The Preferred-Basis Problem and the Quantum Mechanics of Everything

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ABSTRACT

Jereon Vink ([1993]) argued that there are two options for what he called a *realistic* solution to the quantum measurement problem: (1) select a preferred set of observables for which definite values are assumed to exist, or (2) attempt to assign definite values to all observables simultaneously (1810–1). While conventional wisdom has it that the second option is ruled out by the Kochen-Specker theorem, Vink nevertheless advocated it. Making every physical quantity determinate in quantum mechanics carries with it significant conceptual costs, but it also provides a way of addressing the preferred basis problem that arises if one chooses to pursue the first option. The potential costs and benefits of a formulation of quantum mechanics where *every* physical quantity is determinate are herein examined.

1 The preferred-basis problem

The standard unitary quantum dynamics and the standard interpretation of quantum mechanical states make it difficult to explain how observers end up with determinate measurement records. This is the quantum measurement problem. A direct solution to the quantum measurement problem would require one to find a formulation of quantum mechanics that (i) explains how observers end up with empirically accessible determinate measurement records, (ii) makes the standard quantum statistical predictions for these records, and (iii) is compatible with the constraints imposed by relativity. One might think of a solution to the quantum measurement problem as accomplishing (i) under the constraints of (ii) and (iii).

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In a formulation of quantum mechanics with only the unitary dynamics, an ideal measurement of a system S which is initially in a superposition of states $\mathbf{S}_i$ corresponding to different determinate values q_i of the quantity Q

$$\sum_i a_i \mathbf{S}_i \tag{1}$$

leaves the system in a correlated entangled state

$$\sum_i a_i \mathbf{M}_i \mathbf{S}_i \tag{2}$$

where $\mathbf{M}_i$ is an eigenstate of the measuring device pointer determinately recording result q_i. When an observer looks at the pointer, the observer's brain B ends up in the similarly entangled state

$$\chi = \sum_i a_i \mathbf{B}_i \mathbf{M}_i \mathbf{S}_i \tag{3}$$

where $\mathbf{B}_i$ is an eigenstate of the observer's brain determinately recording result q_i.

The problem here is that on the standard interpretation of states, the post-measurement state χ is not a state where the system S has any determinate value for Q, nor is it a state where M's pointer records any particular determinate measurement result, nor is it a state where the observer's brain B records any particular determinate result q_i. Indeed, χ is a state where none of the subsystems S, M and B even have a determinate quantum mechanical state; rather, χ is a state where the object system, the measuring device and the observer are in an entangled superposition of having and recording mutually incompatible values for the physical quantity Q. On the standard interpretation of states, χ is not a state where the observer can be said to have recorded any particular measurement result q_i whatsoever.

The problem involves more than just the standard interpretation of quantum mechanical states. If χ is supposed to represent a complete physical description of the composite system $S + M + B$, and if B is supposed to have a determinate record for the value of Q in this state, then *which specific value does it record*? The state χ fails to select any particular value for Q, so it cannot be taken as a complete description of a system containing an observer who has a determinate measurement record. This is perhaps most striking when all the coefficients in the expansion of χ in the Q basis are equal; but, for the sake of empirical adequacy, χ must be compatible with any measurement result q_i corresponding to a term with a nonzero coefficient in the expansion of χ, so χ cannot determine the measurement result. Moreover, interactions between the composite system $S + M + B$ and the environment will only serve to produce a more complicated entangled superposition. Consequently, one cannot count on decoherence effects to select any particular measurement result. The upshot is that one can provide no explanation here for how the observer could have a determinate measurement result. Of course, in the standard von Neuman-Dirac collapse formulation of quantum mechanics ([1955]), such an explanation is given by the spontaneous collapse of the quantum-mechanical state to an eigenstate of the observable being measured. In this context, the quantum measurement problem takes the form of trying to say why measurement interactions are somehow special (see Albert [1992] or Barrett [1999] for detailed descriptions of the quantum measurement problem from this perspective).

We typically want our physical theories to make empirical predictions. To accomplish this we must find something in the physical theory that can somehow be interpreted as corresponding to the possible experiences of an observer. Bas van Fraassen ([1980]) described one way to do this. On van Fraassen's view, an empiricist seeks a physical theory where there is some observable substructure of a model of the theory that is isomorphic to the possible experiences of observers. Weakened somewhat and translated into slightly less empiricist language, if a physical theory is presented as descriptive of a possible world, the theory is presumably empirically adequate only if one can find something in the world it describes that one can take as what explains one's experience; that is, one must be able to find *something* in the description on which one can take one's experience to supervene. More specifically, one has a *physical* explanation of an observer's measurement records (or experience or mental states) only if one can find some physical property in a world described by the theory on which the records (or experience or mental states) might be taken to supervene. While one might claim empirical adequacy on this standard if one can find *any* physical property on which one's mental states might be taken to supervene, the more plausible the supervenience relation, the more plausible the physical explanation of the observer's experience.

The upshot is that to provide the explanation called for in (i) above, one must find some physical property on which mental states might be taken to supervene, and the explanation is more compelling if it is plausible that our mental states do in fact supervene on that particular physical property. The first step, finding something physical that co-varies with one's experience, is a straightforward physical project; but whether it is in fact a plausible physical candidate for mental supervenience is something that one would expect our best account of cognition to answer. So let's consider the first step first.

