The Pondicherry interpretation of quantum mechanics

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This article presents a novel interpretation of quantum mechanics. It extends the meaning of “measurement” to include all property-indicating facts. Intrinsically space is undifferentiated: there are no points on which a world of locally instantiated physical properties could be built. Instead, reality is built on facts, in the sense that the properties of things are extrinsic, or supervenient on property-indicating facts. The actual extent to which the world is spatially and temporally differentiated (that is, the extent to which spatiotemporal relations and distinctions are warranted by the facts) is necessarily limited. Notwithstanding that the state vector does nothing but assign probabilities, quantum mechanics affords a complete understanding of the actual world. If there is anything that is incomplete, it is the actual world, but its incompleteness exists only in relation to a conceptual framework that is more detailed than the actual world. Two deep-seated misconceptions are responsible for the interpretational difficulties associated with quantum mechanics: the notion that the spatial and temporal aspects of the world are adequately represented by sets with the cardinality of the real numbers, and the notion of an instantaneous state that evolves in time. The latter is an unwarranted (in fact, incoherent) projection of our apparent “motion in time” into the world of physics. Equally unwarranted, at bottom, is the use of causal concepts. There nevertheless exists a “classical” domain in which language suggestive of nomological necessity may be used. Quantum mechanics not only is strictly consistent with the existence of this domain but also presupposes it in several ways.
I. INTRODUCTION

Following Mermin’s recent example,¹ I propose to add another specimen to the quantum cabinet of curious interpretations. Mermin chose to call his specimen the Ithaca interpretation of quantum mechanics (IIQM). By the same naming scheme, what is presented in this article is the Pondicherry interpretation of quantum mechanics (PIQM).

Mermin tries to remove the mystery from quantum mechanics in just ten words: “Correlations 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. They belong to a larger reality which includes consciousness. According to the IIQM, the measurement problem arises in this larger reality, and it arises only when consciousness gets into the story. Being a puzzle about consciousness, it is not a proper subject for a physical theory.

I fully agree with Mermin that “conscious perception... should be viewed as a mystery about us and should not be confused with the problem of understanding quantum mechanics.” However, as I see it, the problem of understanding quantum mechanics either is the measurement problem or concerns the presuppositions that give rise to the measurement problem. It seems to me that in declaring the measurement problem to be a puzzle about consciousness, Mermin does precisely what he warns us against: he confuses the problem of consciousness with the problem of understanding quantum mechanics. The measurement problem ought to be solved, or shown to be a pseudoproblem, without dragging in conscious observers.

Quantum mechanics is, if nothing else, a tool for calculating probabilities. Mermin rightly insists that these probabilities are objective, in the sense that they have nothing to do with ignorance – there is nothing for us to be ignorant of. I share his belief that all the mysteries of quantum mechanics can be reduced to the single puzzle posed by the existence of objective probabilities. What I remain skeptical about is his belief that one can nevertheless achieve a better understanding of quantum mechanics without squarely addressing this puzzle. To my mind, the problem of understanding quantum mechanics is as inseparable from the question of how statistical concepts like “probability” and “correlation” can have “meaningful application to individual systems,” as it is from the measurement problem.

The article is organized as follows. Section II shows that objective probabilities can be assigned only to counterfactuals. Objective probability distributions are distributions over the results of measurements that could have been, but were not, performed. Further it is shown that probabilities are objective if and only if they are calculated on the basis of all relevant facts, including those that are still in the future. This result is reinforced in Sec. III, wherein it is argued that our apparent position and motion in time are as extraneous to physics as are our location and motion in space. Whatever is based on the intuitive notion of an advancing now (for instance, the distinction between the past and the future) has nothing to do with physics. Objective probabilities therefore must be time-symmetric. By the same token, backward-in-time causation must be as possible as forward-in-time causation. If the properties of material objects could be thought of as intrinsic, it would nevertheless be possible to interpret the physics without reference to backward causation. The objectivity of quantum-mechanical probabilities, however, entails that the contingent properties of material objects are extrinsic rather than intrinsic, as is shown in Sec. IV. This means that they are defined in terms of what happens or
is the case in the rest of the world. Further it is shown in this section that, as a consequence, the multiplicity and the distinctions inherent in our mathematical concept of space cannot be intrinsic features of physical space. The notion that the spatiality of the world is adequately represented by a transfinite set of triplets of real numbers, is the principal fallacy preventing us from understanding how probability can be an objective feature of the world.

Section V addresses the widespread misconception that it is the business of quantum mechanics to account for the existence of facts. Quantum mechanics always presupposes, and never allows us to infer, the existence of facts. The state vector serves to assign probabilities to possibilities; it does not warrant inferences to actualities. Nor can it be thought of as an evolving collection of potentialities, for the time dependence of the state vector is a dependence on a stipulated time and not the time dependence of something that evolves in time. The very notion of an instantaneous state that evolves in time is an unwarranted (in fact, incoherent) importation from our successive experience into the world of physics, as is shown in Sec. VI. Where the observed system is concerned, not only isn’t there any actual state of affairs that obtains in the intermediate time between successive measurements, but also there isn’t any intermediate time. The reason this is so is that times, like positions, are extrinsic: The actually existing times are the factually warranted times at which properties are possessed.

Section VII offers answers to a series of questions, posed by Mermin, concerning the role of measurements in quantum theory. The PIQM extends the meaning of “measurement” to include all property-indicating facts. These are external to the theory in the sense that the meanings of such locutions as “actual event” and “(matter of) fact” cannot be defined in purely physical terms. This should not come as a surprise. The factuality of a fact is an ontologically concept as primitive as the spatiality of space or the temporality of time (or, for that matter, the subjectivity of consciousness). Section VIII explains why quantum physics, but not classical physics, confronts us with this truism. While in classical physics actuality attaches itself to a nomologically possible world trivially through the initial conditions, in quantum physics it “pops up” unpredictably and inexplicably with every property-defining fact. Section IX addresses the intriguing question of when a moving object moves. It is shown that the temporal referent of motion is a set of factually warranted moments that is not dense in time.

In Sec. X macroscopic objects are rigorously defined – as rigorously as is possible in view of the objective indefiniteness that is revealed by the existence of objective probabilities. Quantum mechanics not only is consistent with but also presupposes the existence of a classical domain. It is quantitatively consistent with quantum mechanics to think of the positions of macroscopic objects as forming a self-contained system of intrinsic properties that “dangle” causally from each other rather than ontologically from position-indicating facts. This is shown without positing ad hoc limits to the validity of quantum mechanics, and without compromising on the extrinsic nature of all contingent properties. Section XI shows that, although no object ever possesses a sharp position, the “fuzziness” of the position of a macroscopic object exists only in relation to an imaginary background that is more differentiated spatially than is the actual world. That fuzziness therefore exists solely in our minds. This is what gives us the right to treat the positions of macroscopic objects as intrinsic, and to define all positions in terms
of the positions of macroscopic objects. Considering that locations are not intrinsic to space (Sec. IV), this is also the only way in which positions can be defined.

In Sec. XII two points are made. First, although at bottom causal concepts are nothing but anthropocentric projections deriving from our self-perception as agents, they work in the classical domain where the correlations between property-defining facts evince no statistical variations. (They had better work somewhere, for without a modicum of causality it wouldn’t be possible to state the property-defining facts.) Second, quantum mechanics is inconsistent with local realism and the separability that this entails. There are no points on which a world of locally instantiated physical properties can be built. The world is built on facts, and its spatiotemporal properties are supervenient on the facts. To understand how EPR correlations are possible, one needs to understand that, in and of itself, physical space is undifferentiated. At a fundamental level, “here” and “there” are the same place. If EPR correlations require a medium, this identity is the medium.

Section XIII concludes by contrasting the PIQM with the Copenhagen interpretation of quantum mechanics (CIQM). The CIQM stands accused of applying a double standard, treating measurements as physical processes governed by quantum mechanics, and again as constituents of a classical domain existing in an anterior logical relationship to quantum mechanics. By extending the meaning of “measurement” to include all property-indicating facts, the PIQM eliminates the double standard. The property-defining events are not governed by quantum mechanics; they are amenable to classical description, and this not merely “for all practical purposes.” A trait commonly attributed to the CIQM is an epistemic construal of the state vector: the latter represents our knowledge of the factual situation rather than the factual situation itself. The CIQM’s claim to completeness is then understood as an agnosticism concerning the latter: quantum mechanics is complete in the sense that it enables us to say all that can be said with the language and the concepts at our disposal. According to the PIQM, quantum mechanics is complete in the sense that it enables us to say all that needs to be said in order to understand the actual world. If there is anything that is incomplete, it is the actual world. But its incompleteness exists only in relation to a conceptual framework that is more detailed than the actual world.

A glossary of technical terms is provided as an appendix.

