Can Bohmian Mechanics Make Sense of Local Reductive Explanation?

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Abstract

The success of science consists, in large part, in local reductive scientific explanations; however, it's far from clear how to understand these from within the framework of Bohmian Mechanics. That's because local reductive explanations in quantum theory standardly require reference not just to particle positions but additionally to features only found in the wavefunction. And yet, recent Bohmian literature has offered metaphysical interpretations of the wavefunction as a non-local field, law, or universal disposition. In order to make sense of such explanations, the Bohmian should engage with the project of articulating an ontology of effectively localised wavefunctions. I consider ways in which this project may be developed, but note significant technical and conceptual challenges.

Keywords: de Broglie-Bohm; Bohmian Mechanics; Quantum Mechanics; Explanation; Locality; Holism

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1 Introduction

Very many of the scientific explanations with which we are most familiar may be called ‘local reductive explanations’. These are explanations that account for the properties or behaviour of some entity in terms of its parts and their interactions. In this paper I argue that, due to its peculiarly non-local metaphysics, Bohmian mechanics (i.e. the modern formulation of the de Broglie-Bohm interpretation) has trouble making sense of local reductive explanations. In other words, the Bohmian cannot straightforwardly answer the question: in virtue of which local structures are local reductive explanations available?

The core argument is that more than just particle positions are required in order to explain many quotidian properties of familiar objects. Quantum mechanical explanations appeal to locally defined wavefunctions as a matter of course.[1] However, the Bohmian metaphysics includes no viable

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[1] The measurement problem may prompt worries that there are no explanations in ordinary quantum mechanics – the goal of this paper would then be to explore how metaphysical interpretations of Bohmian mechanics can recover the explanations that ordinary quantum mechanics seems to provide.

candidates for localised wavefunctions. As such, all putative local explanations are understood as implicitly referring to the metaphysical counterpart of the holistic global wavefunction.

Explanations of the effects of billiard ball collisions refer to the properties of the balls and some extra local facts. It's also standard for explanations in quantum mechanics of, say, the emission spectrum of carbon dioxide or the stability of atoms to refer to local facts including the locally defined quantum state. This prompts the question for the metaphysical interpretation of Bohmian mechanics: what is the metaphysical counterpart of that locally defined quantum state? Each candidate Bohmian metaphysics considered below posits only global holistic counterparts to quantum states, and it's not at all clear how a local reductive explanation may be recovered from these. I go on to canvass options for resolving this puzzle.

This paper is, thus, motivated by a naturalistic concern – that our vast array of scientific explanations work as they seem to. That is, that they explain in virtue of the local features of the world to which they appear to refer. To reject this claim would be to force a wholesale revision of much of science. So the simplest strategy – the one that I advocate – is that the Bohmians get on board with the programme of identifying local parts of the wavefunction that can play the required explanatory roles. The alternative approach – one that I suspect will be popular among significant parts of the Bohmian research community – is to explain how it is that local reductive explanations seem to be available notwithstanding that the metaphysical backing for such explanations is in fact holistic. Local reductive explanations feature throughout science, and some account of how alternatives to such scientific explanations may be offered is necessary. This strategy, however, requires detailed work elaborating how we could be in such systematic error regarding the referents of our scientific explanations. I discuss this further in §5, and claim that it will require serious engagement with decoherence theory among other technical tools.

My argument does not presuppose that local reductive explanations are always available but rather holds that any adequate interpretation of Bohmian mechanics had better give us the resources to identify sufficiently localised ontology in order to account for those explanations that we find in successful science. Failure to make sense of such explanations would lead to a far more revisionary theory than Bohmian mechanics is claimed to be; in particular, this failure is at odds with the Primitive Ontology approach often marshalled in defence of Bohmian mechanics. Thus, in order to account for the availability of such explanations Bohmians should engage with the non-trivial project of articulating a metaphysics for parts of the wavefunction localised to space-time regions.

In addition to their role in defending Bohmian mechanics, primitive ontology arguments also play a role within the debate over the proper space for Bohmian particles; see Chen (2019) for a review of that debate. Here, I restrict attention to views which take the space of particles to be 3D space. Perhaps it's the case that Albert's 'marvellous point' (see Albert (1996), Loewer (1996), and Ney (2021)) is able to recover a species of local reductive explanation. But such explanations are only local in an extremely high-dimensional configuration space. In our familiar 3-dimensional space, such explanations are still highly non-local. Thus, such theories still offer a radical departure from commonplace scientific practice, and related intuitions: the impenetrability of the table is explained in terms of extremely spread out features of the whole universe. While this approach may satisfy a certain kind of locality constraint, it certainly does not accord with the kinds of local reductive explanation standardly offered in science, and so does not offer a solution to the problem pressed here.

Nor is a solution available via the view sometimes known as 'BoHumeanism' – advocated by e.g. Bhogal and Perry (2017), Esfeld (2014), and Miller (2014), and critiqued by Dewar (2018). The BoHumean may seem to be in a better position with respect to local reductive explanation than the more standard Bohmian – that's because their ontology lacks the non-local wavefunction. However, the BoHumeans are faced with the same dilemma as above: either they must work to construct an effective local wavefunction out of the Bohmian particles – no straightforward feat given that the local particle configuration radically under-determines the local wavefunction, or they must replace all standard scientific explanations that refer to the wavefunction and the particles with substitute explanations that refer just to the particles. BoHumeans have suggestions about how to do the latter on a global basis, but the prospects for providing local explanations without a wavefunction are fairly dim, as discussed further in §2. Otherwise all explanations will depend on the global distribution of particles, from which the global wavefunction is supposed to be recoverable by the BoHumean. While it's conceivable that a BoHumean would be able to come up with an error theory to account for the availability of local reductive explanations in science, this has not yet been done. Thus, in line with the mainstream in recent Bohmian literature, I assume a dualist ontology for Bohmian mechanics where both the particles and the quantum state are both ineliminable ontological posits.

