whole, contra fundamental separability$_1$. It seems that we need a more drastic departure from separability then restricted quantification. Here is an attempt—which I think dovetails with Ney's quote I started this section with. I'll first provide a vague sketch and then move on to a more rigorous formulation. In the broadest terms the view to be developed is that nature comes hierarchically structured in 'levels' of different relative fundamentality that bottom out at an absolutely fundamental level. This is indeed a widespread—if not unproblematic—view. Bliss and Priest ([2019], p. 1) write:

> This picture, or something very much like it, looms large over contemporary analytic metaphysics: a picture according to which reality is hierarchically arranged with chains of entities ordered by relations of ground and/or ontological dependence terminating in something fundamental.

Sider ([2020], p. 11) confirms: 'There is a familiar "levels" picture of reality, in which facts at "higher" levels rest on facts at "lower" levels, with everything ultimately based on a ground floor of fundamental facts'. And these are just two recent examples among many. In the present context this general view is cashed out as follows: There is a fundamental level, the configuration space level (CS-level). The only 'object' in that level is the wave. Crucially, there are no proper parts of the wave at the CS-level. Let me be upfront. This is one crucial detail in which my discussion goes beyond what, for example, Ney explicitly endorses—or any other (alleged) defender of wavefunction mereological priority monism for that matter. Indeed, it turns out that the detail is crucial. And so it stands in need of defence. I will turn to this shortly. Let me finish the sketch first. There is also a derivative level, the three-dimensional level (3D-level). There are many objects at that level including composite wholes. These three-dimensional objects are parts of the wave. Consider one such composite whole w. The state of each of its parts $p_1, p_2, ..., p_n$ is determined by something about the wave. Finally, those

[20] The argument assumes that nothing has a single proper part. Different mereological principles would secure this. I will discuss some such principles in section 6.

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somethings about the wave that determine the individual states of $p_1, p_2, ..., p_n$ also determine the state of w. This is the rough sketch.

There is only one thing missing from such sketch, namely, an argument for the claim that the wave does not have any proper parts at the CS-level. The argument, in a nutshell, is that if the wavefunction had proper parts at the CS-level, it would undermine the very rationale for being a monist in the first place. To see this, note that it follows from wavefunction realism that fixing the states of these (alleged) configuration space parts would fix everything else. Indeed, they would fix everything about the wave, which in turn—as we saw in the rough sketch already—fixes everything else. Thus, one could—and should—take the proper parts of the wavefunction to be fundamental rather than the whole wave. After all, they fix everything.[21] This gets us the desired conclusion. The wave does not have any proper parts at the CS-level—at least, this is what a monist should say.[22]

This vague sketch can be made (relatively) precise on behalf of the defender of wavefunction mereological priority monism.[23] First, let me resort to 'fact-talk and a primitive relation of determination between facts. I do this because it is the somewhat orthodox picture in the literature,[24] and I simply follow suit. There is no need to be unorthodox when there is no need.[25] Importantly, the relation of determination is transitive, and can be plural in the first argument. That is, a collection of facts $[f_1, f_2, ..., f_n]$ can determine a single fact f. The facts we are interested in are arranged in levels of different relative fundamentality. Here we are interested only in two levels, namely, the CS-level and the 3D-level, as per the sketch above. The CS-level contains 'configuration space facts': facts that are, very roughly, the worldly counterpart of propositions that feature only configuration-space vocabulary (for example, wavefunction field, wavefunction field-values, regions of configuration space, amplitudes, and phases)—and logical vocabulary. As an illustration, f_1: 'the fact that the wavefunction field assigns amplitude α and phase π to a configuration-space point p' is a paradigmatic configuration-space fact.[26]

[21] The argument depends on the transitivity of the relevant determination relation. I will indeed assume that it is.

[22] There is one small wrinkle. One might argue for the claim that the wave is gunky at configuration space, that is, every configuration space part of the wave has further configuration space proper parts. If so, one could perhaps run the 'argument from gunk'—see (Schaffer [2010])—in favour of monism. This is way speculative. I take it that the burden of proof lies on the one endorsing the gunk hypothesis here.