II. CORRELATIONS WITHOUT CORRELATA?

The case for the (physical) nonreality of the correlata is this: If one assumes that the correlations are real, the correlata cannot be real. If a composite system consisting of two spin-1/2 particles is (according to the usual phraseology) “in the singlet state,” no values can be assigned to the spin components of the individual particles. The existence of correlations, however, logically entails the existence of correlata. One cannot ascribe physical reality to the correlations and deny it to the correlata. If there is nothing that is correlated, there are no correlations either. This reduces to absurdity the assumption that the correlations (qua correlations between objective probability distributions) are physically real. If it cannot be the case that correlations and correlata are both physically real, then neither correlations nor correlata are physically real.
When both the correlations and the correlata are real in the literal (that is, statistical) sense of “correlations” and “correlata,” the correlata are actually possessed properties, and the correlations are correlations between statistical distributions over such properties. Statistical distributions are probability distributions only in the subjective sense of “probability”; to assign probabilities to the possible results of actually performed measurements is to ignore the actual results. Objective probabilities cannot be assigned to actually possessed properties or to actually obtained measurement results. What sort of thing, then, is capable of being assigned an objective probability? What are objective probabilities distributed over? And what exactly are correlations that are not correlations between statistical distributions? The obvious answer to the first question is: a counterfactual. According to the PIQM, this is also the only correct answer. Nothing but a contrary-to-fact conditional can be assigned an objective probability. Objective probabilities are distributed over counterfactuals. Correlations between objective probability distributions are correlations between probability distributions 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.

This, then, is how we should understand the conclusion that neither the correlations nor the correlata are physically real: The correlata are properties that are not actually possessed, and the correlations are joint distributions over such properties. These distributions assign probabilities to counterfactuals (that is, to conditional statements that tell us nothing about what actually happens or is the case).

It is tempting to attribute the truth of objective probability assignments to an underlying actual state of affairs. It is equally tempting to assume that this actual state of affairs is somehow represented by the state vector. On this view, the singlet state \( |0\rangle \propto |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \) not only serves to assign probabilities but also represents an actual state of affairs that accounts for the probabilities. However, if there were such an actual state of affairs, it would not be described by \( |0\rangle \), for the singlet state does not describe anything; all it does is assign probabilities. The idea that a tool for assigning probabilities to possibilities describes an actual state of affairs is a category mistake. Moreover, if there were an underlying state of affairs, we would have to ask when and for how long it obtains, and it is well known that to this question there is no covariant answer.\(^2\) Finally, and most importantly, if there is a matter of fact about the value taken by a component of either of the two spins at any time after the “preparation” of the singlet state, the probabilities assigned by \( |0\rangle \) are not objective, and the objective probabilities associated with the spin components are not given by \( |0\rangle \).\(^3\)

The reason this is so is that 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 in general are 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. (By “Born probabilities” I mean the probabilities associated with the standard formulation of standard quantum mechanics.) Born probabilities are objective only if there are no relevant future matters of fact.
ABL probabilities, on the other hand, also take into account the relevant future matters of fact. Named after Aharonov, Bergmann, and Lebowitz,\textsuperscript{4} ABL probabilities are calculated using a nonstandard formulation of standard quantum theory known as time-symmetrized quantum theory.\textsuperscript{5-7} This time-symmetric formulation takes due account of the fact that the maximally specified state of a system contains information based not only on initial but also on final measurements. (If a measurement of the $x$ component of the spin of an electron, performed at $t_i$, yields $\uparrow_x$, and a measurement of the $y$ component of the spin of the same electron, performed at $t_f > t_i$, yields $\uparrow_y$, then a measurement of the $x$ component would with certainty have yielded $\uparrow_x$ if it had been performed at an intermediate time $t_m$, and a measurement of the $y$ component would with certainty have yielded $\uparrow_y$ if it had been performed at $t_m$.\textsuperscript{8})

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”). Both types of probability are assigned to possible results of possible measurements. If a possible measurement is actually performed, even the ABL probabilities are calculated on the basis of an incomplete set of facts; they take into account all revelant facts except the result of the actually performed measurement. ABL probabilities are based on a complete set of facts, and are therefore objective, only if none of the measurements to the possible results of which they are assigned is actually performed (that is, only if between the “preparation” or preselection and the “retroparation” or postselection no measurement is performed).

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 matters of fact, including events that haven’t yet happened and states of affairs that are yet to obtain.

### III. TIME AND CAUSALITY

If the objective probabilities associated with contrary-to-fact conditionals depend on events that haven’t yet happened or states of affairs that are yet to obtain, 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. If at $t_m$ the $y$ component of the electron’s spin is actually measured and the results at $t_i$ and $t_f$ are as specified above, nothing compels us to take the view that $\uparrow_y$ was found at $t_m$ because the same result was obtained at $t_f$. We can certainly stick to the idea that causes precede their effects, according to which $\uparrow_y$ was found at $t_f$ 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 causes and effects 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. Equally extraneous, therefore, is the distinction between causes and effects.\textsuperscript{9}

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 that 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 an exclusively future-directed *physical* causality is 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 a simplistic 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.

When I decide on how exactly I should kick a football in order to score a goal, I use my knowledge of the time-symmetric law that governs the ball’s trajectory.\(^{10}\) I think of the kick as the cause and of the goal scored as its effect. This asymmetric causal relation has nothing to do with the time-symmetric physics I exploit in order to produce the desired effect. It has everything to do with my self-perception as an agent and my successive experience of the world. My asymmetric agent causality 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 me. 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 we 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. However, if this is a consistent way of thinking – it is *not*\(^{11}\)– then it is equally consistent to think that a measurement “retropares” a state of affairs that evolves toward the past, as transpires from the work of Aharonov, Bergmann, and Lebowitz.\(^4\)

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 it before the choice is made.\textsuperscript{12}

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 of a system $S$ I mean a property that may or may not be possessed by $S$ 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. By an extrinsic property of $S$ I mean a property that is undefined, and hence nonattributable, unless its being possessed by $S$ can be inferred from what happens or is the case in the “rest of the world” $W - S$. A contingent property that is not extrinsic is intrinsic. A contingent property $p$ of $S$ is intrinsic if and only if the proposition $p = "S is p"$ is “of itself” (that is, unconditionally) either true or false at any time; neither the meaning of $p$ nor the possession by $p$ of a truth value depends on the goings-on in $W - S$.

Properties that can be retrocausally determined by the choice of an experimenter, cannot be intrinsic. If $p$ is an extrinsic property of $S$, the respective criteria for the truth and the falsity of $p$ are to be sought in $W - S$, 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 $S$, $p$ possesses a truth value (that is, it is either true or false) independently of what happens in $W - S$, so \textit{a fortiori} it possesses a truth value independently of what happens there after the time $t$ to which $p$ refers. There is then no fundamental 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 is the experiment of Englert, Scully, and Walther,\textsuperscript{13,14} which I discussed in a previous article.\textsuperscript{11} This experiment enables the experimenters to choose between (i) measuring the phase relation with which a given atom emerges coherently from two slits and (ii) determining the particular slit from which the atom emerges. They can exert this choice after the atom has emerged from the slit plate and even well 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 \textit{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 incompatible (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 events that haven’t yet happened or states of affairs that are yet to obtain. We now see more clearly why it should be so. Our distinction between the past, the present, and the future, as Mermin likewise observes, has nothing to do with physics. Physics “knows nothing of now,” so it cannot know anything of the difference between the past and the future. An objective physical probability therefore cannot depend on a selection of facts that is based on this difference.

IV. THE CONTINGENT REALITY OF SPATIAL DISTINCTIONS

The extrinsic nature of the contingent properties of physical systems is implied by the existence of objective probabilities. To see this, recall that objective probabilities are assigned to alternative properties none of which are actually possessed. 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 (other than 0 or 1) only if the proposition “The atom went through the first slit” is neither true nor false but meaningless. But this can be the case only if the atom’s whereabouts are extrinsic, for predications of intrinsic properties possess truth values at all times.

This result is a first significant step toward understanding probability as an objective feature of the physical world, rather than as a tactical device for coping with our ignorance. The existence of objective probabilities tells us that the contingent properties of things, in particular their positions, are extrinsic. And since “[t]here is nothing in quantum theory making it applicable to three atoms and inapplicable to $10^{23}$,” this must be as true of footballs and cats as it is of atoms and particles. The position of a material object $O$ is defined in terms of what happens or is the case in the rest of the world. It “dangles” from actual events or states of affairs. $O$’s position is what matters of fact imply concerning $O$’s position.

The extrinsic nature of the contingent properties of physical systems has important implications. One of them is the contingent nature of spatial distinctions, as I proceed to show. Let $R$ be a region of space, and let $a$ be the proposition “$O$ is inside $R$.” It is generally considered sufficient for the truth of $a$ that the support of the retarded (“prepared”) wave function associated with $O$’s center of mass is contained in $R$. Considering the time-symmetry of the underlying physics, it ought to be equally sufficient for the truth of $a$ that the support of the corresponding advanced (“retropared”) wave function is inside $R$. According to the PIQM, neither of these conditions is sufficient for the truth of $a$. The necessary and sufficient condition for the presence of $O$ in $R$ at a time $t$ is the existence of a fact that indicates $O$’s presence in $R$ at $t$. If there isn’t any such fact (at $t$ or at any time before or after $t$), and if there also isn’t any event or state of affairs that indicates $O$’s absence from $R$ at $t$, then $a$ is meaningless, and $O$’s position with respect to $R$ is objectively undefined – where $O$ at the time $t$ is concerned, nothing in the world corresponds to the distinction between “inside $R$” and “outside $R$."

