The Governing Conception of the Wavefunction

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Abstract: I distinguish between two different ways in which the wavefunction might play a role in explaining the behavior of quantum systems and argue that a satisfactory account of quantum ontology will make it possible for the wavefunction to explain the behavior of quantum systems in both of these way. I then show how this constraint has the potential to impact two quite different accounts of quantum ontology.

The question of what the wavefunction represents is the central question of quantum ontology.[1] Just as one could not understand classical mechanics if one knew that

$$f = m\frac{d^2x}{dt^2}$$

was one of the dynamical laws but did not know what f, m and x represent, one cannot understand quantum theory if one knows only that Schrodinger's equation

$$i\hbar\frac{d}{dt}\psi = \hat{H}\psi$$

is one of the dynamcial laws but does not know what ψ —the wavefuction—represents

This paper articulates one route by which we might approach the question of what the wavefunction represents. This route starts by focusing on the explanatory role of the wavefunction. I first distinguish between two different aspects this explanatory role, and then argue that it is important that we respect not just one, but *both* of these aspects. The result is what I call *the governing conception of the wavefunction.* The governing conception of the wavefunction isn't itself an answer to the question of what the wavefunction represents, but it places significant and heretofore under-appreciated constraints on the possible ways by which we might answer this question. I don't expect that everyone will endorse the governing conception of the wavefunction,

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[1] I take it that this claim is compatible with a primitive ontology approach as exemplified in Allori et. al 2008 and Allori 2013. As I understand these views, the question of what the wavefunction represents is still central, but it turns out that, given what the wavefunction represents, there must be more to quantum ontology than just the wavefunction.

but for those who don't, the discussion below should help clarify the potential costs of their view. The burden will then be on those who dissent to articulate why those costs are worth paying.

One quick clarification before we begin. Readers who are familiar with debates about the metaphysics of laws will have some sense of the direction in which I am headed, just from the title of the paper. But it's worth emphasizing up front that one can endorse the governing conception of the wavefunction even if one does not endorse the governing conception of laws.[2] (Indeed my reading of the literature suggests that several prominent philosophers do just this.) I won't say anything here about whether that combination of positions is all things considered the best combination. Nor will I say anything about whether one can endorse the specific argument that I give below for the governing conception of the wavefunction without endorsing a similar argument for the governing conception of laws. These are good questions, but they are questions for another time.

1 What the wavefunction must do

Here's a claim that should not be at all controversial: The wavefunction plays a key role in explaining the behavior of quantum systems. Although this claim should not be controversial, it will be important. So it is worth going through a few examples.

1.1 Three examples

First, consider the well-known double-slit experiment that is used to illustrate the fact that quantum particles sometimes exhibit wave-like behavior. In this experiment, we fire a stream of electrons at a wall that has two small slits in it, near the center. Some of the electrons pass through the slits and hit a detection screen on the far side of the wall. If one of the slits but not the other is open, we see an unsurprising result: there are a lot of hits on the detection screen near the center, and fewer as one gets farther toward the top or the bottom. But if both slits are open we see something quite different. Some areas near the center of the screen register a lot of hits, but some areas—areas that registered many hits when only one slit was open—suddenly register few or no hits at all. (More specifically we see what physicists call an *interference pattern*.)

This result is surprising. Any complete account of the behavior of electrons will need to explain it. Any complete account of the behavior of electrons, in other words, will need to give a satisfying answer to the following question:

DS Why is it that when we send lots of particles through a double slit, there

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[2] See Beebee 2000 and Maudlin 2007 for discussion of the governing conception of laws.

will be points near the center of the detection screen that register few or
no hits?

The answer to this question has two parts. First, there is a claim about the wavefunction of the particles when they reach the detection screen. In this experiment, when the particle reach the detection screen, the wavefunction for each particle has an amplitude close to zero at a number of points near the center of the detection screen. Call these points the *central low points*.

Second, there is a claim about the relationship between the amplitude of wavefunction of a particle at a certain point and the probability of finding that particle in that location. According to Born's rule, if the amplitude of the wavefunction is α at a point, then the probability of finding the particle at that point is $|\alpha|^2$. Combined with the initial claim that we made about the amplitude of the wavefunction at the central low points, Born's Rule entails that the probability of finding each particle at one of the central low points is close to zero. This is why, even when we send lots of particles through a double slit, there will be points near the center of the detection screen that register few or no hits.

Here is the second example. We can think of the nucleus of a radium-226 atom as containing a number of alpha particles (each consisting of two protons and two neutrons). The alpha particles themselves do not have enough energy to overcome the forces that keep them bound in the nucleus. But if you observe enough radium-226 atoms, some of them will spontaneously emit an alpha particle. This is an illustration of the phenomena of quantum tunneling. To use a metaphor common in physics texts, we can model the forces keeping the alpha particles in the nucleus as the walls of a well—a "potential well"—that contains the particles. The particles don't have enough energy to get up over the walls of the well, but if you wait long enough you will occasionally see them "tunnel" through those walls.