In §2, I give more detail as to the kinds of local reductive explanation relevant to this paper; I go on to argue that the primitive ontology approach, which is advocated by many Bohmians, presupposes that such explanations are available. In §3 I briefly characterise Bohmian mechanics. In §§4-5 I spell out two different interpretations of Bohmian mechanics: the most popular approaches which are based on non-local metaphysics, and an initial suggestion for a more localised approach. In §6 I consider some metaphysical options for localised Bohmian mechanics. In §7 I conclude.

2 Local Reductive Explanation

Where the properties of a given macroscopic entity may be explained by or derived from the properties of its parts and the details of their interactions, along with some facts about the local environment, local reductive explanations are available. Such local explanations are ontic in the sense that they are underwritten by parts of the world. I do not assume that such explanations are always available or that all properties may be locally reductively explained, but in general the methodology of science is to explain the properties of a whole in terms of the parts, their interactions, and their local environment, and such methodology is often successful; see Glennan (2017) for evidence of the ubiquity of this mode of explanation.

It's the contention of this paper that any adequate metaphysics had better allow us to understand why such explanations work as they do – that is, to show that sufficient local ontology is available to back local reductive explanations. And it would count as a serious strike against any metaphysics if it seemed incompatible with the availability of such explanations. Note that, while such explanations form a major part of the evidence for local reductionism, I am not claiming that any acceptable metaphysics need be compatible with local reductionism if compatibility with local reductive explanation can be otherwise established.

It is, therefore, a constraint on Bohmian mechanics and interpretations thereof that they can make sense of such local reductive explanations. The Bohmian is, at this stage, faced with a choice. They may either argue that such explanations are illusory, or they may articulate how Bohmian mechanics is compatible with such explanations where they are available. The problem with endorsing the former option is that this would render the apparent success of such explanations miraculous. Thus, in this paper, I investigate the latter option. My goal is to pursue ways of establishing compatibility with such explanations notwithstanding the holism advocated by many Bohmians.

To understand local reductive explanations we may consider classical mechanics as a comparison class. One of the differences between classical mechanics and Bohmian mechanics that's salient for our purposes is brought out by Callender (2015), building on Holland (1993).

In the Hamilton-Jacobi formulation of classical mechanics, given a locally defined action, specified by a local classical potential and a particle with an initial position and momentum, one may predict the entire time evolution of that particle's position. One consequence of this is that we can decompose the dynamics into local parts. That is, we can take some set of particles and local potentials, and determine the entire time evolution of those particles' positions.

The difference in Bohmian mechanics is that trajectories of particles depend on global rather than purely local features. In the quantum Hamilton-Jacobi formulation, trajectories depend not only on the local potential but also on what's known as the 'quantum potential', which is defined in terms of the wavefunction ($Q = \frac{\hbar^2}{2m}\frac{\nabla^2|\psi|}{|\psi|}$). Holland (1993, p. 37): "in quantum theory … two particles that start with the same $\boldsymbol{x_0}, \boldsymbol{p_0}$ do *not* in general pursue the same trajectory in the same potential V". Insofar as the wavefunction isn't decomposable into local parts then such trajectories are globally rather than locally dependent.[2] As will be developed in the rest of the paper, the prospects for making sense of local reductive explanations in Bohmian mechanics depend on the extent to which wavefunctions are decomposable into their local parts.

The claim that the wavefunction plays an essential explanatory role should not be controversial. In his discussion of the relationship between Bohmian mechanics and observational evidence Maudlin (2010, p. 124) acknowledges the essential role of the wavefunction to everyday explanations: "If the numbers are painted on [the measurement device], then the locations of the numbers may well be determined more directly by the

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[2] Though, as discussed below, the Bohmian trajectories may be non-locally determined even if the wavefunction is effectively localised.

wavefunction of the device than by its configuration. That's fine, since it has both." As will be discussed in the next section, for Maudlin the wavefunction is highly non-local, thus such explanations are rather more holistic than they might appear.

First, though, it's worth giving a more heuristic account of local reductive explanation in order to have an example in mind for the following discussion. Consider the impenetrability of the surface of a metal table to my hand. A rough explanation of this property is offered by French (2014, pp. 165–166): "the solidity of my table is explained by the way in which electrons occupy the relevant atomic states, which in turn is explained by the Pauli Exclusion Principle, or, more fundamentally, the anti-symmetry of the relevant wave-functions and the role of Permutation Invariance".

Importantly, this explanation depends on the locally defined wavefunction, which includes the relevant states that the particles of the table and of my hand may occupy. Any attempt to explain this just in terms of the positions of those particles would be radically under-determined because the Pauli exclusion principle doesn't hold just of particle positions – two fermions may occupy the same position states so long as their other quantum numbers differ. As such, even this extremely simplified explanation requires reference to local wavefunctions. Below I consider options for providing such wavefunctions within a Bohmian ontology.

To give a more complete explanation of the solidity of the table, one would also have to demonstrate that my hand may not tunnel through the table. This will again involve reference to local or effective wavefunctions, this time via decoherence theory; see Rosaler (2016) for an account of how this is employed in local reductive explanations across various interpretations of quantum mechanics.

Crucially, I do not claim that local reductive explanations are available at every scale for all systems. Quantum entanglement implies that some systems are, at least, non-separable. This means that some of their properties are predictable when considering the whole but not the parts separately. Likewise, Newtonian gravitational theory is non-local, and classical objects' behaviour in the presence of a non-uniform gravitational potential is, thus, not locally reductively explicable. I only require that the metaphysics for Bohmian mechanics allows us to make sense of the apparent success of local reductive explanations in the contexts in which these are found.

