EMPIRICAL ADEQUACY AND THE AVAILABILITY OF RELIABLE RECORDS IN QUANTUM MECHANICS*

JEFFREY A. BARRETT†‡

Department of Philosophy
University of California, Irvine

In order to judge whether a theory is empirically adequate one must have epistemic access to reliable records of past measurement results that can be compared against the predictions of the theory. Some formulations of quantum mechanics fail to satisfy this condition. The standard theory without the collapse postulate is an example. Bell's reading of Everett's relative-state formulation is another. Furthermore, there are formulations of quantum mechanics that only satisfy this condition for a special class of observers, formulations whose empirical adequacy could only be judged by an observer who records her measurement results in a special way. Bohm's theory is an example. It is possible to formulate hidden-variable theories that do not suffer from such a restriction, but these encounter other problems.

1. We say that a theory is empirically adequate over a set of observations when it makes the right empirical predictions to the desired level of accuracy for the observations. One might, for example, test the empirical adequacy of Copernican astronomy by measuring the relative positions of Mars and Jupiter at midnight every night for a year and then comparing the results of these measurements against the predictions of the theory. If the theory makes the right predictions to the desired level of accuracy for the relative positions of the two planets, then one judges that it is empirically adequate over the observations. In order to make such a judgment, one must have epistemic access to records of past observations. In this case, one must have access to records of the relative positions of Mars and Jupiter over the past year. Moreover, for the judgment to be reliable, these records must be reliable. If the real records of the relative positions were secretly replaced by false records so that one was unable to compare the theory's predictions against what actually happened, then one's judgment concerning the empirical adequacy of the theory would be unreliable. It would appear then to be a precondition for the possibility of testing the

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‡Send requests for reprints to the author, Department of Philosophy, University of California, Irvine, CA 92717.

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empirical adequacy of a theory that there be reliable records of past measurement results to which one has epistemic access.

A theory that fails to satisfy this precondition might tell us that an observer generally has no reliable records of past measurement results or that there are such records but that an observer typically fails to have epistemic access to them for one reason or another. If such a theory were true, then the observer would be unable to compare the actual results of her measurements against the empirical predictions of the theory in order to determine whether the predictions were correct. For this reason, if a theory fails to predict the existence of reliable records of an observer's measurement results to which the observer has epistemic access, then we will say that the theory is *empirically incoherent.*[1]

Some formulations of quantum mechanics are empirically incoherent, and others are only empirically coherent for a special class of observers. It is possible, however, to formulate a hidden-variable theory that is empirically coherent for any observer. All the theory needs to do is to guarantee the existence of determinate, epistemically accessible records and predict that they are more or less stable over time. If an observer recorded her measurement results in terms of some physical quantity Q, then a hidden-variable theory would make these records determinate by making Q determinate; and if the observer had epistemic access to the value of Q and if Q were stable under the dynamics of the theory, then the theory would be empirically coherent for the observer—if the theory were true, then the observer would be able to compare her results against its predictions. Choosing a single, just-right physical quantity for a hidden-variable theory to make determinate, however, looks more than a little ad hoc. What we would like to have is a hidden-variable theory that makes *every* physical quantity of a system determinate. Is such a theory possible? Yes. What would one have to sacrifice in order to take such a theory seriously? Plenty (but it may be worth it).

2. How did we get into the business of looking for a new formulation of quantum mechanics in the first place? While the standard theory of quantum mechanics, the theory written down by von Neumann in 1932, is arguably the most empirically successful theory ever, on a critical reading it is logically inconsistent, and on even the most charitable reading it is

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[1] As a quick (and extreme) example of an empirically incoherent theory, consider one that tells me that all of my records of past measurement results are in fact false. I would be unable to determine whether this theory accounts for my past experience since, if the theory were true, I would not know what my past experience was since I would only have epistemic access to false records. For all I know, such a theory might be true. I might in fact have perfectly unreliable records of past events, but this could never be accepted on the basis of empirical evidence gathered over time.

incomplete in an empirically significant way. This is the quantum measurement problem.