This result is surprising. Any complete account of the behavior of alpha particles will need to explain it. Any complete account of the behavior of alpha particles, in other words, will need to give a satisfying answer to the following question:

R Why is it that, if we observe enough radium-226 atoms, we will see some
of them will spontaneously emit an alpha particle?

The answer to this question again begins with a claim about the wavefunction of the particles in a radium-226 atom. In particular the wavefunction of each alpha particle has a non-zero amplitude outside the nucleus that contains it. Combined with Born's Rule, this entails that the probability of each of those particles being found outside the nucleus is greater than zero. This is why, if we observe enough radium-226 particles, some of them will spontaneously emit an alpha particle.

One final example. It is possible to prepare pairs of silver atoms in a special way that puts them into what physicists call *the singlet state*. When two silver atoms are in the singlet state it doesn't matter how far apart they are or how careful we are to keep them from sending signals to one another—if we measure the spin of both particles in a particular direction the measurements will always have opposite outcomes. This is an example of quantum entanglement.

This result is surprising. Any complete account of the behavior of silver atoms will need to explain it. Any complete account of the behavior of silver atoms, in other words, will need to give a satisfying answer to the following question:

S	Why is it that, regardless of how far apart they are, two particles in the singlet state are always measured to have opposite spin?

Once again, the answer to this question begins with a claim about the wavefunction of the particles. But in this case, the particles, taken individually do not have a wavefunction. There is only the wavefunction for the system as a whole. This wavefunction takes as inputs states of the system as a whole—for instance, particle 1 having spin up in the z-direction while particle 2 has spin down in the z-direction, or particles 1 and 2 both having spin up in the z-direction. The wavefunction of a system that is in the singlet state is such that, according to Born's rule, the probability of the two particles having opposite spin in a particular direction is 1 while the probability of the two particles having the same spin is 0. This is why, regardless of how far apart they are, two particles in the singlet state are always measured to have opposite spin.

1.2 Two types of why questions

In all three examples above we had a phenomena that needed to be explained and we did so by appealing to the wavefunction. More carefully, in each case, the question we needed answered was a question about the relative frequency with which the outcome of some experiment was observed. And in each case, the answer involved pointing out that the wavefunction of the system in question had a certain form. In conjunction with Born's rule, this fact about the wavefunction then entailed that the probability of the outcome in question matched the observed relative frequency.

What these examples show, therefore, is that the wavefunction plays a key role in explaining the behavior of quantum systems. This much I think is uncontroversial. But the reason it is uncontroversial is that we haven't said anything at all about what it means to explain the behavior of a quantum system.

Consider again the three requests for explanation that we saw above. One way of interpreting these questions is as questions about about *why we should expect* the behaviors described above:

DS_E Why should we expect that, when you send lots of particles through a double slit, there will be points near the center of the detection screen that register few or no hits?

R_E Why should we expect that, if we observe enough radium-226 particles, we will see some of them will spontaneously emit an alpha particle?

S_E Why should we expect that, regardless of how far apart they are, two particles in the singlet state are always measured to have opposite spin?

Call this kind of why question a *why-should-we-expect question*. The examples discussed above demonstrate that everyone should be on board with the idea that the wavefunction explains the behavior of quantum systems in the sense that the wavefunction plays a key role in answering why-should-we-expect questions. This just follows from the fact that Born's rule is the standard rule for predicting the behavior of quantum systems, and the fact that the wavefunction plays a central role in Born's rule.

Crucially, however, when we asked our original why-questions with respect to each of the examples above, we might have meant something different. We might instead have been asking about the *reason why* the behavior in question happened:

DS_R What is the reason why, when we send lots of particles through a double slit, there are points near the center of the detection screen that register few or no hits?

R_R What is the reason why, if we observe enough radium-226 particles, we see some of them spontaneously emit an alpha particle?

S_R What is the reason why, regardless of how far apart they are, two particles in the singlet state are always measured to have opposite spin?

Let's call these kinds of questions *reason-why* questions.[3]

I think it would be a mistake to try to argue that one—and only one—of the two kinds of why-questions just described is the right kind of question to be interested in when we are looking

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[3] Bradford Skow (2016) has recently made extensive use of the terminology of 'reasons why'. Although there are obvious similarities between my view and his (e.g. causes are paradigm examples of reasons why), there are also important differences (e.g. I take reasons why to provide explanations, whereas Skow does not).

for an explanation of some phenomena. Both have a plausible claim on playing such a role. But I also think that it would be a mistake not to clearly distinguish between which of these two kinds of questions you are after when you are looking for an explanation. This is because it is often the case that we can have a good answer to a why-should-we-expect question without having a good answer to the corresponding reason-why question.[4] Consider, for instance, a case where we have reliable testimony. If someone who has just arrived from the relevant direction tells us that the highway is closed, we might have a good answer to the question of why we should expect the highway to be closed without having any answer at all as to the reason why the highway is closed. Or consider a case in which you have inductive support for something happening. The fact that every sample of salt that you have examined in your chemistry lab has been soluble, for instance, might be a perfectly good answer to the question of why we should expect the next sample of salt to soluble as well, while telling us nothing whatsoever about the reason why the sample is soluble. In general, all you need to establish a good answer to a why-should-we-expect question is a good epistemic rule. But as the examples above show, not all good epistemic rules for figuring out what is the case involve identifying the reason why it is the case.

