SITUATED OBSERVATION IN BOHMIAN MECHANICS

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Abstract. Here we investigate what it might mean for a formulation of quantum mechanics to be empirically adequate. We begin by considering the measurement problem as an empirical problem and distinguishing between stronger and weaker varieties of empirical adequacy. A strongly adequate theory is one that provides a compelling explanation of the experiences of a physically situated observer. A formulation of quantum mechanics that provides such situated empirical adequacy also provides a particularly compelling response to the measurement problem. As a concrete example we consider how Bohmian mechanics explains the experience of a physically situated observer.

1. the measurement problem and situated observation

Bohmian mechanics was proposed as a solution of the quantum measurement problem. To solve the problem, it must provide an appropriately compelling account of our quantum experience. As we will see, Bohmian mechanics provides an account that is both richer and more subtle than just describing the behavior of a directly-observable primitive ontology. Rather, it allows one to explain the experience of a physically situated observer, an observer who might herself be characterized within the theory. Part of the present argument is that this strong sort of empirical adequacy is precisely what one should want from a satisfactory solution to the quantum measurement problem.[1]

The goal is not to give canonically necessary and sufficient conditions for a satisfactory solution to the quantum measurement problem. Rather, the thought is that opting for a solution to the measurement problem involves choosing how to best explain quantum experience and a theory that allows one to account for the experience of a physically situated observer provides a particularly compelling sort of explanation.

At root, the quantum measurement problem is a problem in accounting for determinate measurement records that would explain our experience. The problem itself is a direct consequence of how physical states are represented in quantum mechanics and the linearity of the standard quantum dynamics. On the standard linear dynamics, the unit-length vector $|\psi(t_0)\rangle_S$ representing the state of a physical system S at an initial time t_0 evolves as follows:

$$|\psi(t_1)\rangle_S = \hat{U}(t_0, t_1)|\psi(t_0)\rangle_S$$

Date: August 7, 2021.

[1]Salient to the present discussion, I take this way of thinking about the measurement problem to be very much in the tradition of both David Bohm (1951, 583) and Hugh Everett III (1956, 118–9) and (1957, 183–5)

where $\hat{U}(t_0, t_1)$ is a unitary operator that depends on the energy properties of the system. The problem can be seen by considering an ideal x-spin measurement.[2]

Suppose an object system S begins in the superposition of x-spin states represented by

$$\alpha|\uparrow_x\rangle_S + \beta|\downarrow_x\rangle_S$$

and that an observer F and her measuring device M begin ready to make an x-spin measurement of S. The composite system, then, begins in the state:

$$|\text{“r”}\rangle_F|\text{“r”}\rangle_M(\alpha|\uparrow_x\rangle_S + \beta|\downarrow_x\rangle_S).$$

Suppose that M is a perfect measurement device and F a perfect observer. That is, suppose that M's pointer reading becomes perfectly correlated with the x-spin of S so that $|\text{“r”}\rangle_M|\uparrow_x\rangle_S$ would evolve to $|\text{“}{\uparrow_x}\text{”}\rangle_M|\uparrow_x\rangle_S$ and $|\text{“r”}\rangle_M|\downarrow_x\rangle_S$ would evolve to $|\text{“}{\downarrow_x}\text{”}\rangle_M|\downarrow_x\rangle_S$ when M interacts with S. And suppose that F's measurement record becomes perfectly correlated with M's pointer so that $|\text{“r”}\rangle_F|\text{“}{\uparrow_x}\text{”}\rangle_M|\uparrow_x\rangle_S$ would evolve to $|\text{“}{\uparrow_x}\text{”}\rangle_F|\text{“}{\uparrow_x}\text{”}\rangle_M|\uparrow_x\rangle_S$ and $|\text{“r”}\rangle_F|\text{“}{\downarrow_x}\text{”}\rangle_M|\downarrow_x\rangle_S$ would evolve to $|\text{“}{\downarrow_x}\text{”}\rangle_F|\text{“}{\downarrow_x}\text{”}\rangle_M|\downarrow_x\rangle_S$ when F interacts with M.

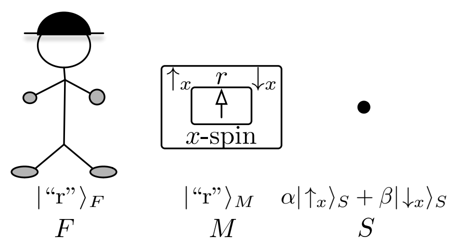

FIGURE 1. The measurement problem setup

Assuming such perfect correlating interactions, since the quantum dynamics is linear, the resultant state of the composite system will be:

$$\alpha|\text{“}{\uparrow_x}\text{”}\rangle_F|\text{“}{\uparrow_x}\text{”}\rangle_M|\uparrow_x\rangle_S + \beta|\text{“}{\downarrow_x}\text{”}\rangle_F|\text{“}{\downarrow_x}\text{”}\rangle_M|\downarrow_x\rangle_S.$$

The problem is that this state does not describe any particular determinate measurement record and hence does not explain there being a single determinate post-measurement observer record.

The measurement problem is an empirical problem. The linear dynamics does not explain how a *situated observer*, an observer as characterized within the theory itself, ends up with a determinate measurement record with the standard quantum probabilities. Inasmuch as the theory fails to make the standard quantum predictions for a situated observer it fails to be empirically adequate. We will reflect further on this way of thinking of empirical adequacy throughout the paper.[3]

[2]The following is, in brief, how both Hugh Everett (1956) and (1957) and Eugene Wigner (1961) set up the measurement problem.

[3]The thought that the quantum measurement problem ultimately involves providing a satisfactory explanation of the experience of a situated observer meshes well with a number of salient historical discussions. Of particular note, Hugh Everett understood the measurement problem as resulting from a failure to consider carefully what an observer would experience when treated as a physical system herself. Everett's strategy was to show that there was a concrete sense in which pure wave mechanics could be taken to make the right empirical predictions for an observer as characterized within the theory. This approach led to his relative-state formulation of pure wave mechanics

There are at least three ways to address the measurement problem.[4] The first is to deny that the state predicted by the linear dynamics is the state that in fact results from such a chain of interactions. The standard collapse theory does this by postulating that whenever a *measurement* is made, the system S randomly, instantaneously, and nonlinearly jumps to an eigenstate of the observable being measured and stipulating that the probability of jumping to $|\phi\rangle_S$ when O is measured is $|\langle\psi|\phi\rangle|^2$. Then if one supposes that a measurement occurs at some point in the chain of interactions, one ends up with the composite state $|``\uparrow_x"\rangle_F|``\uparrow_x"\rangle_M|\uparrow_x\rangle_S$ and hence a record of x-spin up with probability $|\alpha|^2$ or the composite state $|``\downarrow_x"\rangle_F|``\downarrow_x"\rangle_M|\downarrow_x\rangle_S$ and hence a record of x-spin down with probability $|\beta|^2$. This is also the basic strategy used by other collapse theories like GRW. Such theories seek to describe precisely when and how such collapses occur.[5]

A second way to address the problem is to insist that both physically possible x-spin records are in fact fully realized. This strategy, however, leads to two new problems. One must now explain why it appears to a post-measurement observer that she got precisely one of the physically possible determinate measurement results when the final state represents her as in some sense getting both results. And one must explain why the probability of getting the result x-spin up is $|\alpha|^2$ and why the probability of getting the result x-spin down is $|\beta|^2$ when both results are fully represented in the final state. Many worlds formulations of quantum mechanics seek to address the first of these, the determinate-record problem, by insisting that the measurement interaction results in two observers, one of whom gets each of the two possible measurement results. At first thought, this serves to make the second problem all the more puzzling as now the usual forward-looking probability of x-spin up and the usual forward-looking probability of x-spin down are each simply one. While we will discuss briefly a contrast between how Bohmian mechanics and Everettian quantum mechanics explain experience later, there is much more to say about the determinate record and probability problems.[6]

A third way to address the measurement problem is to take the quantum-mechanical state predicted by the linear dynamics to be right but then to add something to the theory that chooses one or the other of the two possible outcomes as the single measurement record that is in fact realized by the measurement interaction. This is the hidden-variable strategy. The hidden variable in a theory like Bohmian mechanics can be thought of as a sort of ontological marker that selects one branch of the quantum-mechanical state as the one that is in fact realized.

