Quantum Mechanics and Elements of Reality

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Abstract

It is widely accepted that a Born probability of 1 is sufficient for the existence of a corresponding element of reality. Recently Vaidman has extended this idea to the ABL probabilities of the time-symmetrized version of quantum mechanics originated by Aharonov, Bergmann, and Lebowitz. Several authors have objected to Vaidman’s time-symmetrized elements of reality without casting doubt on the widely accepted sufficiency condition for ‘ordinary’ elements of reality. In this paper I show that while the proper truth condition for a quantum counterfactual is an ABL probability of 1, neither a Born probability of 1 nor an ABL probability of 1 is sufficient for the existence of an element of reality. The reason this is so is that the contingent properties of quantum-mechanical systems are extrinsic. To obtain this result, I need to discuss objective probabilities, retroactive causality, and the objectivity or otherwise of the psychological arrow of time. One consequence of the extrinsic nature of quantum-mechanical properties is that quantum mechanics presupposes property-defining actual events (or states of affairs) and therefore cannot be called upon to account for their occurrence (existence). Neither these events nor the correlations between them are capable of explanation, the former because they are causal primaries, the latter because they are fundamental: there are no underlying causal processes. Causal connections are something we project onto the statistical correlations, and this works only to the extent that statistical variations can be ignored. There are nevertheless important conclusions to be drawn from the quantum-mechanical correlations, such as the spatial nonseparability of the world.

1. Introduction

Recently the concept of time-symmetric elements of reality, introduced by Vaidman (1996a, 1997), stirred up a lively controversy which culminated in the joint publication of two papers in this journal (Kastner, 1999; Vaidman 1999). Using the standard formalism of standard quantum mechanics, one calculates the Born probability

\[
P_B(a_i) = |\langle \Psi | P_{A=a_i} | \Psi \rangle|,
\]

where the operator $P_{A=a_i}$ projects on the subspace corresponding to the eigenvalue $a_i$ of the observable $A$. $P_B(a_i)$ is generally regarded as the probability with which a measurement of $A$

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performed after the ‘preparation’ of a system $S$ in the ‘state’ $|\Psi\rangle$ yields the result $a_i$. But $P_B(a_i)$ is not the only such probability. Using a nonstandard formulation of standard quantum theory called time-symmetrized quantum theory (Aharonov and Vaidman, 1991; Vaidman, 1998), one calculates the ABL probability

$$P_{ABL}(a_i) = \frac{|\langle \Psi_2 | P_{A=a_i} | \Psi_1 \rangle|^2}{\sum_j |\langle \Psi_2 | P_{A=a_j} | \Psi_1 \rangle|^2}.$$  \hspace{1cm} (2)

ABL probabilities were first introduced in a seminal paper by Aharonov, Bergmann, and Lebowitz (1964). In this paper it was shown that $P_B(a_i)$ can also be thought of as the probability with which a measurement of $A$, performed before what may be called the ‘retroparation’ of $S$ in the ‘state’ $|\Psi\rangle$, yields the result $a_i$. Further it was shown that if a system is ‘prepared’ at the time $t_1$ and ‘retropared’ at the time $t_2$ in the respective ‘states’ $|\Psi_1\rangle$ and $|\Psi_2\rangle$, the probability with which a measurement of $A$ performed at an intermediate time $t_m$ yields (or would have yielded) the result $a_i$, is given by $P_{ABL}(a_i)$.

Born probabilities can be measured (as relative frequencies) using preselected ensembles (that is, ensembles of identically ‘prepared’ systems). ABL probabilities can be measured using pre- and postselected ensembles (that is, ensembles of systems that are both identically ‘prepared’ and identically ‘retropared’). If the Born probability $P_B(a_i, t)$ of obtaining the result $a_i$ at time $t$ is equal to 1, one feels justified in regarding the value $a_i$ of the observable $A$ as a property that is actually possessed at the time $t$, that is, one feels justified in assuming that at the time $t$ there is an element of reality corresponding to the value $a_i$ of the observable $A$ irrespective of whether $A$ is actually measured. Redhead (1987) has expressed this feeling as the following ‘sufficiency condition’:

(ER1) If we can predict with certainty, or at any rate with [Born] probability one, the result of measuring a physical quantity at time $t$, then at the time $t$ there exists an element of reality corresponding to the physical quantity and having a value equal to the predicted measurement result.

The controversy about time-symmetric elements of reality arose because it appeared that Vaidman (1993) made the same claim with regard to ABL probabilities:

(ER2) If we can infer with certainty [that is, with ABL probability one] that the result of measuring at time $t$ an observable $A$ is $a$, then at the time $t$ there exists an element of reality $A = a$.

In response to criticism by Kastner and others (Kastner, 1999; and references therein), Vaidman (1999) clarified that he intended the term ‘element of reality’ in a ‘technical’ rather than ‘ontological’ sense: saying that there is an element of reality $A = a$ is the same as saying that if $A$ is measured, the result is certain to be $a$. In other words, (ER2) is a tautology: if $A = a$ is certain to be found then $A = a$ is certain to be found. In formulating (ER2), Vaidman does not affirm the existence of an element of reality irrespective of whether $A$ is

1 The $\Psi$’s in (2) are related to the ‘pre-/retropared’ $\Psi$’s via unitary transformations $U(t_m - t_1)$ and $U(t_m - t_2)$. 

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actually measured. (ER2) defines what it means to affirm the existence of an element of reality corresponding to \( A = a \). To say that there is such an element of reality is to affirm the truth of a conditional, not the existence of an actual situation or state of affairs. Since ordinarily the locution ‘element of reality’ refers to an actual state of affairs, Vaidman’s terminological choice was unfortunate and has mislead many readers. But beyond that, his reading of (ER2) is unobjectionable. I shall, however, stick to the ordinary, ontological meaning of ‘element of reality.’ In what follows, (ER2) is to be understood accordingly, that is, as affirming an actual state of affairs (the existence of an ‘ordinary’ element of reality) just in case the corresponding ABL probability is one. Hence my showing that (ER2), thus understood, is false, has no bearing on Vaidman’s reading of (ER2). A definition cannot be false.

The aim of this paper is to show that not only (ER2) but also (ER1) is false. In Sec. 2 I discuss the three-box gedanken experiment due to Vaidman (1996b). By calculating the ABL probabilities associated with different versions of this experiment I show that positions are extrinsic, and that, consequently, (ER1) and (ER2) are both false. Since the validity of arguments based on time-symmetric quantum counterfactuals is open to debate, in Sec. 3 I show without making use of ABL probabilities that positions are extrinsic and that (ER1) is false. This leads to the conclusion that the measurement problem is a pseudoproblem, and that all that ever gets objectively entangled is counterfactuals. In Sec. 4 I establish the cogency of the argument of Sec. 2 by showing that the proper condition for the truth of a quantum counterfactual is \( P_{ABL} = 1 \). This necessitates a discussion of objective probabilities, retroactive causality, and the objectivity or otherwise of the psychological arrow of time. In Sec. 5 I argue that since quantum mechanics presupposes the occurrence/existence of actual events and/or states of affairs, it cannot be called upon to account for the emergence of ‘classicality.’ What is more, if quantum mechanics is as fundamental as its mathematical simplicity and empirical success suggest, the property-defining events or states of affairs presupposed by quantum mechanics are causal primaries – nothing accounts for their occurrence or existence.

If this is correct, the remaining interpretative task consists not in explaining the quantum-mechanical correlations and/or correlata but in understanding what they are trying to tell us about the world. I confine myself to pointing out, in Sec. 6, the most notable implications of the diachronic correlations, viz., the existence of entities of limited transtemporal identity, objective indefiniteness, and the spatial nonseparability of the world. The extrinsic nature of positions, finally, appears to involve a twofold vicious regress. Its resolution involves macroscopic objects, which are defined and discussed in Sec. 7. Section 8 concludes with a remark on the tension of contrast between objective indefiniteness and the inherent definiteness of language.