The fact that we can have a good answer to why-should-we-expect questions without having a good answer to the corresponding reason-why questions means that it is quite easy to end up talking past one another when we start talking about the explanatory role of an entity like the wavefunction. Someone who thinks that the wavefunction only needs to answer why-should-we-expect questions about the behavior of quantum systems may be satisfied with a particular account of quantum ontology while someone who thinks that the wavefunction needs to answer reason-why questions finds the very same account lacking. (We will see a concrete example of this in section 2.1.) For this reason alone, it's worth distinguishing these two types of why questions and being more clear about which kind of question one thinks the wavefunction is supposed to answer.

So what exactly does it take to answer reason-why questions? This is a difficult question, and much of what could be said in response to it will be highly controversial. But here is a relatively neutral starting point: paradigm examples of good answers to the question "What is the reason why X" involve identifying either: (i) the cause of X or (ii) the grounds of X. What we want to know, for instance, when we want to know the reason why the highway is closed is what has caused the the closure. And what we want to know, when we want to know the reason why sodium is soluble, is what it is about the nature of sodium that results in it being soluble.[5]

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[4] We can also have a good answer to a reason-why question without having a good answer to the corresponding why-should-we-expect question. Consider, for instance, cases where the explanans confers only low probability on the explanandum. In Scriven's well known example, someone's having syphilis might be the reason why they got paresis, even though their having syphilis is not a good answer to the question "why should we expect them to get paresis?" because having syphilis, though a precondition for getting paresis, still only gives someone a 25% chance of developing the latter condition (Scriven 1959).

[5] As an anonymous referee pointed out to me, we sometimes answer a why-should-we-expect question by pointing to the cause or the ground of the explanandum. For instance, if I asked, "Why should we expect the highway to be

This suggests that good answers to reason why questions in general involve identifying *dependence relations*. Paradigm examples of dependence relations are causation and grounding, but insofar as there are other kinds of dependence relations besides causation and grounding, those dependence relations, too, would underwrite good answers to reason why questions. In principle, at least, reason-why questions could also involve identifying something that stands in a novel dependence relation R to X.[6]

1.3 Why reason why questions must be answered

Returning to the observation that we started with at the beginning of this section, we can now see that two different things that might be meant by the claim that the wavefunction plays a key role in explaining the behavior of quantum systems.

W_E The wavefunction plays a key role in answering why-should-we-expect questions about the behavior of quantum systems.

W_R The wavefunction plays a key role in answering reason-why questions about the behavior of quantum systems.

As I said above, everyone should agree with W_E. W_E just follows from the fact that Born's Rule is the standard rule for predicting the behavior of quantum systems, and the fact that the wavefunction plays a central role in Born's Rule. My view, however, is that we should not only accept W_E. We should accept *both* W_E and W_R. This is what it means to adopt the governing conception of the wavefunction.

Why think that in addition to playing a central role in answering why-should-we-expect questions about the behavior of quantum system, the wavefunction also plays a central role in answering reason-why questions about the behavior of quantum systems? First and foremost

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closed?" it would be reasonable to answer by saying, "Because there is a snowstorm and the plows aren't running." I take this point to be compatible with everything I have said here. In some cases (not all, cf the previous footnote) it is possible to answer why-should-we-expect questions by identifying a dependence relation. But in general answering why-should-we-expect questions doesn't *require* identifying such a relation. What is distinctive about reason why questions is that they do require identifying such a relation.

[6] Some philosophers are rightly cautious regarding the notion of grounding. But note that perhaps the most prominent way of rejecting the notion of grounding, due to Jessica Wilson (2014), is to argue that although there are many distinct non-causal dependence relations, there isn't any single coherent notion of grounding that groups them together. Those who are attracted to Wilson's approach should simply include all of the relevant non-causal dependence relations as possible ways of answering reason-why questions. Those who instead think that there just is no such thing as non-causal dependence at all, should feel free to ignore future references to grounding as a kind of dependence relation (though note that this will make several of the candidate views regarding quantum ontology harder to make sense of).

notice that if we can't answer reason-why questions like DS_R, R_R, or S_R by appealing to the wavefunction, then we can't answer them at all. To give up on W_R is to either admit that there is no reason why quantum systems behave the way they do, or to admit that even if there is such a reason, we cannot identify that reason with our best science.