According to the standard formulation of quantum mechanics the physical state of a system is represented by a unit vector in an appropriate Hilbert space. A system almost always evolves in a continuous, deterministic, linear way that depends only on its energy properties. But, when a system is *measured,* it does something completely different: it instantaneously, nonlinearly, and randomly jumps into an eigenstate of the observable being measured. So why does it do *this?* The standard interpretation of states, which we will count as a part of the standard formulation of quantum mechanics, says that a physical system has some property only if it is in an eigenstate of having the property.[2] On the standard interpretation of states if a system is not in an eigenstate of the observable being measured, then it is senseless to ask what the value of the particular physical quantity is. It is not that we do not know what the value is; rather, the system simply fails to have a determinate value for the quantity. Since a system is generally not in an eigenstate of having a determinate value for a given quantity, when the system is measured it must somehow end up in a state where the measured quantity *does* have a determinate value. According to the standard theory, when the system is measured it instantaneously, nonlinearly, and randomly jumps to a state where the measured quantity has a determinate value with probabilities determined by its premeasurement state.

The nonlinear collapse dynamics plays an essential role in the standard theory of quantum mechanics, and the theory ends up making very accurate statistical predictions. But the standard theory cannot be the whole story. After all, observers and measuring devices are physical systems too. They are presumably made entirely of simpler systems (elementary particles, atoms, molecules, etc.), and according to the standard theory, and our most accurate observations, each of these simple systems follows the *linear dynamics* when it is not itself being observed. How then does the composite system made up of the observer, the measuring device, and the system measured end up following a *nonlinear dynamics?* It is mathematically impossible for a system composed entirely of systems interacting with each other linearly to evolve nonlinearly, so if we assume that observers and measuring devices are composed of simpler systems interacting

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[2] It is often said that the formal theory of quantum mechanics is fine, we just need a better interpretation. But it is difficult to consider the standard theory of quantum mechanics apart from its interpretation. When Born introduced the standard interpretation of states, he was also required to add the nonlinear dynamics to the formal theory in order to make his interpretation work (see Pais 1986 for a discussion of Born's contribution to the standard theory and its interpretation). Physical theories and their interpretations are always developed together. They ought to be evaluated together too.

in their usual linear way, then the standard theory of quantum mechanics is logically inconsistent.

One way to understand the problem here is that *measurement* occurs in the standard theory as an unexpected primitive term. If we interpret the term in the usual sense and suppose that a measurement interaction obeys the same physical laws as any other physical interaction, then we get a logical contradiction—this is a straightforward consequence of having a nonlinear dynamical law that applies only to measurement interactions. But if there is another way to understand measurements, a way that would avoid a logical contradiction, then the standard theory does not tell us what it is, so the theory is at best incomplete. Moreover, since how the term *measurement* is interpreted makes a difference to how we assign states to physical systems (since it is relevant to which dynamical law obtains) and since there is always some physical observable that would at least in principle distinguish between different physical states, the standard theory is at best incomplete in an empirically significant way.

This gives us a good reason not to like the standard theory of quantum mechanics. But if we do not like the standard theory, then we need a new theory.

3. It has often been suggested that one might take quantum mechanics without the collapse postulate to be a complete and accurate physical theory. Before Born introduced the nonlinear collapse dynamics and what has since become the standard interpretation of states, Schrödinger thought that waves, whose time-evolution was always to be described by his linear wave equation, would ultimately replace particles as the real constituents of the physical world. Later, Everett proposed resolving the measurement problem by taking Schrödinger's pure wave mechanics as a complete and accurate physical theory from which the predictions of the standard theory might be deduced as subjective appearances (Everett 1957, 1973). More recently it has been argued that environmental decoherence allows one to take the standard theory of quantum mechanics without the collapse postulate to be a complete and accurate physical theory.[3] There is much to say about Everett's relative-state formulation of quantum mechanics, environmental decoherence, and the suggestive properties of the standard theory of quantum mechanics without the collapse postulate, but my claim here is simple: if one dropped the nonlinear collapse dynamics from the standard theory of quantum mechanics and kept the standard interpretation of states, then one would end up with a theory whose empirical adequacy could not be tested if the theory were true. Dropping the nonlinear dynamics would obviously remove the threat of

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[3] See Zeh 1970, Gell-Mann and Hartle 1990, Omnés 1992, and Saunders 1995 for examples of this approach.

logical inconsistency, but if one kept the standard interpretation of states, then the resultant theory would be empirically incoherent. This stripped-down version of quantum mechanics is called the bare theory.

The problem with the bare theory is that it generally fails to make an observer's records of measurement results determinate. If the linear dynamics were universally true, then even an ideal observer would typically end up in a superposition of recording mutually incompatible results. Since she would fail to be in an eigenstate of recording any particular determinate result, according to the standard interpretation of states, there would be no determinate matter of fact concerning what result she recorded.[4] One's first reaction might be to conclude that since we generally do in fact get determinate measurement results, the bare theory is obviously false. But this is too fast. It turns out that the bare theory can provide interesting explanations for why an observer might *report* and thus *believe* (assuming that the observer's reports generally indicate her beliefs) that she recorded a particular determinate result when she in fact recorded no such result.