2. The Lesson of the Three-Box Experiment

In the following I present a somewhat different but conceptually equivalent version of Vaidman’s (1996b) three-box experiment. Consider a wall in which there are three holes \( A, B \) and \( C \). In front of the wall there is a particle source \( Q \). Behind the wall there is a particle detector \( D \). Both \( Q \) and \( D \) are equidistant from the three holes. Behind \( C \) there is one other device; its purpose is to cause a phase shift by \( \pi \). Particles emerging from the wall are thus preselected in a ‘state’ \( |\Psi_1\rangle \) proportional to \( |a\rangle + |b\rangle + |c\rangle \), where \( |a\rangle \), \( |b\rangle \) and \( |c\rangle \) represent the respective alternatives ‘particle goes through \( A \),’ ‘particle goes through \( B \),’ and ‘particle
goes through \( C \),’ while detected particles are postselected in a ‘state’ \(|\Psi_2\rangle\) proportional to \(|a\rangle + |b\rangle - |c\rangle\).

We will consider two possible intermediate measurements. First we place near \( A \) a device \( F_a \) that beeps whenever a particle passes through \( A \). With the help of the ABL formula one finds that every particle of this particular pre- and postselected ensemble \( \mathcal{E} \) causes \( F_a \) to beep with probability 1, as one may verify by calculating the probability with which a particle would be found passing through the union \( B \cup C \) of \( B \) and \( C \):

\[
P_{ABL}(\subset B \cup C) \propto |\langle \Psi_2 | \mathbf{P}_{B \cup C} | \Psi_1 \rangle|^2 = 0,
\]

where \( \mathbf{P}_{B \cup C} = |b\rangle\langle b| + |c\rangle\langle c| \) projects on the subspace corresponding to the alternative ‘particle goes through \( B \cup C \).’ We obtain the same result by considering what would happen if \( A \) were closed, or if all particles that make \( F_a \) beep were removed from \( \mathcal{E} \). The remaining particles are pre- and postselected in ‘states’ proportional to \(|b\rangle + |c\rangle\) and \(|b\rangle - |c\rangle\), respectively, and these ‘states’ are orthogonal. The result is an empty ensemble: if \( A \) were closed, no particle would arrive at \( D \). Does this warrant the conclusion that all particles belonging to \( \mathcal{E} \) pass through \( A \)?

Let us instead place near \( B \) a device \( F_b \) that beeps whenever a particle passes through \( B \). Considering the invariance of \(|\Psi_1\rangle\) and \(|\Psi_2\rangle\) under interchange of \(|a\rangle\) and \(|b\rangle\), one is not surprised to find that the ensemble \( \mathcal{E} \) would be empty if the particles causing \( F_b \) to beep were removed. Hence if the conclusion that all particles belonging to \( \mathcal{E} \) pass through \( A \) is warranted, so is the conclusion that the same particles also pass through \( B \). If these ‘conclusions’ were legitimate, they would make nonsense of the very concept of localization. Therefore we are forced to conclude instead that an ABL probability equal to 1 does not warrant the existence of a corresponding element of reality (in the straightforward, ontological sense). Taken in this sense, (ER2) is false.

It pays to investigate further. We are in fact dealing with four different experimental arrangements: (i) there is no beeper, (ii) \( F_a \) is the only beeper in place, (iii) \( F_b \) is the only beeper in place, (iv) both \( F_a \) and \( F_b \) are in place. The first arrangement permits no legitimate inference concerning the hole taken by a particle. Assuming that \( F_a \) is 100\% efficient, the second arrangement guarantees that one of two inferences is warranted: ‘the particle goes through \( A \)’ (in case \( F_a \) beeps) or ‘the particle goes through \( B \cup C \)’ (in case \( F_a \) fails to beep). Assuming that \( F_b \) is equally efficient, the third arrangement likewise guarantees that one of two inferences is warranted: ‘the particle goes through \( B \)’ or ‘the particle goes through \( A \cup C \).’ The fourth arrangement, finally, guarantees that one of three inferences is warranted: ‘the particle goes through \( A \)’ (in case \( F_a \) beeps), ‘the particle goes through \( B \)’ (in case \( F_b \) beeps), and ‘the particle goes through \( C \)’ (in case neither \( F_a \) nor \( F_b \) beeps). The following counterfactuals are therefore true: (i) If \( F_a \) were in place, either it would beep and the particle would go through \( A \), or it would fail to beep and the particle would go through \( B \cup C \). (ii) If \( F_b \) were in place, either it would beep and the particle would go through \( B \), or it would fail to beep and the particle would go through \( A \cup C \). (iii) If both \( F_a \) and \( F_b \) were in place, one of the following three conjunctions would be true: \( F_a \) beeps and the particle goes through \( A \); \( F_b \) beeps and the particle goes through \( B \); neither beeper beeps and the particle goes through \( C \).

If we confine the discussion to particles that are emitted by \( Q \) and detected by \( D \), then the following counterfactuals are true: If \( F_a \) but not \( F_b \) were present, the alternatives represented
by $|b\rangle$ and $|c\rangle$ would interfere with each other but not with the alternative represented by $|a\rangle$; as a consequence, they would interfere destructively; therefore $F_a$ would beep and the particle would go through $A$. By the same token, if $F_b$ were the only beeper present, the alternatives represented by $|a\rangle$ and $|c\rangle$ would interfere destructively, $F_b$ would beep, and the particle would go through $B$. Finally, if both beepers were present, no interference would take place; each particle would go through a particular hole, but not all particles would go through the same hole. To my mind, these counterfactuals are unobjectionable. One does not have to delve into the general philosophy of counterfactuals to see that they are true. I concur with Vaidman (1999) that quantum counterfactuals are unambiguous. Quantum counterfactuals are statements about possible worlds in which the outcomes of all measurements but one are the same as in the actual world. The remaining measurement is performed in a number of possible worlds (the number depends on the range of possible values) but not in the actual world.

The three-box (or three-hole) experiment demonstrates that position probabilities cannot be assigned independently of experimental arrangements. More specifically, they cannot be assigned without specifying a set of experimentally distinguishable alternatives. A position probability of 1 depends not only on the way the particle is ‘prepared’ and ‘retropared’ but also on the set $L$ of alternative locations that can be experimentally distinguished. If $L = \{A, B \cup C\}$, the particle is certain to be found in (or going through) $A$, but the inference of an element of reality ‘the particle went through $A$’ is warranted only if the members of $L$ are actually distinguished (that is, only if the corresponding experiment is actually performed).

It follows that the position of a particle is an extrinsic property. By an extrinsic property $p$ of $S$ I mean a property of $S$ that is undefined unless either the truth or the falsity of the proposition $p = ‘S$ is $p’$ can be inferred from what happens or is the case in the ‘rest of the world’ $W - S$. The position of a particle is undefined unless there is a specific set $\{R_i\}$ of alternative locations, and unless there is a matter of fact about the particular location $R_j$ at which the particle is, or has been, present. (By ‘a matter of fact about the particular location $R_j$’ I mean an actual event or an actual state of affairs from which that location can be inferred.)

Positions are defined in terms of position-indicating matters of fact. They ‘dangle’ from actual events or actual states of affairs. And if it is true that ‘[t]here is nothing in quantum theory making it applicable to three atoms and inapplicable to $10^{23}$’ (Peres and Zurek, 1982), this must be as true of footballs and cats as it is of particles and atoms. The positions of things are what matters of fact imply concerning the positions of things.

If this is correct then (ER1) is as false as (ER2). In particular, the ‘sufficiency condition’ (ER1) is not sufficient for the presence of a material object $O$ in a region of space $R$. The condition that is both necessary and sufficient for the presence of $O$ in $R$, is the existence of a matter of fact that indicates $O$’s presence in $R$. If there isn’t any such matter of fact (now or anytime past or future), and if there also isn’t any matter of fact that indicates $O$’s absence

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2 Examples of actual events are the click of a Geiger counter or the deflection of a pointer needle. An actual state of affairs is expressed, for instance, by the statement ‘The needle points to the left.’ Can such events and states of affairs be defined in quantum-mechanical terms? See below.
from \( R \), then the sentence ‘\( O \) is in \( R \)’ is neither true nor false but meaningless, and \( O \)’s position with respect to \( R \) (inside or outside) is undefined.