To give up on W_R, therefore, is a significant cost. In my experience, most philosophers and physicists alike recognize this. But many of them still have the following concern: What if any account of quantum ontology on which W_R comes out true is an account where the wavefunction represents an entity that is strange or novel or otherwise the kind of the thing that we would prefer not to have in my metaphysics? In that kind of case, the costs of giving up on W_R might be worth paying.

In response to this kind of concern, I think it is highly instructive to consider some historical cases in which scientists have found themselves in a similar situation.[7] Consider, for instance, Pauli's introduction of a massless, chargeless, previously undetected particle—the neutrino—in the 1930s to explain the apparent loss of energy and momentum in beta decay. The neutrino was a strange and novel kind of particle. No one wanted to admit the existence of such a particle, and Pauli himself called the neutrino a "desperate remedy". But as strange as it was it had to be admitted. For there had to be *some* reason why energy and momentum appeared to be lost during beta decay.

Or consider Faraday's introduction of the electromagnetic field in the 1850s and the further development of that idea by Maxwell and Thomson. None of these physicists was quite sure *what* the electromagnetic field was, but they were quite certain that it existed.[8] Why? Because there had to be some reason why various electromagnetic phenomena happened in the way that they did.

Or, finally, to take a more contemporary example, consider the introduction of dark energy in cosmology following the observation of the accelerating rate of expansion of the universe in the 1990s. Even today, although there is widespread consensus that dark energy exists, there is little consensus as to what it is. Dark energy is, first and foremost, whatever explains the accelerating rate of expansion of the universe.[9]

All of these cases are nuanced, and deserve a more detailed discussion than I have time for here. But on a relatively straightforward understanding, they all have a common structure. In

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[7] I go through these cases in more detail in Emery ms.

[8] Suggestions ranged from the field being instantiated by an ether of contiguous, unobservable particles which transmitted the electromagnetic forces, to it being a collection of lines of force that existed independently, to it being a fluid filled with vortex tubes. See Faraday 1852, Maxwell 1861, Hesse 1962 (especially chapter 8) and Harman 1982.

[9] See Carroll 2007, lectures 14 - 17. Note that I am using the term 'dark energy' in an expansive sense that encompasses the notion of vacuum energy. This usage is in keeping both with early discussions of dark energy (e.g. Turner 2001) and recent summary discussions (e.g. Carroll 2007), but is not universal. If we reserve the term 'dark energy' for those hypotheses that would provide a *dynamical* explanation, it is no longer true that there is a consensus regarding the existence of dark energy.

each of these cases, physicists observed an unexpected pattern in the data. And in each case they were, however reluctantly, willing to introduce a type of entity that was highly strange or novel (or both) in order to explain that phenomena. Indeed in each case, the kind of entity that was introduced was the kind of thing that provided a good answer to not just the question of why we should expect the pattern in question to occur; it also answered reason-why questions about that pattern. The fact that beta decay results in the production of a neutrino is the reason why there appears to be energy and momentum lost during beta decay. The fact that the magnetic field has a certain form is the reason why the iron filings arrange themselves in a certain pattern. And the fact that there is a certain amount of dark energy in the universe is the reason why the rate of expansion of the universe is accelerating.

What these kinds of cases suggest, then, is that when we have a robust pattern in the data, we need to identify some reason why that pattern occurs, even if doing so comes with costs in terms of the kind of entities that we need to introduce into our metaphysics. What these kinds of cases suggest, in other words, is that even if it commits us to an account of quantum ontology that involves highly strange or novel entities, we ought to find some way to accept both W_R and W_E. Indeed if we take the dark energy example as a guide, then even if all other analyses fail, we should accept the governing conception of the wavefunction.[10] Obviously that is not an ideal situation—ideally we would be able to say something more about what the wavefunction is or subsume it under a category of entity with which we already somewhat familiar. But what the examples above show is that we do not need any guarantee of the ideal situation being actual before accepting that the wavefunction answers the relevant reason why questions. The way in which a theory is explanatorily impoverished if it fails to answer reason-why questions is the kind of consideration that trumps virtually any metaphysical scruples we might antecedently have.

1.4 The governing conception of the wavefunction

Here's where we are so far. I have distinguished between why-we-should-expect-that questions and reason-why questions and argued that the wavefunction must represent the kind of thing that is the reason why quantum systems behave the way they do. I will call this view the *governing conception of the wavefunction*.

> *The governing conception of the wavefunction.* The wave function represents something that is the reason why quantum systems behave the way they do.[11]

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[10] Perhaps, for instance, all we can say is that the wavefunction is a sui generis entity that answers the relevant reason-why questions. See Maudlin 2013.