Suppose that the linear dynamics always correctly describes the time-evolution of every physical system and that an ideal observer M measures the x-spin of a spin-1/2 system S that is initially in a superposition of being x-spin up and being x-spin down. On the standard interpretation of states, S's x-spin is not up, it is not down, it is not both, and it is not neither—S is in a superposition of x-spin up and x-spin down, and this state is empirically distinguishable from either of the two eigenstates of x-spin.[5] According to the linear dynamics, M will end up entangled with S so that neither system has a pure state that can be specified apart from the other. The state of $M + S$ will be a superposition of M recording the result "x-spin up" and S being in a x-spin up state and M recording the result "x-spin down" and S being in an x-spin down state, which again is not a state where M got "x-spin up" and S is up and it is not a state where M got "x-spin down" and S is down. Here's how this looks in more detail:

Initial State: M starts in an eigenstate of being ready to make an x-spin measurement and S starts in a superposition of x-spin eigenstates: $|r\rangle_M(\alpha|\uparrow\rangle_S + \beta|\downarrow\rangle_S)$.

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[4] Note that this is not a matter of imprecision or uncertainty in the record. An observer might record "3.0 mA" when the actual current through a wire is 3.023 mA or might record "27.35 ± .03 kg" for the mass of a sack of potatoes, and we would count these as perfectly determinate results. But if one takes the bare theory to be complete and accurate, then there typically fails to be a matter of fact concerning *which* determinate result an observer has recorded. Consequently, there are generally no determinate records for an observer to compare against any predictions of the theory.

[5] More precisely, if one had a set of systems in any combination of eigenstates of x-spin and another set of systems in identical superpositions of x-spin, then there would be a series of measurements of the systems that would eventually determine which set was which. There is no guarantee that a single measurement would decide the issue, but it might.

Final State: M measures the x-spin of S and its pointer becomes perfectly correlated to the x-spin of S: $\alpha|\uparrow\rangle_M|\uparrow\rangle_S + \beta|\downarrow\rangle_M|\downarrow\rangle_S$.

That M does not end up with one or the other of the two possible x-spin results is what it means to say that M did not get a determinate result. But, while this is not a state where M *recorded* a determinate result, one might argue that this is a state where M *would report that she recorded* a determinate result. That is, if we asked M whether she determinately got one or the other of the two results, either x-spin up or x-spin down, she would tell us that she did. If the final state were $|\downarrow\rangle_M|\downarrow\rangle_S$, then M would have the disposition to answer *yes;* and, if the final state were $|\uparrow\rangle_M|\uparrow\rangle_S$, then M would have the disposition to answer *yes;* so, if the final state were any linear combination of these two states, then the linear dynamics tells us that M would have the disposition to answer *yes* if we asked her whether she had a determinate record of one or the other of the two results.

This may provide a way to account for my reporting that I got determinate measurement results when I in fact did not, but any theory that tells me that there is generally no determinate matter of fact concerning what measurement result I got, even though I may believe that there is a determinate record of the result and that I know what it is, cannot be empirically adequate in the usual sense—if the bare theory were true, then one would be unable to test its empirical adequacy since there would generally be no determinate records to compare against any predictions of the theory.[6]

4. Since the bare theory generally fails to make an observer's records of past measurement results determinate, one might want to add something to the theory that would make such records determinate. One way to do this is to supplement the usual quantum state with a new parameter that represents these records and whose value is always determinate, then to describe how this new parameter evolves. Such a parameter is often called a hidden variable. In the hidden-variable theories that we are interested in here, however, it is misleading to call it hidden since it is the quantity represented by this parameter, not the usual quantum-mechanical state, that most directly accounts for one's experience.[7] Since the added parameter always has a determinate value, there will be determinate records of any measurement results that are recorded in terms of this parameter.

Bell's reading of Everett, what Bell calls "the Everett (?) theory," is one example of a hidden-variable theory. Bell describes this theory as the de

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[6] For more about how far the bare theory might be pushed see Barrett 1994.

[7] Several people have made this point and, as one might expect, Bohm was one. Because of the role played by the hidden variable in a theory like Bohm's, it has been suggested that it be called a *manifest* variable.

Broglie-Bohm pilot-wave theory (which we will consider in the next section) without the trajectories.

