What the Humean Should Say About Entanglement*

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Abstract

Tim Maudlin has influentially argued that Humeanism about laws of nature stands in conflict with quantum mechanics. Specifically Humeanism implies the principle Separability: the complete physical state of a world is determined by the intrinsic physical state of each space-time point. Maudlin argues Separability is violated by the entangled states posited by QM. We argue that Maudlin only establishes that a stronger principle, which we call Strong Separability, is in tension with QM. Separability is not in tension with QM. Moreover, while the Humean requires Separability to capture the core tenets of her view, there's no Humean-specific motivation for accepting Strong Separability. We go on to give a Humean account of entangled states which satisfies Separability. The core idea is that certain quantum states depend upon the Humean mosaic in much the same way as the laws do. In fact, we offer a variant of the Best System account on which the systemization procedure that generates the laws also serves to ground these states. We show how this account works by applying it to the example of Bohmian Mechanics. The 3N-dimensional configuration space, the world particle in it and the wave function on it are part of the best system of the Humean mosaic, which consists of N particles moving in 3-dimensional space. We argue that this account is superior to the Humean account of Bohmian Mechanics defended by Loewer and Albert, which takes the 3N-dimensional space, and its inhabitants, as fundamental.

1. Introduction

In "Why be Humean?" Tim Maudlin (2007) argues that considerations from quantum mechanics stand in tension with one of the two central tenets of Humeanism about laws of nature. These tenets are:

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

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[1]) and the spatio-temporal relations between those points.

Maudlin takes these two theses to comprise Humeanism.[2]

Why think that these theses comprise Humeanism? Put briefly, part of the reason is that the theses imply the truth of two common glosses on Humeanism: **(NM)** The world is fundamentally non-modal; and **(NNC)** There are no necessary connections at the fundamental level. SEPARABILITY and PHYSICAL STATISM imply **(NNC)** because they imply that the fundamental facts are assignments of intrinsic states to each point and a state being intrinsic to an entity means that it can obtain regardless of anything else in the world. They imply **(NM)** because all modal and nomological facts are grounded in actual intrinsic properties of spacetime points and hence are not fundamental.[3]

Maudlin argues that QM poses problems for Humeans because it posits "fundamental, non-Separable physical states of affairs" (Maudlin, 2007, p. 53). That is, QM posits fundamental states of affairs whose inclusion in the total physical state contradicts SEPARABILITY. His example involves the physical quantity, *spin*. A particle in a *product state* of spin has what corresponds to a particular intrinsic spin state: For example, consider the particle, *p*. *p* has spin **up** in the **z** direction, written as $|z \uparrow>_p$. This has a number of consequences, for example, if we put *p* into a well made z-spin measuring device, the output on the device will read "up." An individal particle can also be in a *superposition* of spin states. For example, *p*'s x-spin state is expressed like this: $\frac{1}{\sqrt{2}}|x \uparrow>_p + \frac{1}{\sqrt{2}}|x \downarrow>_p$, which says, among other things, that the there is a 50% chance of getting an "up" result when we feed *p* into a properly calibrated x-spin measuring device. Pluralities, like triples or pairs of particles, can have spin states as well. When a pair of particles, *p* and *q*, are in a product state of z-spin, we write $|z \uparrow>_p |z \downarrow>_q$. In such a case we say that *p* is z-spin up and *q* is z-spin down.

None of the above poses a problem for SEPARABILITY. The spin states described are either intrinsic states of individual particles or (in the case of a pair of particles being in a product state) directly determined by them. Problems arise when pluralities of particles are in *superpositions* of spin-states. For example, suppose *p* and *q* are in the *Singlet state*: $\frac{1}{\sqrt{2}}|x \uparrow>_p |x \downarrow>_q + \frac{1}{\sqrt{2}}|x \downarrow>_p |x \uparrow>_q$. This state of the pair implies nothing about the intrinsic x-spin of either particle on its own. What it *does* imply, is that, if *p* and *q* are each fed into different x-spin measuring devices, there is a 100% chance getting one "up" result and one "down" result, though the chances are 50/50 as to whether it's *q* that's x-spin down and *p* x-spin up or vice versa.

According to Maudlin (2007, p. 58), if "the principle of Separability holds, then each electron, occupying a region disjoint from the other, would have its own intrinsic spin state, and the spin state of the composite system would be determined by the states of the particles taken individually, together with the spatio-temporal relations between them. But, no pure state for a single particle yields the same predictions as the Singlet state."

That is, the fact that *p* and *q* are in the Singlet state is not reducible to facts about their intrinsic spin states (nor, indeed, to any state intrinsic to *p* and *q*). Indeed, no states intrinsic to *p* or *q* could be able to reproduce the *predictions* associated with

the Singlet state. Thus Maudlin's contention is: If the fact that p and q are in the Singlet state is part of the total physical state then the total physical state is not determined by the intrinsic physical states at each spacetime point.

The Humean is apparently, therefore, faced with the following problem. If she wants an adequate account of the physical world, she needs to take seriously entanglement phenomena, like the Singlet state, and the predictions associated with such phenomena. However, to do so she will have to admit that part of the total physical state is not determined by the spatio-temporal distribution of intrinsic physical states to points, which amounts to denying SEPARABILITY.

We think there's a way for the Humean to avoid this problem. The move, put simply, is this: A pair of particles being in the Singlet state is not determined by the intrinsic physical states of those two particles; rather, it's determined by the states of the pair together with the intrinsic physical states at *other* points in the mosaic.

This solution is consistent with both SEPARABILITY and PHYSICAL STATISM. It works because SEPARABILITY does not require that the physical state at some region be determined solely by the intrinsic states of the physical points *making up that region*; rather, it merely requires that every physical state be determined by the intrinsic properties (and spatiotemporal relations) of the spacetime points which make up the whole of the Humean mosaic.

Which other particles/regions, then, does a particular pair of particles being in the Singlet state depend on? We think the right answer to this question is *all of them*. How does this dependence work? In section 2 we present a view, which we call "Two-State Humeanism", on which entanglement phenomena depend on the whole of the mosaic in much the same way as many Humeans think the laws of nature do. We argue that this view offers an elegant account of the physical world, while maintaining SEPARABILITY and PHYSICAL STATISM.

In section 3 we make the case for SEPARABILITY as characteristic of the Humean worldview, and give considerations against self-proclaimed Humean views which reject this principle. We also respond to arguments that a stronger principle than SEPARABILITY (specifically, one which rules out our solution to the problem) would better capture the Humean spirit. section 4 considers objections to two-state Humeanism, and further clarifies the view. In section 5 we apply two-state Humeanism to a realistic physical picture, using Bohmian mechanics as our example, and show how our view is superior to competing Humean accounts (specifically the "marvelous point" ontology defended by Loewer (1996) and Albert (1996)).

