QUANTUM ENTANGLEMENT, BOHMIAN MECHANICS, AND HUMEAN SUPERVENIENCE

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David Lewis is a natural target for those who believe that findings in quantum physics threaten the tenability of traditional metaphysical reductionism. Such philosophers point to allegedly holistic entities they take both to be the subjects of some claims of quantum mechanics and to be incompatible with Lewisian metaphysics. According to one popular argument, the non-separability argument from quantum entanglement, any realist interpretation of quantum theory is straightforwardly inconsistent with the reductive conviction that the complete physical state of the world supervenes on the intrinsic properties of and spatio-temporal relations between its point-sized constituents. Here I defend Lewis's metaphysical doctrine, and traditional reductionism more generally, against this alleged threat from quantum holism. After presenting the non-separability argument from entanglement, I show that Bohmian mechanics, an interpretation of quantum mechanics explicitly recognized as a realist one by proponents of the non-separability argument, plausibly rejects a key premise of that argument. Another holistic worry for Humeanism persists, however, the trouble being the apparently holistic character of the Bohmian pilot wave. I present a Humean strategy for addressing the holistic threat from the pilot wave by drawing on resources from the Humean best system account of laws.

Keywords: holism, Humean supervenience, quantum entanglement, reductionism.

1. Introduction

David Lewis's doctrine of Humean supervenience is one expression of metaphysical reductionism:

> It is the doctrine that all there is to the world is a vast mosaic of local matters of particular fact, just one little thing and then another . . . We have geometry: a system of external relations of spatiotemporal distance between points. Maybe points of spacetime itself, maybe point-sized bits of matter or aether or fields, maybe both. And at those points we have local qualities: perfectly natural intrinsic properties which need nothing bigger than a point at which to be instantiated. For short: we have an arrangement of qualities. And that is all. There is no difference without difference in the arrangement of qualities. All else supervenes on that.
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> [Lewis 1986: ix–x]

Lewis describes a metaphysics of point-sized individuals arranged in space-time and bearing intrinsic properties.[1] Lewis's world, his Humean manifold, is like a pointillist painting: fix the shape of the canvas and the pigment at each point, and all the complexity of the physical world emerges.

Lewis is a natural target for those who believe that findings in quantum physics threaten the tenability of traditional reductive metaphysics.[2] Such philosophers point to allegedly *holistic* properties or entities they take to be the subjects of some claims of quantum theory—specifically, claims concerning entangled quantum systems. Supposedly, these holistic features of the world do not supervene on the Humean manifold and so threaten to undermine not only Humean supervenience in particular but, more generally, any view that attempts to fully account for the properties of complex wholes in terms of the spatio-temporal arrangements of fundamental building blocks bearing intrinsic properties.

Tim Maudlin [2007: 50–77], for example, argues that quantum mechanics, realistically construed, poses an unassailable threat to Lewisian reductionism. Maudlin divides Lewis's Humean doctrine into two independent theses and takes realism about quantum mechanics to be strictly incompatible with one, which he terms 'Separability' [ibid.: 51]:

> SEPARABILITY The complete physical state of the world is determined by (supervenes on) the intrinsic physical state of each spacetime point (or each pointlike object) and the spatio-temporal relations between those points.

According to Maudlin and like-minded philosophers of physics, the realist about quantum mechanics must endorse a holistic thesis:

> METAPHYSICAL HOLISM There exists some whole with intrinsic properties at a time that fail to supervene on the intrinsic properties of and spatio-temporal—i.e. spatial—relations between its point-sized parts at that time.

The quantum realist who endorses METAPHYSICAL HOLISM because of the purportedly non-supervening features of some quantum wholes must give up SEPARABILITY. For suppose both METAPHYSICAL HOLISM and SEPARABILITY were true. Then, according to METAPHYSICAL HOLISM, there would be some system *S* with an intrinsic state at a time that failed to supervene on the intrinsic properties of its parts at that time plus their arrangement. According to SEPARABILITY, the state of *S* should still supervene on some or all of the Humean mosaic (so: just not the proper subset of the mosaic comprising *S*'s fundamental constituents). In that case, however, the state of *S* would not count as intrinsic to *S*, contrary to our supposition.

[1] Roughly, an individual's intrinsic properties are ones that, in contrast to extrinsic or relational properties, are logically and metaphysically independent of other, wholly distinct individuals [Lewis 1983].

[2] I take 'traditional' reductionism to treat the intrinsic properties of wholes as supervening on the intrinsic properties and arrangements of parts. I am not directly concerned with attempts at part-on-whole 'reduction', in which some wholes are taken to be more fundamental than their supervening parts—as in, for instance, Schaffer [2010].