> . . . [I]nstantaneous classical configurations are supposed to exist, and to be distributed in the comparison class of possible worlds with probability $|\psi|^2$. But no pairing of configurations at different times, as would be effected by the existence of trajectories, is supposed. And it is pointed out that no such continuity between present and past configurations is required by experience. (Bell 1981, 133)

The wave function ψ evolves in a perfectly linear way, but the classical configuration jumps from one configuration to another in a random way that depends only on $|\psi|^2$. That is, the current particle configuration is independent of any past or future configurations in the sense that the probability of a particular configuration accurately describing the current position of every particle is determined by the current wave function alone (it is equal to the norm squared of the projection of the current wave function onto the configuration). This means that one's records of measurement results would typically change in a pathological way over time and hence be wildly unreliable as records of what actually happened.

Suppose again that an observer M measures the x-spin of a spin-1/2 system S that is in a superposition of x-spins, but this time consider how the Everett (?) theory describes the interaction. The *quantum-mechanical state* of the composite system will again end up as a superposition of M recording "x-spin up" and S being x-spin up and M recording "x-spin down" and S being x-spin down; but the *classical configuration* will be determinate. This means that, if M records her result in terms of the classical configuration (the positions of particles), she will end up with a determinate record corresponding to one or the other of the two terms in the final state—that is, she is guaranteed to end up with a determinate record of either "x-spin up" or "x-spin down." Which configuration the observer ends up with, hence which determinate physical record she ends up with, is randomly determined, where the probability of M getting a particular record is equal to the norm squared of the amplitude of the wave function associated with the record. If the amplitudes associated with the records "x-spin up" and "x-spin down" are α and β, respectively, then the probability of the observer ending up with a configuration recording "x-spin up" is $|\alpha|^2$ and the probability of the observer ending up with a configuration recording "x-spin down" is $|\beta|^2$. Suppose that the observer gets the result x-spin up for the outcome of her first measurement.

Now what happens if the observer carefully repeats her measurement? The linear dynamics tells us that the quantum-mechanical state after the second measurement will be

$$\alpha|\uparrow,\uparrow\rangle_M|\uparrow\rangle_S + \beta|\downarrow,\downarrow\rangle_M|\downarrow\rangle_S \qquad (1)$$

So what is the classical configuration after this measurement? Again, the probability of the configuration ending up associated with a particular term in the quantum-mechanical state is completely determined by the quantum-mechanical state and is independent of past configurations. It is given by the square of the coefficients on the terms when the wave function is written in the configuration basis. Here, then, there is a probability of $|\beta|^2$ that M will end up with a configuration recording "x-spin down" for the second result even though she actually recorded "x-spin up" for the first result. In other words, there is a probability of $|\beta|^2$ that the observer's second measurement result will *disagree* with her first. Whenever we actually perform repeat x-spin measurements, however, we always get the same result for both measurements if we are careful enough, so one might conclude that the Everett (?) theory is flatly incompatible with experience.

But again this is too fast. If M does in fact get "x-spin down" for her second measurement, the classical configuration will now be one associated with the second term of the above state, which means that M's "record" of her first measurement *will now read* "x-spin down", and it will thus appear, based on an examination of her records, that her two measurements did in fact yield the same result. More generally, one can show that the classical configuration would almost always be such that one's records would exhibit the statistical correlations predicted by the standard theory whenever it makes unambiguous predictions.[8] As Bell put it,

> . . . in our interpretation of the Everett theory there is no association of the particular present with any particular past. And the essential claim is that this does not matter at all. For we have no access to the past. We have only our 'memories' and 'records'. But these memories and records are in fact *present* phenomena. . . . The theory should account for the present correlations between these present phenomena. And in this respect we have seen it to agree with ordinary quantum mechanics, in so far as the latter is unambiguous. (Bell 1981, 135–136)

But is this really all that we want empirically from a theory?

Let us say that a theory is *empirically nifty* if it can explain why an observer's current records of past measurement results have the statistical correlations that they do. The Everett (?) theory is empirically nifty, but in an underhanded way. It does explain why it is to be expected that what I currently *take as reliable records of past measurement results* would have the statistical correlations that they do. But this is little consolation, it seems to me, when it also tells me that most of these "records" are *false*.

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[8] This is because the sum of the norm squared of the amplitudes associated with those classical configurations with records close to the usual quantum statistics is typically close to one. See Farhi, Goldstone, and Gutmann 1989 or Barrett 1994 for recent discussions.