2. Two-State Humeanism

According to the view we develop and defend here, a given pair of electrons, a and b, being in the Singlet state is part of the physical state of the world, and it depends on the intrinsic physical states of spacetime points, though not *merely* on the states intrinsic to a and b. Here's how that works. Two-State Humeanism differs from other Humean theories in what it says about how we arrive at *total* physical state of the world, given the Humean mosaic. The Humean mosaic is the distribution of

physical properties to points in a spacetime, along with the spatiotemporal relations between these points. The mosaic is taken as fundamental.

Humeanism also countenances physical properties had by regions or extended entities. These are *not* metaphysically fundamental, since they are not a part of the mosaic proper. Such states include things like: the mereological sum of particles *p* and *q* having a mass of *n*g (where *n*g is the "sum" of *p*'s and *q*'s masses); the magnetic field in a certain extended region having such-and-such a wavelength (where wavelength is determined by the intrinsic "field value" properties instantiated at points together with their spatial relations); particles *a* and *b* being in the product state $|x \uparrow>_a |x \downarrow>_b$, which is determined by *a* and *b*'s respective, intrinsic, spin states (in this case x-spin up and x-spin down respectively).

What these non-fundamental physical states have in common is that they satisfy STRONG SEPARABILITY:

> STRONG SEPARABILITY: The complete physical state of any region R is determined by (supervenes on) the intrinsic physical states (and relations between) R's sub-regions.

Call the mosaic together with the assignment of the non-fundamental physical states which satisfy STRONG SEPARABILITY to each region/plurality of points in the mosaic (as above) the "M-state." According to what we might call "single-state" or "ordinary" Humeanism, the M-state of the world comprises the *total* physical state of the world. Such a view is guaranteed to satisfy SEPARABILITY, since it satisfies a stronger principle.

However, precisely because STRONG SEPARABILITY is a much stronger constraint than SEPARABILITY, it's consistent that there be physical states which are not part of the M-state but which still depend on the mosaic in a way that satisfies SEPARABILITY. Call the totality of such physical states the "L-state." According to two-state Humeanism, there are, or at least can be, physical states which are part of the L-state. Electrons *a* and *b* being in the Singlet state is an example of just such a physical state. For the two-state Humean, the L-state and the M-state together constitute the total physical state.

This view allows us to retain both SEPARABILITY and PHYSICAL STATISM. Maudlin's argument poses no problem for PHYSICAL STATISM because the Singlet state is accepted as part of the total physical state of the world. SEPARABILITY, similarly, is not violated because the Singlet state is still dependent on the mosaic, and so determined by "the intrinsic physical state of each spacetime point (or each point like object) and the spatio-temporal relations between those points."

According to the specific version of two-state Humeanism we will defend here, the elements of the L-state are grounded holistically, that is they are determined by the *entire* mosaic. This is exactly the sort of story the ordinary Humean accepts for the grounding of physical laws—they are determined by the totality of the mosaic. The two-state Humean extends this account to apply to part of the physical state as well, namely the L-state. In the next section, we present a variant of the best system account, which can be used to generate both the laws and the L-state together.

2.1 Adapting the Best System Account

The traditional BSA is an account of the laws. It takes the mosaic as fundamental and claims that the laws are the axioms that best systematize the facts about the mosaic. More precisely, we take a *base language* where "the primitive vocabulary . . . refer only to the perfectly natural properties" (Lewis, 1983, p. 367–8). We then formulate axiom systems in terms of the base language (subject to the constraint that the axioms cannot together entail any falsehoods about the mosaic) and consider the systems produced by taking the logical closure of the axioms.

The best system is the one which achieves the best balance of Simplicity and Informativeness. Simplicity involves having (syntactically) simple axioms. Informativeness is a measure of how much a system says about the *mosaic*.[4] The axioms of the best system count as the laws. The laws are generated from the mosaic via this systemization procedure.

Our view keeps the core of the systemization procedure but allows it to generate the laws *and the L-state* from the mosaic.

The way we do this is by expanding the language that candidate systems can be formulated in. As before, systems can use vocabulary that refers to perfectly natural properties (the properties that make up the mosaic)—what we've called the "base language." But in addition to this they can introduce and use any other vocabulary *so long as it comes in uninterpreted*.[5]

How does such uninterpreted vocabulary come to have content? It can have content if a system links the novel vocabulary to the base language; that is, if the system contains sentences that contain both novel vocabulary and the already interpreted vocabulary of the base language. For example, a system S could introduce a novel, uninterpreted, predicate $M(x)$ and then say that $M(a)$, $M(c)$ and $M(f)$ obtain while $M(b)$ and $M(d)$ fail to obtain (where the lower-case letters are singular terms in the base language). Here we are giving '$M(x)$' content by linking it to already interpreted terms.

Another example: Imagine S includes the sentence 'All Ms are Gs', where G is a piece of already interpreted vocabulary, meaning, for example, "has positive charge." So the novel vocabulary, M, is linked to the already interpreted vocabulary, G, by there being a sentence in the system that contains them both.

Such claims about M appear as part of the axioms of S. The natural way to interpret this process is that S postulates new elements of the physical state. That is, in introducing a predicate '$M(x)$' and saying that $M(a)$, $M(c)$ and $M(f)$, S is introducing a new property and saying that this property is instantiated by a, c and f. If S turns out to be the best system then these are new elements of the physical state and are part of the L-state. Thus the systemization procedure generates (non-fundamental) physical states as well as laws.[6]

Using this procedure S can postulate more things than properties. It can postulate new entities, or even new spaces (and then postulate entities to inhabit them). Importantly, the novel vocabulary in S is treated just like any other vocabulary when evaluating that system's informativeness and simplicity. And on two-state Humeanism the notions of simplicity and informativeness are unchanged from the original BSA. Sentences using novel vocabulary reduce the simplicity of a system

just like any other sentence. And a system is more informative if it says more about the mosaic.

Even though using novel vocabulary constitutes a cost to simplicity, it can also help to better systematize the mosaic. In fact, we think there are cases where the best system contains novel vocabulary, even though the novel vocabulary comes in uninterpreted. We will show how this is possible in section 4.2.

In summary, on our view the mosaic is fundamental; the L-state and the laws both depend upon the mosaic and so are non-fundamental; and they depend on the mosaic in the same way, they are both generated by the best way of systematizing the world. We claim that the best system of the world contains the Singlet state as part of the L-state.

So, we claim that various quantum mechanical states are part of the L-state. However, our view allows that other sorts of states be part of the L-state as well. In fact, we think that it is plausible that chances will be postulated as part of the L-state. It is a significant advantage of our view that it has the potential of unifying the account of non-fundamental phenomena like the Singlet state and chance. Furthermore, this account of chance as part of the L-state would solve problems faced by the traditional BSA story about chance. On the traditional view it's hard to make sense of what 'chance' refers to and even what makes claims about chance true, since there are no chances in the mosaic. Our view solves this problem because it explains how chances can be part of the physical state without being part of the mosaic.