[23] I do not pretend that what I am about to suggest is either the best or even the unique way to phrase things 'rigorously'.

[24] As a point in case, one needs only to think at one particular determination relation, grounding.

[25] There might be a worry that facts are necessary to even get the argument off the ground. And this signals a theoretical cost that should not be downplayed. First, one may simply agree and then argue that this is a cost worth paying in that it provides a firm consistent foundation for wavefunction mereological priority monism. Second, facts are not strictly speaking necessary. What is truly necessary is a plurality of entities such that (i) there is a proper plurality of those entities—that is, there is more than one; (ii) these entities can be the plural relata of the relevant determination relation; (iii) these entities are somehow related to the wavefunction in that they involve it but—crucially—are not proper parts of it. As long as those entities satisfy (i)–(iii) they could be of any ontological category. For instance, states of affairs, or even events might do—depending on one's views about the metaphysics of states of affairs and events. Thanks to an anonymous referee.

[26] Configuration space facts—and three-dimensional facts for what matters—are closed under logical operations so that, for example, the conjunction of two configuration-space facts is another configuration space fact—if

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Similarly for the 3D-level. It contains three-dimensional facts: these are facts that are, very roughly, the worldly counterpart of propositions that figures only three-dimensional vocabulary (particles, composite three-dimensional objects, regions of space, spatial locations and so on)—and logical vocabulary. As an illustration, f_2: 'the fact that point-particle *pp* is located at spatial point *p*' is a paradigmatic example of a three-dimensional fact. This might not provide an exhaustive—or even completely rigorous—formulation, but it is enough for the purpose of the paper.[27] One can define a purely general notion of relative fundamentality between levels as follows:

(13) Levels-relative fundamentality: Level l_i is more fundamental than level l_j if and only if for every fact f_2 in level l_j there is a fact f_1–or a collection of facts[28]—in level l_i such that f_1 determines f_j.

Next, absolutely fundamental for levels:

(14) Levels-absolute fundamentality: Level l_i is absolutely fundamental—or, in short, fundamental—iff there is no level l_j that is more fundamental than l_i.

Finally, level-derivativeness:

(15) Levels-derivativeness: Level l_i is derivative if it is not fundamental.

This construction is not only in line with the somewhat orthodox attitude in metaphysics, as Bliss, Priest, and Sider reminded us. It is also able to capture something significant in the context of wavefunction realism, namely, that the CS-level is the fundamental level, and that the 3D-level is a less fundamental, derivative one.[29]

Now, recent discussions of wavefunction mereological priority monism tend to be cast in terms of material objects—particles or fields—rather than facts. Thus, strictly speaking one would need to be able to move from fact-talk to object-talk. One promising avenue explored in recent literature is to resort to the notion of 'involvement' or 'aboutness'. Intuitively, fact f_1 above is about the wavefunction field and regions of configuration space, whereas fact f_2 is about particles and regions of three-dimensional space. It is notoriously difficult to pin down precisely the notions of involvement and/or aboutness.[30] Luckily for us, in the present context

there are conjunctive facts.

[27] Indeed, many formulations in the literature provide even less details. It is not the aim of the paper to provide an account of fundamentality.

[28] I will omit this amendment from now on, except when it is indeed crucial for the argument.

[29] Clearly, non-relativistic quantum mechanics is not a fundamental theory. There might be fundamental theories according to which the CS-level is not the fundamental one after all. The claim in the main text should be read therefore as follows: if non-relativistic quantum mechanics were a fundamental theory, then the CS-level would be fundamental. At least this is what defenders of the view either implicitly or explicitly claim. For a more nuanced attitude, see (Schroeren [forthcoming]).

[30] The most systematic account in the literature is in (Yablo [2014]).

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things get a little easier. For we know what the main tenet of wavefunction mereological priority monism is, namely, that the wave is the only fundamental entity and three-dimensional objects are derivative parts of it. Thus, we can safely assume that as far as objects go, all configuration space facts are facts about the wavefunction, whereas all three-dimensional facts are about three-dimensional objects.[31] One can then suggest the following:

(16) Object-absolute fundamentality: An object o is absolutely fundamental if and only if there is a fact f about o—or that involves o—that is in the absolutely fundamental level.