The quantum measurement problem is that, on the standard interpretation of states, there is simply no physical property in the state described by χ on which one might take the observer's mental state to supervene if she in fact has a determinate measurement record. Further, if one insists on the applicability of the standard unitary dynamics for all interactions and insists that there is only one post-measurement mental record, then one must add something to the description of the physical state on which the mental record might be taken to supervene. While this parameter is commonly referred to as a hidden variable, it is the determinate value of this new parameter together with the standard quantum mechanical state that will explain an observer's determinate measurement results.

Bohm's theory ([1952]) is easily the most popular hidden-variable theory.[1] On Bohm's theory, a complete physical description amounts to the standard quantum-mechanical state ψ together with a specification of the always-determinate *position* Q of each particle. Here the always-determinate physical property on which mental states are supposed to supervene is the particle configuration. More specifically, Bohm's theory is empirically adequate if the evolution of the particle configuration relative to the wave function is isomorphic to our experience.

According to Bohmian mechanics, the standard quantum-mechanical state, given by the wave function, always evolves in the standard deterministic unitary way. In the simplest case, this evolution is described by the time-dependent Schrödinger equation

$$i\hbar \frac{\partial \psi}{\partial t} = \hat{H}\psi \tag{4}$$

where $\hat{H}$ is the Hamiltonian of the system.

The determinate particle configuration Q also evolves in a deterministic way. For an N particle system, the particle configuration can be thought of as being pushed around in $3N$-dimensional configuration space by the flow of the norm-squared of the wave function, just as a massless particle would be pushed by a compressible fluid. More specifically, the motion of the particles is given by

$$\frac{dQ_k}{dt} = \frac{1}{m_k} \frac{\mathrm{Im}(\psi^* \nabla_k \psi)}{\psi^* \psi} \tag{5}$$

evaluated at the current configuration $\mathbf{Q}$, where m_k is the mass of particle k.

The compressible fluid in this analogy is the probability distribution in configuration space $|\psi|^2$, and the massless particle is the point representing the particle configuration in $3N$-dimensional configuration space. The motions of real physical particles can then be read off of the motion of the particle configuration. And the experiences of observers can be read off of the particle trajectories relative to the wave function.

Since both the evolution of the wave function and the evolution of the particle configuration are fully deterministic in Bohmian mechanics, in order

1 This description of Bohmian mechanics follows Bell's ([1980], [1981] and [1982]) rather than Bohm's ([1952]) or Bohm and Hiley's ([1993]) quantum-potential description.

to get the standard quantum probabilities one must assume a special statistical boundary condition. This distribution postulate requires that there be a time t_0 where the epistemic probability density for the configuration Q is given by $\rho(Q, t_0) = |\psi(Q, t_0)|^2$. If the distribution postulate is satisfied, one can show that Bohm's theory makes the standard quantum statistical predictions as epistemic probabilities for possible particle configurations. After a measurement, one learns what the new effective wave function is from the determinate measurement record, and the measurement record is determinate because its value is determined by the particle configuration in conjunction with the current wave function, both of which are fully determinate.

In Bohm's theory, particle configuration relative to the wave function is the only directly observable physical quantity. It is the value of this quantity that explains our determinate measurement records. And all other observable physical properties of a system are cashed out in terms of the context-dependent dispositions of particle motion. This is what is meant when it is said that observable physical properties other than particle configuration are *contextual* in Bohmian mechanics. A particle's spin, for example, is here not intrinsic, but rather, is just an expression of the disposition of the particle to move a certain way given the wave function, the Hamiltonian and the joint particle configuration. More generally, in the basic Bohmian theory, all observable properties other than position are to be understood as contextual descriptions of how one expects the particle to be pushed around by the time evolution of the wave function on the Bohmian dynamics.

Since particles in Bohmian mechanics have fully determinate positions that change in a continuous deterministic way, they also have fully determinate velocities and momenta; but the *apparent* particle velocities and momenta that one might infer from one's observations and classical physical assumptions are typically not their *actual* velocities and momenta. This feature of Bohmian mechanics turns out to be important since it is only *observed* momentum, not actual momentum, that is typically conserved in the theory. (See Bell [1980], Englert et al. [1992], and Barrett [2000] for discussions of the nonstandard interpretation of measurement results in Bohmian mechanics.)

Bohmian mechanics might be said to be empirically adequate if determinate particle positions somehow co-vary with our experience. And Bohmian mechanics might be said to explain our experience in the stronger sense if our observations can ultimately be understood as in fact being mediated by the positions of particles—that is, if we can in fact understand our determinate mental states as supervening on Bohmian states given what we learn concerning the actual relationship between mental and physical states. It may be, for all we currently know, that our best cognitive theories will tell us that mental states do not most directly supervene on particle positions, but rather, for example, on energy properties of more complex systems (see Albert's discussions of GRW and Bohmian mechanics [1992] and Barrett's discussion of Bohmian mechanics [1999] for examples of how supervenience relations might fail—the question of whether mental states in fact supervene on determinate particle positions continues to be debated in the literature on Bohmian mechanics, spontaneous collapse theories, and decoherence formulations of quantum mechanics).

This is not simply a question for our best cognitive theories. It may prove that mental states cannot be taken to supervene on particle positions for *physical* reasons. One way this might happen is if our best physical theories end up requiring a field ontology instead of a particle ontology. This was Bell's ([1984]) and Vink's ([1993]) primary reason for wishing to extend Bohmian mechanics to other classical variables (see Malament [1996] for an explanation of why one might take localized particles to be logically incompatible with any relativistic quantum theory). In relativistic field theory, the unitary dynamics describes superpositions of different field configurations in spacetime, and mental states at a particular time simply cannot be taken to supervene on determinate particle positions since there are no particles to have determinate positions. Here mental states would presumably have to supervene on local field values, but it remains unclear how this might work (see Barrett [2002] for a discussion of this point).