Our concern here is with how hidden-variable theories like Bohmian mechanics explain the experience of a situated observer and hence manage to be empirically

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and the various many-worlds theories. See Barrett (2015) and (2020) chapter 9 for discussions of this approach and how it was to work. Jenann Ismael (2007) and (2016) has put the notion of a situated observer to philosophical work on issues like the nature of freewill. Here we are just using it to get clear on the more modest question of how one might think of the explanatory demands of empirical adequacy. As discussed in the next section, the notion of a situated observer is something that routinely arises, at least implicitly, in philosophical discussions of empirical adequacy.

[4]This way of thinking of the measurement problem is discussed, among other places, in Everett (1956), Albert (1992), Maudlin (1995), and Barrett (1995).

[5]See Ghirardi, Rimini, and Weber (1986) for a description of GRW and Barrett (2020) chapter 8 for a discussion of the virtues and vices of alternative formulations of the theory.

[6]See Everett (1956) and (1957) for his original relative-state proposal and Saunders, Barrett, Kent, and Wallace (eds) (2010), Wallace (2012) and Barrett (2018) and (2020) for a start on recent discussions of how one might make sense of it.

adequate. The basic strategy is to find *something* to make determinate that, given the theory's auxiliary dynamics, provides something on which the content of one's determinate measurement records might plausibly supervene.[7] Importantly, the something on which one's records might be taken to supervene may be different from the *something* determinate that was added to the theory to complement the usual quantum-mechanical state. Indeed, as we will see, this is the case for Bohmian mechanics.

We consider in some detail how Bohmian mechanics accounts for a situated observer's experience. This will involve getting clear on what a determinate measurement record is and how it acquires its empirical content in the theory. We will see that how the theory explains the experience of a situated observer is significantly less direct and hence more subtle than one might have thought. Ultimately, this makes the question of the variety of empirical adequacy exhibited by Bohmian mechanics a delicate matter.

We will begin by considering a number of different ways to understand what it might be for a physical theory to be empirically adequate. The strongest of these will require a theory to explain the experience of a situated observer, an observer whose measurement records are modeled within the theory. Finally, we will consider the sort of empirical adequacy exhibited by Bohmian mechanics.

2. VARIETIES OF EMPIRICAL ADEQUACY

Among other things empirical science aims to provide empirically adequate theories.[8] That said, there are a number of ways of understanding what it might mean for a theory to be empirically adequate. The basic idea is that an empirically adequate theory explains our experience. Put another way, we consider a theory to be empirically adequate if it tells us that observers will experience just what they do in fact experience. But how one unpacks this basic idea depends on what one requires of a satisfactory account of an observer's experience for the task at hand. Some ways of accounting for an observer's experience are richer and more compelling than others. The thought is to associate different notions of empirical adequacy with different sorts of explanatory demands.

One might begin by imagining a spectrum ranging from more impoverished to richer varieties of empirical adequacy. In many cases, just being able to formulate an accurate predictive algorithm may be a notable achievement. But a theory that does just this provides only a threadbare variety of empirical adequacy. Consider, in contrast, a theory that provides a dynamical account for how measurement interactions produce physical records on which a situated observer's experience might plausibly be taken to supervene. Such an account, if one can get it, would clearly exhibit a richer and more compelling variety of empirical adequacy. The thought behind such *situated empirical adequacy* is that a theory only really makes the right empirical predictions, and is hence empirically adequate, if it makes the right empirical predictions *for a situated observer*, an observer whose measurement records

[7]Note, in contrast, that this is not a problem for the collapse strategy. On that approach, a measurement-like interaction causes a collapse that puts the composite system in, or near, a particular record eigenstate. As a consequence, one might take one's determinate measurement record to supervene on the quantum-mechanical state itself.

[8]Some take this to be the chief or even only aim of science. As Bas van Fraassen put it, "Science aims to give us theories which are empirically adequate; and acceptance of a theory involves as belief only that it is empirically adequate" (1980, 12).

are modeled and correctly predicted by the theory. One would expect a theory like that also to explain *why* the world looks the way it does. While it would clearly be great to have, one might worry that such a theory is doubly difficult to formulate as it is ultimately answerable both to what we experience and to our beliefs and commitments concerning how our experience supervenes on physical records in the world described by the theory. For the purposes of addressing the measurement problem, however, even just an approximate, plausible account of situated experience might serve as a model to get us started.

In this spirit, we will distinguish between three rough-hewn varieties of empirical adequacy a physical theory like quantum mechanics might exhibit. One might take a theory to be *minimally adequate* over a domain of phenomena if it provides an algorithm for making accurate empirical predictions in that domain. Such a theory need not even purport to describe the physical world or characterize the sequence of events that produce the phenomena we experience. Alternatively, one might take a theory to be *weakly adequate* if it makes accurate empirical predictions and provides something on which one's experience might in principle be taken to supervene. Such a theory might make the right predictions and seek to explain why one experiences what one does, it is just that the explanation it gives is judged to be ad hoc, implausible, or otherwise uncompelling. Finally, one might take a theory to be more *strongly adequate* insofar as it allows one to provide a dynamical account of something on which one's experience might plausibly be taken to supervene given our background beliefs and commitments concerning what physical facts are relevant to the values of our experience. The question here is the extent to which the theory provides a context for one to give a plausible account of a situated observer's records. The theory itself need not provide a full account of the relationship between her physical and experiential states. It just needs to provide a set of determinate facts sufficient to allow one to account, at least schematically, for her experience. It does so if it explains how she ends up with the records she does.

Inasmuch as it might be taken to be descriptive of the physical world, a weakly adequate theory is arguably something more than just a predictive algorithm, but it might not be much more. In contrast, a strongly adequate theory provides a context for explaining why the world looks the way it does to a situated observer, with something like the properties we take ourselves to have, inhabiting the world described by the theory. One should expect judgments of strong adequacy to be informed by our beliefs and commitments regarding how experience in fact supervenes on the physical world, and these, in turn, to depend ultimately on our best understanding of our perceptual and cognitive faculties. Both weak and strong adequacy provide higher-octane explanations than minimal adequacy. They are only possible in theories expressive enough to characterize a situated observer and to provide an account for how such an observer ends up with the records she does.

W. V. O. Quine (1969) famously argued that an appropriately sophisticated empiricist should treat experience itself as a thoroughly natural phenomenon. The sort of situated empirical adequacy we are discussing here might be thought of as a variety of naturalized empirical adequacy. One's physical theory only provides a naturalistic account of an observer's experience if it explains her records as aspects of the world described by the theory.

Situated empirical adequacy also fits well with something like constructive empiricism. Bas van Fraassen takes a theory to be empirically adequate if the structures described in one's observational reports are isomorphic to the observable substructures of a model of the theory (1980, 64). He then appeals to what the theory predicts would in fact be observable to a situated observer, to an observer as characterized by the theory itself, to say what it means for a substructure of a theory's model to be observable (1980, 16 and 56–59).

Judgments regarding situated empirical adequacy involve seeking a reflective equilibrium between two explanatory demands. We want our physical theories to be empirically adequate, and hence, to explain why we see what we do. But we also rely on our best physical theories to explain what it is that we are in fact seeing when we experience the world. One might imagine tuning each direction of explanation as we consider increasingly sophisticated and compelling theories.

Inasmuch as a theory arguably fails to make any empirical predictions whatsoever unless it makes predictions for the records of a situated observer, strong adequacy is clearly an empirical virtue we should want whenever we can get it. Concerning the quantum measurement problem in particular, seems to me that one only has a truly compelling resolution if one can give a plausible account of the measurement records of a physically situated observer.

Some formulations of quantum mechanics provide more or less successful predictive algorithms but are not rich enough to count as even weakly adequate as they do not even begin to explain how a situated observer might end up with the records she does. It is characteristic of information-theoretic formulations of quantum mechanics that the quantum-mechanical state is understood as representing an agent's epistemic or informational state not the state of the physical world.[9] Inasmuch as such theories do not even purport to describe how determinate measurement records might be produced on which a situated observer's experience might be taken to supervene, they lack the sort of descriptive and explanatory ambition of even something like the single-mind theory, which we will discuss in the next section. While implausible on the face of it, something like the single-mind theory allows one to characterize what measurement records are and how records of the sort we find may be produced by interactions between an observer and the systems she observes and is, hence, weakly adequate. That we have formulations of quantum mechanics that are weakly adequate is part of what renders information-theoretic formulations of quantum mechanics unattractive.[10]

A proponent of the information-theoretic approach might argue in reply that it is better to opt for just a predictive algorithm, and hence only a minimally adequate formulation of quantum mechanics, than to endorse a weakly adequate theory. In the former case, one is in suspense concerning the nature of the quantum world while, in the latter, one commits to an implausible account of experience. But one need not commit to a theory's metaphysics to use the theory. Even a theory that appeals to an implausible metaphysics may be useful in guiding one's application of quantum mechanics for predictive purposes. While clearly not the case with the

[9]See Fuchs (2010), Healey (2012), and Bub (2015) for diverse examples of the information-theoretic tradition. See Barrett (2020, 187–9) and Hagar and Hemmo (2006) for explanations of some of the limitations of information-theoretic formulations of quantum mechanics as even just predictive algorithms.