In order to accept the theory, one must first accept that one generally has no epistemic access to the actual results of one's past experiments—indeed, that there are generally no reliable records of these results whatsoever. But as soon as one accepts this one no longer has an empirical basis for choosing one dynamics for the evolution of the configuration over another—more specifically, one can have no empirical justification for choosing the pathological dynamics that Bell specifies for the Everett (?) theory. Even a theory that says that the classical configuration has *always* been just what it is right NOW would be empirically nifty. I take the moral to be that we want more empirically from a theory than what the Everett (?) theory gives us.

Bell disliked his Everett (?) theory. He said that "if such a theory were taken seriously it would hardly be possible to take anything else seriously" (1981, 136). Among the things that it would hardly be possible to take seriously would be any proposed empirical test that required accurate knowledge of past events. Bell attributed to Everett a theory that one might claim, unlike the bare theory, allows for the possibility of there being determinate records of an observer's past observations in terms of the classical configuration (on a very loose reading of what it means to be a *record* of a past observation), but the theory fails to be empirically coherent since the current configuration generally fails to provide accurate records of the observer's past measurement results, records that indicate what actually happened. If such a theory were true, it would be as if someone kept sneaking in and replacing accurate measurement records with false ones, and one cannot test the dynamics of a theory that claims something like this.

5. Another example of how one might add a hidden variable to the usual quantum-mechanical state is given by Bohm's theory (the de Broglie-Bohm-Bell pilot-wave theory). On this theory every particle always has a determinate position and follows a continuous trajectory, and the wave function always evolves in the usual linear way. A particle's motion is completely determined by the position of every particle and the evolution of the wave function. As Bell suggested, Bohm's theory might be thought of as the Everett (?) theory *with* a continuous trajectory for the classical configuration. And, just as the classical configuration in the Everett (?) theory solved the bare theory's determinate record problem, one might expect that the continuous trajectory of the configuration in Bohm's theory would solve the Everett (?) theory's reliable record problem.

If an observer's measurement results were ultimately recorded in terms of particle positions and if the observer had epistemic access to these positions, then giving every particle a determinate position would guarantee that the observer would end up with determinate, epistemically accessible records of her past measurement results. But herein lies the problem. In order to accept Bohm's theory as empirically coherent, we need a good argument that making *positions* determinate would generally give every observer epistemic access to determinate and reliable records of past measurement results. We know, however, that there can be no such argument since it is easy to imagine observers constructed so that determinate positions would *not* guarantee determinate measurement records.

Consider the following story.[9] Suppose that the observer *J* measures the *x*-spin of a particle *S* by sending it through a hole in her head where its *x*-spin becomes correlated with the position of a single particle *B*. *B* acts as a memory register that records "*x*-spin up" if it is in one position, and "*x*-spin down" if it is in another. Since the result of *J*'s measurement is recorded in terms of the position of something, Bohm's theory makes the record determinate.

But now suppose that *J* tries to record the *x*-spin of *S* in terms of the *x*-spin of *B* so that, instead of the position of *B* becoming correlated with the *x*-spin of the measured particle *S*, the wave functions of the two particles become correlated in *x*-spin. If *J* were constructed like this, then making positions determinate would not give her a determinate record. So if this were the end of the story, then Bohm's theory would simply fail to be empirically coherent for *J*. This is not necessarily the end of the story, however. All that it would take for there to be a determinate record of *J*'s measurement on Bohm's theory would be for the effective wave function of some system to become well-correlated in position with the effective wave function of *S* and *B* in *x*-spin. If the effective wave function of even a single particle *P* were so correlated, then there would be a determinate result of the measurement recorded in the determinate position of *P*. This might happen because *J* intentionally records her "result" by writing it down, it might happen when *J* acts on her "result," or it might happen by accident. In any case, as soon as the effective wave function of anything becomes well-correlated in position to the effective wave function of *S* and *B* in *x*-spin, then, regardless of how this happens, there would be a determinate measurement record in terms of the determinate position of that thing. The accuracy of the record might be taken to be proportional to the degree to which the two effective wave functions become correlated. If *J* had epistemic access to enough accurate position records of her measurement results, then Bohm's theory would be empirically coherent for *J*.

The point here is simple. Whether Bohm's theory is empirically coherent for an observer depends on the details of how the observer is constructed. For some imaginable ways that an observer might be constructed the theory would be empirically coherent, and for others it would not be. So even

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[9] This story is adapted from two stories that David Albert tells (1992, 106–110 and 170–176).

if it turns out that *human* observers are constructed so that they record their measurement results in terms of position, one might still worry that the conditions under which Bohm's theory is empirically coherent are too restrictive. One might worry about the built-in bias in favor of observers who record their results in terms of position.