Maudlin claims that any minimally realist interpretation of quantum mechanics will involve a failure of SEPARABILITY:

> The upshot is that no physical theory that takes the wavefunction [formalism of quantum mechanics] seriously can be a Separable theory. If we have reason to believe that the quantum theory, or any extension of it, is part of a true description of the world, then we have reason to believe that the world is not Separable.
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> [2007: 61]

Maudlin is not alone in his bleak assessment of the prospects for Lewisian metaphysics. Paul Teller [1989] and Jonathan Schaffer [2010] are two others who describe quantum mechanics as a threat to reductionism and who take this general threat to pose a specific challenge to Lewis's metaphysical outlook.[3]

Here, I aim to challenge the common conviction that quantum mechanics renders obsolete traditional reductionism, focusing in particular on Maudlin's dour assessment of the prospects for Lewis's Humeanism. After presenting a version of the standard non-separability argument for quantum holism (§2), I offer a brief overview of Bohmian mechanics, emphasizing that this theory plausibly rejects a key premise of the non-separability argument (§3). I point out that, thanks to the role of the pilot wave in Bohmian mechanics, the threat of holism persists (§4), but go on to suggest that a committed Humean may be able to address this threat by drawing on resources from the Humean best system account of laws (§5).

One preliminary clarification. Despite the popularity of the non-separability argument, there is already on offer one way for the Bohmian to retain a commitment to SEPARABILITY, or something close: she may adopt a version of the theory, described by Barry Loewer [1996] and defended by David Albert [1996, 2013], which takes the world to consist, fundamentally, of a single particle in a high-dimensional physical space and a field spread throughout that space. I will consider this view in more detail below (§4), but the main focus in this paper is a novel Humean gloss on a *many*-particle version of Bohmian mechanics, according to which there are, fundamentally speaking, many particles in familiar low-dimensional space-time. This should be a welcome alternative for the Humean who finds adopting Albert's revisionary metaphysics an uncomfortably high price to pay to maintain her reductive commitments.

2. The Non-Separability Argument from Entanglement

What is behind the widespread conviction that quantum theory is incompatible with Humean supervenience? One source is a particular line of reasoning

[3] Teller [1989: 214] puts it this way: 'Unless one takes a starkly instrumentalist attitude toward quantum theory, quantum theory tells us . . . that we must endorse what I call *Relational Holism*', the thesis that there are non-supervening entanglement relations. Schaffer endorses the non-supervenience described in METAPHYSICAL HOLISM and cites Lewis's Humean supervenience as a contemporary example of the 'Democritean pluralism' that 'cannot provide an adequate basis for entangled systems' [2010: 53]. Richard Healey is more measured in his assessment of the quantum threat to reductionism. He points out that a hidden variables theorist might avoid holism, but he does not fill in the details—and he seems to think that the Bohmian interpretation fails to count as a version of realism about quantum mechanics 'itself' [1991: 417fn].

about the formalism of quantum theory: the non-separability argument. The argument focuses on the quantum-mechanical characterization of pairs of particles in entangled states.

Standard quantum mechanics assigns to physical systems—single particles or collections of particles—formal representations, *wave functions*, in mathematical (Hilbert) spaces. The elements of, or vectors in, such a space yield, according to the standard statistical algorithm of quantum theory, functions from possible measurement outcomes to probabilities. To say that a particle has some wave function, or is properly represented by some vector in a given space, is, at least, to say something about how it is likely to behave in certain experimental settings. In so far as we think that a system's probabilistic experimental dispositions manifest some underlying physical states, we also may take ourselves to be describing the particle's real physical properties by associating it with a wave function.

Quantum theory equips us to represent not only single-particle systems, but also compound wholes. A special subset of these wholes are *entangled*. An entangled system is one whose wave function representation is not a straightforward combination or product of familiar wave functions associable with unentangled, single-particle parts. Particles may manifest their entanglement physically by displaying coordinated experimental behaviour, in which probabilities for joint outcomes of 'measurements' on multiple entangled particles are not simply the products of the outcome probabilities pertaining to each particle separately.

For instance, Maudlin's [2007] version of the non-separability argument focuses on the experimental behaviour of pairs of entangled electrons in measurements of particle spin. The property of spin is unfamiliar from classical physics, but is somewhat analogous to the spin classical objects exhibit in magnetic fields, and we might start by conceiving of it as something like intrinsic angular momentum. Experimentally, one can measure a particle's spin with a laboratory device, a Stern-Gerlach magnet, which can be rotated around its axis to any orientation we choose. A particle sent through a Stern-Gerlach magnet will be deflected in a way that, apparently, reflects some property or properties of the particle, a spin state along the magnet's axis of orientation.

The quantum-mechanical representation of an entangled *singlet* pair of electrons underwrites interestingly coordinated predictions about spin measurements performed on its members. Suppose we send each member towards one of two Stern-Gerlach magnets—one in the left laboratory wing and one in the right laboratory wing—set at equal orientations. Given the wave function of the pair and the standard statistical algorithm of quantum theory, which extracts predictions from wave functions, we will in this case expect anti-correlated deflections from the pair: either the left electron will be deflected upwards and the right electron deflected downwards, or the left electron will be deflected downwards and the right electron deflected upwards.

While the wave function for an entangled pair cannot be factored into any familiar component wave functions of the individual pair members, the quantum formalism does afford an individual entangled particle some mathematical representation, via a density matrix, which, mathematically speaking, differs in form from a wave function.[4] The formal representation of an individual singlet particle equips us to predict, for instance, that an individual singlet particle has chance $^1/_2$ of being deflected upwards and chance $^1/_2$ of being deflected downwards through a magnet of any orientation. As Maudlin emphasizes, no wave function assignable to an unentangled particle underwrites these same predictions, since no unentangled particle is equally likely to be deflected upwards as downwards for every magnet orientation.