Our view can make sense of the existence of quantum mechanical states like the Singlet state while maintaining SEPARABILITY and PHYSICAL STATISM. In section 4 we respond to some objections and do more to clarify and elucidate various aspects of the view. But before that, we consider why the Humean should want to accord with Maudlin's definition of Humeanism. In particular, our view is designed to retain SEPARABILITY, but what is the motivation for this; why is SEPARABILITY desirable?

3. Why Separability?

There are two distinct questions regarding the status of SEPARABILITY for the Humean. The first question is: Why is SEPARABILITY desirable? Some Humeans have agreed with Maudlin when he says there is "no credible motivation for Separability" (2007, p. 64) and have responded by simply by dropping SEPARABILITY. Our view is designed to retain SEPARABILITY, but what is the motivation for that?

The second question is: Why is SEPARABILITY *enough* for the Humean? Why shouldn't the Humean demand adherence to something like STRONG SEPARABILITY? Our view does not satisfy STRONG SEPARABILITY, is it therefore insufficiently Humean?

To answer these questions we should consider why the Humean accepted SEPARABILITY in the first place. It seems clear why the Humean accepted PHYSICAL STATISM. The Humean wanted to rule out "spooky" facts that float free of the physical world. PHYSICAL STATISM is necessary for doing this. But it is not sufficient. For example, an anti-Humean might postulate primitive laws of nature, claiming

that such laws are part of the total physical state. This satisfies PHYSICAL STATISM but these primitive laws are the type of thing the Humean wants to rule out. PHYSICAL STATISM is not enough because in addition to ensuring that there are no spooky facts over and above the total physical state, the Humean needs to ensure that there is nothing spooky *in* the total physical state.

SEPARABILITY does this job. It ensures that the physical state is non-modal and contains no necessary connections. Together with PHYSICAL STATISM, this implies that the world is non-modal, **(NM)**, and that the world contains no necessary connections, **(NNC)**. And, as we noted above, **(NM)** and **(NNC)** are two intuitive ways of putting the central Humean thought. You can't be a Humean without accepting (something like) **(NM)** and **(NNC)** and SEPARABILITY is used to imply **(NM)** and **(NNC)**. This is why the Humean accepted SEPARABILITY.

But is there a way for the Humean to do this without SEPARABILITY? There have been Humeans that have dropped SEPARABILITY. Lewis (1994, p. 474) seems to suggest a response which involves denying SEPARABILITY outright. Variations on this approach are also taken by Karakostas (2008); Esfeld (1999), and Darby (2012). This response requires formulating a view that satisfies two key conditions. Firstly, it must drop SEPARABILITY while still remaining distinctively Humean; that is, while still satisfying **(NM)** and **(NNC)**. Secondly, it must avoid Maudlin-style worries, otherwise it has made no progress.

Loewer's (1996) version of the reject-SEPARABILITY response meets these conditions by replacing SEPARABILITY with a closely related principle. We will discuss this view in section 5.

In the rest of this section we will consider the prospects of other variations of the reject-SEPARABILITY strategy and conclude that they look inferior to our strategy which retains SEPARABILITY.

3.1 Rejecting Separability
3.1.1 The Non-Reductive Strategy
One way of implementing the reject-SEPARABILITY strategy is to *directly* require that the total physical state is non-modal, or lacks necessary connections, instead of appealing to a principle like SEPARABILITY to imply that. However, an advantage of an appeal to SEPARABILITY is that it has clear and precise consequences for the nature of the physical state. The claim that "the physical state is non-modal", or "lacks necessary connections", is much less clear. In order to cash out this claim the Humean could try to give a non-reductive account of non-modality (e.g. Earman and Roberts 2005; Carroll 1994). But such views, which effectively take non-modality as primitive, seem uninformative. Any Humean owes us a positive account of what her view says about the space of possibility; we want to know what possibilities are consistent with the Humean picture.[7] Non-reductive views, on their own, don't give us a satisfying answer. Perhaps the Humean should fall back on such an answer if she cannot do any better, but we should look for ways to avoid this answer.

3.1.2 Recombination

A common account that does give us a satisfying characterization of **(NM)** and **(NNC)** appeals to a principle of recombination: the fundamental physical state of the world satisfies **(NM)** and **(NNC)** if the fundamental properties and entities that constitute the physical state obey such a principle. We consider two versions of the recombination approach.

The debate over how to formulate such a recombination principle is nuanced and technical; it will suffice to focus on what the Humean wants such a principle to do. If the Humean is planning to use a principle of recombination as an account of **(NM)** and **(NNC)** it needs to imply that: (i) given a spacetime, any distribution of fundamental properties to regions of this spacetime is possible, (ii) any entities can coexist with any others and (iii) entities can be spatiotemporally related in any (consistent) way. (ii) and (iii) together express the idea that there are no necessary connections between entities and (i) expresses the idea that there are no necessary connection between properties. A recombination principle that satisfies (i), (ii) and (iii) would, plausibly, provide us with an account of what it is for **(NM)** and **(NNC)** to hold.

SEPARABILITY does imply such a principle of recombination, but importantly, recombination does not imply SEPARABILITY. Here's why: there could be a fundamental property of extended regions that "floats free" of the other properties. That is, its instantiation implies nothing about the properties of other regions, and in particular, nothing about the properties of its subregions. Such a case is inconsistent with SEPARABILITY, because there is a property that is not determined by the intrinsic physical states of spacetime points, but it is consistent with recombination.

So recombination is weaker than SEPARABILITY. It might seem, therefore, that we can avoid Maudlin-style problems by dropping SEPARABILITY and appealing to recombination to characterize **(NM)** and **(NNC)**. Unfortunately, this does not seem to be the case. Entanglement phenomena, like the Singlet state, are not states that "float free" of other properties. A pair of particles being in the Singlet state *does* imply something about the properties of its subregions. In particular, it rules out certain combinations of intrinsic spin states of the two particles. And it seems to rule them out with metaphysical necessity—if a state was consistent with all combinations of individual spin states then it would not be the Singlet state. If the Singlet state is fundamental then it violates recombination. All quantum mechanical entanglement phenomena, we conjecture, are like this: inconsistent with recombination if taken as fundamental. Rejecting SEPARABILITY and appealing directly to recombination to formulate the Humean view does not remove the tension with quantum mechanics.

3.1.3 Quiddistic Entanglement

A way to reject SEPARABILITY and retain recombination as a characterization of **(NM)** and **(NNC)** without encountering Maudlin-style problems is to deny that entangled states imply anything about any other states.[8] This view accepts that there is a world where two particles are in a Singlet state but yield matching outcomes to properly calibrated x-spin measurements. This is an option for the Humean. It's major drawback is that it involves a unintuitively quiddistic conception

of entanglement—it violates the intuition that entanglement implies something substantive about the particles so entangled. Perhaps such a quidditism isn't so bad for the Humean, after all if the Humean is to use recombination she will require a quidditistic conception of the properties that make up the mosaic. But our view does not have a quidditistic conception of entanglement; it retains a more intuitive understanding of the phenomena. Furthermore, our view has the advantage of being much more general; it can account for how and why the Humean appeals to other non-fundamental entities, like chances (as we saw in section 2.1) and other physical spaces (as we will see in section 5).[9] The view currently under consideration does nothing to explain what is going on in those cases.