3. Probabilities, Conditionals, Elements of Reality, and the Measurement Problem

In the previous section I made use of the ABL probabilities associated with different versions of Vaidman’s three-box experiment to show that positions are extrinsic, and that, consequently, both (ER1) and (ER2) are false. The validity of arguments based on time-symmetric quantum counterfactuals might be challenged. In the present section I therefore show without recourse to ABL probabilities that positions are extrinsic and that (ER1) is false. In the following section I shall establish the cogency of the argument of the previous section by showing that the proper condition for the truth of a quantum counterfactual is \( P_{ABL} = 1 \). (It is readily verified that \( P_B = 1 \) is sufficient but not necessary for this condition to be met.)

Consider two perfect detectors \( D_1 \) and \( D_2 \) whose respective (disjoint) sensitive regions are \( R_1 \) and \( R_2 \). If the support of the (normalized) wave function associated with the (center-of-mass) position of an object \( O \) is neither wholly inside \( R_1 \) nor wholly inside \( R_2 \), nothing necessitates the detection of \( O \) by \( D_1 \), and nothing necessitates the detection of \( O \) by \( D_2 \). But if the wave function vanishes outside \( R_1 \cup R_2 \), the probabilities for either of the detectors to click add up to 1, so either of the detectors is certain to click. Two perfect detectors with sensitive regions \( R_1 \) and \( R_2 \) constitute one perfect detector \( D \) with sensitive region \( R_1 \cup R_2 \). But how can it be certain that one detector will click when individually neither detector is certain to click? What could cause \( D \) to click while causing neither \( D_1 \) nor \( D_2 \) to click?

That two perfect detectors with disjoint sensitive regions constitute one perfect detector for the union of the two regions forms part of the definition of what we mean by a perfect detector. By definition, a perfect detector clicks when the quantum-mechanical probability for it to click is 1. \( D \) is certain to click because the probabilities for either of the two detectors to click add up to 1. Hence the question of what causes \( D \) to click does not arise. Perfect detectors are theoretical constructs that by definition behave in a certain way. If real detectors would behave in the same way, it would be proper to inquire why they behave in this way. But real detectors are not perfect and do not behave in this way. A real detector is not certain to click when the corresponding quantum-mechanical probability is 1. Hence the question of what causes a real detector to click does not arise. Nothing causes a real detector to click.

What I aim at in this paper is an interpretation of quantum mechanics that takes standard quantum mechanics to be fundamental and complete. My claim that nothing causes a real detector to click is based (i) on this assumption and (ii) on the observation that the efficiency of a real detector cannot be accounted for in quantum-mechanical terms. All quantum-mechanical probability assignments are relative to perfect detectors. If quantum mechanics predicts that \( D_1 \) will click with a probability of 1/2, it does not predict that a real detector will click in 50\% of all runs of the actual experiment. What it predicts is that \( D_1 \) will click in 50\% of those runs of the experiment in which either \( D_1 \) or \( D_2 \) clicks. Quantum mechanics has nothing to say about the percentage of runs in which no counter clicks (that is, is tells us nothing about the efficiency of \( D \), or of any other real detector for that matter). If quantum mechanics predicts that \( D_1 \) will click with probability 1, it accounts for the fact that whenever either \( D_1 \) or \( D_2 \) clicks, it is \( D_1 \) that clicks. It does not account for the clicking of either \( D_1 \) or \( D_2 \). Where
quantum mechanics is concerned, nothing causes the clicking. And if quantum mechanics is as fundamental and complete as is here assumed, then this is true without qualification: nothing causes the clicking.3

Quantum mechanics assigns probabilities (whether Born or ABL) to alternative events (e.g., deflection of the pointer needle to the left or to the right) or to alternative states of affairs (e.g., the needle’s pointing left or right). Implicit in every normalized distribution of probabilities over a specified set of alternative events or states of affairs is the assumption that exactly one of the specified alternatives happens or obtains. If we assign normalized probabilities to a set of counterfactuals, we still assume (counterfactually) that exactly one of the counterfactuals is true. In other words, if we assign probabilities to the possible results of an unperformed measurement, we still assume that the measurement, if it had been performed, would have yielded a definite result. Like all (normalized) probabilities, the probabilities assigned by quantum mechanics are assigned to mutually exclusive and jointly exhaustive possibilities, and they are assigned on the supposition that exactly one possibility is, or would have been, a fact. Even the predictions of the standard version of standard quantum mechanics therefore are conditionals. Everything this version tells us conforms to the following pattern: If there is going to be a matter of fact about the alternative taken (from a specific range of alternatives), then such and such are the Born probabilities with which that matter of fact will indicate this or that alternative.

It is important to understand that quantum mechanics never allows us to predict that there will be such a matter of fact, unconditionally. If the Born probability of a particular event $F$ is 1, we are not entitled to predict that $F$ will happen. What we are entitled to infer is only this: Given that one of a specified set of events will happen, and given that $F$ is an element of this set, the event that will happen is $F$. In order to get from a true conditional to an element of reality, a condition has to be met: a measurement must be successfully performed, there must be a matter of fact about the value of an observable, one of a specific set of alternative property-indicating events or states of affairs must happen or obtain. Quantum mechanics does not predict that a measurement will take place, nor the time at which one will take place, nor does it specify the conditions in which one will take place. It requires us to assume that one will take place, for it is on this assumption that its probability assignments are founded.

3 It is well known that all actually existing detectors are less than perfect. On the other hand, there is no (obvious) theoretical limit to the efficiency of a real detector. It might one day be possible to build a detector with an efficiency arbitrarily close to 100%. However, unless the efficiency of detectors is exactly 100%, it remains impossible to interpret a ‘preparation’ that warrants assigning probability 1 as causing a detector to click. If the preparation is to be a sufficient reason for the click, the detector must always click (that is, it must be perfect). What if it were possible to build perfect detectors? We could then speak of the preparation as the cause of the click, but if quantum mechanics is fundamental and complete, it would still be impossible to explain how the preparation causes the click: ex hypothesi, no underlying mechanism exists. The perfect correlation between preparation and click would have to be accepted as a brute fact. So would the fact that either $D_1$ or $D_2$ clicks when neither of them is certain to click. Causality would be just another name for such correlations, not an explanation.
It follows that (ER1) is false. A Born probability equal to 1 is equivalent to a conditional $c$. The inference of a corresponding element of reality is warranted only if the condition laid down by $c$ is actually met.

It also follows that positions are extrinsic. The condition laid down by $c$ is the existence of a matter of fact about the value taken by some observable. If this observable has for its spectrum a set $\{R_i\}$ of mutually disjoint regions of space, if $R$ is an element of $\{R_i\}$, and if the Born probability associated with $R$ is 1, then $O$ is inside $R$ just in case there is a matter of fact about the particular element of $\{R_i\}$ that contains $O$.

I conclude this section with a few remarks concerning the so-called measurement problem. First some basic facts. Quantum mechanics represents the possible values $q_i^k$ of all observables $Q^k$ as projection operators $P_{Q^k=q_i^k}$ on some Hilbert space $\mathcal{H}$. The projection operators that jointly represent the range of possible values of a given observable are mutually orthogonal. If one defines the ‘state’ of a system as a probability measure on the projection operators on $\mathcal{H}$ (Cassinello and Sánchez-Gómez, 1996; Jauch, 1968, p. 94) resulting from a preparation of the system (Jauch, 1968, p. 92), one finds (Cassinello and Sánchez-Gómez, 1996; Jauch, 1968, p. 132) that every such probability measure has the form $P(W) = \text{Tr}(WP)$, where $W$ is a unique density operator (that is, a unique self-adjoint, positive operator satisfying $\text{Tr}(W) = 1$ and $W^2 \leq W$). [The trace $\text{Tr}(X)$ is the sum $\sum_i \langle i | X | i \rangle$, where $\{|i\rangle\}$ is any orthonormal basis in $\mathcal{H}$.] If $W^2(t) = W(t)$, $W(t)$ projects on a one-dimensional subspace of $\mathcal{H}$ and thus is equivalent – apart from an irrelevant phase factor – to a ‘state’ vector $|\Psi(t)\rangle$ or a wave function $\Psi(x,t)$, $x$ being any point in the system’s configuration space. In this case one retrieves the Born formula (1).