2.1 Primitive Ontology and Local Reductive Explanation

The primitive ontology argument has been developed in most detail by Valia Allori. I'll restrict discussion to two aspects of the argument: that a quantum theory ought to, where possible, maintain similarity to classical modes of reasoning and explanation; and that an adequate fundamental theory ought to posit entities localised in space and time which are sufficient to allow for reductive explanations.

Allori (2013, p. 66) discusses the relationship between quantum and classical explanations as follows:

> the transparency of an object such as a pair of glasses can be explained in terms of the electromagnetic forces acting between the particles composing the glasses, which are such that incoming light rays will pass through them. Similarly for fluids … In addition, the behavior of gases is accounted for by considering them as composed by noninteracting particles colliding with one another. … These examples show how we have a clear and straightforward scheme of explanation in the classical framework: given the primitive ontology at the microscopic level, one can employ standard methods to determine the properties of familiar macroscopic objects. This is possible because classical theories have a primitive ontology, so for any other fundamental physical theory with a primitive ontology we could employ an explanatory scheme developed along the same lines.

This quote exemplifies just how close the explanations considered by Allori are to the reductive explanations considered above. My claim in this paper is that in order to recover the "clear and straightforward scheme of explanation in the classical framework" within Bohmian mechanics, the wavefunction must be localised.[3]

Allori's view is that the recovery of classical modes of explanation and understanding is an important constraint on the metaphysics of quantum theories. I claim that such arguments could equally be applied to justify the use of local reductive explanation as a constraint.

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[3] See Wilson (2013) for a critique of the view that the classical scheme of explanation is straightforward.

A second strand of primitive ontology arguments appeal to the requirement that scientific theories are fundamentally about physical stuff distributed in space-time; it's claimed that this is necessary for "connecting theory to data" (Maudlin (2019, p. 202)) – one finds analogous reasoning in Esfeld et al. (2013) and Goldstein and Zanghì (2013) among others. My aim here is not to undermine such reasoning but to point out that the principle on which such reasoning relies equally tells against non-local wavefunctions insofar as such wavefunctions are an intrinsic part of the theoretical apparatus and are crucial to its explanations and predictions. Therefore, those who advocate primitive ontology arguments ought to be motivated to develop the project of localising the wavefunction ontology as discussed below.[4]

An appeal to locality is made in the contexts of arguments for making sense of local reductive explanation and for primitive ontology. Both theses thus rely on the presumption that in order to connect our theories with the world we need to refer to locally contained parts of the world. On the other hand, while local reductive explanations are found across a wide variety of scientific disciplines, the discussion of primitive ontology is much more local to physics, and rather more historically contingent.[5]

These connections between the arguments illustrate the tension in a position that defends primitive ontology but advocates a holistic metaphysics with a non-local wavefunction. The work in §5 offers a suggestion for the Bohmian primitive ontologist: they might retain primitive ontology if they do the work to localise the wavefunction. In other words, my goal in this paper is to show how one can defend Bohmian mechanics and account for the widespread success of local reductive explanations; the upshot of considering primitive ontology arguments is that many Bohmians already seem to be committed to both positions.

In the following sections I canvass two classes of interpretation of the wavefunction in Bohmian mechanics, and argue that only the interpretation where the wavefunction is effectively localised can account for local reductive explanations.

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[4] For more general critiques of primitive ontology arguments, see e.g. Ney and Phillips (2013).

[5] Though Glennan's (2017) reference to 'entities' or 'parts' may function as a similar argument. Thanks to an anonymous reviewer for this observation.

3 Bohmian Mechanics

Bohmian mechanics has a dualist ontology.[6] The theory consists of a wavefunction that represents the quantum state and evolves deterministically according to the Schrödinger equation, and a configuration of particles whose positions evolve according to the guidance equation.

Assume that the wavefunction is written as $\psi(x,t)$. Then, without loss of generality that wavefunction may be written in polar form as $\psi(x,t) = R(x,t)e^{iS(x,t)}$, where R and S are real functions and S is the phase. The guidance equation for particle k with position q_k is then:

$$\frac{dq_k}{dt} = \frac{\nabla_k S(x,t)}{m_k} \tag{1}$$

This equation tells us that the position of any particle depends on the entire wavefunction. The wavefunction evolves according to the Schrödinger equation:

$$i\hbar\frac{\partial\psi(x,t)}{\partial t} = \hat{H}\psi(x,t) \tag{2}$$

While the evolution of particles' positions depends on the wavefunction, the evolution of the wavefunction is totally independent of particle positions. For further details of Bohmian mechanics see, e.g., Allori and Zanghì (2004), or almost any of the articles cited below.

All the views I'll discuss in this paper hold that the configuration of particles is a configuration in our familiar 3D space. A controversy that I do consider lies, however, in the metaphysics of the wavefunction. In the next two sections I divide interpretations of the wavefunction into two camps: one which holds that the wavefunction is irreducibly non-local in 3D space, and the other which allows that the wavefunction may be effectively localised into regions of 3D space.

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[6] As noted above, I do not consider BoHumean monist views defended by e.g. Miller (2014) because I am much less sanguine about the prospects of making sense of local reductive explanations on these views.

4 Non-local Wavefunction Ontology

A clear account of Bohmian mechanics is found in Maudlin (2019). Maudlin argues that, while the particle configuration is a configuration in 3D space, the quantum state is represented by the wavefunction in 3N-dimensional space. As such, on Maudlin's view the wavefunction is a non-local object. As will be discussed in §6, Maudlin also expresses doubts about the cogency of attempts to localise the wavefunction to regions of 3D space.