We started this section recognizing that one good reason for keeping SEPARABILITY is that it is doing its job in guaranteeing that the world is fundamentally non-modal and that there are no necessary connections. We have said that recombination—the standard Humean account of non-modality—is as much in conflict with quantum mechanics as SEPARABILITY, and the other accounts that reject SEPARABILITY seem unsatisfactory. Especially if we can do better.

And we can do better. Two-state Humeanism keeps SEPARABILITY while avoiding Maudlin-style worries. What's more, we can keep recombination as a characterization of what it is for the world to be non-modal and lack necessary connections. SEPARABILITY guarantees that recombination holds.

We still haven't answered the second question: Is SEPARABILITY enough? Why not demand STRONG SEPARABILITY? The preceding discussion makes the answer to this very simple. SEPARABILITY along with PHYSICAL STATISM is enough to ensure that **(NM)** and **(NNC)** hold. Committing to STRONG SEPARABILITY does not make a view *more* Humean; if **(NM)** and **(NNC)** hold there is no way for the world to be *less* modal or contain *fewer* necessary connections. There is simply no Humean motivation for requiring STRONG SEPARABILITY. It is no disadvantage of two-state Humeanism that it denies STRONG SEPARABILITY.

4. Objections

4.1 The Predicate F Problem

The original version of the BSA avoids a powerful objection known as the "predicate F problem" by only allowing systems to be formulated in vocabulary which denotes the perfectly natural properties.

Here's the problem: Suppose the BSA allowed any language to be used. Then consider a language with a predicate, F, that is instantiated by all and only the things that exist in the actual world (including, for example, spacetime regions and mereological fusions). Then a system with only one axiom, '$\forall x F(x)$', would be extremely simple (remember, simplicity here is syntactic simplicity) and incredibly informative (it rules out all other possible mosaics). Such a system stands a very good chance of being the best system for the actual world. But it is clearly very implausible that '$\forall x F(x)$' counts as the one law of the world.

Radically unnatural properties threaten to trivialize the systemization procedure. Forcing systems to be formulated using only those predicates which denote natural properties and relations rules out such gerrymandered systems. However, two-state

Humeanism allows systems to introduce *all kinds* of novel predicates, and employs no such restriction. Systems are permitted to expand the language in any way they want. If this is right, then wouldn't two-state Humeanism fall prey to the predicate F problem?

No, it wouldn't. The reason the original BSA faced this problem is that, without the restriction on languages, a system could include any predicate it wants and that predicate would *already have an interpretation*. So there could be a system that includes the predicate '$F(x)$', where '$F(x)$' is interpreted as referring to the property instantiated by all and only the things in the actual world. It is the fact that '$F(x)$' has such an interpretation that makes $\forall x F(x)$ so informative.

Two-state Humeanism avoids the predicate F problem because, while systems can introduce any novel physical predicate they want, *they come without an interpretation*.[10] For example, a system on our variant BSA could introduce a predicate, '$F(x)$', and say that $\forall x F(x)$. But, since '$F(x)$' is introduced *uninterpreted*, saying $\forall x F(x)$ doesn't tell us *anything* about the mosaic. A system containing only this axiom would not be informative at all. It would only be informative if we added axioms containing '$F(x)$', such that, given their truth, $\forall x F(x)$ rules out many non-actual mosaics. However, the additional axioms sufficient to do this will have to include *lots* of information about the mosaic, enough so that the system would no longer be simple.

4.2 Simplicity and Informativeness of the L-state

On our view the L-state depends on the mosaic in much the same way the laws of nature do. If the best system of the world contains novel, uninterpreted language and the right kinds of axioms involving those terms, then we say that this language describes novel physical posits, and these new physical notions constitute the L-state.

There's a concern one might have about this account, which is that it requires that the *best* systematization of the mosaic—in the same sense of 'best' used in the ordinary best systems account—contain novel terminology. The objection is this: No system could ever count as best if it included extra bits of language which come in uninterpreted.

Why? A system counts as best insofar as it is the best systematization *of the mosaic*—i.e. it achieves the best balance of simplicity and informativeness. However, so the objection goes, adding novel terminology that posits elements of the L-state comes at a cost to simplicity. On the other hand, it's unclear how novel terminology can contribute to informativeness—since some novel bit of terminology either says nothing about the mosaic (i.e. is a mere stipulation or abbreviation) or it only says things about the mosaic which could be more perspicuously stated in the base language (since the physical significance of novel terminology is established by adding *other* sentences to the system, linking that terminology to the base language).

The role that the L-state plays in systematizing the mosaic is crucial to our view, and understanding *how* it could play such a role is necessary to understand why an objection like this doesn't work. To illustrate, we consider two example worlds. Each world described by two candidates for best system—one of which introduces

novel physical language (as per our theory, described in section 2). The point of this example is to show how the L-state can contribute substantively to simplicity and informativeness.

4.2.1 Two Worlds

Consider a world, w_1, where the mosaic consists of assignments of positions to point particles and the property a spacetime point has when it's occupied by part of a *B-field*. Suppose further that, over the whole history of the world, particles travel inertially until either colliding with another particle or entering a B-field. Every particle has entered at least one B-field at some point during its history. As it turns out, we can divide these particles into two classes, based on their behavior over the whole history of the world. Particles in the first set (call it S_D) have always been *deflected* by B-fields when they enter them, while particles in the second set (S_I) have always *ignored* B-fields, whenever they've gone through them (i.e. *No* particles sometimes ignore and sometimes deflect).

Additionally, of the particles which have ever collided, some did so elastically, while others annihilated on collision with another particle. Let's further suppose that every elastic collision that ever happened was between two members of S_D or two members of S_I, and that every annihilation that ever happened occurred at the collision of one particle from S_D and one from S_I.

Consider two systems of this world. The first, θ, introduces a new physical predicate, '$B(x)$'. '$B(x)$' starts out uninterpreted, but θ also posits that: (i) $B(p_1) \wedge \ldots \wedge B(p_k)$ (where $p_1 \ldots p_k$ are all and only the particles $\in S_D$—i.e. which have ever been deflected by B-fields) and $\neg B(p)$ for all other p's.

In addition to these posits, θ has three axioms: (1) A particle, p, is deflected by B-fields iff $B(p)$. (2) B-particles (particles such that $B(p)$) annihilate on collision with non-B particles and (3) Pairs which are both B-particles or both non-B particles collide elastically.

Now, it turns out that w_1 is a simple enough world that a novel physical predicate is not necessary to best systematize the mosaic. The predicate '$B(x)$', in θ, does no better for informativeness than the base language predicate 'has ever been deflected by a B-field'. Indeed, the second system we'll consider, ϕ, illustrates this.