The physical basis of the non-separability argument is the existence of entangled pairs that are properly assigned significantly *different* wave functions even though their individual members are themselves properly afforded the very same formal representations.[5] In his version of the argument, Maudlin cites another sort of entangled pair, a triplet pair, whose wave function and so predicted and observed behaviour differ interestingly from those of a singlet pair. In particular, there is some magnet orientation x such that, given the triplet wave function, we should expect correlation, rather than anti-correlation, on pairs of x-spin measurements: either both triplet particles will be deflected upwards (chance $^1/_2$) or both will be deflected downwards (chance $^1/_2$).[6] The essential thing to note, though, is that there is no difference in the proper formal representations of individual triplet and singlet particles. One relevant consideration: individual singlet and triplet particles are equally likely to be deflected upwards as downwards for *any* magnet orientation. More generally, Maudlin [2007: 59] points out that 'no local measurement on a single electron can distinguish . . .' individual singlet and triplet particles, even though 'a global measurement on the whole composite system can'.

The holistic moral is supposed to be that singlet and triplet pairs differ because their members stand in distinct non-supervening entanglement relations. That is, particles come to acquire, in virtue of their membership in entangled wholes, novel relational properties of a sort that pose problems for SEPARABILITY. It is a difference in these relational properties of individual singlet and triplet pair members that allegedly underwrites the difference in

[4] To every vector there corresponds a projection operator onto the one-dimensional subspace (or ray) spanned by that vector. We thus can swap our formal representation by vectors with a representation in terms of projection operators, with the advantage that we can expand the mathematical space of representations to include not only projection operators (familiar pure states) but weighted sums of projection operators—with the weights non-negative real numbers adding up to one. These *density matrices* equip us to formally represent the states of individual entangled particles [Hughes 1989: 136–49].

[5] Maudlin [2007] focuses his presentation of the non-separability argument on spin states. While I am drawing on his example of particles entangled with respect to spin, I have offered a formulation of the argument that speaks in terms of wave functions in general, rather than focusing only on spin states in particular, since spin will play a less central role in the coming discussion of Bohmian mechanics (§3). Nothing deeper hinges on my choice.

[6] Maudlin's [2007: 55–60] singlet pair has spin state, $(1/\sqrt{2})|z\uparrow>_l|z\downarrow>_r - (1/\sqrt{2})|z\downarrow>_l|z\uparrow>_r$, and his corresponding triplet pair has state $(1/\sqrt{2})\,|z\uparrow>_l|z\downarrow>_r + (1/\sqrt{2})|z\downarrow>_l|z\uparrow>_r$. There is some direction, x (in particular, with $|z\uparrow> = (1/\sqrt{2})|x\uparrow> + (1/\sqrt{2})|x\downarrow>$ and $|z\downarrow> = (1/\sqrt{2})|x\uparrow> - (1/\sqrt{2})|x\downarrow>$), such that, when we express the singlet and triplet states in terms of x-spin, we see that we should expect differing pairwise outcomes on x-spin measurements. The singlet state becomes $(1/\sqrt{2})\,|x\downarrow>_l l|x\uparrow>_r - (1/\sqrt{2})|x\uparrow>_l|x\downarrow>_r$, and the triplet state becomes $(1/\sqrt{2})\,|x\uparrow>_l|x\uparrow>_r - (1/\sqrt{2})|x\downarrow>_l|x\downarrow>_r$.

the intrinsic physical states of the *whole* singlet and triplet pairs, a difference reflected in their distinct pairwise wave functions.[7]

The non-separability argument aims to arrive at Metaphysical Holism from the observation that there are pairs of entangled systems that differ significantly in their proper formal representations while their single-particle parts do not. The link from formal entanglement to physical holism—the link to get us from a predictively significant difference in the *formal* wave functions of our singlet and triplet pairs to a difference in the *intrinsic properties* of those pairs—is, allegedly, provided by *realism* about quantum mechanics. Even for the realist, however, not all differences in wave functions indicate differences in the intrinsic properties of their corresponding systems [Maudlin 2013]. For one thing, in quantum mechanics two distinct mathematical functions may differ only by a phase factor, and so represent exactly the same physical state, even though they are, mathematically speaking, different functions; classify mere differences in phase factors as *type-a* differences.

Less trivially, it is generally true that the state ascribed to a physical system by some theory may at least partly reflect facts about some of the system's non-intrinsic features. In particular, there can be what are, intuitively, two otherwise identical systems that nonetheless differ with respect to their spatial positions or orientations or velocities—and so require distinct formal representations for that reason alone. For instance, in a classical setting two particles might have the very same masses and even accelerations but, owing to their differing positions, be properly afforded distinct representations. In a quantum setting, there might be two systems with identical spin states whose wave functions differ owing to their differing spatial positions or velocities.[8] To accommodate such scenarios for our present purpose, we can grant that we have the mathematical resources to identify and describe what intuitively amounts to a spatial transformation or velocity boost of a system via some mathematical symmetry transformation(s) on its wave function—equipping us to identify *type-b* differences in the wave functions of systems.