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The conceptual distinctions we make between mutually disjoint regions of space thus may or may not be real for a given object at a given time. The distinction between $R$ and its complement $R'$ is real for $O$ if there is a matter of fact from which $O$'s position with respect to $R$ (inside $R$ or outside $R$) can be inferred; otherwise it is not. It follows that the multiplicity inherent in our mathematical concept of space (a transfinite set of triplets of real numbers) is not an intrinsic feature of the real thing, physical space. If the distinctions inherent in that concept were physically real per se (that is, if they were intrinsic to space), they would be real for every object that exists in space. In particular, the two slits in a double-slit experiment would be distinct for whatever passes through them, and so the individual atom could not pass through the (set-theoretic) union of the slits without passing through a particular slit and without being divided into distinct parts by its passage through the slits. But this is what it does when interference fringes are observed. The existence of the fringes proves that the slits are not distinct for the atoms, and that therefore spatial distinctions cannot be real per se.

According to the PIQM, the notion that the multiplicity and the distinctions inherent in our mathematical concept of space are intrinsic to physical space (and that, consequently, the individual points of space or space-time can be treated as the carriers of physical qualities) is a delusion. This notion perhaps more than any other prevents us from understanding how probability can be an objective feature of the physical world. It is as inconsistent with quantum mechanics as the notion of absolute simultaneity is with special relativity.

V. CAN QUANTUM MECHANICS ACCOUNT FOR FACTS?
CAN ANYTHING ELSE?

It is widely believed that it is the business of quantum mechanics to account for the occurrence/existence of actual events or states of affairs. From the point of view of the PIQM, this too is a misconception. Quantum mechanics assigns probabilities. These are determined by facts (the “preparation” and/or the “retroparation”), and they are assigned to possible facts. And the probability assignments are correct only if one assumes (in the case of objective probabilities, counterfactually) that one of a specified set of mutually exclusive possibilities is a fact.

To illustrate this point, consider two perfect detectors $D_1$ and $D_2$ having the respective (disjoint) sensitive regions $R_1$ and $R_2$. If the support of the wave function associated with the (center-of-mass) position of $O$ 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 $D_2$. Yet if the wave function vanishes outside $R_1 \cup R_2$, it is certain that either of the detectors will 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?

The answer is, nothing. That two perfect detectors with disjoint sensitive regions constitute one perfect detector for the union of their sensitive regions is part 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 respective probabilities for either detector
to click add up to 1. Hence the question of what causes $D$ to click does not arise. If real detectors would behave like perfect detectors, it would be proper to inquire why they do so. But real detectors do not behave like perfect detectors. If the quantum-mechanical probability associated with finding $O$ in $R_1$ is $1/2$, a perfect detector with sensitive region $R_1$ clicks in 50% of all runs of the experiment, while a real detector $D_1^r$ with the same sensitive region clicks in 50% of all runs of the experiment \textit{in which either detector clicks}. Hence the apparent commonplace that no (real) detector is perfect is not as trivial as it seems. Between a real detector and a perfect detector there exists not merely a quantitative difference that might one day be overcome; there exists a qualitative gap that no technological advance can bridge. The quantum-mechanical probability associated with finding $O$ in $R_i$, $i = 1$ or 2, is \textit{conditional on} the existence of a matter of fact about the region containing $O$. Perfect detectors are so defined as to eliminate this conditionality; the definition stipulates that the condition is met. Hence what is a conditional probability for a real detector is an absolute probability for a perfect detector\textsuperscript{17}.

Quantum mechanics thus tells us either of two things: (i) \textit{If} there is going to be a matter of fact about the alternative taken (from a specific range of alternatives) \textit{then} such and such are the subjective probabilities with which that matter of fact will indicate this or that alternative. (ii) \textit{If} there were a matter of fact about the alternative taken (from a specific range of alternatives) \textit{then} such and such are the objective probabilities with which that matter of fact would indicate this or that alternative. \textit{Quantum mechanics always presupposes, and therefore never allows us to infer, the existence of a fact that indicates the alternative taken}. If the quantum-mechanical probability associated with finding $O$ in $R_1$, quantum mechanics accounts for the fact that whenever a detector clicks, it is $D_1^r$ that clicks. Quantum mechanics does \textit{not} account for the fact that a detector clicks. And if quantum mechanics is as fundamental and as complete as I believe it is, there also isn’t anything going on “behind the back” of quantum mechanics that accounts for the clicking.

Redhead\textsuperscript{18} has formulated the following “sufficiency” condition: “If we can predict with certainty, or at any rate with 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.” This condition is \textit{not} sufficient because quantum mechanics never tells us what will be the case, unconditionally. It only tells us what would be the case if some condition or other were met. Even if the Born probability of a particular event or state of affairs $F$ is 1, we are not entitled to infer that $F$ happens or obtains. Even the predictions of the standard formalism are \textit{conditionals}. 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, a matter of fact about the value of an observable must exist, one of a specified set of alternative property-defining events or states of affairs must happen or obtain\textsuperscript{19}.

The failure to recognize and acknowledge the conditionality of quantum-mechanical predictions has spawned an entire industry devoted to solving the so-called “measurement problem.” On the erroneous view that the quantum “state” represents an actual state of affairs, one is led
to believe that there is a process of measurement which includes a “premeasurement” stage during which the apparatus+system “state”

$$|\Psi_1\rangle = a|N\rangle \otimes |a\rangle + b|N\rangle \otimes |b\rangle,$$

where $|N\rangle$ represents the neutral state of the apparatus, evolves into a state of the form

$$|\Psi_2\rangle = a|A\rangle \otimes |a\rangle + b|B\rangle \otimes |b\rangle.$$

The measurement problem is the spurious problem of understanding the transition from the “and” of Eq. (1) or (2) to “or”:

$$|A\rangle \otimes |a\rangle \quad \text{or} \quad |B\rangle \otimes |b\rangle.$$

In truth, there is no such thing as a measurement process [that is, there is no actual state of affairs (1) that evolves into (2), there is no premeasurement stage, and there is no physical transition from (1) or (2) to (3)]. All that (1) tells us, is this: If there were a matter of fact from which the possession either of the property represented by $|a\rangle$ or of the property represented by $|b\rangle$ could be inferred, then that matter of fact would indicate the possession of $|a\rangle$ with probability $|a|^2$, and it would indicate the possession of $|b\rangle$ with probability $|b|^2$. And all that (2) tells us, is this: If there were two matters of fact, one from which the possession by the apparatus of either $|A\rangle$ or $|B\rangle$ could be inferred, and one from which the possession by the system of either $|a\rangle$ or $|b\rangle$ could be inferred, then the two matters of fact together would indicate the possession of both $|A\rangle$ and $|a\rangle$ with probability $|a|^2$, they would indicate the possession of both $|B\rangle$ and $|b\rangle$ with probability $|b|^2$, and they would indicate the possession of both $|A\rangle$ and $|b\rangle$ (or of both $|B\rangle$ and $|a\rangle$) with probability 0. It is self-evident that if there is a matter of fact from which either $|a\rangle$ or $|b\rangle$ can be inferred, and if this matter of fact is taken into account, the correct basis for further conditional inferences is either $|a\rangle$ or $|b\rangle$, depending on which of the two can be inferred. This obvious truism is the entire content of the projection postulate. There is no corresponding dynamical change of an actual physical state.

From the point of view of the PIQM, all attempts to coax “classicality” (actual events, matters of fact) out of quantum mechanics (via environment-induced superselection, decoherent histories, quantum state diffusion, spontaneous collapse, to mention but some) are misconceived and futile. Quantum mechanics takes us from facts to probabilities of possible facts; it cannot take us from possibilities to 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. The step from probability 1 (often wrongly paraphrased as “certainty”) to a factually warranted inference takes us from a set of possible worlds (the framework in which counterfactuals are often discussed) to the real world. Quantum mechanics only takes us from the real world to the realm of possible worlds, and there it leaves us. But not only quantum mechanics fails to return us to reality. Out of that imaginary realm no logical road leads back to the real world. Measurements that are merely possible do not have actual results.
Left to its own resources, quantum mechanics appears to lead us into a Borgesian “garden of forking paths.” Every time a matter of fact about the state of a system $S$ comes into existence such as cannot be predicted with certainty on the basis of previous matters of fact, another object gets entangled with $S$, and the more objects are entangled with $S$, the more rapidly the entanglement spreads. The “many-worlds extravaganza” (to once again quote Mermin) gives shape to this fiction. What it overlooks is that the fiction is set in the realm of possible worlds. The purpose that the state vector serves in the actual world is to assign (Born) probabilities to conditional statements: if there is a matter of fact about the value of some observable, then such and such are the probabilities with which that matter of fact indicates the various possible values. But if there is any such matter of fact, those probabilities are based on an incomplete set of facts and are therefore subjective. All that ever gets objectively entangled is counterfactuals.