Object derivativeness is naturally:

(17) Object-derivativeness: Object o is derivative if and only if it is not fundamental.

This construction nicely captures that the wave is the only fundamental object, and that three-dimensional objects are derivative. More importantly, it seems to deliver a way to save wave-function mereological priority monism from the argument in section 4. Let us explore how in detail.

Consider any composite three-dimensional whole w with parts $p_1, p_2, ..., p_n$. Both the whole w and the parts will be derivative objects. Given the construction I just laid down, it follows that for every fact about any individual part p_i there are facts about the wave that determine such a fact. Consider the following family of three-dimensional facts f_i about each part p_i: 'the fact that part p_i is in state φ_i'. For any such three-dimensional fact, there are configuration space facts f_i^*-s about the wave such that the f_i^*-s determine f_i. The claim is now simply that the configuration space facts that determine the three-dimensional facts about the states of individual parts of w also determine collectively facts about the state of w. Let f_w be: 'the fact that the whole w is in state φ_w'. Then we have that the collection of configuration space facts $[f_1^*, f_2^*, ..., f_n^*]$-s determine f_w.[32] In other words: the state of w is not fixed by the states of its parts. Rather, it is fixed by the states of the wave that fix the states of its parts. The fact that f_w is not fixed by the state of its parts is the reason why all this is consistent with the whole–part determination principle.[33]

The construction I suggested is, as far as I can see, implicit in most discussion of fundamentality within the wavefunction realist camp. One might find it problematic, but it has two noteworthy consequences. These consequence are enough for the construction to earn its keep. First, it seems able to capture what wavefunction realists claim independently of their endorsement of monism. Second, it also undermines the argument in section 4, as I already noted. As for the latter claim, another way of seeing this is to note that the argument I just gave does not rely on separability. Rather, it relies on something similar, yet different:

[31] For the sake of simplicity I take points and regions in the relevant spaces not to be material objects.
[32] Note that the collection of such facts need not be finite. I am just sticking to the finite case for the sake of simplicity.
[33] We will see an application of this strategy shortly.

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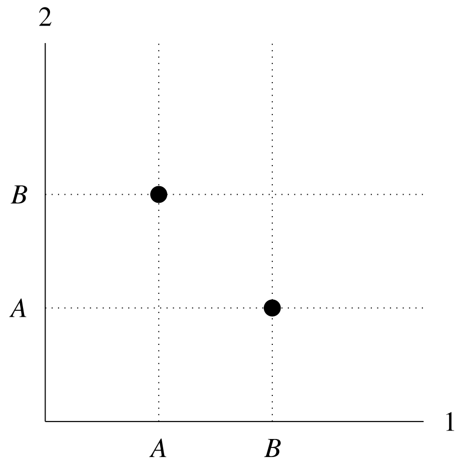

Figure 2. Configuration space representation of a two-particle world.

(18) Separability*: A metaphysics is separable if and only if (i) it admits of composite wholes, and (ii) for any admissible composite whole w with parts $p_1, p_2, ..., p_n$ there are facts $f_1^*, f_2^*, ..., f_n^*$-s such that facts f_i^*-s determine the fact f_i that part p_i is in state φ_i for each p_i, and the collection of facts $[f_1^*, f_2^*, ..., f_n^*]$-s determines the fact f_w that the whole w is in state φ_w.

Wavefunction realism is a separable* metaphysics. Separability* is not inconsistent with the whole–part determination principle exactly because it does not require the determining facts f_1^*-s, f_2^*-s, ..., f_n^*-s to be facts about the parts $p_1, p_2, ..., p_n$. In effect, they will not be—and crucially so.

Let me provide a simple example. This will serve a twofold purpose. On the one hand, it will make clear how separability* works in the present context. On the other hand, it will add to the present discussion of separability* by providing details about the notion that might not be completely transparent from its general formulation in (18). I will refer to Figure 2 below. Figure 2 is a configuration space representation of a two-particle world, that is, a world that only contains particle 1, particle 2 and their mereological fusion w, where the black dots represents regions of configuration space where the wavefunction intensity is high—one can picture such regions as peaks protruding out of the page.