A hidden-variable theory like Bohm's requires us to choose a privileged physical quantity, which is then made determinate in the theory. Choosing a single quantity out of an infinite number of possible quantities to privilege in our most fundamental physical theory has an ad hoc flavor, but further, if we choose the wrong quantity to make determinate, then we fail to provide observers with determinate, epistemically accessible records of their measurements, and consequently we cannot sensibly judge the empirical adequacy of the theory. As a particularly bad choice consider making determinate only the x-spin of a particular neutrino somewhere in the Andromeda galaxy. This would presumably do little to provide me with determinate records of my experiences. In writing down a satisfactory hidden-variable theory we want to make determinate a physical quantity that we are convinced would provide all observers with determinate and empirically accessible records of their measurements.

6. If the only problem with Bohm's theory was that position may be the wrong physical quantity to make determinate, then the situation would not be entirely hopeless. We know how to construct hidden-variable theories very much like Bohm's that make quantities other than position determinate. Bohm (1952), Bohm and Hiley (1984 and 1993), and Bell (1984) describe how to make various field quantities determinate. Moreover, Vink (1993) shows how Bell's approach might be used to make *any* discrete physical quantity determinate. Since a continuous quantity can be represented as a discrete quantity to any level of precision, this means that we have a way to assign a determinate value to virtually any physical quantity we want and to describe how the value changes over time.

On Vink's formulation of quantum mechanics the wave function ψ evolves in the usual linear way and the determinate physical quantities evolve in a random way. Suppose that the current value of some physical quantity is o_m. The probability that the value jumps to o_n in the time interval dt is $T_{mn}dt$, where T_{nm} 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

$$i\hbar\partial_t|\psi(t)\rangle = H|\psi(t)\rangle, \tag{2}$$

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

$$P_n(t) = |\langle o_n|\psi(t)\rangle|^2 \tag{3}$$

and the source matrix J_{mn} is defined by

$$J_{mn} = 2\ \mathrm{Im}\ (\langle\psi(t)|o_n\rangle\langle o_n|H|o_m\rangle\langle o_m|\psi(t)\rangle). \tag{4}$$

Finally, if $J_{nm} \geqslant 0$, then for $n \neq m$

$$T_{nm} = J_{nm}/\hbar P_m; \tag{5}$$

and if $J_{nm} < 0$, then $T_{nm} = 0$.

Let us call this prescription for the time-evolution of the determinate physical quantities the Bell-Vink dynamics. While the Bell-Vink dynamics is generally random, Vink has shown how the random evolution of a particle's position in discrete configuration space approaches Bohm's deterministic theory as the discrete partition of the space is made more fine-grained.

Given that we can make the value of any physical quantity determinate in this way, Vink proposes that we make the value of every physical quantity determinate. The problem with this proposal is that the Kochen-Specker theorem tells us that we can only keep the empirical predictions of the standard theory of quantum mechanics (where it makes unambiguous predictions) and make the value of every physical quantity determinate if we sacrifice the functional relationships between physical quantities.[10] The value of a particle's *position-times-momentum*, for example, would generally not be the value of its *position* multiplied by the value of its *momentum*. Indeed, the situation is worse: on Vink's theory the value of a particle's *position-squared* would generally fail to be the square of the value of its *position*.

To the extent that one worries about losing functional relationships between physical quantities, one might want to choose a single quantity to make determinate. But again not just any quantity will do—this is the worry about choosing position as the privileged observable in Bohm's theory. So what physical quantity should we make determinate? Well, we want determinate, accessible, reliable records of our past measurements, so we want to make determinate whatever physical quantity would make

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[10] See Kochen and Specker 1967, and more recently Mermin 1990. Both Vink (1993) and Bub (1995) have worried about the consequences of the Kochen-Specker theorem for making every physical property determinate. Vink has concluded that it does not cause any serious problems since, he argues, "during a measurement the wave function of the quantum system effectively evolves into an eigenstate of the observable being measured, and then [the usual functional relationships hold] among any set of operators that commute with the one being measured" (1993, 1811). Bub, on the other hand, has concluded that the Kochen-Specker theorem does indeed pose serious problems and that one thus only ought to make determinate a single privileged physical property and the maximal set of properties that can also be made determinate given the current wave function while preserving functional relationships. A feature of Bub's proposal is that, except for the one privileged physical property, what physical properties there are changes over time.

determinate every observer's most immediate physical records of measurements, those records that observers in fact rely on for their judgments concerning what actually happened in the past. Suppose that there is a physical quantity that if made determinate would make every observer's most immediate physical records determinate. Since we have no idea what it is, call it Q. If Q has a determinate value, then by hypothesis all sentient beings have determinate, empirically accessible records of their past measurement results.