Of concern in the non-separability argument are differences in wave functions due neither to phase factors nor to symmetry transformations of the sort described above; the remainder are *type-c* differences. One premise of the non-separability argument seems to be that any realist should grant:

(i) There is a type-c difference in the wave functions of two entangled pairs at a time only if the pairs differ with respect to their intrinsic properties at that time.[9]

[7] There is a debate among holists as to the philosophical import of these non-supervening relations. Some, such as Teller [1989], take entangled pairs to be made up of fundamental particles connected by an entanglement relation. Others may take pairs to be more fundamental, understanding individual particles as derivative aspects. Schaffer [2010] thinks of the entire cosmos as the single most fundamental object, and treats all cosmic subsystems as derivative.

[8] Thanks to Bradford Skow for mentioning the case of velocity boost.

[9] Granted, (i) is stronger than the holist needs. He needs claim only that the (type-c) difference in the wave functions of singlet and triplet pairs marks a difference in their intrinsic properties. I take (i) to reveal the more general presupposition behind this particular claim. The Bohmian profiled here will deny (i) and deny that there is a difference in the intrinsic properties of our particular singlet and triplet pairs.

Then the case of the singlet and triplet pairs, whose wave functions exhibit a type-c difference, is supposed to secure:

> (ii) Some entangled pairs are properly represented, at a time, by wave functions exhibiting a type-c difference even though there is no difference in the intrinsic properties of or spatio-temporal—i.e. spatial—relations between their single-particle parts at that time.

With the simplifying assumption that the single-particle parts of the relevant entangled pairs are point-sized ones, (i) and (ii) together yield METAPHYSICAL HOLISM.[10]

Maudlin's [2007] presentation of the non-separability argument is more involved than my account of it suggests; in particular, I have not presented his entire exposition and defence of (ii). The reason is that, in the present context, (i), rather than (ii), is of primary interest. As I shall argue, (i) is false on one interpretation of quantum mechanics that Maudlin himself recognizes as a realist one. Proponents of this interpretation may take the wave function of any entangled pair of particles to describe *relations* that the pair bears to other parts of the universe and so may insist that even a type-c difference in the wave functions of two pairs marks a difference in their *relational* features.

3. The Bohmian Denial of (i)

Since the non-separability argument turns on a claim about the commitments of realism about quantum mechanics, one might expect a thorough analysis of the argument to require discussion of what exactly realism about quantum mechanics amounts to—a messy and controversial issue. Fortunately, we can skirt much disagreement about the content of realism by limiting our attention to an interpretation of quantum mechanics that Maudlin [2007: 62] and his cohort explicitly count among realist treatments of quantum theory: Bohmian mechanics.

Bohmian mechanics supplements the predictive recipe of standard quantum mechanics to show how a fully deterministic evolution of quantum systems can give rise to measurement outcomes conforming to the probabilistic predictions of textbook quantum theory. Basically, Bohmian mechanics treats the probabilistic predictive recipe of standard quantum theory as providing a useful and maximally phenomenologically accurate approximation of the complete and precise Bohmian description of the world.[11]

A distinctive element of Bohmian mechanics is its supplementation of wave functions and the Schrödinger equation of quantum mechanics standardly used to describe their evolution with another deterministic equation, the guiding equation. What does the guiding equation guide? There are two different ways of answering this question, corresponding to two different

[10] This assumption makes the argument much cleaner but is not necessary; without it, one can arrive at the same conclusion by adding premises to the effect that the intrinsic properties of non-point-sized particles are to supervene on the intrinsic properties of and spatio-temporal relations among their point-sized parts.

[11] For a detailed exposition of Bohmian mechanics, see Dürr, Goldstein, and Zanghì [1992]; for a helpful general overview, see Dürr, Goldstein, Tumulka, and Zanghì [2009]. I draw on both of these here.

ways of filling out the Bohmian ontology. One way defended by Albert [1996, 2013] pictures the universe as consisting, or at least *fundamentally* consisting, of a single particle in a high-dimensional space, with the guiding equation characterizing that particle's gyrations in that space. Our world (or the appearance of our world) of three-dimensional space and time is grounded in the movement of this single particle. The alternative ontological story, which is my focus here, posits a multiplicity of fundamental point-sized particles in ordinary three-dimensional space with the guiding equation characterizing the motions of these particles over time—we might think of the guiding equation as describing a wave that pushes these particles around in space, relating the ordinary evolution of the mathematical universal wave function to changes in the configurations of particles.

On the many-particle story, a complete description of the world of *N* particles at a time *t* includes a specification of the positions $Q_1(t) \ldots Q_N(t)$ of the particles in physical space at *t* and a description of the wave function of the universe $\Psi(t)$, which evolves according to the Schrödinger equation of textbook quantum theory. From a specification of the particle positions we get the configuration Q(t) of all *N* particles, represented by a point in a 3N-dimensional configuration space. Bohmian mechanics treats $\Psi(t)$ as a function within this space—intuitively, as a function over possible configurations of the *N* particles.