The upshot is that we have every reason to avoid committing to mental states necessarily supervening on particular positions. This is a problem for Bohmian mechanics since determinate particle positions are assumed to act as the filter through which we in fact observe the physical world and because of which our experience of the physical world is in fact determinate. On this account, all other observable physical quantities and properties one might wish to infer from one's experience are fictional in that they are nothing more than manifestations of the particle configuration, wave function and Hamiltonian of the system. Bohmian mechanics relies on the assumption that mental states supervene on particle positions with respect to the evolution of the wave function since there is simply nothing else in the world described by the theory on which determinate mental states might supervene.

Insofar as Bohmian mechanics can be taken as explaining our experience, it does so by providing a sort of brain-in-the-vat story about the physical world. Just as what a brain-in-the-vat observes supervenes on the value of the signals sent to the brain rather than on the physical state of the objects that he believes he is observing, and just as his inferences beyond the value of these brain signals to the actual nature of the physical world are typically false, in Bohmian mechanics, an observer's experience supervenes on nothing more than the particle configuration relative to the wave function and particle motion dispositions, and the observer's classical inferences beyond this to the deeper nature of the physical world are typically false. The brain-in-the-vat nature of Bohmian mechanics is a feature of any hidden-variable theory that seeks to explain an observer's experience of the physical world by a preferred determinate physical observable. This is a point to which we will return later.

In assessing how well Bohmian mechanics explains our experience, one might naturally wonder whether determinate particle configurations would make our most immediately accessible measurement records determinate. More to the point, is the relationship between mental and physical states in fact such that our determinate mental states supervene on determinate particle positions, the wave function, and particle dispositions? This is something one might expect someday to be answered by out best account of human cognition. But until we know the actual relationship between mental and physical states, we do not know how good an explanation Bohmian mechanics provides for our having the determinate measurement records we presumably do in fact have. The point is that not just any determinate physical property can be taken as explaining our determinate mental records. Making the total angular momentum of all the sheep in Austria determinate would presumably do little to account for my determinate memory of the password for my local e-mail server. Bohm's theory does provide a physical quantity with the right determinate empirical structure on which our actual experience *might* supervene. In this weak sense, Bohmian mechanics might be taken as explaining our experience. But because Bohm's theory makes only one classical physical determinate, and because we do not know whether mental records are in fact fully determined by particle positions, an assessment of whether Bohmian mechanics in fact explains why we experience what we do is ultimately contingent on the yet-to-be-determined relationships between mental and physical states.

The recurring problem of choosing which observable to make determinate in a solution to the quantum measurement problem is the preferred-basis problem. The problem is that we do not know what determinate physical property *would* make our most immediately accessible physical records determinate.

The preferred-basis problem is often presented as a complaint that any choice of a preferred physical observable looks *mathematically* ad hoc. The argument is that since each complete physical observable corresponds to an orthonormal basis of the Hilbert space used to represent a physical system, and since any complete orthonormal basis is as good as any other for representing the state of the system, from the mathematical perspective, any particular choice of a basis is purely conventional. But the preferred-basis problem is not just a matter of one not wanting one's choice of a preferred observable to look ad hoc. There are simple matters of physical fact at stake here: one's choice of the determinate physical observable is what determines what determinate physical facts there can be in a physical world described by the theory. So if one takes there to be an objective matter of fact concerning what physical facts there are, one cannot take this choice to be simply a matter of personal preference, convenience, or convention. And among the physical facts one wants determinate are those facts concerning the values of our measurement records; but, again, we do not know what determinate physical property would in fact make our most immediately accessible measurement records determinate. This is something that ultimately depends on the relationship between mental and physical states and on exactly how we expect our best physical theories to account for our experience, and this is presumably something physicists would prefer not to address in formulating a satisfactory version of quantum mechanics.

Rather than having to make the embarrassing choice of one physical property to make determinate once and for all, one might introduce a new rule to quantum mechanics designed to dynamically select a preferred observable for a physical system at a time. The most popular sort of rule is designed to use the interaction between a system and its environment to select what physical property will be determinate for the system. We have already seen that the environment does not help select a *determinate value* for a physical quantity, but the hope is that it might help select *which physical quantity is determinate*.

There are several concrete proposals for such a rule, but each immediately faces at least three problems: (i) one must somehow argue that choosing a particular rule for determining which physical quantity is determinate from among the many possible such rules is somehow less ad hoc than directly choosing a determinate physical quantity; (ii) one still has the task of arguing that it is plausible that the particular rule makes determinate that physical quantity on which our mental states in fact supervene, and (iii) in order for the theory to make empirical predictions over time, one must also introduce a hidden-variable dynamics that describes how the *value* of the determinate quantity evolves. Problems (i) and (iii) are directly analogous to problems faced in a classical hidden-variable theory like Bohmian mechanics. Problem (ii) is at least as difficult to solve here as in a classical hidden-variable theory, where one directly chooses an always-determinate physical quantity. Here one would only have to argue that a particular rule correctly selects a physical property on which one's mental state might plausibly be taken to supervene, but since which physical property a particular rule selects as determinate would typically change with a changing environment, one would need to argue that this does not affect the determinateness of an observer's measurement records. The point is just that the preferred-basis problem is as much a problem for a theory that seeks to provide a rule for determining the preferred physical quantities as it is for a classical hidden-variable theory like Bohmian mechanics.