The quantum-mechanical ‘state’ vector (or the wave function, or the density operator) thus is essentially a probability measure on the projection operators on $\mathcal{H}$, specifying probability distributions over all sets of mutually orthogonal subspaces of $\mathcal{H}$. Hence the $t$ that appears in the ‘states’ $W(t)$, $|\Psi(t)\rangle$, and $\Psi(x,t)$ has the same significance as the $t$ that appears in the time-dependent probabilities $P_B(q_i^k, t)$. Now recall that quantum mechanics predicts neither that a measurement will take place nor the time at which one will take place. It requires us to assume that a measurement will take place at a specified time. The time-dependence of the ‘state’ vector therefore is a dependence on the specified time at which a specified observable (with a specified range of values) is measured either in the actual world or in a set of possible worlds. It is not the time-dependence of a state of affairs that evolves in time.

On the supposition that $|\Psi(t)\rangle$ represents a state of affairs that evolves in time (so that at every time $t$ a state of affairs $|\Psi(t)\rangle$ obtains), one needs to explain what brings about the real or apparent discontinuous transition from a state of affairs represented by a ket of the form $|\Psi(t)\rangle = \sum_i a_i(t)\langle a_i|$ to the state of affairs represented by one of the kets $|a_i\rangle$. This is the measurement problem. It is a pseudoproblem because a collection of time-dependent probabilities is not a state of affairs that evolves in time. The probability for something to happen at the time $t$ does not exist at $t$, any more than the probability for something to be located in $R$ exists in $R$.

The probabilities $P_B(q_i^k, t)$ are determined by the relevant matters of fact about the properties possessed by a physical system at or before a certain time $t_0$. In the special case of a
complete measurement performed at $t_0$, they are given by the Born formula

$$P_B(q^k, t) = |\langle \Psi(t)|P_{Q^k=q^k}^*|\Psi(t)\rangle| \quad \text{for } t \geq t_0,$$

where $|\Psi(t)\rangle = U(t-t_0)|\Psi(t_0)\rangle$. $|\Psi(t_0)\rangle$ is the ‘state’ ‘prepared’ by the measurement at $t_0$ (that is, it represents the properties possessed by the system at $t_0$). $U(t-t_0)$ is the unitary operator that governs the time-dependence of quantum-mechanical probabilities (often misleadingly referred to as the ‘time evolution operator’). And $t$ is the stipulated time at which the next measurement is performed, either actually or counterfactually.

Thus all that a superposition of the form $|\Psi(t)\rangle = \sum_i a_i(t)|a_i\rangle$ tells us, is this: If there is a matter of fact from which one can infer the particular property (from the set of properties represented by the kets $|a_i\rangle$) that is actually possessed by the system at the stipulated time $t$, then the prior probability that this matter of fact indicates the property represented by $|a_i\rangle$ is $|a_i|^2$. It is self-evident that if there is such a matter of fact, and if this matter of fact is taken into account, the correct basis for further conditional inferences is not $|\Psi(t)\rangle$ but one of the kets $|a_i\rangle$. This obvious truism is the entire content of the so-called projection postulate (Lüders, 1951; von Neumann, 1955). By the same token, all that an entangled ‘state’ of the form $\sum_i a_i(t)|b_i\rangle \otimes |a_i\rangle$ tells us, is this: If there are two matters of fact, one indicating which of the properties represented by the kets $|a_i\rangle$ is possessed by the first system, and another indicating which of the properties represented by the kets $|b_i\rangle$ is possessed by the second system, then the two matters of fact together indicate $|a_i\rangle$ and $|b_i\rangle$ with probability $|a_i|^2$, and they indicate $|a_i\rangle$ and $|b_j\rangle$ ($j \neq i$) with probability 0. But if there is any such matter of fact, these entangled probabilities are based on an incomplete set of facts and are therefore subjective (that is, they reflect our ignorance of some relevant fact). All that ever gets objectively entangled is counterfactuals.

4. Objective Probabilities, Retrocausation, and the Arrow of Time

What most strikingly distinguishes quantum physics from classical physics is the existence of objective probabilities. In a classical world there are no (nontrivial) objective probabilities: the probability of dealing an ace is not 1/13 but either 1 or 0, depending on whether or not an ace is top card. Objective probabilities have nothing to do with ignorance; there is nothing (that is, no actual state of affairs, no actually possessed property, no actually obtained measurement result) for us to be ignorant of. Then what is it that has an objective probability? What are objective probabilities distributed over? The obvious answer is: counterfactuals. Only a contrary-to-fact conditional can be assigned an objective probability. Objective probabilities are distributed over the possible results of unperformed measurements. Objective probabilities are objective in the sense that they are not subjective, and they are not subjective because they would be so only if the corresponding measurements were performed. In short, objective probabilities are probabilities that are counterfactually subjective.

Probabilities can be objective only if they are based on a complete set of facts. Otherwise they are subjective: they reflect our ignorance of some of the relevant facts. Born probabilities are in general calculated on the basis of an incomplete set of facts; they take into account the relevant past matters of fact but ignore the relevant future matters of fact. Born probabilities are objective only if there are no relevant future matters of fact. Thus they cannot be objective
if any one of the measurements to the possible results of which they are assigned, is actually performed. This is equally true of ABL probabilities: if one of the measurements to the possible results of which they are assigned, is actually performed, they too are calculated on the basis of an incomplete set of facts. They take into account all revelant matters of fact except the result of the actually performed measurement. On the other hand, if none of these measurements is actually performed, ABL probabilities take into account all relevant matters of fact and are therefore objective.

Thus probabilities are objective only if they are distributed over alternative properties or values none of which are actually possessed, and only if they are based on all relevant events or states of affairs, including those that are yet to occur or obtain. In general the objective probabilities associated with contrary-to-fact conditionals depend also on events that haven’t yet happened or states of affairs that are yet to obtain. Hence some kind of retroactive causality appears to be at work. This necessitates a few remarks concerning causality and the apparent ‘flow’ of time.

But first let us note that nothing entails the existence of time-reversed causal connections between actual events and/or states of affairs. To take a concrete example, suppose that at \( t_1 \) the \( x \) component \( \sigma_x \) of the spin of an electron is measured, that at \( t_2 > t_1 \) \( \sigma_y \) is measured, and that the respective results are \( \uparrow_x \) and \( \uparrow_y \). Then a measurement of \( \sigma_x \) would have yielded \( \uparrow_x \) if it had been performed at an intermediate time \( t_m \), and a measurement of \( \sigma_y \) would have yielded \( \uparrow_y \) if it had been performed instead. What would have happened at \( t_m \) depends not only on what happens at \( t_1 \) but also on what happens at \( t_2 \). But if either \( \sigma_x \) or \( \sigma_y \) is actually measured at \( t_m \) (other things being equal), nothing compels us to take the view that \( \uparrow_y \) was obtained at \( t_m \) because the same result was obtained at \( t_2 \). We can stick to the idea that causes precede their effects, according to which \( \uparrow_y \) was obtained at \( t_2 \) because the same result was obtained at \( t_m \). The point, however, is that nothing in the physics prevents us from taking the opposite view. The distinction we make between a cause and its effect is based on the apparent ‘motion’ of our location in time – the present moment – toward the future. This special location and its apparent ‘motion’ are as extraneous to physics as are our location and motion in space (Price, 1996). Equally extraneous, therefore, is the distinction between causes and effects.

Physics deals with correlations between actual events or states of affairs, classical physics with deterministic correlations, quantum physics with statistical ones. Classical physics allows us to explain the deterministic correlations (abstracted from what appear to be universal regularities) in terms of causal links between individual events. And for some reason to be explained presently, we identify the earlier of two diachronically correlated events as the cause and the later as the effect. The time symmetry of the classical laws of motion, however, makes it equally possible to take the opposite view, according to which the later event is the cause and the earlier event the effect. In a deterministic world, the state of affairs at any time \( t \) determines the state of affairs at any other time \( t' \), irrespective of the temporal order of \( t \) and \( t' \). The belief in a time-asymmetric physical causality is nothing but an animistic projection of the perspective of a conscious agent into the inanimate world, as I proceed to show.