ϕ contains three axioms: (1) A particle is deflected by B-fields iff it **has ever (in the history of the world) been deflected by a B-field**. (2) Particles which **have ever been deflected by a B-field** annihilate on collision with particles which **have ever ignored a B-field**. and (3) Particle pairs that have both **ever been deflected by a B-field** or both **ever ignored a B-field** collide elastically.

ϕ is effectively θ where the predicates '$B(x)$' and 'non-$B(x)$' are replaced by coextensive base language predicates (bolded). It has all the same consequences for the mosaic as θ, and so is just as informative, but is much simpler, since it yields these consequences without having to introduce any novel terminology, or introduce posits (like (i), which is a very long conjunction and seriously detracts from simplicity). So, at a world like w_1, a system couched entirely in terms of the base language does better than one which posits new physical states as part of its systematization.

One of the reasons the mosaic at w_1 rendered ϕ a better systematization than θ, was that we stipulated that every particle encountered a B-field at least once in its history. If we drop this assumption, things go very differently. Consider the world w_2, which resembles w_1 in that it contains point particles and B-fields, and that some particles have always been deflected by B-fields while others have always ignored them. Just like in w_1, some particles pairs have collided elastically and others annihilated on collision. Where w_2 differs from w_1 is that, in w_2, some particles *never* enter a B-field at any point in their history.

To put things loosely, but not entirely inaccurately, here's where we're going with this: there are some particles in w_2 which we would, intuitively, want to label as B-particles—based on things like their collision behavior relative to other particles—yet which have *never* encountered a B-field. This is straightforward if we are allowed to posit an L-state. But, as it turns out, a systematization that does *not* posit an L-state, and substitutes for the predicate '$B(x)$' a co-extensive predicate in the base language, cannot accommodate this in a simple and informative way.

The analogues of sets S_D and S_I (the sets of particles which have ever entered a B-field and been deflected or entered and ignored the field, respectively), call them "S_{D2}" and "S_{I2}", don't, taken together, contain all the particles in w_2, since some never enter B-fields at all. However, suppose it's still the case that no particles sometimes ignore and sometimes deflect B-fields. Suppose further that we can divide the whole class of particles in w_2 into two disjoint sets, Q and R, such that every elastic collision that ever happened was between two members of Q or two members of R, and that every annihilation on collision occurred between a pair of particles, one from Q the other from R. Finally, suppose that, as it turns out, $S_{D2} \subset Q$ and $S_{I2} \subset R$.

Now, consider a candidate for best system of w_2 which is an analogue of the system θ, call it "θ_2." θ_2, like θ, introduces a new physical predicate, '$B(x)$'. '$B(x)$' starts out uninterpreted, and θ_2 posits that (i). $B(p_1) \wedge \ldots \wedge B(p_j)$ (where $p_1 \ldots p_j$ are all and only the particles $\in Q$), and $\neg B(p)$ for all other p's. Note the way this system differs from θ: θ_2 posits that all and only the members of Q are B-particles, of which the set of particles which have ever been deflected by a B-field (S_{D2}) is a mere subset. That means θ_2, unlike θ, posits that there are (or can be) B-particles which have never entered a B-field.

θ_2 has the very same axioms as θ: (1) A particle, p, is deflected by B-fields iff $B(p)$. (2) B-particles annihilate on collision with non-B particles and (3) Pairs which are both B-particles or both non-B particles collide elastically.

Consider a particle, q, that never encounters a B-field. "q has, at some point, been deflected by a B-field" and "q has, at some point, ignored a B-field" are both false. Suppose q, at some point in its history, collided elastically with p, which *has* entered a B-field and, indeed, was deflected. According to θ_2, q is a B-particle. Positing that $B(q)$ allows θ_2 to get a grip on such particles, and to explain their behavior in a way that *unifies* it with the behavior of particles that *do* encounter B-fields. θ_2, with its substantive L-state, doesn't just serve to explain the state of the actual mosaic, they also ground counterfactuals. According to θ_2 the counterfactual

"If q had entered that B-field, it would have been deflected" is true, because q is a B-particle.

That which allows '$B(x)$' to get a grip on such particles also makes that predicate extremely difficult to do away with. This means there is no simple analogue of the ϕ system for w_2. ϕ, as a system of w_1, replaced '$B(x)$' in θ's axioms with 'has ever been deflected by a B-field', but w_2 contains particles which have never entered B-fields, so there is no simple predicate couched entirely in the base language which is co-extensive with '$B(x)$' in w_2. To see this, notice that, by (i), a particle satisfies $B(x)$ iff it's a member of Q. What are the necessary and sufficient conditions, expressed in the base language, for membership in Q?

Satisfying the predicate 'has, at some point, been deflected by a B-field' is sufficient but not necessary for membership in Q, since Q includes particles which have never encountered B-fields. Since the only particles which have collided elastically with members of Q have been other members of Q, this means that any particle which collides elastically with a particle in Q must itself be in Q. The disjunction 'has ever been deflected by a B-field OR has ever collided elastically with a particle which has ever been deflected by a B-field' gets closer, but we'd have to add more disjuncts to include particles which collided elastically with particles which collided elastically with ones which were deflected by a B-field, and so on. It doesn't stop there. We'd have to also include a disjunct to capture particles which ever *annihilated* on collision with a particle which has ever *ignored* a B-field; and another disjunct to include particles which ever collided elastically with one of *those*. The result, when expressed in the base language of the mosaic, would be a *very* long disjunction.

If we tried to reproduce the consequences of θ_2 using no novel physical predicates, the resulting system would be hopelessly complicated. Introducing novel physical posits as part of the L-state can help better systematize and unify the mosaic.

4.3 Isn't the Singlet State Fundamental?

Here is an objection to two-state Humeanism: "Two-state Humeanism gets the physical facts wrong because it says of certain physical states that they are *non*-fundamental when they are uncontroversially accepted, in the physics, as fundamental physical states." As it stands this is not a good objection. The confusion underlying this objection depends on the presupposition that the proper subject of fundamental *physics* must be entities and states which are *metaphysically* fundamental. Clearly these are different senses of 'fundamental'. The Humean clearly rejects the claim that the subject matter of fundamental physics must be metaphysically fundamental when she says that the "fundamental physical laws" are metaphysically non-fundamental.