One might now construct a new no-collapse hidden-variable theory by stipulating that Q is the only determinate physical quantity. On this theory, a complete description of the world is given by the usual quantum-mechanical state ψ together with the value of Q, where ψ evolves according to Schrödinger's linear dynamics and Q evolves according to the Bell-Vink dynamics, which depends on the evolution of ψ. Call this the Q-theory.

Unlike Bohm's theory, the Q-theory would guarantee that every observer gets a determinate record for each measurement, but would these records be reliable? If Q were very unstable under the Bell-Vink dynamics, then, like the Everett (?) theory, this new theory would fail to be empirically coherent. Whether or not Q would be stable given the dynamics here depends on several things, but, and this is the important point, it is *entirely possible* that Q is in fact very stable over time. Here, as in classical mechanics, whether or not an observer has epistemic access to stable, reliable records of past events depends on what the recording medium is and how stable it is given the physical situation. Moreover, we know that if Q is stable enough for the proposed hidden-variable theory to be empirically coherent, then the theory makes the same statistical predictions for Q (whatever Q is) that the standard theory makes whenever it makes unambiguous predictions. That is, if this new theory is empirically coherent, then it is also empirically adequate over the nonrelativistic quantum phenomena we have observed so far.

But claiming that a single physical quantity is determinate and that this quantity just happens to be the quantity that makes every observer's mental state determinate has a strong ad hoc flavor to it. In the case of Bohm's theory, it might not seem too farfetched to claim that the position of every particle is determinate. *Position* is a well-entrenched physical term. It is not very plausible on the face of it, however, to claim that the *whatever-it-takes-to-make-every-immediate-record-determinate* quantity is in fact determinate and that this is the *only* determinate physical quantity. This physical quantity depends on the details of observer physiology and practice, which we believe could have been other than they are. Do we really want our most basic physical theory to be contingent on the actual physiology and practice of observers?

There is another option to consider. One might simply accept Vink's formulation of quantum mechanics *as it stands*. In this case no physical quantity would be privileged since every quantity would have a determinate value. But what do we do about the violation of functional relationships? If a particle's *position-times-momentum* is generally not equal to its *position* times its *momentum* and if its *position-squared* is generally not equal to its *position* squared, then these are not the physical properties we are used to. The terms here cannot mean what they are usually taken to mean. Try to picture a particle whose *position-squared* is not equal to its *position* squared—if a particle has a *position,* then as it is usually understood, its *position-squared* simply is the square of its *position*—as it is usually understood, a particle's *position* and the rules of arithmetic logically determine its *position-squared.*

The upshot is that if one wanted to make sense of Vink's theory as it stands, then one would need a radically different notion of how familiar physical properties work—one would have to accept that there are no functional relationships between physical quantities that always hold, only loose statistical relationships. But one might object that this is obviously false since we know, by direct observation, that the functional relationships between physical quantities are never violated.

There are two things to say in response to such an objection. First, the Bell-Vink dynamics has the property that physical quantities that quantum mechanics tells us can be simultaneously observed will bear the usual functional relationships whenever one of them is measured (Vink 1993, 1811). This means the functional relationships between a set of simultaneously observable quantities will only be violated when none of them are being observed, which means that observers will not see the violations. Second, even if the values of such observables did not in fact mesh this way on measurement, one might still argue that observers would not notice the violation of functional relationships. Suppose that the physical quantity Q determines the most immediate measurement records of every observer. Just as in Bohm's theory, where every measurement result is supposed to be determined by position, here every measurement result would be determined by the value of Q. Thus Q would be the only physical quantity that would matter in accounting for the experiences of observers, and since the Bell-Vink dynamics makes the same statistical predictions for the value of Q at a time as the standard theory of quantum mechanics, observers would not notice the violation of functional relationships even if the actual determinate values of physical quantities did not mesh in the way described above.

Since every physical quantity would be determinate, this theory would not put us in the embarrassing position of having to choose a privileged quantity to make determinate. A disadvantage of the theory, however, is that physical quantities would have to be interpreted in a radically new way, a way that would sacrifice the assumption that certain physical quantities necessarily share functional relationships. One might argue, however, that even a theory like Bohm's that makes one physical property determinate and all the rest context dependent already requires a radical change in the way that we understand physical quantities.