I conceive of myself as a causal agent with a certain freedom of choice. But I cannot conceive of my choice as exerting a causal influence on anything that I knew, or could have known, at the time \( t_c \) of my choice. I can conceive of my choice as causally determining only
such events or states of affairs as are unknowable to me at $t_c$. On the simplest account, what I knew or could have known at $t_c$ is everything that happened before $t_c$. And what is unknowable to me at $t_c$ is everything that will happen thereafter. This is the reason why we tend to believe that we can causally influence the future but not the past. And this constraint on our (real or imagined) causal efficacy is what we impose, without justification, both on the deterministic world of classical physics and on the indeterministic world of quantum physics.

In my goal-directed activities I exploit the time-symmetric laws of physics. When I kick a football with the intention of scoring a goal, I make (implicit or explicit) use of my knowledge of the time-symmetric law that governs the ball’s trajectory. But my thinking of the kick as the cause and of the scored goal as its effect has nothing to do with the underlying physics. It has everything to do with my self-perception as an agent and my successive experience of the world. The time-asymmetric causality of a conscious agent in a successively experienced world rides piggyback on the symmetric determinisms of the physical world, and in general it rides into the future because in general the future is what is unknowable to us. But it may also ride into the past. Three factors account for this possibility.

First, as I said, the underlying physics is time-symmetric. If I ignore the strange case of the neutral kaon (which doesn’t appear to be relevant to the interpretation of quantum mechanics), this is as true of quantum physics as it is of classical physics. If the standard formulation of quantum physics is asymmetric with respect to time, it is because we think (again without justification) that a measurement does more than yield a particular result. We tend to think that it also prepares a state of affairs which evolves toward the future. But if this is a consistent way of thinking – it is not (Mohrhoff, 1999) – then it is equally consistent to think that a measurement ‘retropares’ a state of affairs that evolves toward the past, as Aharonov, Bergmann, and Lebowitz (1964) have shown.

Second, what matters is what can be known. If I could know the future, I could not conceive of it as causally dependent on my present choice. In fact, if I could (in principle) know both the past and the future, I could not conceive of myself as an agent. I can conceive of my choice as causally determining the future precisely because I cannot know the future. This has nothing to do with the truism that the future does not (yet) exist. Even if the future in some way ‘already’ exists, it can in part be determined by my present choice, provided I cannot know it at the time of my choice. By the same token, a past state of affairs can be determined by my present choice, provided I cannot know that state of affairs before the choice is made.

There are two possible reasons why a state of affairs $F$ cannot be known to me at a given time $t$: (i) $F$ may obtain only after $t$; (ii) at $t$ there may as yet exist no matter of fact from which $F$ can be inferred. This takes us to the last of the three factors which account for the possibility of retrocausation: the contingent properties of physical systems are extrinsic. By a contingent property I mean a property that may or may not be possessed by a given system at a given time. For example, being inside a given region of space and having a spin component of $+\hbar/2$ along a given axis are contingent properties of electrons.

Properties that can be retrocausally determined by the choice of an experimenter, cannot be intrinsic. [A property $p$ of a physical system $S$ is intrinsic iff the proposition $p = ‘S$ is $p’$ is ‘of itself’ (that is, unconditionally) either true or false at any time.] If $p$ is an extrinsic property of $S$, the respective criteria for the truth and the falsity of the proposition $p = ‘S$ is $p’$ are to
be sought in the ‘rest of the world’ W − S, and it is possible that neither criterion is satisfied, in which case p is neither true nor false but meaningless. It is also possible that each criterion consists in an event that may occur only after the time to which p refers. If this event is to some extent determined by an experimenter’s choice, retrocausation is at work. On the other hand, if p is an intrinsic property of S, p has a truth value (‘true’ or ‘false’) independently of what happens in W − S, so a fortiori it has a truth value independently of what happens there after the time t to which p refers. There is then no reason why the truth value of p should be unknowable until some time t′ > t. In principle it is knowable at t, and therefore we cannot (or at any rate, need not) conceive of it as being to some extent determined by the experimenter’s choice at t′.

A paradigm case of retrocausation at work (Mohrhoff, 1999) is the experiment of Englert, Scully, and Walther (1994; Scully, Englert, and Walther, 1991). This experiment permits the experimenters to choose between (i) measuring the phase relation with which a given atom emerges coherently from (the union of) two slits and (ii) determining the particular slit from which the atom emerges. The experimenters can exert this choice after the atom has emerged from the slit plate and even after it has hit the screen. By choosing to create a matter of fact about the slit taken by the atom, they retroactively cause the atom to have passed through a particular slit. By choosing instead to create a matter of fact about the atom’s phase relation, they retroactively cause the atom to have emerged with a definite phase relation. The retrocausal efficacy of their choice rests on the three factors listed above (in different order): (i) The four propositions \(a_1\) = “the atom went through the first slit,” \(a_2\) = “the atom went through the second slit,” \(a_+\) = “the atom emerged from the slits in phase,” and \(a_-\) = “the atom emerged from the slits out of phase” affirm extrinsic properties. (ii) There exist time-symmetric correlations between the atom’s possible properties at the time of its passing the slit plate and the possible results of two mutually exclusive experiments that can be performed at a later time. (iii) The result of the actually performed experiment is the first (earliest) matter of fact about either the particular slit taken by the atom or the phase relation with which the atom emerged from the slits. Before they made their choice, the experimenters could not possibly have known the slit from which, or the phase relation with which, the atom emerged.

Probabilities, I said, can be objective only if they are based on all relevant matters of fact, including those still in the future. We are now in a position to see clearly why it should be so. Our distinction between the past, the present, and the future has nothing to do with physics. Physics knows nothing of the experiential now (the special moment at which the world has the technicolor reality it has in consciousness), nor does it know anything of the difference between what happened before now (the past) and what will happen after now (the future).

5. The World According to Quantum Mechanics: Fundamentally Inexplicable Correlations Between Fundamentally Inexplicable Events

It is commonly believed that it is the business of quantum mechanics to account for the occurrence/existence of actual events or states of affairs. Environment-induced superselection (Joos and Zeh, 1985; Zurek, 1981, 1982), decoherent histories (Gell-Mann and Hartle, 1990; Griffiths, 1984; Omnès, 1992), quantum state diffusion (Gisin and Percival, 1992; Percival 1994), and spontaneous collapse (Ghirardi, Rimini and Weber, 1986; Pearle, 1989) are just some of
the strategies that have been adopted with a view to explaining the emergence of ‘classicality.’ Whatever is achieved by these interesting endeavors, they miss this crucial point: quantum mechanics only takes us from facts to probabilities of possible facts. The question of how it is that exactly one possibility is realized must not be asked of a formalism that serves to assign probabilities on the implicit assumption that exactly one of a specified set of possibilities is realized. Even the step from probability 1 to factuality crosses a gulf that quantum mechanics cannot bridge. Quantum mechanics can tell us that \( O \) is certain to be found in \( R \) given that there is a matter of fact about its presence or otherwise in \( R \), but only the actual matter of fact warrants the inference that \( O \) is in \( R \).

Quantum mechanics does not predict that a measurement will take place, nor the time at which one will take place, nor does it specify the conditions in which one will take place. And if quantum mechanics is as fundamental as I presume it is, nothing allows us to predict that or when a measurement takes place, or to specify conditions in which one is certain to take place, for there is nothing that causes a measurement to take place. In other words, a matter of fact about the value of an observable is a causal primary. A causal primary is an event or state of affairs the occurrence or existence of which is not necessitated by any cause, antecedent or otherwise.

I do not mean to say that in general nothing causes a measurement to yield this rather than that particular value. Unless one postulates hidden variables, this is a triviality. What I mean to say is that nothing ever causes a measurement to take place. Measurements (and in clear this means detection events) are causal primaries. No detector is 100% efficient. Using similar detectors in series, it is easy enough to experimentally establish a detector’s (approximate) likelihood to click when the corresponding Born probability is 1, but of this likelihood no theoretical account is possible.\(^4\) A fortiori, no theoretical account is possible of why or when a detector is certain to click. It never is.