[11] In general—and certainly in the examples in section 1.1—I take it that the wave function will also answer why-should-we-expect questions about the behavior of quantum systems. Note that we may want to leave open the possibility that the wavefunction plays a role in answering reason-why questions about the behavior of quantum

Given what I said at the end of 1.2 about what it takes to provide a good answers to reason-why questions, the governing conception of the wavefunction can be further spelled out as follows: the wavefunction either represents something that *causes* quantum systems to behave the way they do; or the wavefunction represents something that *grounds* the behavior of quantum systems; or the wavefunction represents something that is in some other way the reason why quantum systems behave the way they do.

Notice that the governing conception isn't itself an account of quantum ontology. It does not tell us what the wavefunction represents. Instead it is a constraint on such accounts. In part 2 of the paper I will say a bit more about how this constraint impacts a couple of candidate theories of quantum ontology. Before going on to discuss what the wavefunction could represent, however, it is worth saying a bit more about two ways in which one might resist the argument just given for the governing conception of the wavefunction.

The first way of resisting the argument is to insist that the only genuine explanatory demands are demands for answers to why-we-should-expect questions. On this view reason-why questions are either unimportant or non-sensical. The first thing to say in response to this option is just that it is surprising. It seems as though we can sensibly distinguish between questions about why we should expect some phenomena and questions about the reason why that phenomena occurred and that the latter are important. But perhaps more concretely, anyone who takes this route owes us some kind of story about what was going on in the historical cases described in section 1.3. Why do we ever feel pressured to introduce surprising new entities to answer reason-why questions about patterns in the data, if reason-why questions aren't important?

The second way to resist the argument in section 1.3 is to try to identify some middle ground between reason-why questions and why-should-we-expect questions, and then to argue that all we need from an account of quantum ontology is something that plays a role in explanation in this "middle ground" sense. On this view, it isn't enough just to identify some epistemic rule that will allow you to predict the phenomena in question. You need to do something more; but that something more falls short of identifying the reason why the phenomena occurred. Of course, before we can really evaluate this way of resisting the argument we need to know more about this "middle ground" sense of explanation. But it is worth emphasizing that any account along these lines will also need to reckon with the historical cases described above.[12] In what sense did the sorts of entities introduced in those cases satisfy the need

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systems even when that behavior has a low probability of occurring. If that is correct then the wavefunction may not always answer why-should-we-expect question about the behavior of quantum systems.

[12] A common thought along these lines involves some sort of appeal to unification. It isn't enough to show that the explanandum is to be expected—you have to show that it is to be expected in a way that unifies it with other phenomena. But what notion of unification is relevant here? Think again about the historical cases. In what way did introducing the neutrino or the electromagnetic field or dark energy unify the phenomena to be explained with other phenomena? I'm not claiming that this question can't be answered. But given how novel the electromagnetic field and dark energy were (in the latter case, still are) a satisfying answer will require quite a bit of philosophical work.

for the relevant kind of explanation? Until we have an answer to this question we should focus on accounts of quantum ontology on which the wavefunction answers reason-why questions about the behavior of quantum systems in addition to why-should-we-expect questions.

2 What the Wavefunction Could Represent

Let's turn now to the question of what the wavefunction could represent. The central idea is that the argument above—which is an argument about what the wavefunction must do—constrains the possible answers to the question of what the wavefunction could represent in interesting ways. Due to space, however, I will have to focus on two specific points. The first, I think, is relatively obvious, but deserves to be stated more clearly in the literature. The second, I think is more surprising.

2.1 The Governing Conception and Subjective Accounts of the Wavefunction

Here is the first point. Given the governing conception of the wavefunction, the wavefunction cannot merely represent the degrees of belief that a particular observer (or group of observers) should have in various possible outcomes of an experiment. Why? Because the degrees of belief that an agent should have just are not the kinds of things that can answer reasons-why questions about the behavior of quantum system.

Consider, for instance, the following accounts of the wavefunction:

> *QBism*. The wavefunction represents the degrees of belief that an observer should have in the outcomes of various measurements given that the observer started with coherent initial degrees of belief and updated consistently using Bayes Theorem.[13]
>
> *Pragmatism*. The wavefunction represents the degrees of belief that observers should have in the outcomes of various measurements given the kinds of creatures that we are and the way in which we are epistemically situated in the world.[14]

Neither of these accounts would allow the wavefunction to provide answers to reason-why questions about quantum phenomena unless one thinks that the reason why quantum phenomena occur is, in part, some fact about us, the agents investigating those phenomena. Let

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[13] See Caves et. al. 2002 and Fuchs et. al. 2014.

[14] See Healey 2012 and 2017.

us call facts about an individual's initial credence distribution, the way in which they update those credences, the kinds of creatures we are and the way we are epistemically situated in the world *epistemic facts*. If we accept both the governing conception of the wavefunction and either QBism or pragmatism, we will be committed to epistemic facts being part of the reason why quantum systems behave the way they do. This is not an inconsistent position, but it is a position that the vast majority of us would, I assume, like to avoid. The reason why quantum systems behave the way they do has nothing whatsoever to do with the details of our epistemic situation as individuals, or as human agents, investigating the world.