VI. DO MEASUREMENTS ACTUALIZE POTENTIALITIES?
THE MYTH OF AN EVOLVING INSTANTANEOUS STATE

The measurement problem is sometimes referred to as “the problem of actualizing potentialities.” The notion that quantum mechanics has something to do with the actualization of potentialities, which goes back to Heisenberg, is misleading inasmuch as it suggests that the transition from potential to actual is a process of some kind (i.e., that it takes place in time and within a single world). If it is at all appropriate to think of a measurement in terms of a transition, this is not a transition in time (that is, not a physical transition from an earlier to a later state of affairs) but a “transition” from one possible world, in which a specified measurement is not performed at a stipulated time, to another possible world, in which the same measurement is performed at the stipulated time, as this section will show.

The idea that the state vector represents potentialities rather than an actual state of affairs is an improvement, but the idea that measurements actualize potentialities misses the point that the time dependence of the state vector is a dependence on a stipulated time, not the dependence of something that evolves in time – not even if this is a collection of propensities or a network of potentialities. Probabilities associated with events that may happen or states of affairs that may obtain, do not exist or evolve in time, anymore than the probability of being found inside a region $R$ is located inside $R$.

What is it that tricks us so persistently into thinking that there must be an instantaneous state that evolves in time? If there is such a state, then of course the quantum formalism leaves us no choice but to identify it with the time-dependent state vector or density operator of the Schrödinger picture. But as soon as we do this, we are confronted with the pseudoproblem of why the state vector sometimes appears to unpredictably “collapse,” and with the equally spurious problem of whether the “collapse” of the state vector is a real physical occurrence or something that happens only “for all practical purposes.” These problems are not solved by construing state-vector “collapses” as transitions from possibilities to facts. They are “solved” by recognizing them as pseudoproblems, created by the fallacious notion of an instantaneous state that evolves in time, and the construal of the state vector as such a state.
To my mind, the root fallacy is the idea that the experiential now has anything to do with physics. The proper view of physical reality is not only what Nagel has called “the view from nowhere” (physical reality is independent of the particular spatial location whence I survey the world); it is also what Price has called “the view from nowhen.” Physical reality is independent of the particular time (the present) whence I survey the spatiotemporal whole. As was shown in Sec. III, this entails that there is no place in physics for the qualitative difference that exists in conscious experience between the past, the present, and the future. It further entails that in this spatiotemporal whole there is no place for a “moving” now, a “flowing” time, or an “advancing” present. In fact, the Whiteheadian concept of an advancing present is incoherent, for the following reasons: it depicts space-time as a simultaneous whole persisting in a time that is extraneous to space-time, and it depicts the present as advancing through this persisting simultaneous whole in that extraneous time. In reality there is only one time, the fourth dimension of space-time. There is not another time in which the present “advances” through space-time as if space-time were a persisting simultaneous whole. Nor is it consistent to think of space-time as a simultaneous whole.

One may select any one-parameter family of spacelike hypersurfaces and call the parameter “time” and the hypersurfaces “simultaneities.” As far as physics is concerned, this association of states with times is all there is to time. One cannot pick a specific time and attach to the corresponding simultaneity the unique reality of the experiential now, let alone picture the now as advancing from simultaneity to simultaneity as if the simultaneities that are past or future relative to “now” existed simultaneously with the now. (These conclusions are independent of the fact that we live in a relativistic world. In a world in which simultaneities are a matter of choice, it is just more obvious that the unique reality of the experiential now cannot be attributed to any individual simultaneity.)

If the concept of an advancing present is an unwarranted (in fact, incoherent) importation from our successive experience into the world of physics, then so is the concept of an advancing instantaneous state. This concept is part of a package of “folk” conceptions about time and causality that we must discard if we want to understand what quantum mechanics is trying to tell us. Here is how the “folk tale” goes: Since the future is not yet real, it cannot influence the present, so retrocausation is impossible. And since the past is no longer real, it can influence the present only by persisting through time (that is, by the persistence right up to the present of something that was real, however it may have changed in the meanwhile). Causal influences reach from the nonexistent past into the nonexistent future by being “carried through time” by the present. There is an evolving instantaneous state, and this not only represents presently possessed properties but also encapsulates everything in the past that is causally relevant to the future. This is how we come to conceive of “fields of force” that evolve in time (and therefore, in a relativistic world, evolve according to the principle of local action), and that “mediate” between the past and the future (and therefore, in a relativistic world, between local causes and their distant effects). It is also how we come to believe that the state vector plays a similar causally mediating role. It is high time that we outgrow these unwarranted (in fact, incoherent) beliefs.
If we find that at times $t_1$ and $t_2$ the system has the properties represented by $|\psi_1(t_1)\rangle$ and $|\psi_2(t_2)\rangle$, respectively, we learn nothing about the properties possessed by it at other times. We learn nothing about an evolving actual state of affairs that obtains in the meantime. If there isn’t any matter of fact about what $S$ is like in the meantime, then there isn’t anything that $S$ is like in the meantime. Hence where $S$ is concerned, there isn’t any actual state of affairs that obtains in the meantime. There is no need for filling the temporal gap between $t_1$ and $t_2$ with an evolving instantaneous state, nor are we justified in doing so.

It stands to reason that what is true of the multiplicity inherent in our mathematical concept of space, is also true of the multiplicity inherent in our mathematical concept of time: neither multiplicity is real *per se*. Neither is space a storehouse of preexistent positions, nor is time a storehouse of preexistent instants. The actually existing positions are not the positions of “the points of space” but the factually warranted positions of material objects. By the same token, the actually existing times are not “the moments of time” but the times of actual events or states of affairs or the factually warranted times at which properties are possessed. It follows that if there isn’t any intermediate time at which $S$ has a factually warranted property, or if (where $S$ is concerned) no actual state of affairs obtains at any intermediate time, then (where $S$ is concerned) there just isn’t any intermediate time. In particular, there isn’t any time at which one could attribute to $S$ a collection of propensities or a network of potentialities.

The transition from a superposition of the form $\sum_i a_i |a_i\rangle$ to one of the kets $|a_i\rangle$, therefore, cannot be a transition from a potential state of affairs that obtains “just before” the measurement to an actual state of affairs that obtains at the time of the measurement (and on to another potential state of affairs that obtains “just after” the measurement). Where the system is concerned, the times “just before” and “just after” the measurement do not exist. The difference between $\sum_i a_i |a_i\rangle$ and a particular ket $|a_i\rangle$ is not a difference in time and within the same world but a difference between possible worlds at the same time. In a world in which $\sum_i a_i |a_i\rangle$ is the correct basis for (prior) probability assignments to counterfactuals, the measurement of the observable whose eigenstates are the kets $|a_i\rangle$ is not performed at the stipulated time. In those worlds in which it is performed at the stipulated time, the property represented by one of the kets $|a_i\rangle$ is actually possessed at that time, and the corresponding ket is the correct (partial) inference basis for probability assignments to counterfactuals pertaining to earlier or later times.

Consider once more a system $S$ that is found to possess the properties represented by $|\psi_1(t_1)\rangle$ and $|\psi_2(t_2)\rangle$ at the respective times $t_1$ and $t_2$. If there isn’t any matter of fact about what $S$ is like in the meantime, we can say that $S$ has *changed* from an object that has the properties represented by $|\psi_1(t_1)\rangle$ into an object that has the properties represented by $|\psi_2(t_2)\rangle$ – but only in the sense that at $t_1$ the system has the former properties and at $t_2$ the system has the latter properties. There is no interpolating state of affairs that evolves from a state in which $S$ has the former properties into a state in which $S$ has the latter properties. The change *consists* in the fact that the properties of $S$ at $t_2$ differ from the properties of $S$ at $t_1$. Nothing can be said about the meantime, not because $S$ is propertyless in the meantime, but because, where $S$ is concerned, *there isn’t any meantime*. Reality is not built on a space and a time that are infinitely and intrinsically differentiated; reality is built on matters of fact,
and the actually existing positions and times are the factually warranted positions of material objects and the factually warranted times at which properties are possessed by such objects. “When” there is no factually warranted property, there is no factually warranted time, and “when” there is no factually warranted time, there is no time – at least where $S$ is concerned.

VII. THE MEANING OF “MEASUREMENT”

Mermin asks: (1) “Why should the scope of physics be restricted to the artificial contrivances we are forced to resort to in our efforts to probe the world?” (2) “Why should a fundamental theory have to take its meaning from a notion of ‘measurement’ external to the theory itself? Should not the meaning of ‘measurement’ emerge from the theory, rather than the other way round?” (3) “Should not physics be able to make statements about the unmeasured, unprepared world?” The answers to these questions are as follows.

(1) If by “measurement” we mean a manipulation that is intended to determine the value of a given observable or that leads to the acquisition of knowledge, the scope of physics is not restricted to measurements. What is relevant is the occurrence or existence of an event or state of affairs warranting the assertability of a statement of the form “$S$ has the property $p$ 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 $S$. Bohr insisted that quantum systems should not be thought of as possessing properties independently of experimental arrangements. By interpreting his sagacious insistence on the necessity of describing quantum phenomena in terms of experimental arrangements as restricting quantum mechanics “to be exclusively about piddling laboratory operations,” one does him an injustice. For “experimental arrangement” read: matters of fact about the properties possessed by the system at a given time. A “measurement result,” properly understood, does not have to be the outcome of a laboratory experiment. Any matter of fact that “is about” (has a bearing on) the properties of a physical system, qualifies as a measurement result.