Quantum physics thus is concerned with correlations between events or states of affairs that are uncaused and therefore fundamentally inexplicable. As physicists we are not likely to take kindly to this conclusion, which may account for the blind spot behind which its inevitability has been hidden so long. But we certainly are at a loss when it comes to accounting for the world of definite occurrences. Recently Mermin (1998) advocated an interpretation of the formalism of standard quantum mechanics according to which “[c]orrelations have physical reality; that which they correlate, does not.” He does not claim that there are no correlata, only that they are not part of physical reality. The correlated events belong to a larger reality which includes

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\(^4\) There are two kinds of probability, the probability that a detector will respond (rather than not respond), and the probability that this (rather than any other) detector will respond given that exactly one detector will respond. The former probability cannot be calculated using the quantum formalism (nor, if quantum mechanics is fundamental and complete, any other formalism). One can of course analyze the efficiency of, say, a Geiger counter into the efficiencies of its ‘component detectors’ (the ionization cross sections of the ionizable targets it contains), but the efficiencies of the ‘elementary detectors’ cannot be analyzed any further. This entails that a fundamental coupling constant such as the fine structure constant cannot be calculated from ‘first principles;’ it can only be gleaned from the experimental data.
consciousness and which lies outside the scope of physics. Thus Mermin agrees that, where physics is concerned, the correlata are fundamentally inexplicable.

The idea that the correlata are conscious perceptions (Lockwood, 1989; Page, 1996), or beliefs (Albert, 1992), or knowings (Stapp, 1993) has a respectable pedigree (London and Bauer, 1939; von Neumann, 1955). If one thinks of the state vector as representing a state of affairs that evolves in time, one needs something that is ‘more actual’ than the state vector – something that bestows ‘a higher degree of actuality’ than does the state vector – to explain why every successful measurement has exactly one result, or why measurements are possible at all. This is the spurious measurement problem all over again. It is spurious because the state vector does not represent an evolving state of affairs. If we were to relinquish this unwarranted notion, we would not need two kinds of reality to make sense of quantum mechanics, such as a physical reality and a reality that includes consciousness (Mermin, 1998), or a potential reality and an actual reality (Heisenberg, 1958; Popper, 1982; Shimony, 1978, 1989), or a mind-constructed ‘empirical’ reality and a mind-independent ‘veiled’ reality (d’Espagnat, 1995), or an unrecorded ‘smoky dragon’ reality and an irreversibly recorded reality (Wheeler, 1983). We could confine ourselves to talking about events that are causal primaries, the inferences that are warranted by such events, the correlations between such events or such inferences, and the further inferences that are warranted by these correlations.

I do not deny that there is a larger reality that includes consciousness and that lies outside the scope of physics. What I maintain is that the interpretative problems concerning quantum mechanics can be solved without appealing to any larger reality, and that such an appeal does not help solving those problems because it is neither necessary nor possible to account for the occurrence of a causal primary. Theoretical physics is partly mathematics and partly semantics. The semantic task is to name the fundamental epistemological and/or ontological entities and/or relations represented by the symbols of the formalism. I cannot think of a more satisfactory choice of a basic (and therefore not further explicable) ontological entity for a physical theory than a causal primary – something that is inexplicable by definition. Ever since the seminal paper by Einstein, Podolsky, and Rosen (1935), it has been argued that quantum mechanics is incomplete (Bell, 1966; Ford and Mancica, 1992; Lockwood, 1989; Primas, 1990). In point of fact, no theory can be more complete (with regard to its subject matter) than one that accounts for everything (within its subject matter) but what is inexplicable by definition. If there is anything that is incomplete, it is reality itself (that is, reality is incomplete relative to our description of it, which is ‘overcomplete’) – but I’m getting ahead of myself.

Because the occurrence/existence of actual events or states of affairs is presupposed by the formalism, locutions such as ‘actual event,’ ‘actual state of affairs,’ ‘matter of fact’ cannot even be defined within the formalism. This conclusion too is unlikely to be popular with physicists, who naturally prefer to define their concepts in terms of the mathematical formalism they use. Einstein spent the last thirty years of his life trying (in vain) to get rid of field sources – those entities that have the insolence to be real by themselves rather than by courtesy of some equation (Pais, 1982). Small wonder if he resisted Bohr’s insight that not even the properties of things can be defined in purely mathematical terms. But Bohr was right. If Bohr (1934, 1963) insisted on the necessity of describing quantum phenomena in terms of experimental
arrangements, it was because he held that the properties of quantum systems are defined by the experimental arrangements in which they are displayed (d'Espagnat, 1976).

For ‘experimental arrangement’ read: what matters of fact permit us to infer concerning the properties of a given system at a given time. The contingent properties of physical systems are defined in terms of the actual events or states of affairs from which they can be inferred. They ‘dangle’ from what happens or is the case in the rest of the world. They cannot be defined in purely mathematical terms, for only intrinsic properties can be so defined. The scope of physics is not restricted to laboratory experiments. Any matter of fact that has a bearing on the properties of a physical system qualifies as a ‘measurement result.’ What is relevant is the occurrence or existence of an event or state of affairs warranting the assertability of a statement of the form ‘S is p (at the time t),’ irrespective of whether anyone is around to assert, or take cognizance, of that event or state of affairs, and irrespective of whether it has been anyone’s intention to learn something about S.

The following picture emerges. The world is a mass of events that are causal primaries. Without any correlations between these events, it would be a total chaos. As it turns out, the uncaused events are strongly correlated. If we don’t look too closely, they fall into neat patterns that admit of being thought of as persistent objects with definite and continuously evolving positions. Projecting our time-asymmetric agent-causality into the time-symmetric world of physics, we think of the positions possessed at later times as causally determined by the positions possessed at earlier times. If we look more closely, we find that positions aren’t always attributable, and that those that are attributable aren’t always predictable on the basis of past events. We discover that positions do not ‘dangle’ from earlier positions by causal strings but instead ‘dangle’ from position-defining events that are statistically correlated but (being causal primaries) are not causally connected. Quantum mechanics describes the correlations but does nothing to explain them. Not only the correlata but also the correlations are incapable of (causal) explanation. Causal explanations are confined to the familiar macroworld of deterministic processes and things that evolve in time. This macroworld with its causal links is something we project onto the correlations and their uncaused correlata, but the projection works only to the extent that the correlations are not manifestly probabilistic. There are no causal processes more fundamental than the correlations and their correlata, processes that could in any manner account for the correlations or the correlata.

6. Spatial Nonseparability

The remaining interpretative task thus consists not in explaining the correlations but in understanding what they are trying to tell us about the world. Here I will confine myself to discussing some of the implications of the diachronic correlations (the correlations between results of measurements performed on the same system at different times).

Perhaps the first insight one gleans from the correlations is the existence of persisting entities. If the correlations did not permit us to speak of such entities, we could not think of

5 This is discussed in the last two sections.

6 The implications of the synchronic (EPR) correlations have been discussed elsewhere (Mohrhoff, submitted).
the correlata as possessed properties, extrinsic or otherwise. Suppose that we perform a series of position measurements. And suppose that every position measurement yields exactly one result (that is, each time exactly one detector clicks). Then we are entitled to infer the existence of an entity $O$ which persists through time (if not for all time), to think of the clicks given off by the detectors as matters of fact about the successive positions of this entity, to think of the behavior of the detectors as position measurements, and to think of the detectors as detectors. (The lack of transtemporal identity among particles of the same type of course forbids us to extend to such particles the individuality of a fully ‘classical’ entity.) The successive positions of $O$, however, are extrinsic: they are what can be inferred from the pattern of clicks. All that can be inferred concerning $O$’s positions at times at which no detector clicks, is counterfactual and probabilistic. There is a persistent entity all right, but there is then no actually possessed position to go with it.

The next lesson to be learned from the correlations is that the positions of things are objectively indefinite or ‘fuzzy.’ This does not mean that $O$ has as fuzzy position. It means that statements of the form ‘$O$ is in $R$ at $t$’ are sometimes neither true nor false but meaningless. This possibility stands or falls with the extrinsic nature of positions and the existence of objective probabilities. Take the counterfactual ‘If there were a matter of fact about the slit taken by the atom, the atom would have taken the first slit.’ We can assign to this counterfactual an objective probability iff the proposition ‘The atom went through the first slit’ is neither true nor false but meaningless. The reason why this proposition can be meaningless is that positions are extrinsic. It is meaningless just in case there isn’t any matter of fact about the slit taken by the atom.