Given the problems one encounters in selecting a specific physical quantity as preferred and in selecting a dynamical rule for selecting a preferred physical quantity, one might be tempted to solve the preferred-basis problem by brute force. One might, for example, suppose there is some physical quantity Q that would in fact make every measurement record determinate, *stipulate* that Q is always determinate, then give a dynamics for Q so that its determinate value exhibits the standard quantum statistics. While there are methodological problems with the first two steps in this solution, one might be encouraged by the fact the last step is relatively straightforward.

John Bell ([1984]) showed how to give a stochastic extension of Bohm's dynamics for discrete field variables; and, following Bell, Vink ([1993]) described a natural way to extend Bohm's theory to almost any discrete physical quantity. Here, just as on Bohm's theory, the standard quantum-mechanical state ψ evolves in the usual unitary deterministic way and a second dynamics describes the time-evolution of the determinate physical quantity, but here the dynamics is stochastic. Suppose that the current value of the discrete physical quantity is Q is q_m. The probability that the value jumps to q_n in the time interval dt is $T_{mn}dt$, where T_{mn} is an element in a transition matrix that is completely determined by the evolution of the wave function. More specifically, the wave function evolves according to the time-dependent Schrödinger equation

$$i\hbar\partial_t|\psi(t)\rangle = H|\psi(t)\rangle \tag{6}$$

where H is the global Hamiltonian. The probability density P_n is defined by

$$P_n(t) = |\langle q_n|\psi(t)\rangle|^2 \tag{7}$$

and the source matrix J_{mn} is defined by

$$J_{mn} = 2\ \mathrm{Im}(\langle\psi(t)|q_n\rangle\langle q_n|H|q_m\rangle\langle q_m|\psi(t)\rangle) \tag{8}$$

Finally, if $J_{mn} \geq 0$, then for $n \neq m$

$$T_{mn} = J_{mn}/\hbar P_m \tag{9}$$

and if $J_{mn} < 0$, then $T_{mn} = 0$. On analogy with the Bohmian particle dynamics, here one can think of the change in the discrete value of Q as a discrete random-walk in Q-space biased by a compressible fluid with current J_{mn}.

Vink showed that if one takes the discrete determinate quantity Q to be position and takes the lattice to be fine-grained enough, then this stochastic dynamics approximates Bohm's position dynamics over an appropriate time interval. More generally, Vink showed that if the distribution postulate is satisfied, then his dynamics makes the standard quantum statistical predictions for the value of the determinate quantity *Q*.

So let's take *Q* to be whatever physical quantity would in fact make mental states and processes determinate, suppose that *Q* is in fact always determinate, adopt Vink's dynamics for *Q*, and call the result *Q*-theory (the *Q*-theory is discussed and compared to Albert and Loewer's single- and many-minds theories in Barrett [1999], 204–6). Here *Q* plays the role that position plays in Bohmian mechanics. In a world described by *Q*-theory, when one sets out to determine the position of a particle or the energy of a physical system or the value of a field variable, one is in fact doing nothing beyond determining the value of *Q* and interpreting this value in the context of the current quantum-mechanical state. Here the world would appear the way it does because of the behavior of *Q* relative to the wave function and because mental states and processes in fact supervene on these determinate facts. In this sense, *Q* would serve as a filter through which one observes the physical world. One's classical inferences concerning the objects that populate the world and their determinate properties would typically be false, since there would in fact fail to be any such objects exhibiting any such determinate properties. Nevertheless, *apparent* physical objects are guaranteed to behave in the standard quantum-mechanical way since *Q*, which is assumed to make mental states and processes determinate, is in fact determinate and will under the Bell-Vink dynamics exhibit the standard quantum statistics if the distribution postulate is satisfied.

While *Q*-theory would explain our experience, it is unclear whether it is ultimately preferable to Bohmian mechanics. Like Bohmian mechanics, *Q*-theory tells us that most of the classical inferences we make about the objects, properties, and structure of the physical world are simply false; if one does not like Bohmian mechanics for this reason, then one won't like *Q*-theory either. Unlike Bohmian mechanics, *Q*-theory guarantees that we have an account of our determinate measurement records; but while this is supposed to be the comparative advantage of *Q*-theory, it is unclear how excited one should be. Since *Q* is characterized by nothing more than the condition that its determinate value be sufficient to account for our determinate measurement records (whatever they may be), *Q*-theory secures determinate accessible records *by stipulation*, and the choice of the preferred basis is in this sense maximally ad hoc. That the choice is ad hoc is made particularly striking by the fact that we do not even know what *Q* is. Indeed, it is not even clear, at least to me, that there is any physical quantity that would, once and for all, make determinate all physical records for all observers at all times.

Jeffrey Bub ([1997], 138–45) has at least implicitly provided another brute-force resolution of the preferred-basis problem. Bub used Vink's dynamics to describe the time-evolution of the determinate observable *R*, where *R*, it seems, is simply stipulated to be whatever physical quantity one wants to be determinate in a particular experiment in order to account for one's determinate measurement record. Call this the *R*-theory. The *R*-theory differs from the *Q*-theory in that *R* is flexible and can be selected to be whatever one would take as providing an appropriate explanation of one's determinate measurement records. That one is free to choose to make determinate whatever one needs in a particular context in order to get determinate measurement records has a nice pragmatic, instrumental feel to it. The problem is that there is presumably a matter of fact about what physical properties are in fact determinate, and what physical quantities, if determinate, would in fact explain our determinate measurement records. And if this is right, the choice of what quantity to make determinate cannot be a matter of convenience or convention. One might concede that this choice cannot be a matter of convention if one were interested in a true description of the physical world, but argue that since one cannot ultimately know (for whatever reason) the truth about the physical world or about how mental states in fact supervene on physical states, the choice of preferred observable might as well be a matter of convenience. Given his empiricist commitments, it is not surprising that van Fraassen's presentation of his modal formulation of quantum mechanics ([1979] and [1991]) has something of this feel to it. While Bub also thinks of his theory as being a modal formulation of quantum mechanics, it seems that while Bub ([1997]) implicitly takes the choice of *R* to be a matter of convenience or convention, van Fraassen ([1980]) explicitly holds that what aspects of the physical world are in fact observable is itself a matter for empirical inquiry to determine, not a matter of convenience or convention.