[10]See Barrett (2020, 187–9) for further discussion.

book theory of the next section, the single-mind theory serves well as a heuristic for understanding subtle no-collapse experiments.

Before considering that, this is a good place consider something closely related to the notion of situated empirical adequacy. The notion of *empirical incoherence* also involves considering a situated observer. A descriptive theory is empirically incoherent if a situated observer could have no empirical evidence for accepting the theory if the theory were in fact true. If an empirically incoherent theory were true, the nature of the physical world the situated observer inhabits would prevent her from having reliable evidence in favor of the theory. Remarkably, there are a number of formulations of quantum mechanics that are empirically incoherent. There is hence a transcendental argument for not accepting an empirically incoherent theory. If it were true, empirical inquiry would be impossible. This issue is perhaps most salient in the Everett no-collapse tradition.[11]

3. THE WAYS OF WEAK ADEQUACY

Here we will briefly discuss two weakly adequate theories. The first is fanciful. The second is more useful but perhaps ultimately no more plausible.

Consider an omniscient god who imagines creating the universe we take ourselves to inhabit but then decides not to do it. Being omniscient, she knows what each agent would have experienced had she decided to create the universe we take ourselves to inhabit, so she decides to create a radically different sort of universe instead. The universe she creates contains just one object, a book that records in full detail every experience each agent would have had if the universe we take ourselves to inhabit had in fact been created. Suppose that theory T fully and accurately describes this book universe.

By construction, theory T describes *something* on which one's experience might be taken to supervene—namely, an agent might take the intricately detailed descriptions in the book to ground her experience. In this sense T is weakly adequate. But inasmuch as we find it highly implausible that our experience supervenes on the sort of physical records described by T, we cannot take T to be strongly adequate. More specifically, among other beliefs and commitments, we take our experience to supervene on more or less reliable physical brain records produced by interactions between us and the physical systems we observe. So while T provides something on which one's quantum experience might be taken to supervene, it is not a plausible something. Indeed, given such beliefs and commitments, T might as well just be a minimal predictive algorithm as it fails completely in providing a compelling narrative for *why* we experience what we do.

While one should be willing to entertain nonstandard, perhaps strikingly counter-intuitive, accounts of experience, it is not the case that anything goes, particularly

[11]See Barrett (1996) and (1999, 116–7 and 189) for discussions of empirical incoherence in the context of pure wave mechanics (the bare theory) and other no-collapse theories (like the single- and many-minds theories). In brief, if the bare theory were true, a situated observer could have no empirical evidence that it was. Similar considerations apply to situated observers in some many-worlds formulations regarding evidence of forward-looking quantum probabilities. See Barrett (2020) for a discussion. Along similar lines, Huggett and Wüthrich (2013) consider the empirical coherence of quantum theories of spacetime. Putting their point in the language we are using here, it is unclear how one might even make sense of a situated observer making observations in theories of quantum gravity that postulate spacetime as an emergent structure.

if one has other theoretical options that better satisfy our shared explanatory demands. But that said, clearly not all of our explanatory demands are fully shared. In the context of deciding between alternative formulations of quantum mechanics, competing arguments are often grounded in conflicting commitments regarding what one ought to care about most in one's physical theories. Lacking a canonical way of answering such questions, we formulate options that are as attractive as we can make them, then aim to decide on cost-benefit grounds how we might best satisfy our background explanatory commitments. While there is no reason to suppose that such reflections will lead to consensus on a single clear winner in every case, we sometimes find common ground. One should expect wide agreement that the book theory T is unattractive in spite of its stipulated empirical virtues.

The book theory T is minimally adequate because it provides an algorithm for predicting what one will experience (just look at what T says of the book). It is also weakly adequate, because there is something in the world on which one might take ones experience to supervene (the descriptive expressions in the book). But it is not strongly adequate because our best accounts of perception and cognition suggest that one experience supervenes on something like particle positions and/or field configurations in brains, not descriptive expressions in a book. A failure of strong adequacy is a failure in compatibility with our background commitments regarding the sort of physical facts one needs to explain the experience of a situated observer. In the book theory it is difficult even to make plausible sense of a situated observer.

David Albert and Barry Loewer's (1988) single-mind formulation of quantum mechanics is another example of how a theory might make the right empirical predictions yet give an implausible account of experience. The single-mind theory is significantly richer than the book-universe theory, though perhaps ultimately not that much more plausible. But significantly, its dynamical account of experience makes it more than just a predictive algorithm.

On the single-mind formulation of quantum mechanics, every physical observer is associated with a nonphysical mind that possesses an always-determinate mental state. When a physical observer performs a measurement and ends up with a superposition of different physical brain records, the observer's mind randomly becomes associated with precisely one of the branches with probabilities determined by the norm-squared of the amplitude of each branch. The observer's mind then directly experiences the associated branch state. In the post-measurement state

$$\alpha|``\uparrow_x"\rangle_F|``\uparrow_x"\rangle_M|\uparrow_x\rangle_S + \beta|``\downarrow_x"\rangle_F|``\downarrow_x"\rangle_M|\downarrow_x\rangle_S.$$

This means that F's mind ends up associated with the first branch and hence the experience of seeing M's pointer pointing at the result "$\uparrow_x$" with probability $|\alpha|^2$, and F's mind ends up associated with the second branch and hence the experience of seeing M's pointer pointing at the result "$\downarrow_x$" with probability $|\beta|^2$. The single-mind theory is a sort of hidden-variable theory, one where the observer's mind selects a branch of the standard quantum-mechanical state and the selected branch determines the experiential state of the observer's mind.

One must specify somewhat more than this to get a complete mental dynamics for the theory, but it should be clear that one can do so in a way that predicts the standard quantum probabilities.[12] The resulting theory is consequently empirically adequate over the quantum experiments we have performed so far. Further, the single-mind theory provides *something* on which an observer's experience might be taken to supervene. Here it is something that one might take to *directly* determine her experience—the state of her nonphysical mind.

That said, the very effectiveness of its explanation of experience reveals how ad hoc the single-mind theory is. Indeed, rather than seeking to provide a compelling dynamical account of how reliable measurement records on which a situated observer's experience might plausibly be taken to supervene are produced by measurement interactions, here one simply stipulates the right quantum experience for the observer directly. The theory does little to explain why one experiences what one does, and in this it is very like a minimally adequate predictive algorithm. Indeed, take *any* purely predictive theory, then just postulate the existence of a mind that has precisely those predicted experiences and one has explanations that are in many ways akin to those of the single-mind theory.

Given its implausible narrative and the metaphysical assumptions on which it depends, one might take the single-mind theory's account of quantum experience to be no more compelling than the book-universe account. On the book-universe theory, the physical system on which my mental state would have to supervene, the static ink marks on the pages of a book in a static world, is not the sort of physical system that we in fact take to provide an acceptable explanation of experience. On the single-mind theory, there is nothing whatsoever physical on which my experience might be taken to supervene, also contrary to our firmly held beliefs and commitments. Both theories provide *something* on which my experience might be taken to supervene, but in neither case it is a compelling something given our background commitments. Hence, in neither case is the theory strongly adequate.

But these negative comparisons ignore the single-mind theory's heuristic virtues. While its description of the world is implausible, the theory is significantly more than a minimal predictive algorithm. Since physical states always evolve in a linear way and since mental states do nothing to affect the evolution of physical states, the single-mind theory provides a useful framework for thinking through the empirical predictions of no-collapse formulations of quantum mechanics generally. Such a framework is particularly welcome when analyzing counterintuitive measurement interactions like those involved in Wigner's friend self-measurements.[13] Significantly, it is precisely this sort of predictive problem that minimal information-theoretic formulations of quantum mechanics often muddle.[14] This is one way in which a theory that is only weakly adequate may be more useful than a minimally adequate predictive algorithm that seeks to be agnostic about physical states and processes.