There are three different configuration space facts we are interested here: two local ones, so to speak, and a global one. The local facts are: f_1^*, 'the fact the wavefunction has intensity such and such at region AB', and f_2^*, 'the fact that the wavefunction has intensity such and such at region BA'—here and henceforth I neglect constants. They determine the global fact f^* 'that the wavefunction has intensity such and such at region (AB, BA)'. Fact f^* determines individual facts of the three-dimensional particles 1 and 2. In particular, it determines f_1, 'the fact that particle 1 in state φ_1', represented by density matrix $|A\rangle\langle A| + |B\rangle\langle B|$, and f_2, 'the fact particle 2 in state φ_2', represented by density matrix $|A\rangle\langle A| + |B\rangle\langle B|$. It also determines facts about the whole w of which particle 1 and particle 2 are parts. In particular, it determines f_w, 'the fact

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that w is in state φ_w', represented by the Hilbert-space vector $|A\rangle_1 |B\rangle_2 - |B\rangle_1 |A\rangle_2$. Given that we assumed that determination is transitive, it follows that the collection of local facts about the wave determine both the individual states of the parts of w and the state of the whole w itself, exactly as separability* demands. Crucially, these local facts are not facts about proper parts of the wavefunction—indeed, values, or configuration space regions are not proper parts of the wavefunction. We saw the reason already: if they were one could take those proper parts to be fundamental. If one wonders why separability* deserves its name in the present context, the answer is readily given: local facts about the wave determine the global facts about the wave.

However, the entire discussion above should also make clear that there are compelling reasons to claim that separability* is deflationary enough so as to differ in spirit, not just in letter, from separability—at least in the present context. The best way to appreciate this in the following: Consider any three-dimensional quantum whole w. Its state will not be fixed by its parts $p_1, p_2, ..., p_n$—as separability demands. Rather, it will be fixed by something—the wave—of which w itself is part! This is exactly why separability* is not in tension with whole–part determination. In the present context, where determining facts f_1^*-s, f_2^*-s,..., f_n^*-s are facts about the wavefunction, separability* represents a form of Top-Down determination—as whole–part determination. By contrast, as we saw, separability is a paradigmatic form of Bottom-Up determination. This different direction of determination renders the principles crucially different. This is important. Or so I contend. Recall the separability argument, the master argument for wavefunction realism. If we replace separability with separability* in its premises we get:

(19) Separability* and locality are desirable features of a (fundamental) metaphysics.

(20) Wavefunction realism is the only metaphysics of quantum mechanics that is both separable* and local.

Given the substantive differences between the notions in the premises, arguments in favour of the original premises (8) and (9) will not be, ipso facto arguments in favour of the new premises (19) and (20). Indeed, it is far from clear that, for example, (20) is true. It seems that a substantive new argument is needed. This is enough to deliver the following conclusion: On the one hand, separability* is deflationary enough to assuage—if not eliminate—the tension between the requests of a separable metaphysics and a monistic metaphysics, a tension we first uncovered in section 4. On the other hand, one might worry that it is too deflationary in that it is unclear whether it is able to underwrite the master argument for wavefunction realism—when phrased with premises (19) and (20).

7. Mereology and Location

Independently of the arguments in sections 4–5, wavefunction mereological priority monism has surprising consequences when it comes to mereology and location. Let's start with mereology.

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First, one should be reminded that, crucially, the wave does not have any parts at the CS-level. Here is another way to see that. Consider yet another version of separability obtained by simply restricting the quantifiers to the CS-level[34]:

(21) Configuration space separability: A metaphysics is configuration space separable$_1$ if and only if (i) it admits of composite wholes at the CS-level, and (ii) for any admissible configuration space composite w with configuration space parts $p_1, p_2, ..., p_n$, the states of the parts $p_1, p_2, ..., p_n$ determine the state of the whole w.