With $\Psi(t)$ describing possible particle configurations and Q(t) specifying the configuration actually obtaining, Bohmian mechanics characterizes the over-time trajectory of every particle; the trajectory of motion for a particle is given by an equation that relates the instantaneous velocity of that particle at *t* to the actual configuration of *all* the *N* particles and the universal wave function at *t*. Remarkably, it turns out that deterministic Bohmian mechanics, with its supplementary particle positions and guiding equation, is able to match the experimental predictions of orthodox quantum mechanics and to accommodate the macroscopic appearance of our world.[12]

In the context of the non-separability argument, two features of Bohmian mechanics are especially noteworthy. First, at least on one way of understanding the Bohmian story, the fundamental facts about the particles are facts about their positions.[13] More specifically, the Bohmian may choose to deny that there is any *fundamental* or *intrinsic* property of spin for particles. Does the claim, 'There is a particle with upwards x-spin' therefore turn out to be false? The Bohmian may, consistent with her foregoing denial, still choose to speak in terms of spin and embrace the spin state ascriptions of textbook quantum mechanics as true, presenting her disagreement with the orthodox interpretation of quantum mechanics as a disagreement over *what it is* for there to be a particle with upwards spin in some direction [Daumer, Dürr, Goldstein, and Zanghì 1996].

[12] Since the Bohmian theory supplements the quantum wave function with particle positions, the standard specification of a system's wave function is an *under*-specification of the system's state. However, a consequence of the Bohmian account is that we, as epistemic agents, are unavoidably ignorant of any information about a system that is not in a sense already contained within the wave function of that system [Dürr, Goldstein, and Zanghì 1992].

[13] Particle masses may also be intrinsic according to the Bohmian, in which case facts about particle masses can count among the fundamental facts as well.

According to such a Bohmian, for there to be such a particle is for it and the other particles within the universe to be moving in such a way as to be certain to produce an *up* indication among the particles of a relevant 'x-spin measuring device'—here the Bohmian capitalizes on the fact that 'spin measurements' involve spin being recorded or indicated by a change in the *position* of something, such as a test particle itself or a needle on a dial. Plausibly, then, the attribution of an entangled spin state to a particle pair makes a claim not about the intrinsic state of the pair but about the present and future motions of it and of other particles in the universe—it makes a claim about the relations the pair presently bears to others, and so casts doubt on (i). The Bohmian need not concede that the difference in the wave functions of some singlet and triplet pairs marks a difference in their intrinsic properties.

The relational treatment of spin is not in itself a fatal blow to the holist's argument. For the holist might try to generate a parallel holistic worry for reductionism based on systems entangled not with respect to spin but with respect to *position*, which is of fundamental importance for the Bohmian. The thought would need to be that the wave functions of two pairs differently entangled with respect to position might attribute an intrinsic physical difference to the pairs, a difference that can still get us to Metaphysical Holism. Relevant here, though, is a second noteworthy feature of Bohmian mechanics: arguably, *any* attribution of a wave function to some entangled physical system—even one entangled with respect to position—or to any other proper subsystem of the universe at least partly ascribes relational properties to that system.

Bohmian mechanics is an explicitly non-local theory, which we can see from the fact that the trajectory of each particle depends on the present configuration of all the particles in the universe. In fact, strictly speaking, only the *entire* universe has a wave function according to the Bohmian, and the role of this universal wave function is to contribute to the specification of all the particles' positions over time. Sometimes the universal wave function takes a form that allows us to attribute, at least for all *practical* purposes, quantum states to proper subsystems of the universe of particles. In such a case we say that a subsystem has an *effective* wave function [Dürr, Goldstein, and Zanghì 1992]. Effective wave functions arise when the interactions in the universe of particles are such that the positions of particles in one subsystem of the universe turn out to be more or less insensitive to the positions of particles in the others. In this case, the configuration and motions of all the particles and the form of the universal wave function are such that we can then treat proper parts of the universe as each separately evolving in accordance with the Schrödinger equation.

However, even if the state of a system is independent from other systems for all practical purposes, strictly speaking—for non-practical purposes—there is essential dependence between them; the position of even one particle at a time is bound up with the configuration of *all* the particles in the universe. The Bohmian may interpret this dependence as evidence that any attribution of an effective wave function to any proper part of the universe describes some *relations* that part bears to others over time. For some part of the universe to be properly attributed a given (effective) wave function is for the entire universe to behave in such a way that the evolution of the part is sufficiently isolable from that of its environment. The Bohmian then may capitalize on this element of her view to interpret cases in which two entangled pairs allegedly differ with respect to some non-supervening intrinsic properties as cases in which the pairs actually differ with respect to their relational features—features that may ultimately supervene on the mosaic of point-sized individuals.

Note that the contention is not that two systems that differ with respect to their wave functions *cannot also* differ with respect to some intrinsic features—say, with respect to whether they possess the property of having two point-sized parts three metres apart. Rather, the Bohmian endorses two claims. First, (i) is false on her view because not every type-c difference in wave functions marks a difference in intrinsic properties. In particular, cases of entanglement that holists cite as problematic for reductionism are cases in which significant differences in wave functions are due to differences in the *relational* properties of entangled systems. Second, while some systems that differ with respect to their wave functions may *also* differ with respect to their intrinsic properties, these differences do not secure METAPHYSICAL HOLISM; any lingering differences in the *intrinsic* properties of two pairs bottom out in differences in the intrinsic properties of and spatio-temporal relations between their respective single-particle parts, preserving SEPARABILITY.