The preferred-basis problem involves selecting a physical quantity, or a rule for dynamically selecting a physical quantity, that tells us what determinate physical facts there are. Having to make such a choice is particularly unsettling for physics since, in order to explain our experience, those physical facts on which our experiences (or mental states or processes) in fact supervene must be among the determinate physical facts. One might claim to have an empirically adequate physical theory if one's theory describes *any* substructure that can be taken as representing our actual experience. But better would be to have good empirical reason to think that the particular substructure represents something that is in fact observable. And one has a plausible explanation of our experience only if one has good reason to suppose that the observer's phenomenal experiences (or mental states or processes) in fact supervene on the particular substructure. Since the preferred-basis problem involves fundamental questions concerning the relationship between physical and mental states and what it means for a physical theory to explain our experience, it is a problem that requires special care. Ideally, at least from a physical point of view, one would like to avoid the preferred-basis problem altogether.

2 How to solve the preferred-basis problem

One can avoid the preferred-basis problem by supposing that no physical quantity is determinate, then either by denying that there are in fact any determinate measurement records (as in the bare theory; Albert [1992], 112–25) or by denying that our determinate records are *physical* (as in the many-minds theories; Albert [1992], 126–33). Another way to avoid the preferred-basis problem is by supposing that *every* physical quantity is determinate. This was Vink's proposal. Call the formulation of quantum mechanics where one adopts the Bell-Vink dynamics and makes every physical quantity determinate *E*-theory (for *everything*). The conventional wisdom is that *E*-theory cannot be considered to be a satisfactory formulation of quantum mechanics.

The standard argument against making every physical quantity determinate goes something like this. The Kochen-Speaker theorem says that it is impossible to assign determinate values to all physical quantities and preserve the standard quantum statistics for these quantities without violating the standard functional relationships between the quantities (Kochen and Specker [1967] and, for further discussion of the theorem, Bub [1997], 73–82). And since (i) we know by direct observation that the standard quantum statistics are satisfied for each physical quantity, (ii) we also know by direct observation that the standard functional relationships between physical quantities are satisfied, and (iii) one arguably cannot even understand what it would be for the standard functional relationships between physical quantities to be violated (What is kinetic energy if the value of the kinetic energy of a particle is not one-half the mass times the square of the value of its velocity? And perhaps more puzzling, what is position-squared if not the square of the value of the position of the particle?); by the Kochen-Specker theorem, one cannot assign determinate values to every physical quantity.

The problem is not with the structure of the argument but with the assumptions. Consider assumption (iii). This assumption is arguably violated by even the standard formulation of quantum mechanics with the standard interpretation of states. The standard formulation of quantum mechanics allows for the value of a physical quantity to be fully determinate when the values of its functional components are not determinate. A particle might, for example, be in a state where its energy would classically be a function of its position and in fact have a fully determinate energy, but fail to have a determinate position (consider, say, the electron in a hydrogen atom in ground state). Insofar as one is willing to take the standard formulation of quantum mechanics seriously, one must consequently acknowledge that the determinate value of one physical quantity cannot typically be thought of as being a function of the values of other classically related quantities, since the other physical quantities may not even be determinate.

One might reply that the classical functional relationships between determinate values of physical quantities still hold on the standard formulation of quantum mechanics *whenever the physical quantities do in fact have determinate values*. But Vink argued that something similar is also true if one takes every physical observable to be simultaneously determinate. In his response to the Kocher-Specker theorem, Vink acknowledged that on his dynamics the classical functional relationships between the values of physical quantities fail to hold even when the quantities are represented by commuting observables. Vink nevertheless argued that 'during a measurement the wave function of the quantum system effectively evolves into an eigenstate of the observable being measured, and then [the classical functional relationships] hold among any set of operators that commute with the one being measured' (Vink [1993], 1811). His argument, then, was that the classical functional relationships between determinate values hold whenever one is in a position to in fact measure those values, whenever one *can know* that the physical quantities do in fact have determinate values. And one might take this to be close enough to how violations of the classical functional relationships are handled on the standard formulation of quantum mechanical for it to be similarly acceptable.

On Vink's dynamics, the determinate value of each quantity evolves stochastically and in this sense independently of the values of the other quantities. This one reason is why Vink must acknowledge that the values of even commuting observables might not bear the standard functional relationships. But since the determinate value of each quantity evolves stochastically, it is unclear exactly why Vink thought that the standard functional relationships would hold between the values of all quantities that commute with an observed quantity. There are several ways to reconstruct what he might have had in mind here, but it is worth noting that Vink's dynamics might easily be modified to give the standard quantum statistics and to preserve the classical functional relationships between determinate values for all quantities for which the current quantum mechanical state is an eigenstate by using the classical functional relationships to coordinate the values of the other quantities on the value of any one quantity selected from the set. The upshot is just that, while it may be difficult to determine exactly what Vink had in mind in claiming that the values of quantities that commute with an observed quantity will bear the standard functional relationships, his more general point is certainly right: if one can understand properties by way of their functional relationships in standard quantum mechanics, then there is no special problem for understanding quantities when one takes the values of all physical quantities to be always determinate *even if their values typically fail to bear the standard functional relationships*.