There is, however, a more powerful objection along the same lines. Two-state Humeanism, the objection goes, is in conflict with scientific practice because it does not allow for certain possibilities that are countenanced by physicists. In particular, the L-state is determined by the mosaic, so it's not possible for the mosaic to be the same while the L-state is different. Since a pair of particles' being in the Singlet state is an element of the L-state of the world, it's not possible, according to two-state Humeanism, for there to be any difference in facts about which particles are in the

Singlet state without there being some difference in the mosaic. However, quantum mechanics allows for cases where there are two separate possibilities which differ in the facts about what particles are in the Singlet state, but match in all other respects.[11]

We acknowledge that this is a genuine issue, but it isn't a new problem for the Humean. The physical laws, on any Humean theory, depend on the mosaic, which means it is impossible for there to be two possibilities where the mosaic is the same but the laws are different. However, scientists countenance possibilities like this all the time. (Many anti-Humeans argue for this point, e.g. Tooley (1977, p. 669), Carroll (1994, pp. 57–67), Maudlin (2007, p. 67)). So our answer to the problem is that two-state Humeanism is in no worse a position than ordinary Humeanism with respect to these concerns, and the responses available to the Humean in the law case can be easily adapted to answer the corresponding worry about the L-state.[12]

5. Two-state Humeanism and Quantum Mechanics

So far we have discussed two-state Humeanism in very broad terms. In this section, we get a bit more specific and demonstrate how this account would apply to contemporary physical theories. In the first part of this section, we argue that there's good reason to think that, even in a world where the Humean mosaic, at first blush, doesn't seem to have any characteristically "quantum mechanical" states *in* it, still the best systematization of that mosaic may well be one which posits quantum mechanical states, laws, and entities. We will use Bohmian mechanics as our example. The second part of this section will contrast this account with another Humean theory, defended by Barry Loewer in his (1996), which engages with quantum mechanics (and Bohmian mechanics in particular). We argue that two-state Humeanism's account of a Bohmian world provides a more intuitive picture, with a clearer metaphysical structure and fewer primitive commitments than Loewer's. We respond to objections, both defending Loewer's account and directly criticizing the two-state Humean account of Bohmian worlds.

Consider a world where the mosaic consists of a 4-dimensional spacetime populated by n particles, travelling along various trajectories (in what follows, we will sometimes describe this as "n particles moving about in a 3-D space over time"). The only fundamental intrinsic qualities of spacetime points in this world are particle positions. Suppose that there are a great many particles, and that they move in a "Bohmian-looking" way, where this means that their trajectories correspond to what some Bohmian mechanical model (and a certain choice of wavefunction) would predict about the motion of n particles over time.[13] Of course, in this world—at least at the fundamental level—there are no wavefunctions or anything like that. We're just assuming that the particles in it move in a way which a Bohmian mechanical theory would predict (given the appropriate background conditions).

We submit that, given our assumptions about how the particles within it behave, the best system of this world ought to be one which looks *something* like Bohmian mechanics. The two-state Humean can account for this intuition with ease.

Let's call the *Bohmian Mechanical* two-state system one whose L-state includes: (1) a novel space, (2) a particle in that space, and (3) a field living on that space. As we've mentioned before, a system has to include axioms which link up the L-state and the mosaic, in some way, in order for these posits to have any significance. The new space, Q, and the particle, ω, are connected to the mosaic as follows: Take an arbitrary origin with four orthogonal axes (three spatial and one temporal) in ordinary spacetime. Posit that Q is a space for which an origin and axes can be selected such that each axis in Q stands in one-to-one correspondence with the pair $\{p, i\}$ consisting of a particle, p, in ordinary spacetime, and one of the three spatial axes, $i = x$, y, or z, from the mosaic. Posit further that the position of ω along a given axis, $x_{\{p,i\}}$, in Q (i.e. the point along $x_{\{p,i\}}$ which is closest to ω) is determined by the position of p along axis i.[14]. It follows that Q is a $3n$-dimensional space, where $n =$ the number of distinct particles in the mosaic, and Q's geometric structure (topological and metrical) is entirely and straightforwardly grounded in the geometric structure of the mosaic. Because every location in Q corresponds to a unique configuration of n distinct points in space, we may call Q a "configuration space." The third element of the L-state, the field living on Q, is the wave function. The wave function, $\Psi(x)$, has an amplitude at every point in the configuration space. Posits are also included specifying the value of $\Psi(x)$ for the points in Q.

This system has two laws. The first, the Schrödinger equation, only directly concerns elements of the L-state: it describes how the wave function, Ψ, evolves through time. On its own, it has no direct consequences for the mosaic (and so makes no contribution to informativeness). Things change, however, when we add the Guiding Equation. The Guiding equation describes how the shape of Ψ determines how ω, the world particle, moves through Q. Though we just described the content of the Guiding equation while only talking about the L-state, this *does* have consequences for the mosaic. The axioms posited in the last paragraph link Q and the position of ω to the spatial configuration of the n particles in the mosaic, so motion of ω corresponds to changes in the global configuration of particles in the mosaic. Since the Guiding Equation takes Ψ as one of its inputs, and the Schrödinger equation describes how Ψ evolves through time, the Schrödinger equation *is* genuinely informative about the mosaic. This system, while somewhat complicated, will be far more elegant and informative than any system formulated solely in terms of particle positions in 3-space.

Two-state Humeanism is able to account for the intuition that the best systematization of a mosaic consisting of an ordinary spacetime containing point particles moving in a "Bohmian-looking" way should, plausibly, involve the laws of Bohmian mechanics. Since the laws of Bohmian mechanics appeal to so much more than position in spacetime, it's hard to see how the ordinary Humean could get this result.[15]

5.1 Another Humean Account of Bohmian Mechanics

In his (1996), Barry Loewer defends a Humean account of a Bohmian mechanical world. He avoids Maudlin-style worries by rejecting SEPARABILITY and accepting a weakened variant:

FUNDAMENTAL STATE SEPARABILITY: The complete physical state of the world is determined by (supervenes on) the intrinsic physical state of each point in the fundamental space of that theory (and on the geometric relations between points in that fundamental space).

Loewer thinks Humeans should avoid a clash with quantum mechanics by choosing a *different* space (i.e. not ordinary spacetime) to be the "fundamental physical space." Loewer counts a property as part of the mosaic just in case it is an intrinsic quality of points in a $3n$-dimensional space. Because Loewer takes this high dimensional space to be fundamental (i.e. to be space over which the mosaic is distributed), this account violates SEPARABILITY, since there are elements of the total physical state which are not determined by the intrinsic qualities of *spacetime* points. However, unlike most SEPARABILITY rejecting Humean views, Loewer's view avoids the problems outlined in section 3, because FUNDAMENTAL STATE SEPARABILITY can be used to ground versions of **(NM)** and **(NNC)**.

The advantages of Loewer's view come at the price of a radical shift in ontology. On his account, fundamentally, the physical world consists of a single "world particle" located in, and the amplitudes of a physical field over, a $3n$-dimensional "configuration" space, and the laws of the best system of the world are generalizations about this particle and the high-dimensional wavefunction. We put 'configuration' and 'world particle' in scare quotes because, on this view, there are no configurations for this space to represent. This is more than just a semantic worry. It means that the very complicated structure of this $3n$-dimensional space has to be taken as brute. Two-state Humeanism, to contrast, directly grounds the geometric structure of configuration space in the structure of a spacetime containing n particles. Loewer's account cannot rely on such grounds for his $3n$-dimensional space.