Wavefunction realism together with the claim that the wave has configuration space parts is a configuration space separable metaphysics. But, once again, this picture would be in tension with monism. I made this argument several times already. If the wave had parts at the CS-level one could take these parts to be fundamental. After all, given configuration space separability, these parts would fix everything else. Thus, I repeat, the wave does not have any configuration space parts. Now, consider the mereological sum of all the three-dimensional objects. Call it s. s is a derivative three-dimensional object, which is, according to mereological priority monism a part of the wave w_f. It is also distinct from the wave. For example, w_f is fundamental, whereas s is derivative. Standard mereological definitions entail that s is not just a part, but a proper part of w_f. There are two infamous mereological principles that will now get the defender of wavefunction mereological priority monism into trouble:

(22) Weak supplementation: If x is a proper part of y, then there is a part of y that does not share any part with x.

(23) Strong supplementation: If y is not a part of x, then there is a part of y that does not share any part with x.

If one takes $x = s$ and $y = w_f$ one immediately see that both the antecedents of (22) and (23) hold. The consequents dictate that there is a part of the wave that does not share any part with any three-dimensional object. But we also saw that the wave does not have any parts at the CS-level. Where does this hidden part come from then? Naturally enough, one can discard both (22) and (23)—and mereologies without them have been surely explored.[35] However, such consequence should be noted. In effect, not every defender of wavefunction mereological priority monism can give up (22) and (23) that easily. For instance, Schaffer's broader case for monism crucially depends on the endorsement of classical extensional mereology, which features both (22) and (23) as theorems—or axioms, depending on the chosen axiomatization.[36] And Ney ([2021], pp. 240–41) herself recognizes that 'Not any proper ordering is a parthood

[34] The formulation builds upon the construction in section 5.
[35] See (Cotnoir and Varzi [2021]).
[36] See (Cotnoir and Varzi [2021]).

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relation, but one may include additional principles (e.g., [Weak] Supplementation) [...] in order to further distinguish the parthood relation from other proper orderings'.[37]

The consequences for location are even more surprising, for the fundamental wave and its derivative three-dimensional parts are located in very different spaces, configuration space and three-dimensional space respectively. By contrast we usually take parts and wholes to share the space they are located in. Ney ([2021], p. 240) recognizes this problem explicitly: 'Some may be concerned about viewing the relationship between the wave function and microscopic particles as one of whole and parts due to the fact that parts and their wholes seem typically to be located in a common spatial framework'. Ney replies that it is not a general mereological requirement that wholes and their parts are located in the same space. As she writes:

> However, this is not a general requirement for mereological relations to apply to a system of parts and wholes (as stated explicitly by Varzi 2016). Indeed, one might think that abstract entities not located in space or spacetime at all may exhibit mereological relations. ([2021], p. 240)

Ney is absolutely right in insisting that mereology per se does not impose any requirements on the relations between the locations of parts and wholes. The (formal) theory that does impose constraints between the locations of parts and wholes uses mereology, but it's not mereology. It is a formal theory of location.[38] And if we look at formal theories of location, we see that wavefunction mereological priority monism entails highly controversial consequences.[39] This is best appreciated by introducing, informally, two notions that have been central to all extant theories of location—at least to my knowledge.

The first one is 'exact location'.[40] The following is the somewhat orthodox gloss on it: 'an entity x is exactly located at a region y if and only if x has (or has-at-y) exactly the same shape and size as y and stands (or stands-at y) in all the same spatial or spatiotemporal relations to other entities as does y' (Gilmore [2018], section 2.1). The other is 'weak location'.[41] Weak

[37] As it stands, there is nothing in this passage that suggests that Ney has in mind a somewhat non-standard mereology. However, certain other passages—for example, (Ney [2020], p. 4245, [2021], p. 242)—may be interpreted as an implicit endorsement of 'fuzzy mereology'. The main tenet of fuzzy mereology is that parthood comes in degrees, and that x can be part of y at any degree $0 < d \leq 1$. Fuzzy mereology is admittedly non-standard. By contrast, I use standard, that is, non-fuzzy, mereology throughout. This represents, so the thought goes, another significant departure of my presentation from Ney's views. But it should be noted that the arguments that crucially depend on mereological notions, such as the mereological and locational arguments in this section, will go through even if fuzzy mereologoy is endorsed. One simply needs to rephrase the relevant principles. By way of illustration, weak supplementation becomes weak supplementation*: if x is a proper part of y at degree $d_i > 0$, then there is a z such that z is part of x at degree d_j and z and y do not share any part at any degree. The argument in the main text goes through because, even if degrees of parthood are considered, there is no such z. The same applies, *mutatis mutandis* for other principles. Thanks to an anonymous referee.