> The wavefunction assigns a complex number (or a complex spinor) to every point in this abstract [3N-dimensional configuration] space. The second ontological posit of our theory [after the particles in 3-dimensional space] is a real, physically objective quantum state, which is represented (somehow) by this wavefunction … Our total theory, at this point, has the following structure. There is a classical space-time, with three spatial dimensions. The local beables in this space-time are N particles, which always have definite positions and move around. Each particle is characterised by a mass m_k. There is a single nonlocal beable, the quantum state, which is represented by the wavefunction ψ.
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> [Maudlin (2019, pp. 140, 142)]

Maudlin (2013) claims that the quantum state is *sui generis*, that it's universal, and that quantum states of sub-systems are ontologically posterior to quantum states of the world. This does seem to grant a degree of holism. The question is whether one can still make sense of local reductive explanations notwithstanding this holism – I'll argue that we cannot.[7]

First, though, I will canvass two alternative ontologies for the wavefunction in Bohmian mechanics. Both candidates are reviewed in Esfeld et al. (2013), which focusses on nomological interpretations of the wavefunction. Setting aside the BoHumean option, both remaining options are dualist with a configuration of particles in 3D space and the wavefunction as a disposition, or as a governing law.

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[7] Note that, unlike Norsen (2010) and Norsen, Marian, and Oriols (2015) I am not motivated by worries about the space in which the wavefunction is defined. Thus, if Maudlin's approach were able to make sense of local reductive explanations I would not find it objectionable. I consider Norsen et al.'s approach further in §5.2.

According to the dispositional approach, "there is exactly one disposition that fixes the form of motion of all the particles by fixing their velocities, thus fixing the temporal development of the configuration of particles. That single disposition is sufficient to account for the motion of any particle (or any sub-collection of particles) in all possible circumstances." (Esfeld et al. (2013, p. 787)). Some worries are considered that the disposition will then be time-dependent, since the wavefunction evolves, but these aren't the subject of my analysis here.

One stated advantage of dispositional approaches over realism about the wavefunction defined in configuration space (see e.g. Albert (1996) and Ney (2021)), is that the disposition lives in the same space as the particle configuration. This is claimed to obviate a particular worry, namely, that a wavefunction in configuration space could not interact with the particle configuration in 3D space. This worry is considered, for example, in Callender (2015).

An alternative to the wavefunction-as-disposition is to consider the wavefunction simply as a law. This is the view advocated by Goldstein and Zanghì (2013). One reason they think it's appropriate to consider the wavefunction as a law, notwithstanding its apparent contingency and time evolution (to which they have other rejoinders) is that "in Bohmian mechanics there's no back action, no effect in the other direction, of the configuration on the wave function … A second point is that for a multiparticle system the wave function … is a weird field on configuration space … The fact that Bohmian mechanics requires that one take such an unfamiliar sort of entity seriously … suggests to us … that you should think of the wave function as describing a law, not as some sort of concrete physical reality" (Goldstein and Zanghì (2013, p. 97)).

So, amongst the Bohmians who include the wavefunction in their ontology there are three major options: the wavefunction defined in 3N-dimensional configuration space represents the non-local quantum state in 3-dimensional space; the wavefunction represents a single disposition; or it represents a law.

The question going forward is whether a reading of any of these options allows one to understand the widespread availability of local reductive explanations. In order to address this question, I'll consider how our heuristic local reductive explanation – that of the impenetrability of the table – may proceed. In §5 I'll consider how the wavefunction may be localised.

Maudlin's ontology for the wavefunction is the most explicitly holistic: "[u]ltimately, the entire physical universe is one large interacting entity. But as a practical matter we can never treat it as such" (Maudlin (2019, p. 150)). Maudlin goes on to argue that we can explain the fact that we can break up our physical theories into localised subsystems by reference to the 'local beables'. For Maudlin, then, the fact that Bohmian particles have local positions is as much locality as the Bohmian can achieve.

However, this alone isn't sufficient to allow for local reductive explanations. Just based on the particle positions it's not possible to explain the impenetrability of the surface of my table. Such an explanation – as discussed in §2 – requires reference to the wavefunction of such particles. That wavefunction is locally radically under-determined by the particle positions. In fact, the entire global particle configuration is required to specify the parts of the wavefunction that represent observed physics, as opposed to the physics found in other branches of the universal wavefunction.[8] Therefore, any explanation of the impenetrability of a table would require reference to the global field and particle configuration distributed over the entire universe.[9] This is clearly a holistic picture unless it is somehow possible to define localised parts of this field – an option considered in the next section.

On the disposition view, there is a 'single disposition' for all the particles. Taken literally this also implies radical holism. A traditional view that includes dispositions would specify local manifestation conditions, while the universal single disposition on the Bohmian view would only have universally specified manifestation conditions. Yet that disposition is required to explain the impenetrability of the table. In other words, the table would not manifest impenetrability because of the condition or disposition of its constituents but because of some conditions spread throughout the entire universe. As such, if the world only has one disposition, local reductive explanations are not available.

As Esfeld et al. (2013, p. 793) note "[t]he holistic disposition grounding the law is part and parcel of the primitive ontology because it is not

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[8] Thanks to an anonymous reviewer for pressing me on this point.

[9] The multifield approach (Belot (2012) and Hubert and Romano (2018)) is somewhat better off. Since the multi-field lives in three-dimensional rather than 3N-dimensional space it can, in principle, be broken down into local parts, however the dynamical evolution of such parts is wholly non-local; so, unless a programme of the kind considered in §5 is carried out, this approach will also not account for local reductive explanation.

derived from anything and belongs to that which the quantum formalism represents or refers to. It is a beable existing in three-dimensional space, albeit not a local one".