7. In order to judge whether a theory is empirically adequate one must have epistemic access to reliable records of past measurement results that can be compared against the predictions of the theory. Some formulations of quantum mechanics fail to satisfy this condition. The bare theory predicts that there would generally be no reliable records of measurement results, Bell's Everett (?) theory predicts that there would generally not be enough reliable records, and Bohm's theory would only be empirically coherent for a special class of observers. Whatever formulation of quantum mechanics we end up with it ought to be one where we are able to tell a coherent story in the context of the theory that explains how we came to have reliable empirical evidence for its acceptance.

If there were a physical quantity Q that most directly determined what observers take as reliable records of past measurement results, then a hidden-variable theory where Q is determinate and evolves according to the Bell-Vink dynamics would make observers' records determinate, and these records would have the right statistical properties. But if taking Q to be the only determinate physical quantity seems too ad hoc a way to get an empirically coherent theory, then one might take Vink's suggestion seriously and make every quantity determinate. One would then lose the usual functional relationships between physical quantities, but, if Q most directly determined all of one's measurement records, then the lack of functional relationships between the actual values of the physical quantities would never be noticed.

REFERENCES

Albert, D. Z. (1992), *Quantum Mechanics and Experience*. Cambridge, MA: Harvard University Press.

Barrett, J. A. (1994), "The Suggestive Properties of Quantum Mechanics without the Collapse Postulate", *Erkenntnis 41:* 233–252.

Bell, J. S. (1981), "Quantum Mechanics for Cosmologists", in *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press, pp. 117–138.

———. (1984), "Beables for Quantum Field Theory", in *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press, pp. 173–180.

Bohm, D. (1952), "A Suggested Interpretation of the Quantum Theory in terms of Hidden Variables, I and II", *Physical Review 85:* 166–179 and 180–193.

Bohm, D. and Hiley (1993), *The Undivided Universe: An Ontological Interpretation of Quantum Theory*. London: Routledge.

Bub, J. (1995), "Interference, Noncommutativity, and Determinateness in Quantum Mechanics", *Topoi, Vol. 14, No. 1:* 39–43.

Everett, H., III. (1957), " 'Relative State' Formulation of Quantum Mechanics", *Reviews of Modern Physics 29:* 454–462.

-. (1973), "Theory of the Universal Wave Function", in DeWitt, B. S. and N. Graham (eds.), *The Many-Worlds Interpretation of Quantum Mechanics.* Princeton: Princeton University Press, pp. 3–140.

Farhi, E., J. Goldstone, S. Gutmann (1989), "How Probability Arises in Quantum Mechanics", *Annals of Physics, V192, N2:* 368–382.

Gell-Mann, M. and J. B. Hartle (1990), "Quantum Mechanics in the Light of Quantum Cosmology", in W. H. Zurek (ed.). *Complexity, Entropy, and the Physics of Information, Proceedings of the Santa Fe Institute Studies in the Sciences of Complexity, vol. VIII* Redwood City, CA: Addison-Wesley, pp. 425–458.

Kochen, S. and Specker, E. P. (1967), "On the Problem of Hidden Variables in Quantum Mechanics", *Journal of Mathematics and Mechanics 17:* 59–87.

Mermin, N. D. (1990), "Simple Unified Form for the Major No-Hidden-Variables Theorems", *Physical Review Letters 65:* 3373–3376.

Omnès, R. (1992), "Consistent Interpretations of Quantum Mechanics", *Reviews of Modern Physics, Vol. 64, No. 2:* 339–382.

Pais, A. (1986), *Inward Bound: Of Matter and Forces in the Physical World.* Oxford: Oxford University Press.

Saunders, S. (1995), "Time, Quantum Mechanics, and Decoherence", *Synthese, V102, N2:* 235–266.

Vink, J. C. (1993), "Quantum Mechanics in Terms of Discrete Beables", *Physical Review A 48:* 1808–1818.

von Neumann, J. (1932), *Mathematische Grundlagen der Quantenmechanik.* Berlin: Springer. Reprinted and translated as *Mathematical Foundations of Quantum Mechanics,* R. Beyer (trans.). Princeton: Princeton University Press.

Wheeler, J. A. and W. H. Zurek (eds.) (1983), *Quantum Theory and Measurement.* Princeton: Princeton University Press.

Zeh, H. D. (1970), "On the Interpretation of Measurement in Quantum Theory", *Foundations of Physics 1:* 69–76.