If it is true that the atom went through the union of the slits (that is, if the atom was emitted on one side of the slit plate and detected on the other side), and if it is meaningless to say that the atom went through the first slit (in which case it is also meaningless to say that it went through the second slit), then the conceptual distinction we make between the two slits has no reality for the atom. If that distinction were real for the atom (that is, if the atom behaved as if the two slits were distinct), the atom could not behave as if it went – as a whole, without being divided into distinct parts – simultaneously through both slits. But (if quantum mechanics is fundamental and complete) this is what the atom does when interference fringes are observed.

Thus there are objects for which our conceptual distinction between mutually disjoint regions of space does not exist. It follows that the distinction between such regions cannot be real per se (that is, it cannot be an intrinsic property of the world). If it were real per se, the following would be the true: at any one time, for every finite region $R$, the world can be divided into things or parts that are situated inside $R$, and things or parts that are situated inside the complement $R'$ of $R$. The boundary of $R$ would demarcate an intrinsically distinct part of the world. But if this were the case, exactly one of the following three propositions would be true of every object $O$ at any given time: (i) $O$ is situated wholly inside $R$; (ii) $O$ is situated wholly inside $R'$; (iii) $O$ has two parts, one situated wholly inside $R$ and one situated wholly inside $R'$.

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7 The detectors of the present scenario are assumed to be time-specific: a click not only indicates a position but also the time at which it is possessed.
If there is anything that (standard) quantum mechanics is trying to tell us about the world, it is that for at least some objects all of these propositions are sometimes false.

It follows that the multiplicity and the distinctions inherent in our mathematical concept of space – a transfinite set of triplets of real numbers – are not intrinsic features of physical space. The notion that these features of our mathematical concept of space are intrinsic to physical space – in other words, the notion that the world is spatially separable – is a delusion. This notion is as inconsistent with quantum mechanics as the notion of absolute simultaneity is with special relativity. ‘Here’ and ‘there’ are not per se distinct. Reality is fundamentally nonseparable. Like the positions of things, spatial distinctions ‘dangle’ from actual events or states of affairs. Reality is not built on a space that is differentiated the way our mathematical concept of space is differentiated. A description of the world that incorporates such a space – and a fortiori every description that identifies ‘the points of space (or space-time)’ as the carriers of physical properties – is ‘overcomplete.’ Reality is built on matters of fact, and the actually existing differences between ‘here’ and ‘there’ are the differences that can be inferred from matters of fact. In and of itself, physical space – or the reality underlying it – is undifferentiated, one.

7. Macroscopic Objects

The extrinsic nature of positions appears to involve a twofold vicious regress. To adequately deal with it, I need to talk about macroscopic objects. A macroscopic object $M$ is an object that satisfies the following criterion: any factually warranted inference concerning the position of $M$ at any time $t$ is predictable (with certainty) on the basis of factually warranted inferences about the positions of $M$ at earlier times. (A factually warranted inference is an inference that is warranted by some matter of fact.) Thus, to the extent that they can be inferred from actual events, the successive positions of a macroscopic object evolve deterministically. This makes it possible to ignore the fact that the positions of macroscopic objects, like all actually possessed positions, depend for their existence on position-indicating events. We can treat the positions of macroscopic objects as intrinsic properties and assume that they follow definite and causally determined trajectories, without ever risking to be contradicted by an actual event.

I do not mean to say that the position of $M$ really is definite. Even the positions of macroscopic objects are fuzzy, albeit not manifestly so: the positional indefiniteness of $M$ does not evince itself through unpredictable position-indicating events. Nor do I mean to say that the positions of macroscopic objects really are intrinsic. They too ‘dangle’ from actual events. But they do so in a way that is predictable, that does not reveal any fuzziness. We may think of macroscopic objects as following definite trajectories, or we may think of them as following fuzzy trajectories. Since all matters of fact about their positions are predictable, it makes no difference: the fuzziness has no factual consequences. Classical behavior results when the factually warranted positions fuse into a not manifestly fuzzy trajectory. It has little to do with the ‘classical limit’ in which the wave packet shrinks to a continuously moving point, for
the wave packet (of whatever size) is a bundle of probabilities associated with time-dependent counterfactuals, not the actual trajectory of an object.\footnote{Good examples of how not to get from quantum to classical are the unsuccessful attempts to obtain the exponential decay law, which pertains to factually warranted inferences and is consistent with all experimental data, from the Schrödinger equation, which tells us how the probabilities associated with counterfactuals depend on time (Onley and Kumar, 1992; Singh and Whitaker, 1982).}

By saying that matters of fact about the positions of macroscopic objects are predictable I do not mean that the \textit{existence} of such a matter of fact is predictable. Once again, a Born probability equal to 1 does not warrant the prediction \textit{that} an event will happen or \textit{that} a state of affairs will obtain. Only if it is \textit{taken for granted} that exactly one of a range of possible events or states of affairs will happen or obtain, does a Born probability equal to 1 allow us to predict \textit{which} event or state of affairs will happen or obtain. What I mean by saying that matters of fact about the (successive) positions of a macroscopic object are predictable, is this: what an actual event or state of affairs implies regarding the position of a macroscopic object is consistent with what can be predicted with the help of some classical dynamical law on the basis of earlier position-defining events. Everything a macroscopic object does (that is, every matter of fact about its present properties) follows via the pertinent classical laws from what it did (that is, from matters of fact about its past properties).\footnote{The above definition of ‘macroscopic’ does not stipulate that events indicating departures from the classically predicted behavior occur with zero \textit{probability}. An object is entitled to the label ‘macroscopic’ if no such event \textit{actually} occurs during its lifetime. What matters is not whether such an event \textit{may} occur (with whatever probability) but whether it ever \textit{does} occur.}

When I speak of the \textit{existence} of a matter of fact, I mean the occurrence of an actual event or the existence of an actual state of affairs. It is worth emphasizing that this is something that cannot be undone or ‘erased’ (Englert, Scully, and Walther, 1999; Mohrhoff, 1999). According to Wheeler’s interpretation of the Copenhagen interpretation, ‘no elementary quantum phenomenon is a phenomenon until it is registered, recorded, “brought to a close” by an “irreversible act of amplification,” such as the blackening of a grain of photographic emulsion or the triggering of a counter’ (Wheeler, 1983). In point of fact, there is no such thing as an ‘irreversible act of amplification.’\footnote{Note that an apparatus pointer is not a macroscopic object according to the above definition. In general there is nothing that allows one to predict which way the needle will deflect (given that it will deflect). Only \textit{before} and \textit{after} the deflection event does the needle behave as} As long as what is ‘amplified’ is counterfactuals, the ‘act of amplification’ is reversible. No amount of amplification succeeds in turning a counterfactual into a fact. No matter how many counterfactuals get entangled, they remain counterfactuals. On the other hand, once a matter of fact exists, it is \textit{logically} impossible to erase it. For the relevant matter of fact is not that the needle deflects to the left (in which case one could ‘erase’ it by returning the needle to the neutral position). The relevant matter of fact is that \textit{at a time} \(t\) the needle deflects (or points) to the left. This is a timeless truth. If at the time \(t\) the needle deflects to the left, then it always has been and always will be true that at the time \(t\) the needle deflects to the left.

Note that an apparatus pointer is not a macroscopic object according to the above definition. In general there is nothing that allows one to predict which way the needle will deflect (given that it will deflect). Only \textit{before} and \textit{after} the deflection event does the needle behave as
a macroscopic object. Is not such a definition self-defeating? It would be so if it were designed
to explain why the needle deflects left or right (rather than both left and right). But such an
explanation is neither required nor possible. If past events allow us to infer a superposition of
the form $\alpha|\text{left}\rangle \otimes |a\rangle + \beta|\text{right}\rangle \otimes |b\rangle$, they allow us to infer the following: if there is a matter
of fact about the direction in which the needle deflects, it warrants the inference ‘left’ with
probability $|\alpha|^2$, and it warrants the inference ‘right’ with probability $|\beta|^2$. Nothing allows us
to predict the existence of such a matter of fact. The deflection event is a causal primary,
notwithstanding that it happens with a measurable probability, and that by a suitable choice
of apparatus this probability can be made reasonably large.