Of course, if one is willing to give up the governing conception of the wavefunction—if one thinks that the wavefunction merely plays a role in answering why-should-we-expect questions about the wavefunction—either a QBist account or a pragmatic account would appear to be perfectly well equipped to meet the explanatory demands that arise from observing the behavior of quantum systems. The details of our epistemic situation as individuals and as human agents investigating the world are *of course* quite relevant to why we should expect quantum systems to behave in various ways. This is worth emphasizing. If you don't care about reason-why questions, there is no explanatory pressure to go beyond the kind of epistemic view capture by QBism or pragmatic accounts.

So although the point that if one accepts the governing conception of the wavefunction then one should not endorse QBism or pragmatic accounts is straightforward, this is only true because we have been clear as to what kind of explanatory demand is involved in this way of understanding the wavefunction. Insofar as one just says, for instance, we should not adopt QBism because QBism doesn't respect the explanatory role of the wavefunction, it is quite easy to end up in a rather confusing dialectic. In my experience, this happens often in conversation, but it has also played out explicitly in the literature. Consider, for instance, the worry voiced in Timpson 2008 and the reply found in Fuchs and Schack 2015. Timpson complains that QBism has "troubles with explanation" because "we are not interested in agents' expectation that [a certain quantum system will behave a certain way]; we are interested in why it in fact does so" (2008, p. 600). Timpson, in other words, wants any interpretation of the quantum formalism to be able to answer reason-why questions about the behavior of quantum systems. Fuchs and Schack respond that the "explanation offered by quantum theory have a similar character to explanations offered by probability theory" and that "probability theory explains the agent's expectations" (2015, 7-8). In other words, their response is that a QBist interpretation does a perfectly adequate job in answering why-should-we-expect questions about the behavior of quantum systems. The disagreement here is not really over what QBism can do, it is over what kind of explanation is required from a scientific theory of the sort that QBism purports to be.

2.2 The governing conception of the wavefunction and configuration space

realism

Let's turn now to a second way in which the governing conception of the wavefunction constrains possible accounts of what the wavefunction represents. One currently popular account of the wavefunction is what I will call *configuration space realism*.[15] According to this view, the wavefunction represents a field in an extremely high-dimensional space.[16] I will argue that the governing conception of the wavefunction makes it quite difficult to be a configuration space realist.

One of the main motivations for configuration space realism is that it is supposed to be the most straightforward way of interpreting the quantum formalism. This motivation has two distinct components. The first is the idea that the wavefunction must represent a physical object. Philosophers of physics often point, for instance, to an analogy with classical mechanics similar to the one made at the beginning of this paper. Just as Newton's second law describes how the properties of certain physical objects—particles—change over time, we should think of Schrodinger's equation as describing the properties of a physical object—whatever the wavefunction represents—changing over time.[17] The second component of the motivation is the idea that if the wavefunction represents a physical object, then it must represent a field. This thought turns on the fact that the wavefunction is a function—it takes inputs from a specified domain and outputs a value. In other mathematical formalisms—for instance in the formalism for classical electromagnetism—functions are associated with fields.[18]

At this point, however, the configuration space realist faces a complication. Think back to the example involving quantum entanglement at the end of section 1.1. What that example showed is that the wavefunction is not defined over a space where each point corresponds to the possible properties of individual particles. Instead it is defined over a space where each point in the space corresponds to a complete specification the degrees of freedom of the system as a whole. This means that if the wavefunction represents a field, it does not represent as field in ordinary 3-D space. Instead it represents a field in an extremely high dimensional space where each dimension corresponds to one degree of freedom for the system.[19] The wavefunction of the universe as a whole, therefore, will represent a field in a space that has something like 3x10^{80} dimensions.[20] This space is often called *configuration space*.

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[15] This view also goes by the name *wavefunction realism*.

[16] Advocates of configuration space realism include Albert 1996, Loewer 1996, Ney 2012 and 2013 and North 2013. I have argued against this view on quite different grounds in Emery 2017. The papers in Albert and Ney 2013 provide a helpful introduction to the topic.

[17] See Albert 1996, 277; Ney 2012, 532, Lewis 2004, 714.

[18] See Albert 1996, 278.

[19] See the appendix of Ney 2012 for a detailed discussion of this point.