The law view is more complicated to analyse. If we are to think of the law as productive, then this ontology is holistic because there's nothing local which makes it such that the law produces the impenetrability of the table. In some sense, the same story should be told here as in the disposition case. Local reductive explanations presuppose that knowledge of the initial conditions of some local system together with the laws allows one to predict and explain the future of that system. The Bohmian who interprets the wavefunction as a universal law has no such option. Their view entails that no local facts or entities underwrite explanations of the properties of my table, and that such explanations instead depend on reference to the prior state of the entire universe. This is apparent when one compares classical with Bohmian Hamilton-Jacobi theory, as in §2. While classically, given the locally defined action, one may predict the trajectory of a single particle; in Bohmian mechanics this is not possible – one needs, in addition, the quantum potential which depends on the entire universe; as discussed below, effective wavefunctions may be formulated in cases where the quantum potential is negligible, but the question how to construct the nomic counterpart of the effective wavefunction has not been addressed. Thus, it's clear that even on the law view, Bohmian mechanics will fare far worse in allowing us to make sense of local reductive explanation than classical mechanics.

The consequence is that explanations of quotidian phenomena such as the impenetrability of a table and the trajectory of a bouncy ball require reference to the rest of the universe; in order to explain properties of tables positions of particles are insufficient and we must refer to the wavefunction, but on the views considered in this section the wavefunction corresponds to a global irreducible entity. We can no longer claim that reductive explanations of the properties of tables refer just to parts of tables and their interactions, rather such explanations must refer to something not localised to *any* sub-region of the entire universe. As such, this metaphysics amounts to radical holism.

One possible objection to these claims is that any explanations which depend on laws or dispositions are intrinsically non-local for any theory. If the explanatory force rests on the nomic facts or entities rather than on some local states of affairs, then perhaps non-locality should be abandoned altogether. However, it's important to note that the non-locality of the Bohmian wavefunction law/disposition is far more radical than that found in classical theories: the way in which the wavefunction law/disposition operates requires reference to the entire global state. That is, the wavefunction law/disposition is not only non-local in the way that every nomic entity is, there is a far more significant degree of non-locality found here.

All those views which hold that the wavefunction is fundamentally irreducible to its effectively localised parts are committed to holism, and, thus, it's difficult to see how one could allow for local reductive explanations on such views; this is because the local configurations of particle positions are insufficient to explain the properties of everyday objects.

5 Local Wavefunction

The guiding presumption for this paper is that quantum mechanics does apply to local systems. It's standard practice to apply the Schrödinger equation to subsystems and this practice is successful. The problem is that this practice is, on the face of it, at odds with the metaphysics defended by Bohmians and canvassed above. In this section I articulate a number of routes that a Bohmian might take in order to make sense of how quantum mechanics is in fact used.

Then, in §6, I discuss some candidate metaphysical options which build upon the physics discussed in this section. The project in both sections is by no means complete, but, in the following, I suggest potential avenues of exploration.

I'll first argue that the degree of holism identified in the ontology of non-local wavefunctions is not required by quantum theories as a consequence of Bell's results. I'll then consider the most prominent recent Bohmian option for localising the wavefunction, known as the 'conditional wavefunction'. I'll argue that the conditional wavefunction is unable to do the required work. Lastly, I'll consider an alternative localisation which appeals to effective wavefunctions and local quantum states, and I'll end this section by raising some further issues posed by this approach.

5.1 Locality

An urgent rejoinder will likely have occurred to some readers. This is that the consequence of violating the Bell inequalities is some degree of non-locality. As such, in order to be empirically adequate any realist quantum theory had better be somewhat non-local. I agree with this, but I demonstrate that an ontology may be non-local and yet fall short of full-blown holism, and suggest that a novel metaphysics for Bohmian mechanics may inhabit this intermediate space.

Consider the following distinction between kinds of locality:

> *Local Action*
>
> If A and B are spatially distant things, then an external influence on A has no immediate effect on B.
>
> *Separability*
>
> Any physical process occurring in spacetime region R is supervenient upon an assignment of qualitative intrinsic physical properties at spacetime points in R.
>
> [Healey (1997, pp. 23–24)]

Healey (see also e.g. Myrvold (2016)) argues that in order to satisfy the empirical violation of the Bell inequalities an interpretation of quantum mechanics need only violate Separability, while Local Action may be retained. Although violation of either principle would undermine some putative local reductive explanations, the versions of Bohmian mechanics considered above would seem incompatible with all such explanations.

Non-Separability is rather a broad notion, but, as defined above, it is compatible with local properties being explained in terms of the parts of local systems. Thus, in principle, non-Separability is consistent with the fairly thoroughgoing availability of local reductive explanations. On the other hand, violation of Local Action would seem to undermine local reductive explanations to a far greater degree. Insofar as entities in one region are influenced by those arbitrarily far from them, local predictions and local explanations of properties are under threat; however this may be mitigated if such dynamical dependence on distant entities can be relatively contained. Bohmian mechanics involves violation of Local Action for particles by construction; but if wavefunctions can be shown to exhibit effective separability in some contexts, the prospects for compatibility with local reductive explanation are significantly rosier. The strategy is, thus, to see just how far the Bohmian may go in containing the failures of locality within their metaphysics.

5.2 Conditional Wavefunction

In the literature advocating for Bohmian mechanics, descriptions of proper subsystems of the universe generally appeal to the conditional wavefunction. This is our first candidate for a localised wavefunction. Maudlin (2019, pp. 153–154) explains the strategy. He notes that in general we cannot express the system and environment states as a product state: "[s]ince the wavefunction in this theory [Bohmian mechanics] never collapses, systems get more and more entangled. Even if two systems start out in a product state, interactions can easily entangle their wavefunctions".