[12]One must, for example, say what happens when one repeats a measurement or another observer performs the same measurement. See Albert and Loewer (1988), Albert (1992), and Barrett (1999) for discussions of the single-mind theory and its dynamics.

[13]See Albert (1986) and (1992) chapter 8 and for descriptions of such experiments.

[14]See Hagar and Hemmo (2006) and Barrett (2020, 187–9) for discussions of the predictive inadequacies of information-theoretic formulations, inadequacies not shared by the single-mind formulation.

4. STRONG ADEQUACY AND THE NOTION OF PRIMITIVE ONTOLOGY

A weakly adequate formulation of quantum mechanics like the single-mind theory might allow for impressive empirical predictions and be heuristically useful yet fail to provide a compelling account of experience. For strong adequacy it is not enough that there be something on which the empirical content of one's experience might in principle be taken to supervene. One requires, rather, a formulation of quantum mechanics that provides a compelling explanation of a situated observer's measurement records given our background commitments regarding how an observer's experience in fact supervenes on the physical world. Such a theory would address the quantum measurement problem by providing a plausible explanation of the physical records that explain our quantum experience.

A currently fashionable approach to getting an appropriately compelling account of quantum experience is to insist that a satisfactory formulation of quantum mechanics admits of a *primitive ontology* of objects whose motions in three-dimensional space explain our experience. The argument goes something like this.[15] A fundamental physical theory is supposed to account for our experience of the physical world. Since the physical world appears to be constituted by three-dimensional macroscopic objects in motion, the theory should describe the world in terms of a primitive ontology, objects that can be considered to be the fundamental building blocks of ordinary three-dimensional macroscopic objects. By describing how these fundamental objects move, one explains the motions and properties of ordinary macroscopic objects and hence provides a compelling account of experience. The thought is that a theory provides a satisfactory explanation of our *manifest experience* if and only if it puts the right objects in the right places at the right times.

This approach seems to get something intuitively right. Neither the book-universe example nor the single-mind theory provide a primitive ontology of objects in motion that might be taken to be constitutive of the manifest physical world. The book-universe theory describes a world whose physical structure is very different from appearances. And the single-mind theory fails to provide anything *physical* on which one's experience might be taken to supervene. The tempting thought here is that opting for a theory with a primitive ontology of three-dimensional objects in motion allows one to return to a theory like classical mechanics where one has something like a direct account of the manifest physical world of ordinary objects doing ordinary things.

But this thought is poorly motivated. While classical mechanics is broadly compatible with our background assumptions regarding how we form reliable records when we observe the world, and is hence arguably strongly adequate, at least in the domain of classical phenomena, it is not because its primitive ontology of particles is somehow directly manifest. One does not see a table through unmediated apprehension of the positions and motions of its constituent particles. Rather, classical mechanics provides a context where one might tell a compelling story for how a physically situated observer might end up with reliable records of the table's properties on observation. To be sure, the story involves a primitive ontology of

[15]The following description follows Allori's (2013) line of argument. See Allori, Goldstein, Tumulka, and Zanghi (2014) for more on how a primitive ontology is supposed to capture the manifest image of the world.

particles and fields in ordinary three-dimensional space, but that's because the ontology of classical mechanics happens to be a primitive ontology, not because there is anything canonical or special about such an ontology.

Similar considerations hold for explaining situated experience in Bohmian mechanics. While one can characterize the theory in such a way that it admits of a primitive ontology (by appealing to three-dimensional particle positions rather than the full particle configuration and by finding a suitable three-dimensional surrogate for the wave function over configuration space), a situated observer would not have any special epistemic access to the positions or motions of such objects by dint of their being part of a primitive ontology. Indeed, as we will see, there is a concrete sense in which a situated observer in Bohmian mechanics does not *see* particles or configurations of particles at all.

So even if one describes Bohmian mechanics in terms of a primitive ontology, the objects in the primitive ontology are not what a situated observer *sees*. Rather, the empirical content of a situated observer's physical records is determined by the *effective wave function* selected by the full particle configuration.[16] Since the effective wave function depends on the universal wave function and on the positions of potentially distant particles, it is not at all well conceived of as a well-localized object in motion in ordinary three-dimensional space, and hence is not a candidate for an element of a primitive ontology. In this sense, how Bohmian mechanics explains the experience of a situated observer undermines the motivation for adopting a primitive ontology in the first place.

To see how this works, we will consider how Bohmian mechanics explains the measurement records, and hence the experience, of a physically situated observer and the sense in which one might take the theory to be strongly adequate. The story is much richer and more compelling than the one provided by the single-mind theory, and perhaps significantly more subtle than one might expect. The theory's ontology plays a role in the account, but there is no special reason to take that ontology to be primitive.

The first step is to get a sense of how the theory describes physical systems generally.

[16]Dürr, Goldstein, and Zanghì (1992) introduced the notion of an effective wave function to explain how epistemic probabilities work in Bohmian mechanics. That one has, at most, epistemic access to the effective wave function in Bohmian mechanics is a recurring theme in the literature. While he was not ideally clear on the point, Bohm himself sometimes seems to have recognized this in his initial presentation of the theory (1952, 374 and 383). As we will see, Bell also had a sense of this. Later, Albert (1992, 156–60) and Valentini (1992, 33) explicitly showed that if one knew the particle configuration in the context of an EPR set up with more precision than allowed by the effective wave function, then it would allow one to send superluminal signals, violating the predictions of quantum mechanics. That one does not have epistemic access to precise particle positions in the theory also plays a key role in Brown and Wallace's (2003) argument that Bohmian mechanics has no advantages over Everettian quantum mechanics. We will also return to this point later. The present argument is that, inasmuch as it determines the full empirical content of the situated observer's records, the effective wave function is what a situated observer most directly sees. So while one might say that the theory's primitive ontology explains one's experience, if one sets Bohmian mechanics up that way, it is only by dint of the role it plays in determining the effective wave function. And there is no need for the ontology to be primitive to play this role.

5. Bohmian mechanics

One might think of the single-mind theory as a hidden-variable formulation of quantum mechanics where the always-determinate hidden variable is the mental state of the observer. This choice of hidden variable provides a direct, but blatantly ad hoc, account of one's quantum experience. In contrast, the hidden-variable in Bohmian mechanics is particle configuration, which provides a more subtle, indirect account of experience. How plausible one ultimately finds the account will depend on the background assumptions one brings to one's evaluation of the theory.

Bohmian mechanics might be characterized by following rules:[17]

1. *representation of states*: The complete physical state of a system S at time t is given by the wave function $\psi(q,t)$ over configuration space and a point in configuration space $Q(t)$.
2. *interpretation of states*: The position of every particle is always determinate and is given by the current configuration $Q(t)$.

3I. *linear dynamics*: The wave function evolves in the standard unitary way. In the simplest case

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

3II. *particle dynamics*: Particles move according to

$$\frac{dQ_k(t)}{dt} = \frac{1}{m_k}\frac{\text{Im }\psi^*(q,t)\nabla_k\psi(q,t)}{\psi^*(q,t)\psi(q,t)}\Big|_{Q(t)}$$

where m_k is the mass of particle k and $Q(t)$ is the current configuration.

4. *distribution postulate*: The epistemic probability density of the configuration $Q(t_0)$ is $|\psi(q,t_0)|^2$ at an initial time t_0.[18]

Here both the wave function $\psi(q,t)$ and the current particle configuration $Q(t)$ evolve in $3N$-dimensional configuration space, where N is the number of particles in the system S. One might think of the probability density $|\psi(q,t)|^2$ as describing a compressible probability fluid in configuration space. As John Bell put it

> *No one can understand this theory until he is willing to think of ψ as a real objective field rather than just a 'probability amplitude.' Even though it propagates not in 3-space but in $3N$-space.* (1987, 128; emphasis in the original)

The wave function evolves deterministically according to the linear dynamics (rule 3I), and as the probability fluid flows about in configuration space, it carries the point representing the particle configuration $Q(t)$ along as described by the particle dynamics (rule 3II). In brief, the particle configuration moves as if it were a massless particle carried by the probability current in configuration space.

Under this dynamics, if the epistemic probability density for the particle configuration is ever given by the standard epistemic quantum probabilities $|\psi(q,t)|^2$, then it will continue to be until one makes an observation. The distribution postulate

[17] This follows Bell's (1987) formulation of Bohm's (1952) theory.