[38] For the application of formal theories of location to physics, see, for example, (Gilmore [2006]; Balashov [2010]; Pashby [2016]).

[39] For somewhat similar points, see (Calosi [2018]). The arguments in that paper are different and weaker then the one presented here, for they rely on stronger assumptions.

[40] See, for example, (Casati and Varzi [1999]; Hudson [2001]; Sattig [2006]; Hawthorne [2008]; Donnelly [2010]).

[41] See (Parsons [2007]; Eagle [2019]).

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location is location in 'the weakest possible sense', as Parsons ([2007], p. 203) puts it: x counts as weakly located at a spatial region r if and only if r is not completely free of x. Given these informal glosses it should be clear that the following principle should hold:

(24) Exact part–weak whole: If x is part of y and x is exactly located at region r, then y is weakly located at r.

This is because r is not completely free of y. The dilemma for those who endorse wavefunction priority wavefunction monism is now the following: either they deny the very plausible principle (24) or they are forced to accept that the wavefunction is somehow also located in three-dimensional space. To see this, consider the admittedly incredibly exceptional case in which the wavefunction has non-zero value at only one point in the $3n$-dimensional configuration space. This represents a case in which n particles will be exactly located at n different three-dimensional regions. By wavefunction mereological priority monism these particles are all parts of the wave. Consider one such particle. The antecedent of (24) holds true for it. The consequent yields that the wavefunction is (weakly) located in three-dimensional space after all. Neither horn of the dilemma—the wave is in three-dimensional space versus discard (24)—seems particularly attractive. One possible way to resist the argument is to point out that the case I just described is, once again, incredibly exceptional. Generally, the wavefunction is spread out in configuration space, and the n particles do not have exact locations in three-dimensional space. In such case, (24) is vacuously true. Granted. But there is a weaker principle that delivers the same conclusion that spelled trouble for wavefunction mereological priority monism. This is because the weaker principle has a weaker antecedent than (24) but the same consequent. Therefore, it yields the same problematic conclusion, namely, that the wave is in three-dimensional space. The principle is the following:

(25) Weak part–weak whole: If x is part of y and x is weakly located at region r, then y is weakly located at r.

The antecedent of (25) is arguably true even in the cases in which the wavefunction is spread out. Actually, some philosophers go as far as claiming that being weakly located in three-dimensional space is actually definitional of concrete material objects.[42] The argument I just gave can be strengthened. Let me take weak location location as a primitive notion, and let me define[43]:

(26) Entire location: x is entirely located at r if and only if every region that x is weakly located at overlaps r.

[42] Historically, this is the position defended by Descartes. For a contemporary defence, see (Markosian [2000]).
[43] These are standard definitions. I am using this particular theory of location because it does not have the so-called exactness principle among its theorems. According to exactness, roughly, everything in space has an exact location. And we are considering quantum situations in which particles might not have exact locations.

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(27) Pervasive location: x is pervasively located at r if and only if every region that overlaps r is a region x is weakly located at.

(28) Exact location: x is exactly located at r if and only if it is both entirely and pervasively located at r.

I already introduced exact location. As an illustration of entire and pervasive location, I am weakly located in my office, and pervasively located where my heart is. Now, suppose one holds the following:

(29) Whole–parts location: The exact location of a whole w is the sum of the exact locations of its proper parts $p_1, p_2, ..., p_n$.[44]

Then both (24) and (25) are not just plausible principles, they are actually theorems. To see this, consider an exact location r of one part, say p_1 of w. By whole–parts location and the definition of pervasive location w is pervasively located at r. Now, the theorem

(30) Pervasive-weak: If x is pervasively located at r, then x is weakly located at r

establishes that w is weakly located at r. This proves (24). (25) follows from (24). Hence the predicament: either concede that the wavefunction is (weakly) located in three-dimensional space, or give up the extremely plausible principles (24), (25), (29).