(2) The (proper) notion of “measurement” is external to the theory in the sense that locutions such as “actual event,” “actual state of affairs,” “matter of fact” cannot be defined in quantum-mechanical terms. This view is not likely to be popular with theoretical 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 bits of “stuff” that have the insolence to be real by themselves rather than by courtesy of some equation. Small wonder if he resisted Bohr’s insight that not even the properties of things can be defined in purely mathematical terms. But that’s the way it is. The properties of things are objectively defined in terms of what actually happens or obtains, and the meaning of “what actually happens or obtains” is beyond the reach of quantum-mechanical definition. This point is important enough to be made in a section of its own – the next.

(3) Physics is able to make statements about the unmeasured world, but only in the terms of the measured world (that is, only in terms of counterfactuals) – perhaps with one exception. While in the first place quantum mechanics is about statistical correlations among facts, to a certain extent it seems to let us infer an underlying reality. Suppose that we perform a series of position measurements, and 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. If each time exactly two detectors click, and if no distinguishing properties are detected, the following is neither true nor false but meaningless: A particular click at one time and a particular click at another time indicate the presence of the same particle.

On closer examination we find that the “underlying” reality – in our examples a single entity \( O \) or a system of exactly two particles – “dangles” as much from the facts as do the positions that we attribute to its “constituents”. There is a determinate number of objects because every time the same number of detectors click, and if we take the possibility of pair creation/annihilation into account, there is a determinate number of objects only at the times at which they are detected. In other words, not only the properties of things but also the number of existing things supervenes on the facts. The true constituents of reality therefore are not things but facts.

**VIII. PHYSICAL THEORY AND THE FACTUALITY OF FACTS: A SECOND LOOK**

Quantum mechanics never predicts that a measurement will take place, nor does it predict the time at which one will take place, nor does it specify the conditions in which one will take place. The PIQM takes quantum mechanics to be complete in the sense that these things simply cannot be predicted or specified: Nothing necessitates the existence of a property-defining fact. 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 particular value rather than that. 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. Quantum physics 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 by which its inevitability has been hidden so long. To the best of my knowledge, Mermin is the first who has bitten the bullet, for by denying physical reality to the correlata, he in effect declares that, at least where physics is concerned, the existence of the correlata (that is, the existence of factually warranted properties or of property-defining facts) is fundamentally inexplicable.

Mermin thinks that there nevertheless must be something that accounts for the actuality of actual events and states of affairs, and, like several other quantum theorists, he believes that consciousness has something to do with it. As I see it, the idea that the factuality of facts needs to be accounted for has its roots in an inappropriate way of thinking about possibilities.
Here are the possibilities to which quantum mechanics assigns probabilities, so where is the source of the actuality that some of them are blessed with? The fallacy lies in the antecedent. Where is “here,” and what does “are” mean? We must not let the copula “are” fool us into thinking that possibilities enjoy an existence of their own. It would be unnecessary to point out such an obvious category mistake, were it not for the widespread habit of endowing the “state” vector with a reality of its own. If one thinks of a tool for assigning probabilities to possibilities as a state of affairs that evolves in time, one needs something that is “more actual” than this state of affairs – something capable of bestowing “a higher degree of actuality” – in order to explain why every successful measurement has exactly one result. If one needs something “more actual” than the state vector, then consciousness is an obvious candidate. But it seems to me more straightforward to acknowledge that there is only one kind of actuality, that possibilities are just possibilities, and that the factuality of facts is not something that needs to be accounted for, any more than we are required to give an answer to the question of why there is anything at all, rather than nothing.

A comparison with classical physics might help to make this point. In classical physics one has, on one side, a theoretical description or account of the world and, on the other side, the world. The latter possesses something that every theory, concept, or description lacks – it’s real. Yet nobody expects a classical theory to account for the realness of the world. Nobody expects a classical theory to define this peculiar “property” of the world. The very idea of theoretically defining or accounting for the realness of the real is inherently absurd. How could one explain why there is anything rather than nothing? How could any theory account for or define the factuality of facts? This is an ontological concept as primitive as the spatiality of space, the temporality of time, the subjectivity of consciousness, or the blueness of blue. (Actually it’s more primitive, for if there aren’t any facts, then nothing is here, now, conscious, or blue.) And this is true independently of whether or not the world is classical.

The essential difference between classical and quantum physics lies in their respective ways of relating theory, possible worlds, and the one actual world. Classical physics describes (nomologically) possible worlds, and it describes them as causally closed. The name of the game is to find the laws according to which any given set of initial conditions, if it were realized, would evolve deterministically. If a particular set of initial conditions is realized, so is the entire future evolving from it in accordance with the classical dynamical laws. If a particular set of initial conditions is not realized, neither is the future determined by these initial conditions. The determinism of classical physics ensures that a possible classical world is either actual en bloc or not actual at all. The relation between possible worlds and the actual world is therefore trivial: The actual world is just one of the possible worlds described by classical physics.

Quantum physics describes neither (nomologically) possible worlds nor the actual world. We do not have, on one side, theoretical descriptions of possible worlds and, on the other side, the actual world. What we have is, on one side, rules for assigning objective probabilities to counterfactuals and, on the other side, a totality of uncaused facts, on the basis of which objective probabilities are assigned to counterfactuals. (If future facts are ignored, those rules can also be used to assign subjective probabilities to the results of measurements that are yet to be made.) Thus in quantum physics facts and counterfactuals are inextricably entwined.
Quantum theory takes us from facts to probabilities of possibilities, and this has created the impression that it is incomplete. There ought to be something that takes us back to the facts. But this is an error. Actuality comes in statistically correlated but causally disconnected “bits and pieces” that just happen to be. Nothing can “take us to” a causal primary. At bottom the factuality of the facts is as ineffable as the reality that attaches itself to one of the possible worlds of classical physics, but now it looms large because it no longer enters through initial conditions (which, except in cosmology, are of no particular interest) but instead “pops up” unpredictably and inexplicably with every property-defining fact.

IX. WHEN DOES A MOVING OBJECT MOVE?

If property-defining facts are uncaused, we cannot say that they are created. Hence, strictly speaking, it wasn’t correct to say, as I did in Sec. III, that the experimenters can choose between creating a matter of fact about the slit taken by the atom and creating a matter of fact about the atom’s phase relation. All they can do is create conditions that permit the existence of either matter of fact, and optimize the likelihood of its existence by optimizing the efficiency of the corresponding apparatus. Measurements are not made; they are only made possible or likely. By the same token, particles do not trigger detectors (that is, they do not cause them to respond); at most they enable them to respond, with a likelihood that depends on both the “preparation” of the particles and the efficiency of the detectors. Conversely, detectors do not localize particles (that is, they do not cause them to be in a specific region of space); at most they enable them to be in a specific region of space, with a likelihood that again depends on both the “preparation” of the particles and the efficiency of the detectors. Thus causal terms are out of place not only where the interfactual relations are concerned, but also where the relations between the decisions of experimenters, the property-defining facts, and the properties of things are concerned.

Where the properties of things are concerned, even temporal language is inappropriate. Physical systems do not acquire properties when a property-defining event occurs. They do not change in response to a measurement. Nothing happens to $S$ at $t_2$ if $S$ is found to possess at $t_2$ the properties represented by $|\psi_2(t_2)\rangle$. The measurement warrants the system’s having these properties at $t_2$, and that’s all. Nothing justifies the idea that $S$ acquires these properties at $t_2$ or that its properties change at $t_2$. The only legitimate change that can be attributed to $S$ consists in the fact that its properties at $t_2$ differ from its properties at the preceding actual moment $t_1$, as we saw in Sec. VI. This change takes place neither at $t_1$ nor at $t_2$, nor does it take place in the (for $S$) nonexistent interval between $t_1$ and $t_2$.

So when does a quantum system change? In particular, when does it move (change its position)? This question is reminiscent of Zeno’s famous third paradox. Zeno’s argument goes like this: A flying arrow is in a particular location at every instant; at no instant does it change its location; therefore it is altogether at rest. Modern calculus enables us to resolve the paradox by treating motion as a local property – but only in a classical world. The “local” property is defined by a limiting process that involves vanishing intervals of space and time, and in the actual world such a limiting process has no physical meaning. Nature’s answer to Zeno has to be different. Zeno’s conclusion is right: If time were a “continuous” set of instants
(that is, if a finite time span contained an infinite set of moments at which the arrow has factually warranted positions), the arrow could not move, as the quantum effect named after Zeno\textsuperscript{61-63} demonstrates. What is wrong is the premise. Where the arrow is concerned, time is a discrete set of actual moments at which the arrow possesses factually warranted positions. The finite time span between any two consecutive such moments is nonexistent for the arrow. What allows the arrow to move is the gaps in the arrow’s “experience” of time – the gaps between moments that are real for the arrow. This doesn’t mean that the arrow moves during those gaps. To move is to be in different places at different times. The temporal referent of the arrow’s motion “between” two consecutive actual moments is not the (nonexistent) interval between these moments but the pair of moments itself. The temporal referent of the change that consists in the properties of \( S \) at \( t_2 \) being different from the properties of \( S \) at \( t_1 \) is the pair of moments \( \{ t_1, t_2 \} \). This is also the temporal referent of the acquisition, by \( S \), of the properties represented by \( |\psi_2(t_2)\rangle \).