Maudlin proposes the conditional wavefunction as a resolution. Consider the wavefunction of 100 particles $\psi(q_1, q_2, \ldots, q_{100})$. Then "represent the actual locations of the particles with capital letters: $Q_1, Q_2, \ldots, Q_{100}$" (ibid.). Then, if, say, we are interested in just the subsystem comprising the first 25 particles, we just plug in the "actual location" of the environment, which comprises the remaining 75 particles (note that the environment-subsystem split is arbitrary):

$$\phi_{\text{cond}}(q_1, q_2, \ldots, q_{25}) =_{\text{df}} \psi(q_1, q_2, \ldots, q_{25}, Q_{26}, Q_{27}, \ldots, Q_{100}) \tag{3}$$

Here, ϕ_{cond} is the conditional wavefunction of the subsystem, but it does not involve abstracting from the wavefunction in other regions, it only leaves out explicit reference to the particle positions in other regions. That is, while the written form of $\phi_{\text{cond}}(q_1, q_2, \ldots, q_{25})$ does not mention the positions of particles 26-100, the mathematical object still depends on the positions of such particles. If, at some later time, those particles are in different positions (which, generically, they will be) the wavefunction will take a different form, and its local description in the region that describes particles 1-25 will also change. While the global wavefunction does not depend on the particle configuration, the local wavefunction that represents the properties of a local system will differ if the local particle configuration changes. To see this consider the case where the particles that correspond to q_7 and Q_{56} are entangled. The measurement that determines the spin of Q_{56} in some basis may force q_7 to behave rather differently than it would have if Q_{56} had been measured in some other basis or not measured at all. It's not the case that by formulating our physics in terms of the conditional wavefunction we've avoided such non-locality.

As such, this wavefunction is not localised; with respect to the metaphysics of the wavefunction, this approach is equivalent to that considered in the previous section. As Maudlin (2019, p. 154) notes "[f]rom an ontological point of view, then, the conditional wavefunction does not postulate anything new. The fundamental ontology of the theory still is completely specified by just the universal quantum state, the space-time structure, and the particles".

By contrast, Norsen (2010) and Norsen, Marian, and Oriols (2015) suggest an approach which also depends on the conditional wavefunction, though takes so-called 'single-particle wave functions' to be ontologically primary. While this does satisfy their stated motivation of understanding the wavefunction in 3D space, it does not allow one to make sense of local reductive explanations. This is because each single-particle wavefunction requires as input the instantaneous positions of every other particle in the universe, and thus is not localised to any particular region of 3D space.[10]

The fact that conditional wavefunctions are not effectively localised and are not independent from *any* part of the universal wavefunction in other regions is a direct consequence of entanglement and the non-Separability it engenders. A more sophisticated approach is needed to excise some part of the wavefunction of an entangled system, and, thereby, to allow for local reductive explanations that refer to the localised wavefunction.

An alternative to the conditional wavefunction is the conditional density matrix (W_{cond}) advocated by Dürr et al. (2005). However W_{cond} is defined along the lines of the conditional wavefunction discussed above; I paraphrase their account: define subsystems S_1 and S_2 as encompassing all those particles in regions R_1 and R_2. When we condition on some particular subsystem, we are conditioning on the region containing that subsystem. Assume that q_i describes the configuration of particles comprising S_i in R_i. The trick is then to insert Q_2 into our equations representing the actual configuration of particles in R_2. The conditional density matrix is

$$\hat{W}_{\text{cond}} = |\psi(q_1, Q_2)\rangle \langle\psi(q_1, Q_2)| \tag{4}$$

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[10] The second approach discussed in Norsen, Marian, and Oriols (2015) likewise depends on conditional wavefunctions, but also suggests a new theory, and so, given its in-principle empirical distinguishability, should be assessed by experiment.

The distribution Q_1 given Q_2 can be calculated by taking the partial trace; this can be used to give an effective dynamics for Q_1. Dürr et al. (2005, p. 463) note: "W_{cond} depends on the actual value of Q_2 and yields the true Bohmian velocity".

Once again this object depends on the actual global configuration of Bohmian particles, so cannot be taken to provide an effective localisation sufficient to underwrite the availability of local reductive explanations.

5.3 Prospects for a Solution

At this stage, we have exhausted the range of solutions offered in the recent Bohmian literature, and none abstracts away from non-local degrees of freedom; all, in effect, hide rather than abstract from such non-local parts. And such an approach does not give us the resources to account for the success of local reductive explanations.

So, how might progress be made in solving this issue and developing a metaphysics with spatially localised components? So far, we've considered top-down, or global-to-local approaches, and found that these do not do the required work. An alternative, and perhaps more promising strategy is to consider bottom-up or local-to-global approaches.

This latter strategy would more closely follow the practice of quantum physicists in representing the properties of quantum systems via a local quantum state, either in the form of a wavefunction or density matrix. Take some set of particles, and construct a Hamiltonian that takes into account relevant features of the local quantum system. This object is effectively localised and may evolve, under the right conditions, according to effectively local dynamics. A class of issues relating to particle individuality alongside questions about how the relevant part of the quantum state is to be identified remain. As such, this requires significant work, but, I claim, this is exactly the kind of work that a Bohmian metaphysician needs to do if their framework is to be adequate to local reductive explanations.

Under what conditions would the local quantum states provide an accurate representation of the properties of the quantum system in some spacetime region? When interference between systems is sufficiently suppressed, the local quantum state of a system accurately represents that system. If, on the other hand, there is significant interference between multiple systems, they are accurately represented only by the combined state.