One possible response has it that what the argument shows is that quantum mechanics forces us to revisit principles of location. We took them for granted—the argument continues—only because we were thinking in classical terms all along.[45] This is an interesting suggestion. But it should be noted that it is not just quantum mechanics that forces us to discard the principles (24), (25), and (29). Rather, it is quantum mechanics together with the claim that 'particles are parts' of the wavefunction. In the light of the considerations above, one might prefer to give up this last claim rather than the locative principles.

8. Exploring Combinations

The arguments in sections 4–6 do not offer a conclusive refutation of wavefunction mereological priority wavefunction monism. But they highlight some difficulties that might be serious enough to explore different combinations of monism and realism about the wavefunction. To conclude, I just want to point out some such combinations, by looking back at the different varieties of monism and realism in section 1, thus closing the circle. I should be clear upfront. I will simply put forward what I think are some interesting combinations. I do not mean to

[44] In general, one may need to tweak these principles in order to account for the possibility of multilocation—see, for example, (Calosi and Costa [2015]). On multilocation in the quantum realm, see (Pashby [2016]).

[45] Many thanks to Alyssa Ney for this point, and for conversations about this.

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argue in favour of any such combination. Also, I will restrict myself to different versions of priority monism.[46] If one wants to endorse wavefunction realism, an interesting possibility is to combine it with substance priority monism:

(31) Substance priority wavefunction monism: The wave is the only (fundamental) substance and the many three-dimensional objects are (derivative) modes of such substance, ways the substance could be.

Conversely, if one wants to endorse mereological priority monism, an interesting package is the following: The wavefunction represents a property-like entity that (indirectly) attributes properties to four-dimensional regions of spacetime. This resembles closely Timpson and Wallace's spacetime state realism.[47] This yields:

(32) Spacetime mereological priority monism: The entire spacetime is the only fundamental entity and its proper parts, its sub-regions, are derivative.

In this case, the monistic argument would be that the spacetime state encoded in the universal wavefunction determines that of the different proper parts of spacetime (in general represented by density matrices) but the converse does not hold. Alternatively, one can think of the wavefunction as a multi-field and then argue that it is better understood as assigning primarily a global property to the entire spacetime, and only derivatively (non-local) properties to its sub-regions.[48]

Looking beyond mereological priority monism and wavefunction realism one can consider other options. For example, one can combine the view that the wavefunction is a highly structured object with some version of monism. Wilson ([]2011], p. 79) is explicit: 'At the fundamental level, the ontology is monistic—there is just one single structured object, the universal quantum state'.[49] But which kind? An interesting suggestion is to go for pattern priority

[46] That is, I will ignore existence monism.

[47] See (Timpson and Wallace [2010]). Ismael and Schaffer ([2020]) discuss this at length. Rightly so, I would add.

[48] I owe the last suggestion to an anonymous referee for this journal. It is interesting to note that both the proposals fall a step short of vindicating the monistic picture in which every derivative entity stands in one relation—in this case, proper parthood—to the fundamental entity, spacetime. This is because, for all that has been said, there might be other derivative entities, namely, material objects that are not, strictly speaking, proper parts of spacetime. At this juncture there are (at least) two options. First, one can give up the claim that every derivative entity stand in the same relation to the fundamental one, and explore less systematic monistic pictures—I will discuss a few of them shortly. Second, one can endorse 'Supersubstantivalism', roughly the view that every material object is strictly identical to a spacetime region. The endorsement of supersubstantivalism would indeed turn both the proposal into full-bloodied examples of spacetime mereological priority monism in the strictest sense. Thanks to an anonymous referee for prompting this discussion.

[49] In his assessment of wavefunction realism, French ([2013], p. 79) considers something close to this view, and relates it explicitly to monism:

> Taking the former option would ultimately yield [...] one global particular—the 'universal' wave function. Here one might turn to the monist's wardrobe for a possible metaphysical suit of clothes with which to dress this view [...] has all the characteristics of a field-like global particular, where the underlying thought seems to be that a field can be regarded as a vast universe-spanning substance, or 'jello-stuff'.