4. Holism and the Pilot Wave

While the Bohmian plausibly rejects a key premise of the non-separability argument, the committed holist may construe the Bohmian blockage of this argument as merely a Pyrrhic victory for the reductionist. For one natural way to be a realist about the many-particle version of Bohmian mechanics is to believe that, fundamentally, the world contains *two* sorts of object, point particles in physical space and the pilot wave, described by the Bohmian guiding equation, which pushes the point particles around in space in a way that is 'choreographed' by the universal wave function in high-dimensional configuration space [Goldstein and Zanghì 2013].[14] This brand of Bohmian realism looks metaphysically holistic regardless of the (lack of) cogency of the non-separability argument. For, apparently, the state of the entire world is not fixed by the intrinsic properties of and spatio-temporal relations between point-sized individuals because there is a distinct fundamental entity, the pilot wave, existing alongside the point particles.[15] Thus, it appears the Bohmian realist about quantum mechanics is committed to METAPHYSICAL HOLISM despite her rejection of (i).

[14] A clarification concerning the way in which at least Bohmian *particles*—if not the pilot wave—seem to be at home in a separable metaphysics: the Bohmian has a mosaic or field of points of space-time of a sort that Lewis describes. Then facts about particles can bottom out in facts about patterns in the points' intrinsic states of 'occupation' or 'unoccupation', or we can add to the space-time points particles that can stand in occupation relations to points based on their spatio-temporal arrangement.

[15] For the most part I use 'pilot wave' or 'guiding wave' when talking about some *physical* thing described by the *mathematical* universal wave function. Confusingly, it is common in this sort of discussion to use 'universal wave function' to name both the mathematical and the physical things.

There is another way to put what is, at root, the same worry. Suppose we grant that, on the Bohmian story, the (effective) wave function of any proper subsystem of the universe partly describes the relational features of that subsystem; perhaps this is plausible enough given the primacy of the universal wave function. But what about this wave function—for the *entire* universe *itself*? It is not obvious that the wave function of the whole universe at a time can partly describe its relational properties, for *to what* is the universe relevantly related?

Consider a universe consisting of some configuration of particles—or even just a single particle—at a time. Presumably, this state of affairs is consistent with any number of universal wave functions. For, as we saw earlier, the Bohmian naturally understands the wave function of the universe as in some sense encoding different ways the universe could evolve and, correspondingly, different sets of trajectories along which the particles in the universe could be guided. The wave function provides a probability distribution over those ways even though only *one* possibility *actually* obtains. Thus it seems that the global state of the world cannot supervene on just the actual configuration of particles.

Because of the pilot wave, then, Bohmian mechanics may seem to lose the war for the reductionist even though it arguably wins the battle of blocking the non-separability argument. Loewer [1996] offers one way out: the reductionist can adopt a version of Bohmian mechanics defended by Albert [1996, 2013] and take fundamental space to be a high-dimensional physical space directly corresponding to mathematical configuration space inhabited by the universal wave function. On this view, there is not a fundamental pilot wave guiding the motions of particles in physical three-dimensional space because there are not multiple fundamental particles in such a space. Instead the universal wave function describes a field in a very-high-dimensional space, and each point in the field has an intrinsic state specified by the amplitude and phase of the mathematical wave function at the corresponding point in configuration space. Located within the field is a single fundamental particle; instead of N particles in a three-dimensional physical space, there is, fundamentally, one particle in a $3N$-dimensional physical space. Evolution of the universal wave function over time just describes changes in the values at points in the high-dimensional space and attendant changes in the motion of the particle.

A Humean who adopts Albert's gloss on Bohmian mechanics can recover Lewisian Separability if she is willing to allow that 'spatio-temporal relations' relevant to the thesis may be ones that live within this high-dimensional space. Then the global state of Albert's world does supervene on the intrinsic properties of and spatio-temporal relations between point-sized individuals—elements of a high-dimensional field, plus the single fundamental point particle. The world just turns out to be strikingly different than we expected. The Humean who adopts the Albert-style metaphysics but who wishes to retain some intuitive fit with our experiences in a world of objects in three-dimensional space (or four-dimensional space-time) then needs to offer some account of how this more familiar world arises as a non-fundamental side effect of Albert's revisionary portrayal of fundamental reality.

There is another option for the reductionist partial to many-particle Bohmian mechanics, however. She can recover SEPARABILITY by following a suggestion of Goldstein and Zanghì [2013], attaching to the universal wave function *nomological* status. Although it is quite natural to interpret the Bohmian guiding equation as describing a fundamental physical object, the Bohmian may, according to Goldstein and Zanghì, choose instead to think of the guiding equation and the universal wave function as expressing a physical *law* that guides or describes the motions of particles from moment to moment.

The Bohmian who treats the universal wave function as describing a nomological element of physical reality may count as a realist about it; a realist attitude towards Bohmian mechanics may require the belief that the intrinsic and supervening relational properties and spatio-temporal positions of particles evolve in accordance with the guiding equation, but it need not require belief in some extra non-supervening non-nomological entity, the pilot wave. The attribution of some wave function to the universe, construed as a claim about the physical laws, is still, in Maudlin's [2007: 61] terms, 'part of a true description of the world'.