**X. MACROSCOPIC OBJECTS**

While the Moon isn’t only there when somebody looks,\textsuperscript{64} it is there only because of the myriads of matters of fact about its whereabouts. Position-indicating matters of fact are constitutive of the Moon’s being there. 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. This means that 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 \textit{ad infinitum}. Again, the properties of things “dangle” ontologically from what happens or is the case in the rest of the world. Yet what happens or is the case there can only be described by describing material objects, and their properties too “dangle” from the goings-on in the rest of the world. This seems to send us chasing the ultimate property-defining facts in never-ending circles. Somewhere the buck must stop if the PIQM is to be a viable interpretation of quantum mechanics. In this section I show that the buck does stop, without positing ad hoc limits to the validity of quantum mechanics, and despite the fact that all contingent properties are extrinsic.

The existence of objective position probabilities tells us that the positions of things are objectively indefinite or “fuzzy.” This does not mean that \( O \) has a fuzzy position. It means something like this: one can always conceive of a sufficiently small region \( R \) of space such that the proposition “\( O \) is in \( R \) at \( t \)” not only lacks a truth value but also lacks a trivial probability (a probability of either 0 or 1). However, there are objects, which I will call “macroscopic,” the positions of which are not \textit{manifestly} indefinite.

Let me explain. A \textit{macroscopic object} \( M \) is an object that satisfies the following criterion: every factually warranted inference to the position of \( M \) at any given time \( t \) is predictable on the basis of factually warranted inferences to (i) the positions of \( M \) at earlier times and (ii) the positions of other objects at \( t \) or earlier times. (By saying that a factually warranted inference to the position of a macroscopic object is predictable, I do not mean that the existence of the position-indicating fact is predictable, but that the position indicated by the fact is
predictable.) To put it negatively, nothing ever indicates that $M$ has a position different from what is predictable on the basis of the pertinent classical laws and earlier position-defining facts. Thus we may say that the positions of macroscopic objects are not manifestly indefinite, in the sense that the indefiniteness in their positions is not evidenced by the existence of unpredictable facts. Every matter of fact about $M$’s present position follows via the pertinent classical laws from matters of fact concerning $M$’s past position and the past and present positions of other objects.

The notion that the unpredictability of a position-indicating fact reveals a positional indefiniteness, requires some care. The position of an object $O$ can be indefinite with respect to a region $R$ only if the proposition $a = “ O \text{ is in } R “$ has a nontrivial probability assigned to it. In this case there exist two possibilities: (i) If there is a matter of fact about the truth value of $a$, this is unpredictable, but its unpredictability does not reveal $O$’s positional indefiniteness with respect to $R$. If $a$ has a truth value, the probability associated with $a$ is subjective, so $O$’s position is not indefinite with respect to $R$. (ii) If there isn’t any matter of fact about the truth value of $a$, $O$’s position is indefinite with respect to $R$, but this positional indefiniteness is not revealed by any unpredictable matter of fact. What is revealed by the unpredictability of an actual position-indicating event $e$ is a counterfactual indefiniteness: the indefiniteness that would have obtained had $e$ not occurred (other things being equal).

Note that the definition of a “macroscopic object” does not stipulate that events indicating random departures from the classically predicted positions occur with zero probability. An object is entitled to the label “macroscopic” if no such event actually occurs. What matters is not whether such an event may occur (with whatever probability) but whether it ever does occur.

Now, an unpredictable matter of fact about the position of $O$ can exist only if there are detectors whose sensitive regions are small and localized enough to probe the space over which the position of $O$ is distributed. The existence of such a matter of fact entails the existence of detectors $D_i, i = 1, \ldots, n,$ with sufficiently “sharp” positions. (A detector – more precisely, an $O$-detector – is anything that is capable of warranting the presence of $O$ in a particular region of space.) The existence of an unpredictable matter of fact about the position of any of the detectors $D_i$ in turn entails the existence of detectors $D_{ik}, k = 1, \ldots, m,$ whose sensitive regions are small and localized enough to probe the space over which the position of $D_i$ is distributed, and so on. It stands to reason that one sooner or later runs out of detectors with sharper positions. There will be “ultimate” detectors the positions of which are too sharp to be manifestly fuzzy.

Let me say this again. If $O$’s position is to be manifestly indefinite, there must exist detectors capable of probing the space over which the position of $O$ is distributed. To probe this space, they must have positions that are sharper than $O$’s position, and sensitive regions that are smaller than the space over which $O$’s position is distributed. But detectors with sharper positions and sufficiently small sensitive regions do not always exist. There is a finite limit to the sharpness of the positions of material objects, and there is a finite limit to the spatial resolution of real detectors. There are objects whose positions are the sharpest in existence. Hence not every object can have a manifestly indefinite position. Macroscopic objects exist. We
cannot be certain that a given object qualifies as macroscopic, inasmuch as not all matters of fact about its whereabouts are accessible to us. But we can be certain that macroscopic objects exist, and that the most likely reason why \( M \) is macroscopic is the nonexistence of detectors with positions that are sharper than the position of \( M \), and with sensitive regions that are smaller than the space over which \( M \)'s position is distributed. (\( M \) could also be macroscopic for the unlikely reason that such detectors, though they exist, never indicate a departure from \( M \)'s classically predicted position.)

Another word of caution. We must desist from thinking of \( O \)'s position as being distributed (“smeared out”) in any actual sense. Saying that \( O \)'s position is distributed over a set of mutually disjoint regions \( \{ R_i | i = 1, \ldots, n \} \), is the same as saying that the probability of finding \( O \) in \( R_i \) is positive for several or all values of \( i \). If the probabilities are subjective, what is distributed (in the literal statistical sense) is an ensemble of identically “prepared” systems. If the probabilities are objective, \( O \)'s position is not actually but counterfactually distributed (that is, it is distributed over contrary-to-fact conditionals). But if \( O \)'s position is counterfactually distributed over a set of mutually disjoint regions, there isn’t any matter of fact about the particular region that contains \( O \). In this case the multiplicity and the distinctness of those regions are not real for \( O \) (Sec. IV), so there is nothing over which \( O \) is actually distributed.

We are now in a position to resolve the apparent vicious regress pointed out at the beginning of this section. The buck does stop. There are ultimate detectors; there are objects whose positions are not manifestly indefinite because they are the “most localized” objects in existence. Although no object ever follows a definite trajectory, there are objects whose positions evolve in a completely predictable fashion. This makes it possible to think of the positions of such objects as forming a self-contained system of positions that “dangle” causally from each other, rather than ontologically from position-indicating facts. We can treat the positions of macroscopic objects as if they were intrinsic, without ever risking being contradicted by the implications of an actual event or state of affairs. The Moon is there because of the myriad of facts that betoken its presence, but its position “dangles” from them in a way that is predictable, a way that does not reveal any (counterfactual) fuzziness. It is therefore completely superfluous to apply to the positions of macroscopic objects the language of statistics, to assign to them probabilities, and to treat them as extrinsic.

Matters of fact about the positions of macroscopic objects are correlated in a way that permits us to project our asymmetric agent causality into the time-symmetric world of physics (Sec. III), and to think of the positions possessed at later times as causally determined by the positions possessed at earlier times. This isn’t the way it really is. In reality there are no causal links. It nevertheless is not quantitatively wrong to think of the positions of macroscopic objects as forming a self-contained system of intrinsic properties tied to each other by causal strings, and to quantitatively define all positions in terms of the not manifestly indefinite positions of macroscopic objects. There aren’t any sharper positions in terms of which positions could be defined.

Bohr 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
The existence of a “classical domain” – a domain adequately described in classical language – is perfectly consistent with quantum mechanics. What Bohr was stressing is that the actual events or states of affairs presupposed by quantum mechanics cannot be described without referring to the (changeable) properties of persistent objects. (Try to describe an experiment without talking about persistent objects and their changing properties!) Thus, on the one hand, quantum mechanics requires the use of classical language – the language of persistent objects and properties that to some extent evolve predictably. (Unless properties evolve in a sufficiently predictable fashion, they cannot be thought of as the properties of a persistent object because they cannot be thought of as the properties of the same object at different times.) On the other hand, the use of this language is consistent with quantum mechanics, despite the extrinsic nature of all contingent properties. Macroscopic objects exist, and it is legitimate to describe them in the language of persistent objects and causally connected properties. The use of causal terms is legitimate not because there is anything that forces macroscopic objects to evolve in a certain manner, but because the factually warranted positions of macroscopic objects are predictable – they do not evince any indeterminism.

Note that an apparatus pointer is not a macroscopic object according to the above definition. In general nothing allows us to predict which way the pointer will deflect (given that it will deflect). However, before and after the deflection the pointer behaves as a macroscopic object, and this is sufficient for its initial and final positions to be defined independently of what happens elsewhere. Hence the deflection event – the unpredictable transition from the initial to the final position – is also defined independently of the rest of the world. The system property indicated by the deflection event explicitly presupposes the deflection event, but the latter is sufficiently described in terms of intrinsic properties; in order to describe it, we need not refer to other property-defining events.