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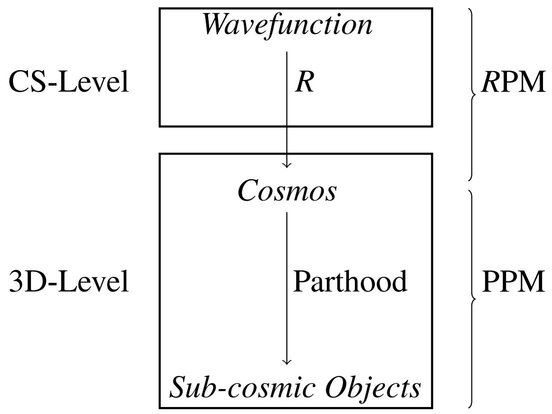

Figure 3. *R*-priority monism and mereological priority monism.

monism, to yield:

(33) Structure pattern priority monism: The wave is the only fundamental structure and the three-dimensional objects are (derivative) patterns in it.[50]

Finally, I want to discuss, albeit briefly, an interesting—if less systematic—proposal. Suppose that faced with the location argument in section 6, one endorses the view that the wavefunction is really not in space and three-dimensional objects that are in space are not part of it. Indeed, suppose one goes further and claims that to be in space is definitional of being a concrete object. It follows that the wavefunction is not a concrete object after all. One may still endorse the following view: The wavefunction is the absolutely fundamental object. But one can also ask what is the most fundamental concrete object, that is, the concrete object such that no other concrete object is more fundamental than it. Indeed, that is exactly how Schaffer ([2010]) phrases the issue of monism and pluralism. With this restriction in play, the following becomes an interesting position: There is one absolutely fundamental object, the wavefunction. There is only one fundamental concrete object, the cosmos—again, the mereological sum of all three-dimensional concrete objects. A version of *R*-priority monism—with $R \neq$ parthood—holds between the wavefunction and the cosmos, so to speak, whereas mereological priority monism holds at the 3D-level. A picture is worth a thousand words, it is said. Figure 3 provides such a picture.

As I already mentioned—see footnote 4—the suggestion above is vulnerable to a systematicity charge: all else being equal, we should prefer systematic accounts of fundamentality.[51]

[50] The thesis that three-dimensional material objects are patterns in the wavefunction is defended, independently of monism in, for example, (Wallace [2012]). More in general, an ontology of patterns as genuine yet derivative ontological posits is defended in (Ladyman and Ross [2007]).

[51] There is another less systematic account that is worth considering briefly. One can hold that simple particles are proper parts of the wave and that mereologically complex three-dimensional objects are fusions of such particles, but are not themselves proper parts of the wave. Note that this would not violate transitivity of parthood. Indeed, Ney describes Albert's ([1996], [2013], [2015]) functionalism as involving something akin to this strategy in (Ney [2020], p. 4236, [2021], p. 212). Perhaps this is a non-standard mereological picture that Ney might be

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Perhaps 'all else is not equal' in this case. Perhaps there is even a reading of (Ismael and Schaffer [2020]) according to which they are actually proposing something similar to this. If so, one can perhaps marshal their arguments to support the view. The combinations I explored are only some possible ones. They seem worth exploring to me. In the end, monism might be false, but it is not, as Naphta would have it, boring.

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willing to endorse—though she does not explicitly do. This would constitute a final departure from the account I discussed in the paper. However, this non-standard picture raises more questions than it answers. For example, consider the following questions: why is mereological simplicity a necessary condition for something to be a literal part of the wave? Consider now a three-dimensional mereologically complex whole. Given that it is built up from its particles, does it mean that it is more fundamental than its parts—even if it is still derivative? Given that only simple objects are literal parts of the wave, what role is left for any notion of separability to play? And so on. As a final remark, it should be noted again that the endorsement of this non-standard view might help with some of the arguments in the paper, for example, the mereological arguments in section 7, but it will not make any difference for others, for example, the locational arguments in the same section. Indeed, such arguments explicitly consider only simple particles.

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