[18] There is a long tradition of trying to weaken this assumption. For a notable example see Dürr, Goldstein, and Zanghì's (1992) discussion of quantum equilibrium. While there is much to say regarding the status of probability in Bohmian mechanics, here we set aside the question of whether the distribution postulate can be replaced by something weaker and follow Bell's formulation of the theory. That said, Dürr, Goldstein, and Zanghì's notion of an effective wave function is essential to the argument that follows.

(rule 4) stipulates that one assign a prior epistemic probability density $|\psi(q, t_0)|^2$ to the particle configuration at time t_0. As a result, Bohmian mechanics predicts the standard quantum probabilities for particle configurations, and consequently, it predicts the standard quantum distribution of particles, and hence the objects they constitute, in ordinary three-dimensional space.

The upshot is that if it were ever possible for an observer to see the particles, and hence precisely where they were, one would expect to find them statistically distributed as predicted by quantum mechanics. It might thus seem trivial to recover the standard quantum statistical predictions for the observation of particle positions. While this is not how the theory explains our experience, even well-informed proponents often talk this way.

Bell himself sometimes seems to have suggested that Bohmian mechanics accounts for our experience of the motions of three-dimensions objects in ordinary three-dimensional space in an entirely straightforward way:

> The fundamental interpretative rule of the model is just that [the value the particle position variable $Q(t)$] is the real position of the particle at time t, and that observation of position will yield this value. Thus the quantum statistics of position measurements ... [are] recovered immediately. But many other measurements reduce to measurements of position. For example, to 'measure the spin component σ_x' the particle is allowed to pass through a Stern–Gerlach magnet and we see whether it is deflected up or down, i.e. we observe position at a subsequent time. Thus the quantum statistics of spin measurements are also reproduced, and so on. (1987, 34)

On this description, one might imagine that the theory explains experience because we directly see where things are and find them to be distributed in the standard quantum way. Since the theory predicts the standard quantum probabilities for the positions of things, it makes the standard quantum predictions insofar as every measurement is in fact ultimately a measurement of position. So, one might conclude, the theory's primitive ontology of *things with always-determinate positions* immediately explains our measurement records and corresponding experience.[19]

Bell also suggested that predicting the right "positions of things" might reasonably be taken to be both a necessary and a sufficient condition for a theory to provide a satisfactory account of experience. On this view, since we see things move just as the theory predicts, Bohmian mechanics is empirically adequate. Put another way, Bohmian mechanics is empirically adequate because it admits of a primitive ontology of objects in motion in ordinary three-dimensional space and puts the objects in the right places statistically at the right times.

But how Bohmian mechanics explains experience of a situated observer is significantly more subtle and much less intuitive than this might suggest. It is not empirically adequate because it describes a primitive ontology of directly observable three-dimensional objects in motion; rather, it is empirically adequate because the

[19]Importantly, one might take what Bell says in this quotation to be strictly true and hold that it just needs careful unpacking. Everything turns on what it means to say that *we see whether* the electron is deflected up or down. This is the sort of unpacking that we will aim to do in the next two sections.

particle configuration together with the wave function provides an emergent structure, the effective wave function, on which the content of measurement records might be taken to supervene. Hence, insofar as Bohmian mechanics might be taken to be strongly adequate, it is not because it admits of a directly observable primitive ontology but because the ontology, whether primitive or not, suffices to provide an emergent structure that might serve as to explain experience.

6. A simple spin story in Bohmian mechanics

Always-determinate particle configuration plays a role in explaining determinate measurement records and hence experience in Bohmian mechanics, but not by directly representing the empirical content of those records. We will get at what it means to see something in Bohmian mechanics and how one does so in two steps. First, we will consider what the theory predicts regarding the motion of a particle in an x-spin measuring device of the sort described by Bell. Then we will consider how a situated observer might observe the position of that particle in the theory. Each story requires us to track the evolution the wave function and the resultant evolution of the particle configuration.

Consider the sort of x-spin measurement Bell describes. With only one particle, we can tell an idealized version of the story in ordinary three-dimensional space.[20] An x-spin up flavored wave packet would evolves as follows as it is deflected by

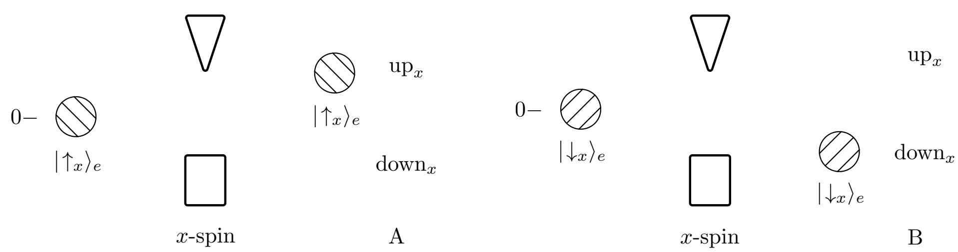

Figure 2. How x-spin up and x-spin down flavored wave packets move

inhomogeneous field associated with the Stern-Gerlach magnets (as in figure 2A):

$$|\uparrow_x\rangle_e|0\rangle_e \rightarrow |\uparrow_x\rangle_e|\text{up}_x\rangle_e.$$

And an x-spin down flavored wave packet would evolve like this (as in figure 2B):

$$|\downarrow_x\rangle_e|0\rangle_e \rightarrow |\downarrow_x\rangle_e|\text{down}_x\rangle_e.$$

If an electron is associated with one of these wave packets it would be carried along by the probability current (as in figure 3).

[20]Among other idealizing assumptions, we will suppose that the wave function is spherically symmetric with a uniform probability density. See Sebens (2020) for a more detailed account of how the state of an electron evolves in the context of a Stern-Gerlach apparatus.

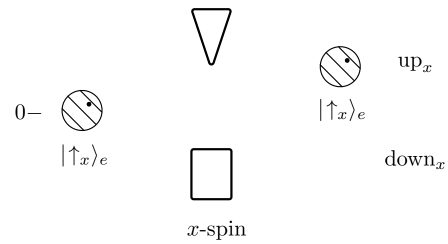

FIGURE 3. An x-spin up flavored wave packet guiding an electron

Since the wave function dynamics (3I) is linear, a z-spin up wave packet would evolve as follows:

$$|\uparrow_z\rangle_e|0\rangle_e = \frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|0\rangle_e + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|0\rangle_e$$
$$\downarrow$$
$$\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|\mathrm{up}_x\rangle_e + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|\mathrm{down}_x\rangle_e$$

Because of the symmetry in the probability currents produced by this evolution, an electron that starts in the top half of the initial z-spin wave wave packet will end up associated with the x-spin up wave packet (as in figure 4). And an electron that starts in the bottom half of the initial z-spin wave wave packet will end up associated with the x-spin down wave packet. Since, according to the distribution

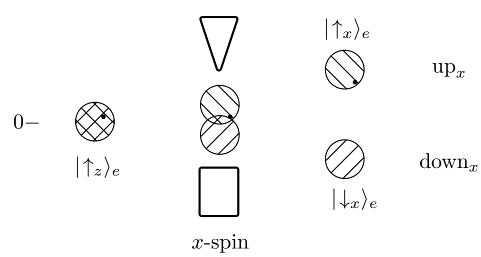

FIGURE 4. An effectively z-spin up electron selecting an x-spin up flavored wave packet

postulate (rule 4) the initial position of the electron can be thought of as being randomly determined by the standard quantum probabilities, the probability of the electron being deflected up and the probability of it being deflected down are each 1/2 in this case. To measure the x-spin component of the electron, the particle is allowed to pass through appropriately-aligned Stern-Gerlach magnets, then, as Bell puts it, we see whether it is deflected up or down. Since it is equally likely to be deflected up and down here, his suggestion is that the standard quantum statistics are immediately reproduced in the present case.

More generally, the theory's dynamical laws predict that if particles are ever distributed according to the standard quantum statistics (and rule 4 says they are at time t_0), then they will always be so distributed.[21] Hence, if as suggested by

[21]See Barrett (2020) for a discussion of this point.

the primitive-ontology approach, all one needs to do is to put objects in the right positions at the right times to explain experience, then one might imagine that Bohmian mechanics provides an immediate and direct account of our quantum experience.