The deflection event is part of the history of an object that is adequately described in classical language. Such an object can be thought of as possessing a persistent reality of its own, and events in its history can be thought of as deriving their actuality from this persistent reality. Hence there is a viable alternative to thinking of the actuality of the deflection event as “popping up” unpredictably and inexplicably. The event happens unpredictably and inexplicably, but it owes its reality (as distinct from its particular nature) to the persistent reality of the pointer. While it is fundamentally correct that actuality – the actuality of possessed properties – comes in “bits and pieces” that are statistically correlated but not causally linked, the possessed properties of macroscopic objects, and even of pointer needles, are so correlated that their actuality can be grounded in the continuous reality of a persistent object.

XI. THE SPATIAL DIFFERENTIATION OF THE WORLD: FACT AND FICTION

How real is the indefiniteness of a position that is not manifestly indefinite? The answer is, not real at all. The “most objective” way for the position of an individual object $O$ to be distributed over a set of mutually disjoint regions $\{R_i | i = 1, \ldots, n\}$, recall, is to be counter-factually distributed. If $O$’s position is so distributed, there isn’t any matter of fact concerning
the particular region $R_i$ that contains $O$. The reason why there isn’t any such matter of fact is either the absence of suitable detectors or their failure to indicate the position of $O$. If $O$ is not a macroscopic object, either such detectors could have been in place but were not, or they were in place but none did respond. In either case the multiplicity and the distinctness of the regions $\{R_i\}$ are not real for $O$. On the other hand, if $O$ is macroscopic, the most likely reason why there isn’t any matter of fact about the particular region containing $O$ is that there are no detectors capable of probing the space over which $O$’s position is distributed. In this case the multiplicity and the distinctness of the regions $\{R_i\}$ fail to be real not only for $O$ but for every object in existence. If there are no detectors to realize the distinctness of those regions, then nothing in the actual world corresponds to our conceptual distinction between those regions.

We have this inveterate tendency to visualize everything against an infinitely and intrinsically differentiated backdrop. Since spatial distinctions are not intrinsic to space (Sec. IV), such a backdrop does not exist. The actually existing spatial distinctions are those that are warranted by facts. Like all contingent properties, they “dangle” from what happens or is the case. And since there is a finite limit to the spatial resolution of real detectors (Sec. X), a finite region $R$ of space contains at most a finite number of regions that are actually distinct. For any object $O$ located within $R$, at most a finite number of distinct positions (“inside $R_i$,” where $\{R_i\}$ is a partition of $R$) are available as possible attributes.

Suppose that $\{R_i\}$ is a partition of $R$ at the limit of resolution achieved by actually existing detectors. How should we visualize this partition? Certainly not as a set of sharply bounded regions! Since no object ever possesses an exact position, no detector ever has a sharply bounded sensitive region. Even the boundaries of the ultimate detectors are fuzzy. But since they cannot be manifestly fuzzy, the mental picture of fuzzily bounded regions is more detailed than the finitely differentiated reality it is supposed to represent. The fuzziness exists only in relation to a more differentiated backdrop, and this exists only in our imagination. Where the regions $\{R_i\}$ or the sensitive regions of ultimate detectors are concerned, nothing in the actual world corresponds to the spatial distinctions implicit in the notion of a fuzzy boundary – a boundary distributed (“smeared out”) over a multiplicity of mutually disjoint regions. By the same token, nothing in the actual world corresponds to the spatial distinctions implicit in the indefiniteness of the position of a macroscopic object. And this is the same as saying that nothing in the actual world corresponds to the indefiniteness of the position of a macroscopic object. This indefiniteness exists solely in our minds.

It seems to me that we must reconcile ourselves to the existence of objects the positions of which are neither sharp nor fuzzy, and which evolve neither in a deterministic, causal fashion nor in an unpredictable, indeterministic fashion. The notion that “sharp” and “fuzzy” are jointly exhaustive terms has its roots in an inadequate theoretical representation of the world’s actual spatial determinations. That notion rests on the assumption of an intrinsically and infinitely differentiated space, and this assumption is inconsistent with quantum mechanics (Sec. IV). In a world that is spatially differentiated only to the extent that spatial relations and distinctions can be inferred from the facts, no object has a sharp position. But there are objects that have the sharpest positions in existence, and these positions are not fuzzy in any real sense; they are
fuzzy only in relation to an unrealized degree of spatial differentiation. Their fuzziness exists exclusively in our heads.

If space is neither intrinsically nor infinitely differentiated, there are no points that could serve as the substrate for physical qualities. There are no points on which a world of locally instantiated properties could be built. This is why reality is built on facts (Sec. VI), and why the spatial properties of things (including the actual spatial differentiation of the world) are extrinsic – they “dangle” from the facts. The extrinsic nature of possessed properties makes room for objective probabilities (Sec. IV), and these evince themselves counterfactually, through the unpredictability of some factually warranted properties. Quantum mechanics is our tool for calculating those probabilities. And if quantum mechanics is complete, what is unpredictable (and therefore uncaused) is not just the outcomes of some successfully performed measurements but the existence of every property-defining fact (Sec. VIII). This implies that nothing behaves the way it does out of nomological necessity (compelled by causal laws) (Secs. VI and IX). There are nevertheless things that evolve predictably, in the sense that their factually warranted positions are predictable on the basis of earlier position-defining facts. Thus there are objects that evolve neither deterministically (by nomological necessity) nor unpredictably.

XII. EPR CORRELATIONS AND THE MYSTERY OF ACTION AT A DISTANCE

Perhaps the most impenetrable aspect of the physical world consists in the correlations that are observed on systems in spacelike separation. The paradigm example of such correlations is (Bohm’s version of) the experiment of Einstein, Podolsky, and Rosen (EPR). Suppose that at the time \( t_0 \) two spin- \( \frac{1}{2} \) particles are in the singlet state (that is, there is a matter of fact by which this inference is warranted). At \( t_1 > t_0 \) Alice measures the spin component of the first particle with respect to some axis, and at \( t_2 > t_0 \) Bob measures the spin component of the second particle with respect to the same or a different axis. The temporal order of \( t_1 \) and \( t_2 \) is irrelevant. Whenever Alice and Bob choose the same axis, their results are perfectly anticorrelated.

Can there be a causal explanation for this phenomenon? That the common-cause explanation fails is well known. Nor is agent causality involved, for two reasons. First, the correlations are perfectly symmetric. If Alice and Bob obtain the respective results \( \uparrow_A \) and \( \downarrow_B \), the following statements are equally true: (i) Alice obtained \( \uparrow_A \) because Bob obtained \( \downarrow_B \) (and because she measured the \( x \) component), (ii) Bob obtained \( \downarrow_B \) because Alice obtained \( \uparrow_A \) (and because he measured the \( x \) component). At the same time both statements are overspecific. If there is no objective criterion to decide which of two correlated events is the cause and which is the effect, causal concepts are inappropriate. Second, Bob’s choice exerts no causally determining influence on the result obtained by Alice (and vice versa): no matter which axes they choose, the odds that Alice will obtain \( \uparrow \) or \( \downarrow \) are always fifty-fifty. Einstein was absolutely right: “the real factual situation of the system \( S_2 \) is independent of what is done with the system \( S_1 \).”

Once again, the concepts of action and causation are out of place. Diachronic correlations that are not manifestly indeterministic can be passed off as causal explanations. We can impose on them our agent causality with some measure of consistency, even though this compels us
to use a wrong criterion: temporal precedence takes the place of causal independence as the criterion which distinguishes the cause from the effect. But when we deal with EPR correlations or correlations that are manifestly indeterministic, the imposition of agent causality does not work. Trying to causally explain these correlations is putting the cart in front of the horse. It is the correlations that explain why causal explanations work to the extent they do. They work in the classical domain where we are dealing with macroscopic objects, and where the correlations between property-indicating facts evince no statistical variations (dispersion). In this domain we are free to use language suggestive of nomological necessity. But if we go beyond this domain, we realize that all regularities are essentially statistical, even when statistical variations are not in evidence, and that our belief in nomological necessity is an unwarranted anthropocentric projection deriving from our self-perception as agents. What lies beyond the classical domain is out of bounds to the concept of causation. The correlations are fundamental. There is no domain of underlying causal processes. There is a domain in which causal terms can be used, but this is defined by the specific condition that the statistical correlations evince no variations. It is the correlations that account for the limited usefulness of causal language. There is no underlying causation that could explain the correlations.

And still one wants to know how it can be like that—not how EPR correlations work but simply how they are possible at all. To answer this question, one must point out the fallacy that makes them seem impossible. As I see it, the fundamental stumbling block is the view known as local realism and the separability that this entails. According to local realism, “...all there is to the world is a vast mosaic of local matters of particular fact, just one little thing and then another.... We have geometry: a system of external relations of spatiotemporal distance between points.... And at those points we have local qualities: perfectly natural intrinsic properties which need nothing bigger than a point at which to be instantiated.... And that is all.... All else supervenes on that.” If an atom can pass through a double slit without passing through either slit in particular and without being divided into parts by its passage through the slits, the slits cannot demarcate spatial locations that are intrinsically distinct (Sec. IV). Neither space nor time are intrinsically differentiated. There are no points on which a world of locally instantiated properties can be built. The world is built on facts (Sec. VI), and its spatiotemporal properties (including the actual extent of its spatial and temporal differentiation) are supervenient on the facts. In and of itself, physical space—or the reality underlying it—is undifferentiated.