Such conditions correspond to an effective version of the superorthogonality condition discussed by Maroney (2005). Two wavefunctions are superorthogonal if they are non-overlapping in the configuration space representation. They are effectively superorthogonal if they have relatively little overlap, and the quantum potential is negligible, see Bohm, Hiley, and Kaloyerou (1987); Rosaler (2015) develops related ideas in the framework of decoherence. When the wavefunction is effectively factorisable, we may treat spatially separated systems as effectively independent. The corresponding effectively localised quantum states or effective wavefunctions will count as sufficiently independent to represent local systems.

We need to consider superorthogonality and decoherence because otherwise we have no justification of the claim that our local quantum states accurately represent the physics in that region. If the goal is to explain how local reductive explanations work, we need to focus on circumstances where details of distant goings-on are (approximately) irrelevant. Those circumstances are precisely ones where interference between the regions is suppressed and the wavefunction overlap is minimised.

While those articles just referenced develop the physical conditions for localising Bohmian mechanics, none is focussed on the metaphysical questions that motivate the physicists and philosophers considered in §4. For example, Bohm, Hiley, and Kaloyerou (1987, p. 344) describe how, upon interaction with external systems,"quantum non-local correlations will be destroyed" and the system is to be modelled using effective wavefunctions. But, in the absence of specific advocacy for any particular ontology of the wavefunction, the question of what worldly entity the effective wavefunction represents is left unaddressed. Without such a localised ontology we cannot account for the success of local reductive explanations.

Note that the effectively localised wavefunctions are not absolutely local in the sense that they describe individual particles. Entanglement between nearby particles will rarely be suppressed sufficiently for an absolutely localised wavefunction to represent the physical situation even approximately. Thus, absolutely localised wavefunctions do not play a role in local reductive explanations. However, wavefunctions effectively localised to relatively small spacetime regions do play such a role.

Two further issues are notable, both of which may well be resolvable, but neither of which has been properly engaged with to this point. The first issue is to develop a framework for stitching together these local quantum states along with their entanglement relations in order to represent the nonlocal properties of combined quantum systems. The second is to account for the relation between the set of local quantum states and the global quantum state that governs the evolution of the trajectories of the Bohmian particles.

First, particular challenges will be associated with the representation of entanglement relations, though perhaps strategies considered in Glick and Darby (2020) will allow for progress. More generally, the global quantum state represents all the branches of the global quantum superposition, many of which correspond to radically different physics and would not normally be represented in any standard local wavefunctions. Thus the local wavefunctions will hugely underdetermine the global quantum state. In §6 I suggest that appeal to the concept of emergence may help us out here.

Second, recall that the quantum state in Bohmian mechanics has a dual role: it both represents some of the properties of quantum systems, and it determines the evolution of the Bohmian particles. However, localisation will, in general, require abstraction away from the entanglement relations between distant parts of our quantum systems. As such, approximation is involved in constructing local quantum states. According to Bohmian mechanics, particles have determinate positions at all times. In order to avoid inconsistencies between the trajectories predicted by different local quantum states, and in order for violation of Bell inequalities to be recovered, only the unique global wavefunction can determine the particles' trajectories.

One might worry that the radically holistic determination of the Bohmian particle trajectories would undermine any hope of recovering local reductive explanations. However, it's worth recalling that the predictions of Bohmian mechanics are probabilistic, and the actual particle trajectories are never directly observed. In fact, this is also partly the basis on which Bohmian Quantum Field Theories have been mooted; as Deckert, Esfeld, and Oldofredi (2019, p. 767) note: "while the statistics about the particle positions (which are encoded in the wave functions of the excitations thanks to Born's law) are Lorentz-invariant, the actual particle trajectories generated by the velocity law … are not". Given that our observed physics is Lorentz-invariant, such trajectories must remain hidden!

We now have a distinctly programmatic proposal for a localised version of Bohmian mechanics: there are localised particles with determinate positions, and local quantum states. These local quantum states may then be thought of as the effectively localised description of many properties of the system and a good local approximation to aspects of the global wavefunction which determines the trajectories. In the next section, I'll sketch out some metaphysical options for the relations between the global and local quantum states.

The question is whether, if sufficiently developed, this proposal would allow us to recover local reductive explanations. Given the empirical inaccessibility of the Bohmian trajectories, and the fact that the trajectories do not play a role in standard quantum mechanical explanations, I'd claim that the prospects for making sense of local reductive explanations are significantly improved. Armed with determinate local particle positions, and local quantum states in each region, we can make use of all the reductive explanatory tools developed within textbook quantum mechanics.

Note that the weirdness and counter-intuitive nature of Bohmian trajectories, see e.g. Norsen (2013) and Stomphorst (2002), is further evidence that these do not feature in standard quantum mechanical explanations. Rather, such explanations depend on features encoded in the local quantum state. We may explain the impenetrability of the table exactly as was done in §2 – the Pauli exclusion principle and the states available to quantum particles together with the positions of those particles determine the higher-level properties of the table.

To sum up the proposal: local quantum states in different regions of space-time represent the local properties of quantum systems and the non-local corelations between these states encode the non-Separability of the metaphysics. While the Bohmian particles have determinate, locally defined positions, the trajectories of such particles are determined non-locally. To reiterate, this proposal contains many technical and philosophical lacunae. Metaphysical options for an approach of this kind are considered below.

6 Local Wavefunction Ontology

Whereas in §4 I set out non-local metaphysical interpretations of Bohmian mechanics, in §5 I discussed strategies for localising Bohmian mechanics.

This begs the question: how should the latter framework be interpreted metaphysically?