The nomological conception of the guiding wave clears some wiggle room for the committed reductionist. Right away, it enables her to recover SEPARABILITY. Arguably, the Bohmian who gives the universal wave function the status of a law can say that the complete global physical state of the world is *exhausted* by, and so certainly supervenes on, these motions of particles—on the intrinsic properties of and spatio-temporal relations between point-sized individuals in the Humean mosaic.

However, it can appear as though the reductionist who makes this move to spare SEPARABILITY does so at the expense of a second reductive commitment, which Maudlin [ibid.: 51] identifies as the Lewisian thesis of 'Physical Statism':

> PHYSICAL STATISM All facts about the world, including modal and nomological facts, are determined by its total physical state.

The thesis of PHYSICAL STATISM adds to SEPARABILITY an expression of the Humean's philosophical commitments concerning, among other things, the nature of laws. On the Humean picture, by fixing what actually does happen at each point, we fix what—according to the physical laws—*could have* happened and *can* happen. The goal here is to rule out the possibility of there being physical facts that are not fixed by even the entire four-dimensional Humean mosaic.

It is true that *one* way for the Bohmian to protect her separable metaphysics is to grant that there are physical facts, namely, nomological facts about the universal wave function, that fail to supervene on the global mosaic of point-sized individuals bearing intrinsic properties and standing in spatio-temporal relations. This way naturally follows from the suggestion that the Bohmian pilot wave *guides* the particles, which evokes an anti-Humean conception of laws in tension with PHYSICAL STATISM. However, a *Humean* about laws might also try to adopt a nomological conception of the pilot wave, as suggested by Michael Esfeld, Dustin Lazarovici, Mario Hubert, and Detlef Dürr [forthcoming].[16] Since Humean laws merely describe, rather than guide, the evolutions of the intrinsic properties of and spatio-temporal relations between individuals, the idea here would have to be that the guiding equation and universal wave function express a merely descriptive Humean law and that the pilot wave, in so far as it exists at all as a sort of nomological entity, itself somehow describes or helps to describe the motions of the Bohmian particles over time.

5. BSA Bohumianism

I claim that the committed Humean Bohmian—the Bohumian—may already have available a strategy for combining realism about Bohmian mechanics, and, in particular, realism about the pilot wave, with Humeanism, thereby preserving both SEPARABILITY and PHYSICAL STATISM. The manoeuvre starts with the best system account (BSA) of Humean laws, which takes physical laws to be a set of special systematic generalizations about the space-time mosaic, a summary of how the world evolves over time that strikes the optimal balance of simplicity and strength and perhaps some other relevant theoretical virtues [Lewis 1994; Loewer 2004; Hall unpubl. ms].

My proposed Bohumian treatment of the pilot wave draws its inspiration from the Humean BSA treatment of objective chance. Objective chances for a best system Humean may arise as something like a side-effect of physical laws. A Humean may say that a world contains objective chances when its best system of laws is indeterministic, when it leaves open multiple possible courses of worldly evolution, and offers a probability distribution over the multiple options it identifies. Roughly, the summary of how the physical world evolves that strikes the best balance of informativeness and simplicity and any other relevant theoretical virtues is one that gives us, based on some state of the world at a time, a probability distribution over different ways the world could evolve rather than a fully detailed—perhaps unwieldy and so less-than-best—specification of an entirely certain course of events.

An essential insight is that, for the Humean about chances, *what it is* for there to *be* objective chance is for the world to be such that its best system of laws has this sort of indeterministic character; it is for that best system of laws to earn its status of best partly by speaking in terms of chances. An anti-Humean about objective chances is not happy with this kind of realism about chance; he may insist that objective chances must be primitive,

[16] Esfeld and his co-authors suggest that Bohmian mechanics may be combined with a Humean account of laws, but it is not clear from their discussion exactly how they expect this to go and, especially, whether they take this to be a *realist* treatment of the Bohmian pilot wave. My proposal may be read as a suggestion in a similar Humean spirit, one that fleshes out a (distinct, explicitly realist) Humean treatment of the pilot wave by way of an analogy to a Humean account of objective chance and that offers this treatment as a response to the non-separability argument. Thanks to Zee Perry, who, along with Harjit Bhogal, has been developing a similar Humean treatment of entanglement, for helpful comments encouraging me to distinguish between the present proposal and the sort of nomological account mentioned by Esfeld and his co-authors.

indeterministic dispositions of objects, and the Humean does not countenance these. But the Humean nonetheless takes claims about chance to be literally true descriptions of objective reality. To change the facts about the chance of some event is to make a change in the distribution of intrinsic properties across or the spatio-temporal arrangement of individuals in the Humean mosaic.

Ned Hall [unpubl. ms: 27] suggests that a Humean may offer an account of some non-fundamental magnitudes that parallels this account of chances. Consider, for example, mass and charge in a roughly Newtonian world of particles moving about in empty space. Hall suggests that mass and charge may be introduced in this world not as 'fundamental, perfectly natural magnitudes . . .' but as something akin to objective chances. Perhaps the only fundamental facts in our Newtonian world are facts about the locations of particles, but 'a candidate system is now allowed to hypothesize, as it were, that particles are also characterized by additional magnitudes, and introduce equations connecting the values of these magnitudes to particle positions.' Then:

> What would make it the case that there *are* masses and charges is just that there is a candidate system that says so and that, partly *by* saying so, manages to achieve an optimal combination of simplicity and informativeness (informativeness, remember, only with respect to particle positions).
>
> [loc. cit.]