[20] Philosophers of physics get this number by assuming that all degrees of freedom can be captured by thinking about the location of a particle in 3D space. (For instance, the way that we measure spin is by sending the particles through a magnetic field that separates the particles into two groups. We then interpret one group as the particles that have spin up in the relevant direction and one group as the particles that have spin down in that direction.) A

So configuration space realism is the view that the wavefunction represents a field in configuration space. But of course configuration space is not the space of our ordinary experience. Nor is it the space in which we do physics. The kinds of experiments described in section 1.1—the kinds of experiments that led to the development of the quantum formalism—are experiments in 3D space involving 3D entities. The configuration space realist therefore faces a challenge: they need to explain how the wavefunction-field in configuration space is related to the 3D entities like electrons and silver atoms and magnets and detection screens in 3D space. Following Callender (2015), let's call this the *lost in space problem*.[21]

Configuration space realists are well aware of the lost in space problem. In response they strive to come up with an account of how the wavefunction might "enact" 3D entities or how to "find" the 3D world in the wavefunction.[22] But once one accepts the governing conception of the wavefunction, it becomes more clear what a satisfactory response to this problem would need to involve. If we adopt the governing conception of the wavefunction and configuration space realism, then we must think that the wavefunction-field in configuration space is the reason why 3D entities in 3D space behave the way they do. In other words, an advocate of the governing conception of laws who wants to be a configuration space realist will be explicitly committed to there being dependence relations between the high-dimensional space in which the wavefunction field exists, and the 3D space in which our physics labs and experiments are located. In order to resolve the lost in space problem, the configuration space realist will therefore need to make sense of these inter-spatial dependence relations.[23] That is to say, the configuration space realist will need to make sense of a dependence relation in which the relata exist in distinct physical spaces.

Now, inter-spatial dependence relations aren't always strange of novel. Consider a 3D cube and the 2D square that makes up one side of that cube. There are straightforward inter-spatial dependence relations between these two entities: the 2D square is a part of the 3D cube. But in the case of configuration space realism the issue is more complicated. As everyone in the debate agrees, no three of the dimensions within the high-dimensional space correspond to our ordinary 3D space. There is no sense in which 3D space is a part of the high-dimensional space. Instead each dimension of the high-dimensional space corresponds to one degree of freedom in the

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rough estimate is that there are 10^{80} particles in the universe. So if the above assumption is correct then we can capture all of the degrees of freedom by using a space of 3×10^{80} dimensions.

[21] As I read it, the lost in space problem is the same problem that Ney (2017 and forthcoming) calls 'the macro-object problem'.

[22] The "enacting" terminology is found in Albert 2015. Ney 2017 uses the terminology of "finding" the world in the wavefunction.

[23] Once the lost in space problem for configuration space realism is laid out so explicitly, configuration space realists may want to retreat to a somewhat different version of their view. According to this alternative version, which I call configuration space monism, the wavefunction field in the high-dimensional space is all that there is. The 3D entities of our everyday experience (and our physics labs) are just an illusion. Configuration space monism neatly eliminates the lost in space problem as stated above, since there no longer is a 3D space or 3D entities. But it does so by giving up on the governing conception of the wavefunction. The wavefunction no longer answers reason-why questions about the behavior of quantum systems. (It might, of course, still answer reason-why questions about aspects of our experience that seem like they are quantum systems.)

system that exists in the 3D space.[24]

The configuration space realist who wants to make sense of the governing conception of the wavefunction, therefore, must either make sense of inter-spatial causation, inter-spatial grounding, or some kind of novel inter-spatial dependence relation.[25]

I suspect that most philosophers will think that positing these kinds of inter-spatial dependence relations is costly--all else being equal it would be better to have a single space in which things depend on one another than to have two genuine physical spaces such that what happens in one of those spaces is the reason why the entities in the other space behave the way they do. So the question becomes whether the costs associated with these kinds of inter-spatial dependence relations worth paying. A full answer to this question would require an in depth examination of the alternatives to configuration space realism, and I don't have space to go in to that sort of examination here. But let me say something briefly about why I think configuration space realism faces a real challenge here.

As I noted above, the most commonly cited motivation for configuration space realism is that it is a straightforward interpretation of the quantum formalism. But now that the lost in space problem is clearly on the table, we should ask *straightforward in what sense?* Yes, the the configuration space realist has faithfully followed the standard ways of interpreting the formalism of classical theories, but by doing so they have introduced a kind of dependence relation that is wholly foreign to classical physics. Why think that it is really so important to be straightforward in the very specific way that the configuration space realist is straightforward, when their theory is not at all straightforward in other ways.

A second, often mentioned motivation for configuration space realism is that it preserves locality at the fundamental level.[26] I don’t have space to go into a full explanation of locality (and the related concept of separability) here. Suffice it to say that any interpretation of the quantum formalism that involves only 3D space and 3D entities will involve a non-local dynamics in the following sense: it will admit that what happens at one point in 3D space depends on what happens at other points in 3D space without there being any kind of signal or causal influence that travels through space to connect those two points. Configuration space realism avoids this kind of non-locality in the space in which the wavefunction is defined. Consider a case in which there are two particles that are separated in 3D space but that are nonetheless entangled with respect to their spin states. In configuration space, this system doesn’t involve multiple particles at all. There is only the wavefunction-field, which has different amplitudes at different points, each

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[24] Ney 2012 section 3 includes a helpful discussion of this point and why this also makes the high-dimensionality of configuration space different than the high-dimensionality of other physical theories, like string theory.