This worry leads us to a further issue with Loewer's account. It's not just that the view says that ordinary spacetime and its inhabitants are derivative entities, but we find its account of how these entities arise from the fundamental structure of a lonely point wiggling about in a high-dimensional space unsatisfactory.[16]

Consider a "projection of the world particle onto [a certain 3-dimensional] subspace of" the $3N$-dimensional "configuration space" (the account sketched in this paragraph, and all quotes, are from Albert (2013)). This sort of projection is a higher-dimensional version of the sort of mathematical operation that takes a three dimensional object and maps it to its two-dimensional "shadow." According to Albert, these projections will exhibit the same behavior, and bear the same causal relations[17] to one another as the analogous particles moving in a fundamentally 3-D space would. If we have "anything in the neighborhood of a functionalist understanding of what it is to be" a particle, then these projections "must really be" particles. Non-fundamental material objects, like tables, baseballs, or persons,

are identical to projections of the world particle onto tensor products of each of 3-dimensional sub-space which corresponds to one of the "particles" they are "composed" out of.

So ordinary material objects are identical to mathematical constructions from projections of the world particle onto subspaces. This is a complicated and unintuitive account of ordinary objects and the spacetime in which we conduct our science. Two-state Humeanism does much better in this regard. Since it takes spacetime, and the particles in it, as fundamental, it has access to a very natural account of the objects of our experience. Moreover, it has a clear account of the high-dimensional space and the world particle in it—the high-dimensional space simply encodes the possible configurations of the n particles, with the world-particle occupying the point representing actual configuration.

5.2 Objections and Replies

The first objection comes from David Albert. Albert thinks there are independent reasons to take a $3n$-dimensional "configuration" space as fundamental. Albert argues that "the set of all possible trajectories of a quantum-mechanical world [with such laws] is simply not going to be *representable* on a space whose dimension is smaller than $3n$" (Albert, 1996, p. 281)[emphasis in original]. If right, this argument would imply that any world without a $3n$-dimensional space would not be able to have a system which has the right quantum mechanical laws and possibilities. However, this isn't a problem for the two-state Humean, since her account *does* accept the existence of a $3n$-dimensional space on which to represent the possible world trajectories, she just grounds this space in the mosaic!

Can we extend this objection to cast doubt on whether it's possible to ground the existence and structure of configuration space in the n particles distributed over a 4-dimensional mosaic? Definitely not. While it's certainly true that the set of all possible quantum mechanical trajectories wouldn't be representable *as trajectories* in a 4-dimensional space, there's no such barrier to these possible trajectories being *encoded* in the $3 * n$ degrees of freedom of n particles moving in 3 dimensions. Indeed, this is the whole point of a *configuration* space—that it reflect the structure inherent in the original space and the degrees of freedom available to its particles. There is nothing "extra" to the $3n$ space than what's already in the mosaic.

It might also be argued that $3n$ space needs to be taken as fundamental in order to capture the right dependencies. Specifically, the motion of physical particles, in Bohmian mechanics, is dependent on the state and evolution of the wavefunction, not on their relative distances in physical spacetime. However, despite taking spacetime as fundamental, two-state Humeanism is able to capture these dependencies, since the Bohmian best system includes laws describing the evolution of the wavefunction which show how the spatial motions of physical particles depend on it.[18,19]

Another worry: is two-state Humeanism sufficiently realist about the wavefunction? It depends on what you mean by 'realism'. Two-state Humeans are wavefunction realists in the same way that they (and ordinary Humeans) are realists about laws or objective probabilities. The ordinary Humean believes there are such

things, but distances herself from the kind of realist who take laws and probabilities to be fundamental entities which push things around or metaphysically explain stochastic behavior. The ordinary Humean accepts a more moderate realism about laws and probabilities, and the same goes for the two-state Humean's stance on entities like the wavefunction and configuration space, and states like the Singlet state.

It might also be objected that we were too quick to think that the Bohmian Mechanical system could plausibly be the best systematization of a world with a mosaic which consists of nothing more than the world histories of some point particles. The concern is that, even if the behavior of these point particles is "Bohmian-looking", such an impoverished mosaic just doesn't have enough *going on* to require a system so complex as to posit not just the global wavefunction defined over a $3n$-dimensional configuration space, but also the complicated laws of Quantum and Bohmian Mechanics.

This worry, that mere positional facts wouldn't be complicated enough to distinguish something like Bohmian Mechanics as the *best* system of that world, strikes us as far too pessimistic. One of the key motivating thoughts behind the best system account is that whatever an ideal scientist, if she was fully rational and knew everything about the state of the mosaic, would take to be the best overall theory given the evidence is the best system of that world.

Actual scientists are not ideal reasoners and they do not have access to the entirety of the facts about the mosaic. Of the elements of the mosaic, actual scientists only have *direct* access to facts about positions. This is a common Bohmian point. Scientific measurements of physical magnitudes like spin or magnetic charge don't measure these quantities directly. Rather, they correlate values of these quantities with position.[20]

If we look to actual scientific practice, we see that physicists, even with access to only a tiny slice of the position facts, have a great deal of confidence that the world is quantum mechanical (and consider this position very well confirmed). If this, in the grand scheme of things, *meager* set of position facts is enough to satisfy non-ideal working scientists, then we see very little reason to be skeptical that the ideal scientist, with access to *all* the position facts at our Bohmian world, would settle on a Bohmian Mechanical physical theory. As such, we reject the claim that the mosaic of a Bohmian world is too "simple" or "impoverished" to ground a complex, quantum mechanical, best system.[21]

6. Conclusion

Maudlin argues that Quantum Mechanics, and specifically non-local entanglement phenomena, gives us reason to reject SEPARABILITY, and challenges the Humean to find justification to save it. We hope to have met this challenge. We have argued that SEPARABILITY is the most natural way for the Humean to guarantee that the world be fundamentally non-modal and lacking in necessary connections, and that the plausible alternative accounts of these notions will end up in the same sort of conflict with QM. We've developed a Humean view which maintains SEPARABILITY,

while providing a satisfying treatment of entanglement phenomena that doesn't come into conflict with QM. The view we defend here, two-state Humeanism, avoids the conflict by allowing entanglement phenomena to be part of the physical state of the world without being fundamental. This is done in a way which is closely analogous to how the ordinary Humean allows that laws are part of the physical world while accepting that they are not fundamental.

That it gets out of the conflict with QM in an elegant way is good reason for a Humean to accept this view, but two-state Humeanism can do much more. Our view demonstrates how the Humean can take seriously certain elements of the physical world without having to take them as fundamental. We've suggested that cases of objective chance, and of configuration space in Bohmian mechanics, are good examples of this. But our view has the potential to extend to many other cases, and so to unify the Humean account of the non-fundamental elements of physics.

Notes

[1] For the remainder of the paper, we will omit this qualification.