There is more to say about assumption (iii), but let's first briefly consider assumptions (i) and (ii). As suggested by the earlier brain-in-the-vat discussion, assumptions (i) and (ii) are at best misleading, and arguably false, in the context of a hidden-variable theory. In Bohmian mechanics, one only ever directly knows the value of one physical quantity, i.e. particle configuration (since there are no other observable quantities), and even this knowledge is always limited by the distribution postulate (since if one ever knew more about the configuration than allowed by the standard quantum statistics, the epistemic probabilities predicted by Bohm's theory would no longer agree with the standard quantum statistics). Consequently, in a world described by a classical hidden-variable theory like Bohmian mechanics, one does not know *by direct observation* that the standard quantum statistics are satisfied for each physical quantity; nor does one know *by direct observation* that the standard functional relationships between physical quantities are satisfied. In the world described by Bohmian mechanics, everything one ever knows empirically must be inferred from what one knows about the particle configuration and the evolution of the quantum-mechanical state. One can sometimes infer from this empirical knowledge what the value of other physical quantities would have to be if the classical functional relationships did in fact hold. But one cannot have independent empirical evidence that the functional relationships do in fact hold, since particle configuration is the only observable physical quantity in Bohmian mechanics. And even if one added other physical quantities to the theory, as long as it is assumed that all observations are mediated by particle configuration, the values of other physical quantities might routinely violate the classical functional relationships and an observer inhabiting a world described by the theory would never know. Such is the brain-in-the-vat nature of hidden-variable theories generally and Bohmian mechanics in particular.

This leads to an argument from Bohmian mechanics that one need not make assumption (iii) either. Bohm's theory shows how assumptions (i) and (ii) might be false by showing how everything one knows about the physical world might be mediated by the value of a single physical quantity and the standard quantum mechanical state. Moreover, the contextual way that one understands other physical properties in Bohmian mechanics shows how one might understand physical quantities without making assumption (iii). More specifically, one understands the values of all *observable* physical quantities as nothing more than manifestations of the evolution of the wave function and the value of whatever physical quantity in fact determines the value of one's measurement records. So, if one is comfortable with how Bohmian mechanics handles physical quantities other than position, then one should not worry about making every physical property determinate and violating functional relationships in *E*-theory since quantities other than that quantity on which our measurement records in fact supervene can be understood in precisely the same way.

The problem with Bohmian mechanics and *Q*-theory is not the assumption that there is *some* physical quantity on which one's experience might be taken to supervene at a time. Something like this is presumably assumed even in the context of classical mechanics. Indeed, unless one assumes that there is some physical property or quantity on which our experience supervenes, it is unclear how *any* physical theory could be taken to explain why we observe what we do. The problem with Bohmian mechanics is that we do not know whether particle configuration is in fact the quantity on which our experience supervenes, and the problem with the *Q*-theory is that simply stipulating that *Q* is the quantity on which our experience supervenes and that this quantity happens to be the only determinate physical quantity is clearly ad hoc and does not allow for the possibility that the relationship between mental and physical states changes over time. By supposing that all physical quantities are determinate in *E*-theory, we automatically guarantee that *Q* is determinate *whatever it happens to be for an observer at a time* and we arguably accomplish this without making any ad hoc physical assumptions.

There is a close relationship between how experience is explained in Bohmian mechanics, *Q*-theory, and *E*-theory. Just as in *Q*-theory, one supposes in *E*-theory that everything a particular observer observes at a time is mediated by the values of some quantity *Q* and the standard quantum mechanical state. But what *Q* happens to be makes no difference for any physical facts in the world described by *E*-theory. In *E*-theory there are also the actual, unmediated values for every other physical quantity. While the values of these quantities can also be expected to exhibit the standard quantum statistics, they will, by the Kochen-Specker theorem, violate standard functional relationships. But the statistical evolution of the values of physical quantities other than *Q* and their ubiquitous violation of standard functional relationships will never matter to the results of one's measurements since, by hypothesis, one's mental state, mental processes, and experiences, supervene on the value of *Q* and the standard quantum mechanical state. Just as in Bohmian mechanics, one can suppose that functional relationships are satisfied in one's inferences from the value of *Q* to the values of certain *contextual* quantities. What contextual quantities can be assigned consistent values depends on the value of *Q* and the current quantum mechanical state, and the values assigned to them need not be the same as the values taken by the unobservable physical quantities that *E*-theory describes. Since *Q* can be expected to exhibit the standard quantum statistics on the Bell-Vink dynamics with the distribution postulate, the values of contextual physical quantities inferred from the value of *Q* and the quantum-mechanical state can clearly also be expected to exhibit the standard quantum statistics.

One might argue that this solves only part of the problem posed by assumption (iii). If one understands almost all of the observable quantities as contextual inferences concerning the value and behavior of one genuine observable quantity in *E*-theory, just as one does in Bohmian mechanics and in *Q*-theory, then how is one to understand the other real, but unobservable, physical quantities (those always-determinate quantities to which, on the assumption that one's mental state supervenes on just one physical quantity at a time, one has no direct empirical access)? The easiest thing to do is simply to take all the unobservable determinate quantities in *E*-theory as primitive. There is, however, a bit more one might say about them. While their values will violate the classical functional relationships, these values will nonetheless remain statistically correlated. Indeed, the expectation values for physical quantities will satisfy the standard functional relationships whenever they are well-defined. So while the values of the unobservable quantities will have no impact on the empirical world, one might still be said to understand what these physical quantities are.