As I have stressed elsewhere (Mohrhoff, 1999), what is true of particles in double-slit
experiments is equally true of cats in double-door experiments. Except for the myriads
of matters of fact about the door taken by the cat, ‘the door taken by the cat’ is objectively
undefined. This seems to entail a vicious regress. We infer the positions of particles from the
positions of the detectors that click. But the positions of detectors are extrinsic, too. They are
what they are because of the matters of fact from which one can (in principle) infer what they
are. Thus there are detector detectors from which the positions of particle detectors are inferred,
and then there are detectors from which the positions of detector detectors are inferred, and
so on ad infinitum. However, as we regress from particle detectors to detector detectors and
so on, we sooner or later (sooner rather than later) encounter a macroscopic detector whose
position is not manifestly fuzzy. There the buck stops. The positions of things are defined in
terms of the not manifestly fuzzy positions of macroscopic objects.

It is therefore consistent to think of the deflection of the pointer needle as one of those
uncaused actual events on which the (contingent) properties of things depend. Prima facie we
have another vicious regress: Like all contingent properties, the initial and final positions of the
needle are what they are because of what happens or is the case in the rest of the world. They
thus presupposes other ‘deflection events,’ which presuppose yet other ‘deflection events,’ and
so on ad infinitum. But since before and after its deflection the needle behaves as a macroscopic
object, its initial and final positions are quantitatively defined independently of what happens
elsewhere. They are positions of the kind that are used to define positions. Hence the deflection
event – the transition from the initial to the final position – is also independent of what happens
elsewhere.

8. Language and the Indefinite

My chief conclusion in this paper is that (ER1) and (ER2) are both false. The sufficient
and necessary condition for the existence of an element of reality $A = a$ is the existence of an
actual state of affairs, or the occurrence of an actual event, from which $A = a$ can be inferred.
The contingent properties of all quantum systems – and in clear this means the positions of
all material objects and whatever other properties can be inferred from them – are extrinsic.
They are defined in terms of the goings-on in the ‘rest of the world.’ The reason why this does
not send us chasing the ultimate property-defining facts in neverending circles, is the existence
of a special class of objects the positions of which are not manifestly indefinite. Everything
a macroscopic object does (that is, every matter of fact about its present properties) follows
via the pertinent classical laws from what it did (that is, from matters of fact about its past
properties). This makes it possible to ignore the fact that the properties of a macroscopic object, like all contingent properties, ‘dangle’ from external events and/or states of affairs. Instead of having to conceive of the successive states of a macroscopic object as a bundle of statistically correlated inferences warranted by a multitude of causal primaries external to the object, we are free to think of the object’s successive states as an evolving collection of intrinsic properties fastened only to each other, by causal links.

The familiar macroworld with its causal links and deterministic processes is something we project onto the fundamental statistical correlations and their uncaused correlata. This projection works where the correlations are not manifestly probabilistic (that is, where the statistical correlations evince no statistical variations). Diachronic correlations that are not manifestly probabilistic can be passed off as causal links. We can impose on them our agent-causality with some measure of consistency, even though this results in the application of a wrong criterion: temporal precedence takes the place of causal independence as the criterion which distinguishes a cause from its effect.

Quantum mechanics presupposes the macroworld: it assigns probabilities to conditionals that refer to events or states of affairs either in the actual macroworld or in a possible macroworld. This is the reason why Bohr (1934, 1958) insisted not only on the necessity of describing quantum phenomena in terms of the experimental arrangements in which they are displayed, but also on the necessity of employing classical language in describing these experimental arrangements. Classical language is the language of causal processes, of definite states that evolve deterministically, of definite objects and of definite events – in short, the language of the macroworld. Thus in one sense the microworld is fundamental (macroscopic objects are made of particles and atoms), and in another sense the macroworld is fundamental (the contingent properties of particles and atoms are defined in terms of the goings-on in the macroworld). The mutual dependence of the quantum and classical ‘domains’ has often been remarked upon (e.g., Landau and Lifshitz, 1977), but I’m not sure it has been adequately appreciated.

It seems to me that what is ultimately responsible for this mutual dependence is the conflict between a real, objective indefiniteness and the intrinsic definiteness of language. Language is inherently ‘classical.’ Discourse is of things – the discrete carriers of significance that appear as the subjects of predicative sentences. Things fall into mutually disjoint classes according to the properties they possess or lack. For any two different classes \( C_1 \) and \( C_2 \) there exists a property \( p \) such that ‘\( x \) has \( p \)’ is true of all members of \( C_1 \) and ‘\( x \) lacks \( p \)’ is true of all members of \( C_2 \). This seems to warrant the following Principle of Completeness (Wolterstorff, 1980): for every thing \( x \) and every property \( p \), \( x \) either has \( p \) or lacks \( p \). Reality, however, doesn’t play along with this linguistic requirement. Sometimes ‘\( x \) has \( p \)’ is neither true nor false but meaningless. There are situations in which nothing in the real world corresponds to the linguistic (or conceptual) distinction between ‘\( x \) has \( p \)’ and ‘\( x \) lacks \( p \)’. In such situations it is nevertheless meaningful to consider what would have happened if one had found out whether \( x \) has \( p \) or lacks \( p \), and to assign objective probabilities to the alternatives ‘\( x \) has \( p \)’ and ‘\( x \) lacks \( p \)’.

Given the intrinsic definiteness of language, the natural way to express an objective indefiniteness is to use counterfactuals. One then has one counterfactual for each alternative (‘if \( Q \) were measured, the result would be \( q_k \)’), and at least one of them comes with a nontrivial objective probability (that is, an objective probability other than 0 or 1). The linguistic
requirement of definiteness is met by the use of counterfactuals the respective consequents of which conform to the Principle of Completeness: each consequent explicitly affirms the truth of one alternative and implicitly denies the truth of the other alternatives. The objective indefiniteness finds expression in the fact that the counterfactuals are assigned nontrivial objective probabilities rather than truth values.

Objective indefiniteness thus leads to the use of counterfactuals with nontrivial objective probabilities, and nontrivial objective probabilities, as we have seen, entail that the properties affirmed by the counterfactuals’ consequents are extrinsic: they are defined in terms of the goings-on in the macroworld, notwithstanding that the objects of the macroworld are made up – or shall we say, manifested by means – of nonmacroscopic objects. This mutual dependence of the two ‘domains’ would amount to a vicious circle if the properties of the macroworld were in their turn defined in terms of the microworld. But this is not the case.

Since the contingent properties of things are defined in terms of events or states of affairs in the macroworld, quantum mechanics presupposes the macroworld. In particular, it presupposes such matters of fact as ‘the needle deflects to the left’ or ‘the needle is pointing left.’ By itself this does not guarantee that quantum mechanics is consistent with the existence of the macroworld - quantum mechanics (or the interpretation of quantum mechanics put forward in this paper) could lack self-consistency. But self-consistency only requires that the needle’s position too is fuzzy, and that it ‘dangles ontologically’ from the goings-on in the rest of the world. Quantum mechanics permits it to ‘dangle’ from them in such a way that, before and after the deflection, it is not manifestly fuzzy. If the needle’s position is not manifestly fuzzy, the needle behaves as a macroscopic object, and we can consistently conceive of its successive positions as ‘dangling causally’ from each other – except for one gap in the causal chain, the deflection event. But being a (probabilistic) transition between states embedded in the causal nexus of the macroworld, this too forms part of the macroworld.

Quantum mechanics not only presupposes and admits of the existence of macroscopic objects, it also entails it. The existence of an unpredictable matter of fact about the position of O entails the existence of detectors with ‘sharper’ positions; the existence of an unpredictable matter of fact about the position of one of those detectors entails the existence of detectors with yet ‘sharper’ positions; and so on. It stands to reason that one sooner or later runs out of detectors with ‘sharper’ positions. There are ‘ultimate’ detectors the positions of which are not manifestly fuzzy, and which therefore are macroscopic.
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