A key observation made in previous sections is that the wavefunction in Bohmian mechanics has a dual role: it provides many of the details that are crucial to quantum mechanical explanations, and it governs the trajectories of the Bohmian particles. I argued that, in order to make sense of local reductive explanations, one has to pull apart these two roles. The local reductive explanations should be understood in terms of local quantum states together with particle positions, whereas the role in governing trajectories will be played by the unique global quantum state.

Separating these roles of the wavefunction creates challenges for some of the metaphysical options set out in §4. Both the dispositions and laws accounts of Bohmian metaphysics are realist about the wavefunction but crucially tie it to its role in determining the particle trajectories. On both accounts, the primary role of the wavefunction is to fix the evolution of the particle configuration.

Since the local quantum states do not determine the particle trajectories, there is no straightforward way of interpreting these objects as dispositions or laws. While there may be alternate ways of thinking about weakly emergent dispositions or higher-level laws, the development of such proposals would take me beyond the scope of this paper.

The remaining option is to understand the quantum state as outlined in Maudlin (2013; 2019). Maudlin's suggestion is that the quantum state is a *sui generis* entity "which is represented (somehow) by this wavefunction" (Maudlin (2019, p. 140)). Instead, one could think of a very large number of effectively localised *sui generis* entities, such as local quantum states in different regions of space-time. One would, in addition have the particles and their trajectories. These trajectories would then be determined by the global quantum state.

The next question is how to understand the relation between the global quantum state and local quantum states. Maudlin (2015) writes in favour of the distinction between fundamental and derivative ontology. Although he claims that the conditional wavefunction can play the role of derivative ontology, I argued above that it's better to think of this in terms of local quantum states, as only these are sufficiently localised to allow us to make sense of local reductive explanation. This derivative ontology may then be understood to emerge from the global quantum states.

One strategy for conceptualising the emergence relation is found in Wallace (2012) and Wallace and Timpson (2010); this builds on a real patterns framework where the localised density matrices correspond to real parts of the quantum state insofar as they represent stable patterns.

However, the Bohmian is likely to reject this option for reasons developed in Brown and Wallace (2005): the real patterns framework seems to reify all the empty branches of the wavefunction. Those parts of the wavefunction which do not contain particles may also instantiate stable patterns. The consequence is that the real patterns framework would imply that Bohmian mechanics also contains many worlds and that the particles are, in some sense, epiphenomenal; hence this is known as the 'Everett-in-disguise' objection. I do not wish to comment on the cogency of this objection here, rather I note that the Bohmians' best response is to reject the real patterns framework as an appropriate metaphysics for Bohmian mechanics.

The suggestion is, then, that we can think of the holistic global quantum state and the emergent local quantum states as both parts of our metaphysics, but reject the real patterns approach. One way to proceed would be to consider the fundamental quantum state as a unique *sui generis* entity from which the local quantum states weakly emerge in certain conditions. This would be compatible with local reductive explanations if an adequate account of weak emergence were available; see e.g. Franklin and Robertson (2022) and Knox (2016). The question how to account for weak emergence without implicitly endorsing a real patterns framework is not taken up here.

Note that I haven't ruled out other metaphysical options, nor, indeed, do I claim that a re-interpretation of the laws/dispositions approach won't allow for a localised metaphysics of Bohmian mechanics. I think that these are not only open research topics, but ones that Bohmians ought to pursue!

7 Conclusion

I have demonstrated that the Bohmian metaphysics, as standardly presented in recent literature, is inadequate to local reductive explanation and that philosophical and technical work remains to make it fit for purpose. The question is whether it is incumbent on the Bohmian to work to carry out that programme. I have argued that it is – that losing out on local reductive explanations would be to lose quantum theory, for that theory's success is constituted in large part by the vast array of local reductive explanations which it engenders.

One further consequence of failing to account for local reductive explanation is that Bohmian mechanics would be rather less intuitive than is often suggested. This would seem to undermine some of the claims made by advocates of the primitive ontology argument, discussed in §2.1. This argument has, in recent years, played a significant role in the defence of Bohmian mechanics in the philosophy literature.

As such, if advocates of Bohmian mechanics are to offer an adequate metaphysics, they had better get on board with this programme. My principal claim in this paper is that Bohmian mechanics is not straightforwardly compatible with local reductive explanations, however I do not wish to claim that the suggested solution is the only or best option for resolving this incompatibility; rather, other resolutions have not yet been offered in the literature.

To accept local reductive explanation involves localising the wavefunction. §5 gives us a programmatic discussion of how this might be carried forward. Whether or not that is adequate will of course depend on the precise way in which this picture is worked out. But I suggested above that some such explanations are feasible on this approach. Thus, the cost of this approach is, primarily, that there is a lot more work to be done both philosophically and with the technical aspects of the physics.

One might want to claim that the aim of the Bohmian metaphysical programme is to provide a fundamental metaphysics and that such a metaphysics should be holistic. The effectively localised metaphysics discussed here might therefore be dismissed as merely epistemic, and my project might be viewed as offering an error theory for local reductive explanations.

Insofar as error theories in terms of the conditional wavefunction are already available, I claim that these are inadequate. As such, what's developed here may be viewed as a suggestion for an alternative error theory which can explain how it is that local quantum mechanical descriptions and explanations are available. While I prefer to view this project as an alternative effectively localised metaphysics for Bohmian mechanics, I take it that either view provides sufficient motivation for advocates of Bohmian mechanics to engage.

The overall argument of this paper is that mere locality of particles, in a theory with a non-local wavefunction ontology, is insufficient to make sense of local reductive explanations but that there is a great deal of evidence that these are available. Any acceptable position must at least tell a detailed story to explain away the appearance of such explanations. While such a story has not been provided, the standard Bohmian account is incomplete.

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