One might naturally wonder what is to be gained by postulating an infinite set of primitive, unobservable physical quantities. Since one presumably could have no good empirical reasons to do this, it is perhaps unsurprising that what good reasons there are here are explanatory. First, supposing that all physical quantities are determinate saves one from the embarrassment of having to choose a single special physical quantity or rule of determining the single special physical quantity as the one and only always-determinate property that accounts for the values of all determinate measurement records. Moreover, supposing that all physical quantities are determinate explains why it doesn't matter in any way whatosoever which physical quantity in fact makes one's measurement records determinate at a time. It explains why the physical world would look pretty much the same regardless of the precise relationship between one's mental and physical states. In short, supposing that all physical quantities are determinate allows one to avoid the preferred-basis problem and once again frees our best physical theories from having to provide any *special explanation* for how observers end up with determinate measurement records. Here, just as in classical mechanics, measurement records are determinate simply because all physical quantities are determinate, and here the world can be expected to exhibit the standard quantum statistics simply because all physical quantities can be expected to exhibit the standard quantum statistics.

E-theory requires no assumption about the relationship between mental and physical states beyond the general assumption that there is *some* physical quantity on which mental records can be taken to supervene at a time. If one never has unmediated epistemic access to more than one physical quantity at a time, one can never compare the values of different physical quantities to observe the inevitable violation of functional relationships. If *Q* is the physical quantity on which an observer's mental records supervene at a time, *Q* can be expected to exhibit the standard quantum statistics. And since experience is taken to supervene on the value of Q, the theory predicts that the standard quantum statistics hold for the results of an observer's measurements. So E-theory solves the preferred-basis problem by guaranteeing determinate measurement records that can be expected to satisfy the standard quantum statistics without requiring one to choose a physically preferred determinate quantity. While the quantity Q clearly plays a role in explaining how we get the determinate measurement records we do, it does not matter what Q happens to be since one would expect to get the standard quantum statistical predictions for *any* physical quantity. Again, all one needs to know about the relationship between mental and physical states is that there is some physical quantity on which mental records supervene at a time. And something like this is what one needs in any physical theory in order to claim that the physical theory explains one's experience.

3 Relativistic constraints

There is still at least one significant problem with taking E-theory to provide an entirely satisfying solution to the quantum measurement problem. Since the Bell-Vink dynamics assumes a single standard of simultaneity for all inertial frames, it is incompatible with relativity as usually understood. The space-like separated results of an EPR experiment are explained in E-theory, just as in Bohmian mechanics, by the simultaneous coordinated evolution of the observed physical quantity at each end of the EPR apparatus. And since all observers in all inertial frames must agree on the value of the local observed quantity (since they can observe it and compare notes), each of these theories requires a frame-independent standard of simultaneity. So, if one requires a dynamics that is compatible with the dynamical constraints usually taken to be imposed by relativity, then the Bell-Vink dynamics, like Bohm's original dynamics, is unsatisfactory. But it is unclear that any hidden-variable dynamics can do better. (Curiously, Bell himself seems to have taken the proper moral of Bell's theorem to be that a hidden-variable theory cannot do better than Bohmian mechanics in getting compatibility with the constraints of relativity, and he seems to have taken this fact as grounds for liking Bohmian mechanics.)

There are at least two options one might consider. Faced with the conflict between his dynamics and relativity, Vink, following Bell, suggested adopting local field variables as the determinate physical quantities. While assigning a frame-independent dynamical state to an extended system requires a frame-independent standard of simultaneity, assigning a frame-independent dynamical property to a local spacetime region does not. And since a field can be defined in terms of its local field variables (defined at each point in Minkowski spacetime, say), adopting a field ontology is a natural first step to getting compatibility with relativity. But one still needs a dynamics for the field quantities. And it will not be easy to find one that is compatible with relativity.

The basic argument goes as follows. In order for the dynamics to give the right empirical predictions for the results of a field-variable version of the EPR experiment, the determinate values of the field variables in space-like separated regions must be instantaneously correlated in the laboratory frame. And since all observers must in all inertial frames agree on the values of observable determinate field variables, one must have a frame-independent standard of simultaneity in order to specify the dynamics. There are, of course, several implicit assumptions in this argument that one might reasonably question (that there are no conspiracies in the determinate values of the field variables in space-like separated regions, etc.). But for a hidden-variable theory to make the right empirical predictions for EPR experiments in terms of records given in the determinate values of field quantities, and for it to explain these records, requires some account of how the correlations in the determinate observed field variables in space-like separated regions were formed. To provide this account in a way that is compatible with the constraints of relativity will at minimum require some ingenuity and will most likely require one to deny some physical assumptions that are typically assumed without question.

It is not that such an account is impossible. If one were willing to adopt a blatantly ad hoc dynamics, one might simply stipulate the determinate field quantities in Minkowski spacetime to be whatever they need to be in order to provide the standard statistically distributed quantum measurement records that we in fact expect to find. This theory would, by stipulation, be empirically adequate, and it would arguably be consistent with relativity, but the dynamics here is so ad hoc as arguably not even to qualify as a dynamics (it is more just a list of all actual events along all possible world lines). On the other hand, this forces us to confront questions of precisely what one should mean by compatibility with relativity and what it should mean for a physical theory to have a dynamics. (The former question is considered in Aharonov and Albert [1981], and is reconsidered in Maudlin [1994] and [1996] and Albert [1999]; the latter question concerns what it means for a theory to be ad hoc as much as it concerns what we mean by a dynamics.) Setting these questions aside, the point is just that while getting compatibility with special relativity in a hidden-variable theory like *E*-theory is not impossible, it may well require us to decide what it is we want *most* in a satisfactory physical theory.