The problem is that none of this explains how a situated observer sees whether the electron is deflected up or down. To be sure, if the distribution postulate is satisfied, then the electron is in fact deflected up or down with the standard quantum probabilities, but we have not said anything about how an observer, as characterized by the theory, sees where the electron is. Being able to tell that part of the story is essential to how Bohmian mechanics address the measurement problem. Indeed, it is essential to how the theory manages to be empirically adequate at all.

Of central importance is that the situated observer never sees the electron itself. If any observer were ever able to see an object, and hence where it is, she would be able to use the theory's deterministic dynamics to predict its motion with more precision than the standard quantum statistics allow. To see why, suppose one could directly see that the electron was in fact in the top half of the initial z-spin wave packet. One would then know that it will be found to be x-spin up with probability 1 given the setup of the spin measurement apparatus. But the standard quantum statistics require this probability to be 1/2. So, if one could do better than chance in making this prediction, it would violate the standard predictions of quantum mechanics, which have been repeatedly borne out by experience. The upshot is that if one ever saw where any object was, this would immediately threaten the empirical adequacy of Bohmian mechanics. So it better be that a situated observer never directly sees where the electron is. The theory itself tell us why one never does.[22]

Rather than providing objects in motion in three-dimensional space for us to see, the empirical role of the particle configuration in Bohmian mechanics is to select an effective wave function. In the simple spin experiment above, as the wave function pushes the particle about, the particle's position selects the effective wave function to be either $|\uparrow_x\rangle_e|\text{up}_x\rangle_e$ or $|\downarrow_x\rangle_e|\text{down}_x\rangle_e$. In figure 4, for example, the effective wave function selected by the particle position is $|\uparrow_x\rangle_e|\text{up}_x\rangle_e$. The effective wave function is what determines the empirical content of a situated observer's measurement record. But to see how this works, we need to consider what the situated observer is doing when she observes the position of the electron.

[22]More generally, since Bohmian mechanics is fully deterministic, if one ever knew the exact state (the particle configuration, the wave function, and the Hamiltonian), one would be able to predict precisely where the electron would be at all future times. It is also the case that if one ever knew the configuration with better precision than allowed by the standard quantum statistics, then one would always know it with better precision than allowed by the standard quantum probabilities. This is why if one wants to drop the distribution postulate, one needs to adds something else to the theory like a special standard of typicality as suggested by Dürr, Goldstein, and Zanghì (1992). Note that no matter how natural such a standard of typically may seem, just as with the distribution postulate, it has real work to do in explaining why one cannot know more than what is allowed by the standard quantum probabilities given that the theory is fully deterministic. Important for present purposes, whatever one does to get the standard quantum probabilities in Bohmian mechanics, one will not know the precise particle configuration by observation, or by any other means, if there is any spread in the wave function as that would violate the standard quantum probabilities.

7. A SITUATED OBSERVER IN BOHMIAN MECHANICS

It is a manifest empirical virtue that Bohmian mechanics allows for a consistent internal model of measurement in terms of a situated observer, a system that can reliably record determinate measurement outcomes and whose behavior is itself fully characterized by the theory. This is what makes the theory a compelling response to the quantum measurement problem.

To say what it means for an observer to see an electron in Bohmian mechanics, we need to say how it is that a situated observer, as described by the theory, might reliably record the motion of an electron. To model a situated observer, we need to characterize a physical system capable of producing determinate records given the theory's ontology. In brief, since positions are determinate, one gets determinate records by correlating the position of one's recording system with whatever one is measuring of the object system.

We will consider a situated observer who measures position and records her result in position in the context of a two-path experiment where we re-interfere the two x-spin components of the wave function. We will begin by describing the object system, then add a simple system to serve as the observer's physical record.

Consider the Stern-Gerlach two-path experiment represented in figure 5. If an

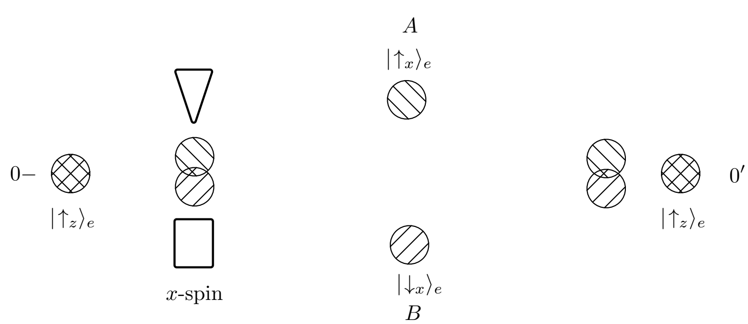

FIGURE 5. A single-particle two-path experiment in three-dimensional space

x-spin up wave packet would evolve as follows:

$$|\uparrow_x\rangle_e|0\rangle_e \to |\uparrow_x\rangle_e|A\rangle_e \to |\uparrow_x\rangle_e|0'\rangle_e$$

and if an x-spin down wave packet would evolve as follows:

$$|\downarrow_x\rangle_e|0\rangle_e \to |\downarrow_x\rangle_e|B\rangle_e \to |\downarrow_x\rangle_e|0'\rangle_e$$

then, by the linearity of the dynamics, a z-spin up wave packet would evolve as follows:

$$
\begin{array}{c}
|\uparrow_z\rangle_e|0\rangle_e = \frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|0\rangle_e + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|0\rangle_e \\
\downarrow \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|A\rangle_e + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|B\rangle_e \\
\downarrow \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|0'\rangle_e + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|0'_x\rangle_e = |\uparrow_z\rangle_e|0'\rangle_e.
\end{array}
$$

The upshot is that an electron that began in the top half of an initial z-spin up wave packet would move as indicated in figure 6. Since there is still only one

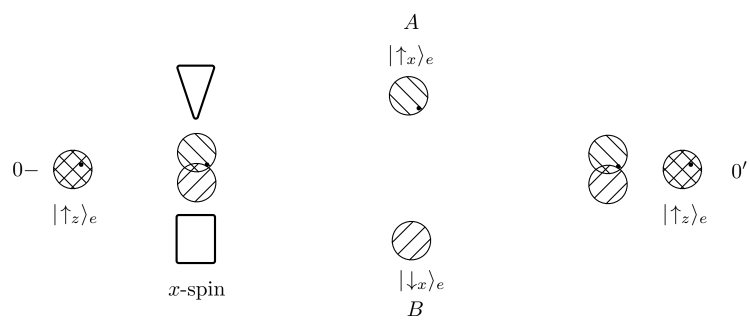

FIGURE 6. The same setup with an electron that gets pushed along path A

particle, one can imagine the electron as being pushed along by the probability current evolving in ordinary three-dimensional space. Importantly, note that while the electron is effectively x-spin up when it is on path A, it is effectively z-spin up again when it gets to region $0'$. This is because the two x-spin wave packets overlap again in three-dimensional space reproducing the original z-spin up flavored packet which then determines the dispositional properties of the electron.

We will add a recording particle p to the composite system to serve as the situated observer's physical record. Suppose that the situated observer records the position of electron e in the position of particle p by correlating p's position with e's position as represented in figure 7. Here the interaction between e and p is arranged so that the recording particle p shifts from position a to position b if and only if the electron e travels path B. The position of the recording particle p will select the record of the situated observer.

The specified interaction between e and p means that an initially z-spin up wave function evolves as follows as the two particles interact:

$$
\begin{gathered}
|{\uparrow_z}\rangle_e|0\rangle_e|a\rangle_p = \\
\frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e|0\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e|0\rangle_e|a\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e|A\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e|B\rangle_e|a\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e|A\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e|B\rangle_e|b\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e|0'\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e|0'\rangle_e|b\rangle_p
\end{gathered}
$$

Since the composite system consists of two particles, the dynamics describes the wave function is evolving in $3N$-dimensional configuration space (since $N = 2$, this is a 6-dimensional space) with the probability current pushing the single point that simultaneously represents the two particles.