Arguably, a Humean who makes this move is a realist about mass; she just says that what it is for there to be masses is for the world to be such that the best system of laws speaks in terms of them. Of course, in this world the mass of a particle is not intrinsic to the particle; it does not supervene on the intrinsic properties of that particle alone. However, the particle's mass nonetheless supervenes on some larger portion of the Lewisian manifold, on motions of fundamental particles over time.

The Bohumian offers an account of the Bohmian pilot wave that parallels the BSA account of chance and this account of mass in the Newtonian world. The Bohumian insists there is a physical pilot wave described by the universal wave function; we can make objectively true claims about it. However, what makes it the case that there is a pilot wave is that the best system description of the physical world speaks in terms of it, and this description speaks in terms of it because it is part of an efficient and effective summary of what is fundamental: the positions of particles in space over time.

Reconsider now the worry that a single actual configuration of particles at a time might be compatible with multiple distinct universal wave functions—intuitively, ones describing different possible but unactualized configurations. What the Bohumian should claim here is that unactualized components of the competing wave functions in these cases are incorporated in descriptions of the motions of the particles *over time*. The Bohumian thus denies that the wave function of even the entire universe at a time describes only its intrinsic state and so grants that there can be a physical fact at a time—a fact about the wave function of the universe—that is not fixed by the *present, intrinsic* global physical state of the universe. Nevertheless, she need not grant that the physical fact fails to supervene on the *complete* Humean manifold, the distribution of intrinsic properties across not only present individuals but across points of space *and time*. The entire wave function may still be fixed by the motions of the particles over time because the evolving wave function—unactualized components and all—offered by the equations of Bohmian mechanics is part of the best summary of the over-time behaviour of particles.

Some unactualized possibilities encoded in the present universal wave function may be relevant to actual past or future configuration of particles, and some may simply be incidental formal artefacts of an overall best system that speaks in terms of the universal wave function. Just as in the Newtonian world facts about the mass of a single particle at some time t may supervene not on that particle's intrinsic properties alone but rather on some larger portion of the Humean mosaic, in our Bohmian world facts about the pilot wave at time t, though they may fail to supervene on the actual configuration of particles at t alone, may still be fixed by the four-dimensional Lewisian manifold—and *that* supervenience is all the Humean needs to retain not only SEPARABILITY, the adamance of proponents of the non-separability argument aside, but also PHYSICAL STATISM.

To be fair, there is another case that the Bohumian *cannot* accommodate, one in which a single *four*-dimensional mosaic is equally well associated with two distinct wave functions. There is a technical issue here of whether this is a pressing threat, whether we can expect the actual configurations of particles over time to pin down the unactualized components of the universal wave function at even a single time—which, since the wave function evolves deterministically, would also serve to pin it down over time. At least in some cases, the Humean may need to be prepared to bite a bullet, to grant that pronouncements of the quantum formalism might outstrip the physical facts. This possibility need not threaten the Bohumian's realist status, however. Compare: a Humean may deny that there is any fact about whether the chance of some event occurring is really 0.5000 or really 0.4999 and yet, it seems, still count as a thoroughgoing realist about chance.

The Bohumian manoeuvre I am advocating is one application of a general strategy available to the Humean, that of locating the truthmakers for claims about some entity or entities in facts about the BSA description of the Humean mosaic. Perhaps all it is for there to *be*, say, electric charge and gravitational attraction is for the best system of laws to speak in terms of them. While the general BSA strategy offers the Humean a promising way of extricating herself from what might otherwise amount to burdensome fundamental commitments, it is not all sweetness and light, even from the Humean's own perspective. Can a rogue Bohumian, for instance, legitimately insist that there are *really, fundamentally* only N–27, rather than N, particles and then go on to say that what it is for there to be these non-fundamental particles is for the BSA laws to speak in terms of them? Or can a rogue and narcissistic Bohumian legitimately insist that only the particles in her immediate vicinity fundamentally exist, even though the laws speak in terms of lots of other non-fundamental things?[17]

Suppose we agree that there ought to be *some* limits on the application of the strategy. Then we face a difficult question. Upon what principled basis do we restrict its application? Now, one sort of opponent of Humeanism has a hostile suggestion on this front: *any* application of the strategy is too much. He sees the Humean, in implementing her BSA strategy even for chance or for the pilot wave, as trying to carve out some conceptual space between a sort of flat-footed realism and full-blown instrumentalism where there is, by his lights, *none* to be found. That is, he sees the Humean who avails herself of the strategy as forfeiting her realist credentials—she is, by his lights, an instrumentalist in disguise.

The Humean, of course, does not agree, and perhaps rightly so. After all, her hostile opponent claims that a *real* realist even about chances cannot avail herself of the BSA manoeuvre. In addition, her opponent owes us some explanation of whether, by his lights, anyone can count as realist about *anything* she takes to be non-fundamental and, if one can, why applications of the BSA strategy are nevertheless problematic. But in so far as the Humean wishes to proactively distance herself from her instrumentalist counterpart, she will seek to place some principled limits on the BSA strategy and, in the light of the availability of that strategy, to develop a distinction between her brand of realism and instrumentalism.[18]

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