Another option is to settle for explaining why relativistic constraints *appear* to be satisfied in *E*-theory when they are in fact violated. This might be thought of as a weak sort of compatibility with relativity (see Albert [1999] for a discussion of just this). Since *E*-theory makes the standard quantum mechanical predictions for each determinate physical quantity, and since there is a no-signaling theorem for standard quantum mechanics, one cannot send superluminal signals in *E*-theory. In *E*-theory, as in Bohmian mechanics, this result is contingent on the distribution postulate being satisfied, since one would be able to send superluminal signals in either theory if one ever knew the value of the observable determinate quantity (*Q* or configuration, respectively) more precisely than allowed by the standard quantum probabilities. So if all one means by compatibility with relativity is the inability to communicate superluminally, *E*-theory can be said to be compatible with relativity even though its dynamics is incompatible with relativistic constraints as typically understood.

It is perhaps worth noting that, given the limits of one's empirical access in the theory, there is a sense in which the relativistic constraints as typically understood may not even by applicable in *E*-theory.[2] Consider the brain-in-the-vat analogy again. Suppose that the relativistic constraints appear to be satisfied by observers whose experience is mediated by *Q* in the sense that one concludes that there is no superluminal signaling. So are relativistic constraints as typically understood *in fact* satisfied here? Since space time properties, like all other physical properties, are supposed to be mediated by *Q*, the positions of objects and the behavior of clocks is simply a function of the values of *Q* on which one's phenomenal experience supervenes. Consequently, in hidden-variable theories generally and in *E*-theory specifically, the real physical world need have nothing like the space time structure of the physical world as experienced. If any such hidden-variable theory were true of our world, then we never in fact had good empirical reason to accept relativity in the first place! Because of the brain-in-a-vat nature of experience, such a theory describes a world so rich in illusion that the dynamical constraints of relativity are irrelevant.

The point here is just that *E*-theory *might* correctly describe the physical world that we inhabit given all we can know empirically if it is true. How it treats physical quantities is generally no more objectionable than how the standard formulation of quantum mechanics or Bohmian mechanics or any other hidden-variable theory treats them. And *E*-theory makes the standard quantum statistical predictions without one having to make any ad hoc assumptions about what physical quantities are in fact determinate or having to specify any special relationship between physical and mental states. If one likes *E*-theory, it is simply a feature of the theory that one does not have access to the sort of empirical evidence that would tell one whether or not relativity is genuinely satisfied in the time evolution of determinate values of quantities or is just an artifact of appearances mediated by that physical quantity on which

[2] I take this point to be similar to one made by Bradley Monton in a talk he gave at the PSA 2000 meetings.

our experience supervenes. For better or worse, *E*-theory relegates relativity to a position subordinate to its own account of our determinate experience.

One might complain that, since all empirical observations in *E*-theory are mediated by *Q*, physical quantities other than *Q* are thus superfluous, and *Q*-theory ought to be adopted instead on grounds of metaphysical economy. While physical quantities other than *Q* clearly do no empirical work in *E*-theory, there is an explanatory advantage to keeping them. If one instead opts for *Q*-theory, one gets metaphysical economy but only at the cost of making the ad hoc stipulation that whatever needs to be determinate in order for us to have determinate records is in fact the only physically determinate quantity and postulating an incomplete theory since we do not know what *Q* is. The ontological extravagance (or, perhaps better, the ontological richness) of *E*-theory buys a robust explanation for why we have determinate measurement records (because all physical quantities are determinate) and a simple explanation for why the world exhibits the standard quantum statistics (because every physical quantity individually can be expected to exhibit the standard quantum-mechanical statistics on the stochastic dynamics). So while there are arguably no good empirical reasons for preferring *E*-theory over *Q*-theory, there are good explanatory reasons for preferring *E*-theory.

4 Conclusion

The Kochen-Specker theorem tells us that one can only make every physical quantity determinate and get the right quantum statistics for each quantity if one gives up the standard functional relationships between physical quantities. Losing functional relationships between physical quantities comes at a significant conceptual cost. But one is arguably no worse off here than in the standard formulation of quantum mechanics where there are typically no determinate values that *might* satisfy or not satisfy a particular functional relationship or than in a hidden-variable theory like Bohmian mechanics where the satisfaction of the standard functional relationships is a product of one's using these functional relationships to infer the values of fictional contextual quantities from the determinate particle configuration.

In *E*-theory, unlike in a collapse theory, there is nothing special about measurement interactions; unlike in Bohmian mechanics, one does not have to specify any special relationship between mental and physical states; and unlike *Q*-theory, one does not have to select a special physical quantity to make determinate. What the quantity *Q* happens to be in *E*-theory is simply determined by the actual relationship between mental and physical states and has no physical implications whatsoever. By making all physical quantities determinate, *E*-theory is sure to make determinate whatever in fact needs to be determinate in order to account for our determinate measurement records, beliefs, experiences, mental processes, or whatever else one wants to supervene on the physical state.

E-theory, then, might be said to solve the quantum measurement problem by providing determinate physical records that are distributed according the standard quantum statistics and by providing a way to explain determinate measurement records without requiring a preferred basis and at the same time rendering relativity irrelevant. While its dynamics is not compatible with the constraints of relativity, just as one will never observe violations in the standard functional relationships between physical quantities, if the distribution postulate is satisfied, one will never observe superluminal signaling or discover any preferred inertial frame.

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