[25] As I understand it, the account found in Ney 2021 (section 7.4), according to which three-dimensional entities are part of the wavefunction involves a inter-spatial dependence relation—specifically inter-spatial constitution. According to Ney, three-dimensional objects are part of the high-dimensional wavefunction. Ney acknowledges that this stretches the ordinary notion of ‘part’ according to which a part and a whole occupy the same physical space, but points out that we also think that abstract objects have parts, even though they don’t exist in physical space at all.

[26] See the discussion in Ney forthcoming section 3.

of which represent a complete specification of the properties of the system as a whole in 3D space.[27]

Philosophers of physics have rarely been explicit about why exactly they think that preserving locality at the fundamental level is important.[28] Of course, having a non-local dynamics makes doing science significantly harder—we can't rule out possible sources of influence on some phenomenon just by examining what is nearby and testing for causal signals entering the relevant region.[29] But surely the configuration space realist can care about *this* reason for prioritizing locality. After all, the space in which we do science is 3D space, and the configuration space realist is still committed to the dynamics being non-local in *that* space. They have only eliminated non-locality in the high-dimensional, fundamental space, and we don't do science in the high-dimensional, fundamental space.

Another reason why one might want to avoid non-locality is that a non-local dynamics is novel or strange. In short, if one is at all conservative in one's metaphysics then one should want to avoid non-locality.[30] But notice that once we have accepted the governing conception of laws, the configuration space realist is also committed to something quite novel and strange. The configuration space realist is positing multiple physical spaces, connected by genuine dependence relations--that is far from a conservative account of what the world is like!

All in all, the configuration space realist who also accepts the governing conception of the wavefunction seems to be on fairly shaky footing. On the one hand, the main motivations for their theory seems to be premised on the idea that it is relatively straightforward and conservative. On the other hand, in order to make sense of the fact that the wavefunction-field answers reason-why questions about the behavior of quantum systems, they need to explicitly accept a metaphysics that is deeply surprising. This doesn't mean configuration space realism is a non-starter. But in order to defend their view against rival accounts of quantum ontology, the configuration space realist is going to need to get deep in the weeds with respect to precisely what kind of straightforwardness and precisely what kind of conservatism is important when interpreting physical theories, and why. These kinds of arguments are rarely decisive.

3 Conclusion

When making claims about the explanatory role of the wavefunction it is important to distinguish between the claim that the wavefunction plays a role in answering why-should-we-expect questions about the behavior of quantum systems, and the claim that the wavefunction plays a

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[27] In the Bohmian version of configuration space realism, the high-dimensional space will include the wavefunction field *and* a single "uber particle". I will set this complication aside.

[28] Ney forthcoming, section 3, contains the first real in-depth treatment of this question.

[29] This idea can be traced back to Einstein 1948.

[30] As I read her, this is the position that Ney forthcoming ultimately ends up endorsing.

role in answering reason-why questions about that behavior as well.

If we only accept the former, then the explanatory role of the wavefunction places few, if any significant constraints on what the wavefunction can be. One of the key claims of this paper, however, has been to argue that we should not only accept the former claim--we should accept the latter claim as well. The view that the wavefunction also plays a role in answering reason-why questions about the behavior of quantum systems is what I call 'the governing conception of the wavefunction'.

Insofar as we accept the governing conception of laws, it will constrain the possible accounts of quantum ontology that we might give. First, and most obviously, we should reject QBism and pragmatic accounts of the wavefunction. Second, it will be quite challenging to be a configuration space realist. And of course these are only the first steps in a much more detailed analysis that would involve the discussion of alternative accounts of quantum ontology besides the ones mentioned here and the ways in which the governing conception of the wavefunction impacts those accounts.[31] That is work yet to be done. But in closing let me also note that insofar as we accept the governing account of the wavefunction, our understanding of what the wavefunction could be will only be as good as our understanding of various possible dependence relations. It may be, then, that those who are attracted to this view should not focus exclusively on the existing literature on quantum ontology, but also make sure they are immersed in discussions of causation, grounding, governance, and other kinds of dependence relations that tend to take place in metaphysics texts. A better understanding of these relations has the potential to reveal both surprising complications for existing accounts of quantum ontology, and to inspire alternative accounts that have been overlooked or misunderstood in the current literature.

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[31] One might wonder whether the governing conception of the wavefunction is compatible with the view that the wavefunction represents a law or the view that the wavefunction represents the dispositional properties of the particles in the quantum system. The answer is that it will depend on whether one can make sense of the idea that laws or dispositional properties either cause the behavior of quantum systems, ground the behavior of quantum systems, or stand in some other dependence relation to that behavior. One way to put this is to say that combining the governing conception of the wavefunction with a nomological or dispositional account of the wavefunction will require making sense of the idea that laws or dispositional properties are able to govern.

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