If the electron begins in the top half of the initial wave packet, then the two-particle system evolves as indicated in figure 7 in ordinary three-dimensional space. And the single point representing the positions of each of the particles is pushed

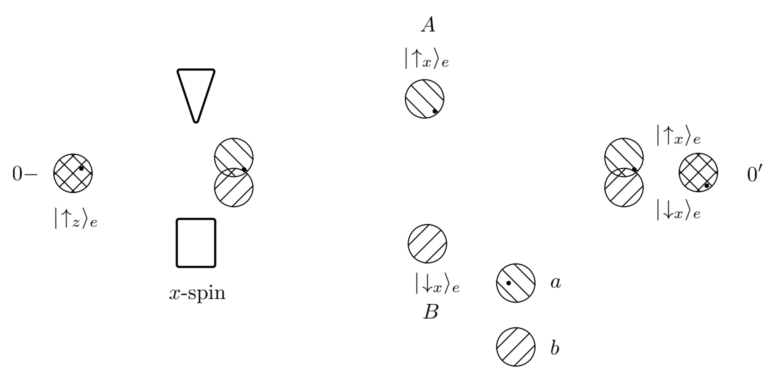

FIGURE 7. Situated observation of position in three-dimensional space producing an x-spin (path A) up record

along by probability currents as indicated in figure 8. Here the resultant particle configuration selects the $|{\uparrow_x}\rangle_e$-flavored wave packet as the effective wave function. Note that while the two x-spin wave packets end up in the same region of three-dimensional space at $0'$, they do not overlap in configuration space. Hence the configuration remains associated with the x-spin-up flavored wave packet which now serves as the effective wave function.

If the electron begins in the bottom half of the initial wave packet, then the two-particle system evolves as indicated in figure 9 in ordinary three-dimensional

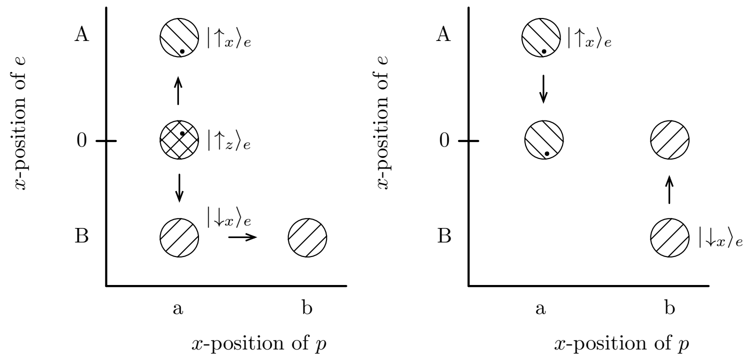

FIGURE 8. Situated observation of position in configuration space producing an x-spin up (path A) record

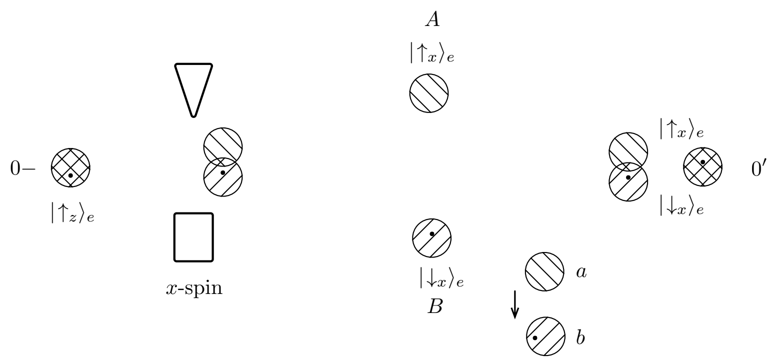

FIGURE 9. Situated observation of position in three-dimensional space producing an x-spin down (path B) record

space. And the single point representing the positions of each of the particles is pushed along by probability currents as indicated in figure 10. Here the resultant particle configuration selects the $|\downarrow_x\rangle_e$-flavored wave packet as the effective wave function. And again, while the two x-spin wave packets end up in the same region of three-dimensional space, they do not overlap in configuration space. In this case, the configuration remains associated with the x-spin-down flavored wave packet which now serves as the effective wave function.

In each case, the two-particle configuration selects an effective wave function that reliably records the path taken by e. It also reliably records that the electron ends up effectively x-spin up in the first case and effectively x-spin down in the second. Because of the displacement generated by the position correlation between e and p, the two x-spin wave packets do not overlap in configuration space, so the measurement record selected by the two-particle configuration ensures that e will exhibit the same effective x-spin even if one repeats the first measurement when it is in the interference region $0'$. The situated observer's record, then, both acts

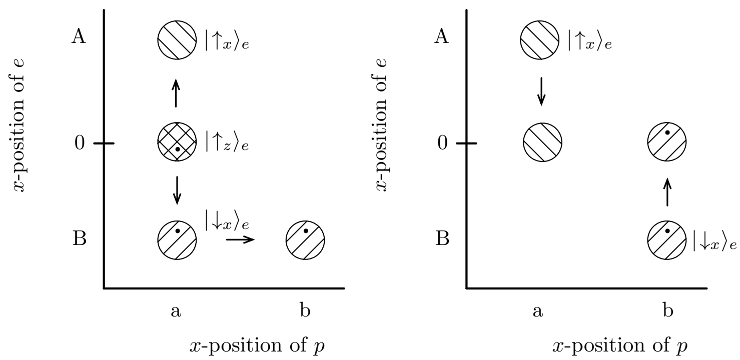

FIGURE 10. Situated observation of position in configuration space producing an x-spin down (path B) record

as a reliable record and causes the electron to behave as if it had an intrinsic, fully-determinate x-spin.[23]

Importantly, the situated observer does not now directly see the position of p any more than she directly sees the position of e. Rather, her physical record, and hence her experience, are simply determined by the effective wave function selected by the two-particle configuration.

It is in this way that the effective wave function determines both the empirical content of one's record and the subsequent dispositional properties of one's object system. This can be seen concretely in the two cases above. The empirical content of the record in the first case (figure 8) is that the $|\uparrow_x\rangle_e$-flavored wave packet is the effective wave function for the two particles. This makes e effectively x-spin up. The empirical content of the record in the second case (figure 10) is that the $|\downarrow_x\rangle_e$-flavored wave packet is the effective wave function for the two particles. This makes e effectively x-spin down. And the situated observer's knowledge of the electron's position is precisely what the standard quantum statistics allow for this setup given her knowledge of how her apparatus works. In this sense, her position measurement and the imprecise information she gains from it are optimal.

The moral is simply that the empirical content of a measurement record in Bohmian mechanics is bounded by the effective wave function selected by the particle configuration. This is the most that a situated observer can have epistemic access to given her record. And, in this sense, it is also what she most directly *sees* when she looks for the electron.[24] While a reliable measurement record allows one to infer something about the electron's position, it does not tell one where it is. Again, it is essential to the empirical adequacy of the theory that one can never see where any object is in any sense that allows one to know more than what can be

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[23]See Barrett (2000) and (2020, 208–214) for detailed discussions of Bohmian surreal trajectories in this sort of two-path experiment.

[24]One might be tempted to say that the content of the situated observer's record is the approximate position of the electron. But it is more than that. The precisely sort of approximation is given by the shape of the effective wave function. And that the observer knows what the effective wave function is explains her ability to predict what will happen on subsequent spin measurements. Such is the argument that it is the effective wave function that determines the empirical content of her experience.

inferred from the effective wave function. If one could, one would be able to make empirical predictions that violate the standard quantum probabilities.

It is because the determinate particle configuration satisfies the standard quantum statistics that the effective wave function it selects does too. So by specifying *something* determinate, the particle configuration, Bohmian mechanics provides something on which our quantum experience might be taken to supervene, the effective wave function selected by the particle configuration. And since this something exhibits the standard quantum statistics and satisfies the standard quantum probabilities, the theory is at least weakly adequate. The extent to which one takes it to be strongly adequate depends on how plausible one finds the claim that our experience in fact supervenes on effective-wave function records.

The upshot is that inasmuch as the content of one's experience supervenes on something to which one might epistemic access, the experience of a situated observe can supervene on nothing more informative than the effective wave function selected by the determinate particle configuration if the distribution postulate is satisfied. And if the situated observer's does supervene on the effective wave function, the theory explains why she can have precisely the limited epistemic access to the positions of things described by the standard quantum statistics.[25]

As both turn on the fact that particle configurations are not directly observable in Bohmian mechanics, the present argument is closely related to an argument that Harvey Brown and David Wallace (2003) offer against the theory. The difference in the two arguments is instructive.