[2] We think a third thesis is required for a correct formulation of Humeanism as a thesis about the fundamental nature of the world:

> FUNDAMENTALITY: Facts about the distribution of intrinsic physical states to each spacetime point (or pointlike object) are fundamental.

For simplicity's sake, we will assume this principle in what follows.

[3] Of course, it is still open that there is a conception of Humeanism that denies PHYSICAL STATISM or, more plausibly, SEPARABILITY but still implies **(NM)** and **(NNC)**. We consider the prospects for such a conception in section 3.

[4] Though it isn't obvious exactly how to understand this gloss. For the purposes of this paper we can think of informativeness as involving the ruling out of other possible mosaics.

[5] The stipulation that the novel vocabulary comes in uninterpreted is very important. If we allowed systems to introduce new vocabulary that comes with an interpretation then we would would face the much-discussed "Predicate F problem." More on this in section 4.1.

[6] Two-state Humeanism is a way of making sense of the view gestured to by Ned Hall in his unpublished MS (2010). Hall suggests that the Humean accept *only* particle positions as part of the mosaic. Then, as he puts it, "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)" (p. 27). According to our view, this would amount to putting mass and charge (or whatever other element of the physical state that isn't position) into the L-state. Though this proposal can be subsumed under our view, the two-state Humean is not committed to it (also Cf. our note 9).

[7] Some complexities arise here due to the fact that some Humeans take Humeanism to be metaphysically necessary and some do not. But all Humeans should be able to provide some informative answer to the question: If Humeanism is necessary, what does the space of possibilities look like?

[8] This view was suggested to us by Michael Hicks and Marco Dees.

[9] In fact, these two advantages interestingly combine. Just as the two-state Humean can have a non-quidditistic account of entanglement phenomena, she also has the resources to provide a non-quidditistic account of any aspect of the physical state she takes as non-fundamental (i.e. as part of the L-state). What's more, although we don't advocate such a view, a two-state Humean could take things like mass, charge, and spin to be part of the L-state, and thus could give a non-quidditistic account of even these properties.

[10] Again, the predicates in the BSA's base language come packaged with an interpretation; they denote the perfectly natural properties and relations instantiated by the spacetime points (and/or their occupants) which constitute the mosaic.

[11] It might turn out that, in some cases, the mosaic for the entire history of the world is detailed enough to rule out any physical possibilities except for ones where p and q are in the Singlet state at t (e.g., if p and q are prepared a particular way just before t and exhibit certain behaviors after t). However, even if this is possible, it is not at all guaranteed. For example, suppose p and q came into existence in the Singlet state and never once encountered a spin measuring device of any kind. Nothing in the M-state would have any positive bearing on their spin state whatsoever.

[12] That's our official answer. Unofficially, there are some Humean responses we are especially partial to. In particular, one response distinguishes between two kinds of modality. There is the space of metaphysical possibility, which is given by the space of possible worlds (however they are generated). And there is the space of scientific possibility, which contains possibilities corresponding to each model of every possible set of physical law. It is *scientifically* possible that the mosaic is the same and the L-state different just in case there exists a model of the laws where this is the case. This is consistent with the L-state being *metaphysically* dependent on the mosaic and thus it being metaphysically impossible for the mosaic to be the same and the L-state different.

The project of fully reconciling these two kinds of modality is outside the scope of this paper, but it is one that any Humean ought to pursue if she is to do justice to our scientific modal reasoning. For instance, at worlds where the laws are probabilistic, the truth conditions of many counterfactuals at that world will depend on what the probabilities are. The laws assign probabilities to scientifically possible models, they are not a part of the metaphysically possible worlds as such. To take these probabilities seriously is to take these models seriously. So the Humean is already committed to taking the space of scientific possibility seriously as a guide to some modal truths.

[13] We are assuming that these positions don't correspond to the predictions of some aberrant solution to the Bohmain mechanical laws.

[14] So, if the axis $x_{\{p,i\}}$ in Q is mapped to the particle-axis pair $\{p, i\}$, then the distance between the point on i which is closest to p and the spatiotemporal origin is, according to this axiom, the same as the distance between the point on $x_{p,i}$ closest to ω and the corresponding origin in Q.

[15] There is a Humean view which *can* account for certain Bohmian worlds without having to abandon spacetime or posit an L-state. Miller (2013) reads the position gestured at in Esfeld et al. (2014)—that the wavefunction to be interpreted as "nomological" (following a speculative suggestion in Dürr et al. (1995)), i.e. to be just a fixed parameter on the Guiding equation rather than a fundamental physical entity (analogous to the Hamiltonian in classical mechanics)—as an example of such a view. Miller takes this issue to task for being insufficiently "realist", but there's a deeper problem with this sort of view.

Taking the wavefunction to be "nomological", where this means a parameter in a descriptive physical law, requires that the wavefunction not be a physical *entity*. Most significantly, this means denying that it be the sort of thing that evolves through time (This is because saying it changes over time would amount to taking the wavefunction as a physical *posit* governed by the Schrödinger equation, rather than mere parameter in a descriptive dynamical law which is, by construction, *only* about particle positions in spacetime). As such, the only Bohmian worlds this account would apply to would be ones with a static, i.e. non-evolving, wavefunction. Dürr et al. (1995) explicitly embraces this apparent limitation of the view, and point out that the wavefunction of the actual world, for all we know, may well be one of this sort.

[16] See Albert (2015) for more. Thanks to an anonymous referee for pointing us towards this account.

[17] Presumably the causal relations appealed to here are understood in terms of counterfactual dependence.

[18] Of course, there is a stronger sense of 'dependence' on which particle positions do not, on our account, depend upon the wavefunction. But this is just the sense in which, for the Humean, parts of the mosaic are basic and do not depend on *anything*.

[19] Many thanks to an anonymous referee for bringing this issue to our attention.

[20] Whether that is position of some pointer in a laboratory, or, in the case of spin measurement via a Stern-Gerlach apparatus, of the position of the very particle being measured.

[21] We don't need to restrict ourselves to Bohmianism. Two-state Humeanism provides a general account of the mechanism by which non-fundamental physical ontology can be grounded in the mosaic. As such, it can be applied to any realistic physical theory as long as it postulates at least some ontology which satisfies STRONG SEPARABILITY. This includes GRW, in both its mass-density and flash ontology versions (Bell 2004). One prominent account which this condition rules out is Everettian mechanics, which postulates only the wavefunction, and no local beables (i.e. no strongly separable ontology). While two-state Humeanism cannot incorporate the standard Everettian picture, it is able to incorporate a close cousin, the mass-density "many-worlds" picture, which Allori et al. (2011) outline, and attribute to Schrödinger. (Thanks to an anonymous referee for pushing us to get clearer on this point.) Miller (2013) has independently developed a Humean response to Maudlin-style problems which is very much in the spirit of two-state Humeanism. Her account also draws on the analogy to the ordinary Humean's account of chance, but her account is only developed for, and explicitly restricted to, Bohmian theories.

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