In brief, Brown and Wallace argue that since one does not have epistemic access to particle configuration in Bohmian mechanics, one is left with just the unitarily evolving wave function to explain one's experience, and hence one is no better off than in Everettian quantum mechanics. To be sure, on the sort of Everettian account they have in mind, the wave function, under plausible physical conditions, will exhibit the structure of decohering branches, each of which might be taken to represent a different measurement record for a physically situated observer in that each branch provides something, at least in principle, on which the observer's experience might be taken to supervene.[26] Significantly, unlike in Bohmian mechanics, there is no particle configuration to select a *single* post-measurement branch or effective wave function. But Brown and Wallace do not take it to be a problem that Everettian quantum mechanics fails to select a single post-measurement branch as physically privileged. In brief, they hold Everett's position that a situated observer would never notice that there was in fact more than one measurement outcome.[27] Hence, on their view, Bohmian mechanics is Everettian quantum mechanics but with a superfluous particle configuration that can serve no legitimate explanatory

[25]One can formulate versions of Bohmian mechanics where observables other than position are selected as determinate. See Bell (1987, 173–180) and Vink (1993), (2018), and (2020) for examples of how to do so. On such formulations, the value of the hidden-variable selects an effective wave function, but depending on the sequence of interactions, it will typically not be the same sort of effective wave that would have been selected by particle configuration.

[26]There is good reason here to find Maudlin's (2010) argument against Brown and Wallace that the wave function alone cannot possibly explain experience unconvincing. All one needs for such an explanation is a suitable target for experiential supervenience. And insofar as classical field configurations might serve as a suitable target, so might the wave function with decoherence considerations. More on Maudlin's argument below.

[27]See Barrett (2020, 141–87) for an extended discussion of how this is supposed to work for both Everett and more recent Everettian approaches.

purpose since particle positions are never in fact observable. As a consequence, Bohmian mechanics loses to Everettian quantum mechanics on grounds of relative parsimony.

In contrast, the present argument is that since one does not have epistemic access to particle positions in Bohmian mechanics, one cannot take a situated observer's experience to supervene directly on objects in motion in three-dimensional space and hence there is nothing special in opting for a primitive ontology. That said, contrary to what Brown and Wallace argue, the theory does provides something more than a set of mutually incompatible decoherent substructures as a possible target of supervenience. Namely, inasmuch as it reflects precisely the limits of one's epistemic access, one might take a situated observer's experience to supervene on the effective wave function selected by the post-measurement particle configuration. And insofar as one takes the effective wave function to be a suitable target for experiential supervenience, Bohmian mechanics is a good candidate for strong adequacy.

It matters that Bohmian mechanics provides a potential target for supervenience not found in Everettian quantum mechanics. Indeed, if one wants to explain standard forward-looking quantum probabilities, the probabilities one assigns to the outcomes before performing a measurement, this is pure explanatory gold. Inasmuch as every physically possible measurement record is fully realized in Everettian quantum mechanics, there is a straightforward sense in which the forward-looking probability one assigns to each possible outcome before performing the measurement is simply one. But in Bohmian mechanics, each possible record is predicted with the standard forward-looking quantum probabilities as epistemic probabilities. And precisely one of these possible records is selected by the particle configuration as it determines the effective wave function. Further, while the observer does not know where in the effective wave packet her test particle is, she can nevertheless understand her forward-looking probabilities as probabilities for approximately where the particle will be and her physical record as an approximate record of its actual current position.[28] Indeed, the precise sense in which the record is approximate is given by the effective wave function. This goes hand-in-hand with the effective wave function's role as the structure on which the empirical content of the observer's record supervenes. She may use this rough-hewn content to predict subsequent particle motions and hence infer forward-looking epistemic probabilities for the results of future measurements.

So Bohmian mechanics provides explanations of a sort that one cannot get in Everettian quantum mechanics. That said, these explanations do not work the way that the Bohmian primitive ontologist might have initially imagined. In particular, they require one to take the effective wave function as a suitable target for supervenience.

There is another closely-related argument that may be helpful. Tim Maudlin (2010) argues that one of the virtues of Bohmian mechanics is that it provides something physical, namely the positions of particles, that quantum probabilities are probabilities for (2010, 122–4, 130, 136). But just having determinate configurations for physical objects is not enough. Maudlin also argues that they must also

[28]Note that this is true even in the context of surreal trajectories. What one cannot do is use one's classical intuitions to infer what the particle's trajectories *were*. See Barrett (2020, 208–214) for a discussion of surreal trajectories in Bohmian mechanics.

be *visible*. Namely, we should want a physical theory that allows us to say, at least schematically, how people who look at physical objects like measurement pointers can reliably tell where they are. And, he believes, Bohmian mechanics allows one to do precisely this (2010, 122).

The right reply here depends in part on how one understands Maudlin's italicized *visible*. As we have seen, if one sets things up right, Bohmian mechanics allows one to infer approximate particle configurations from one's measurement records. So if *that* is what it means to be *visible*, then one might take Maudlin's line to mesh well with the present argument. Indeed, we have seen in some detail how one might infer the approximate position of an electron by determining the effective wave function associated with the electron and a recording particle. But again, this sort of explanation only works if one takes the effective wave function to be a suitable target for supervenience of a situated observer's experience, and it is unclear whether that meshes well with Maudlin's account.

Importantly, one need not solve the mind-body problem or provide a detailed prescription for how to fill the logical gap between the derivable consequences of one's physical theory and sense experience in order to judge Bohmian mechanics to be strongly adequate.[29] But one does need commitments regarding how experience supervenes on physical states that goes well beyond a vague sense that our experience is best explained in terms of the manifest motions of objects in three-dimensional space.

Two last points regarding primitive ontology. First, inasmuch as the effective wave function is an emergent entity determined by the universal wave function and the positions of all the relevant particles given the precise details of the situated observer's measurement interaction, it is not at all well conceived of as a three-dimensional object and is hence decidedly not part of the theory's primitive ontology. Second, since one never directly observes the particle positions that select the effective wave function, there can be no good *empirical* reason for taking particles with always-determinate positions in three-dimensional space to be a required part of the theory's ontology. In particular, there is no empirical reason not to embrace some variety of configuration-space realism and take one's basic ontology to be the wave function and the total particle configuration. Either way, each ultimately provides the same something, the effective wave function, on which one's experience might be taken to supervene.[30]

8. SITUATED EMPIRICAL ADEQUACY

We have considered what it might mean for a formulation of quantum mechanics to be empirically adequate and have seen how the notion of a situated observer allows one to distinguish between weaker and stronger varieties of empirical adequacy. The general moral is that one should want a physical theory that supports a plausible sort of situated empirical adequacy whenever one can get it.

A theory that is minimally adequate just provides a predictive algorithm that makes the right empirical predictions. A weakly adequate theory makes the right empirical predictions for a situated observer as characterized by the theory. And a theory is more strongly adequate the better it allows one to account for a situated observer's experience given our beliefs and commitments regarding how our

[29]See Maudlin (2010, 141) for this sort of worry.
[30]See Albert (2013) for a characterization of this sort of wave function realism.

experience in fact supervenes on the state of the world. The suggestion is that one should not settle for anything less than a strongly adequate formulation of quantum mechanics as a resolution to the measurement problem.

For a formulation of quantum mechanics to be strongly adequate, one needs *something* determinate that provides something on which the content of a situated observer's determinate measurement outcomes might plausibly supervene. In the case of Bohmian mechanics the *something* is the particle configuration and universal wave function and the something is the effective wave function selected by the particle configuration, the emergent structure that explains the existence and empirical content of a situated observer's records.

As we have seen, Bohmian mechanics is not empirically adequate because it admits of a primitive ontology of objects in motion then puts the objects in the right places at the right times in order that their manifest positions might be directly apprehended. Rather, it is empirically adequate because it predicts the records in terms of the effective wave function for a physically situated observer. And the story one tells about how this works is arguably just as compelling whether one tries to tell it in three-dimensional space or in configuration space as we have here. In either case, the effective wave function is an emergent structure on which one's experience might be taken to supervene.

The empirical content of a situated observer's experience is given by the effective wave function selected by the particle configuration. This is what her record records and hence what she most directly *sees*. It is what she has epistemic access to. As a result, Bohmian mechanics should be judge strongly adequate precisely insofar as one takes the effective wave function to be a suitable target for experiential supervenience.

Bohmian mechanics provides a consistent, rich, and compelling internal account of how an observer ends up with determinate effective wave function records. And it explains why a situated observer should expect her records to exhibit the standard quantum statistics and why she should assign the standard forward-looking quantum probabilities as credences for future measurement records. That it predicts the right effective wave functions for situated observers is what makes it a serious contender for providing a satisfactory resolution to the quantum measurement problem.[31]

[31] I would like to thank Craig Callender, Jeroen Vink, Chip Sebens, Thomas Barrett, and the editor and two anonymous reviewers for comments on an earlier draft of this paper.

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