Newton’s law of gravity created a problem concerning which Newton himself refused to “frame hypotheses”: How is action at a distance possible? Field theories are often hailed as providing the solution to the perceived paradox of unmediated action across space. But what enables field theories to do so is their commitment to the principle of local action (a.k.a. local causality), according to which the “local matters of particular fact” at a point \( P \) are influenced only by the “local matters of particular fact” in the infinitesimal neighborhood of \( P \)– as if the electromagnetic interaction were explained by, rather than contributed to explain, what goes on when a hammer strikes a nail. Since space-time points are not intrinsically distinct, the principle of local action is without application, and the field theoretic “solution” is no solution. Nor is a solution needed, for the problem of action at a distance arises only if space-time points are conceived as intrinsically distinct. The same applies to the problem of how EPR correlations...
are possible. If in and of itself “here” is not distinct from “there,” there is no problem. What happens or is the case “here” can be correlated with what happens or is the case “there” because, fundamentally, “here” and “there” are identical, not in the qualitative sense of exact similarity, but in the strict sense of numerical identity. At bottom there is only one place, and it is everywhere. If action at a distance or EPR correlations require a medium, that identity (or this ubiquity) is the medium.

XIII. CONCLUSION: PONDICHERRY VERSUS COPENHAGEN

Here is a list of wishes that many theoretical physicists harbor and, simultaneously or alternatingly, know to be chimerical: “Suppose that there’s just one world. And suppose that there’s just one complete story of the world that’s true. And suppose that quantum-mechanical state vectors are complete descriptions of physical systems. And suppose that the dynamical equations of motion are always exactly right.” The PIQM endorses the first two items and rejects the remaining two. State vectors are not complete descriptions of physical systems because they do not describe physical systems (Sec. VIII). Nor can one say that the dynamical equations (in the simplest case, the Schrödinger equation) are always (and everywhere) exactly right, given the usual acceptations of “always” and “everywhere” (“at every instant of time” and “at every point of space,” where time and space are conceived as sets with the cardinality of the real numbers). Once again, the spatial properties of things and the times at which they are possessed exist to the extent that they can be inferred from facts, and facts do not warrant the inference of an infinitely differentiated space or time. Between the factually warranted times that make up the history of a system, there are gaps; there are “periods of time” that do not exist for the system (Sec. VI). Everything that can be said about those periods is counterfactual. The state vector assigns (prior) probabilities to the possible results of measurements that are not performed during such a period, or else it assigns subjective probabilities to the possible results of the measurement that is performed at the end of the period. The time dependence of the state vector is a dependence either on the time of an unperformed measurement, which time is nonexistent for the system, or on the time of the measurement that is performed at the end. The “dynamical” equations are “always” exactly right only in the sense that they correctly spell out this time dependence.

The CIQM equally denies that state vectors are descriptions of physical reality, and that they always evolve in accordance with the “dynamical” equations. It further agrees with the PIQM in that the state vector is a tool for calculating the probabilities of measurement results, that values can be attributed only to observables that are actually measured, and that “measurement” must be treated as a primitive concept, incapable of physical analysis. The PIQM goes beyond the CIQM in that it extends the meaning of “measurement” to include all property-indicating facts. For the PIQM, the primitive concept is “(matter of) fact.” This eliminates the CIQM’s Janus-faced portrayal of measurements: as physical processes governed by quantum mechanics, and again as constituents of a classical domain existing in an anterior logical relationship to quantum mechanics. The property-indicating events or states of affairs are not governed by quantum mechanics. They are amenable to classical description, in terms of objects whose positions behave exactly like deterministically evolving intrinsic positions (in
the sense that nothing indicates that they don’t) – except when they themselves indicate the possession, by another object, of a property that wasn’t predicted by the classical dynamics on the basis of the relevant earlier facts. Even pointer positions are extrinsic; they too would not be attributable if they couldn’t be inferred from the (classically describable) goings-on in the rest of the world. Even the properties of the classical domain “dangle” from a myriad facts in the classical domain, but in a way that allows us to ignore the network of inferences from facts to properties which supports the classical domain, and to imagine in its stead a network of causal connections between intrinsic properties.

Strictly speaking, there is no such thing as the CIQM. Often but not always the CIQM is associated with a subjective or epistemic construal of “measurement”: The state vector represents our knowledge of the factual situation rather than the factual situation itself.75 The CIQM’s claim to completeness is then construed as an agnosticism concerning the factual situation: what is responsible for the experimental results and their statistical correlations is forever beyond our ken. Here is how Stapp76 has characterized the conceptual innovation due to the CIQM: “The theoretical structure did not extend down and anchor itself on fundamental microscopic space-time realities. Instead it turned back and anchored itself in the concrete sense realities that form the basis of social life.” The PIQM is in full agreement with the first part of this statement, but it rejects the pragmatism of the second part. Science is driven by the desire to know how things really are. It owes its immense success in large measure to the belief that this can be discovered. There is no need to trade this powerful “sustaining myth”77 for the pragmatic notion that physics deals only with perceived and communicable phenomena. The theoretical structure is anchored in facts.

According to Stapp, “[t]he rejection of classical theory in favor of quantum theory represents, in essence, the rejection of the idea that external reality resides in, or inheres in, a space-time continuum. It signalizes the recognition that ‘space,’ like color, lies in the mind of the beholder.” The PIQM fully agrees with the first part of this statement but rejects the subjectivism of the second part. Surely there are other ways of thinking about the spatial and temporal aspects of the world. The fact that reality is not built on an intrinsically and infinitely differentiated space does not imply that there is no objective space. Spatiality and temporality are objective aspects of the world, but the world is spatially and temporally differentiated only to the extent that spatial and temporal distinctions are warranted by the facts.

Stapp’s non sequitur is symptomatic of one of the two deep-seated misconceptions that prevent us from understanding quantum mechanics – the idea that the set-theoretic description of space with its inherent multiplicity and distinctions provides the only possible way of thinking about the spatiality of the world. (The other misconception is the notion of an evolving instantaneous state.) If this were true, the external world would be nonspatial and hence definitely beyond our ken. Quantum mechanics would be complete in the sense that it enables us to say all that can be said with the language and the concepts at our disposal. According to the PIQM, quantum mechanics is complete in the sense that it enables us to say all that needs to be said in order to understand the material world. (This is very different from the notion that the state vector itself describes the material world.) What is incomplete is not quantum mechanics but reality itself; that is, reality is incomplete relative to a description of reality that
is “overcomplete.” The seemingly intractable problem of understanding quantum mechanics is a consequence of our dogged insistence on obtruding onto the world, not a spatiotemporal framework, but a spatiotemporal framework that is more detailed than the world.

We think of the statistical regularities quantum mechanics is concerned with as statistical laws – as being what they are of necessity. (Otherwise we could not employ quantum-mechanical probability assignments counterfactually; we could not assign objective probabilities to unperformed measurements.) But this necessity cannot be the nomological necessity of a causal law. So what sort of necessity is it? Is there something “behind” the statistical regularities, something that is responsible for or revealed by them? According to the PIQM, the answer is positive: what is revealed is an objective indefiniteness in the positions of nonmacroscopic objects. It has been said that, although the terminology of indefinite or fuzzy values is prevalent in some elementary textbooks, what is really intended is that a certain observable does not possess a value at all. But there is more than that to the indefiniteness of a position. The statistical laws warrant assigning objective probabilities; they allow us to associate with an individual object an objective probability distribution over mutually disjoint regions of space. Hence they warrant the notion of an objectively indefinite position. Indefiniteness is an irreducible feature of the world. Qualitatively this is easy enough to grasp, although giving it exact quantitative expression is tricky. It involves (apart from renunciation of two deep-seated misconceptions about space and time) objective probabilities, counterfactuals, the extrinsic nature of contingent properties – in fact, the entire conceptual apparatus put together in this paper.

APPENDIX: GLOSSARY

ABL probability. The probability $P_{ABL}(a_i) = \frac{|\langle \Psi_2 | P_{A=a_i} | \Psi_1 \rangle|^2}{\sum_j |\langle \Psi_2 | P_{A=a_j} | \Psi_1 \rangle|^2}$ with which a measurement of the observable $A$ performed on a system $S$ between the “preparation” of the state $|\Psi_1\rangle$ and the “retroperation” of the state $|\Psi_2\rangle$ yields the result $a_i$. The operator $P_{A=a_i}$ projects on the subspace corresponding to the eigenvalue $a_i$ of $A$. ABL probabilities are based on past and future matters of fact about the properties of $S$.

Agent causality. The time-asymmetric causality of the goal-directed activities of a conscious agent in a successively experienced world. It is often wrongly superimposed on the time-symmetric causal links of classical physics and the time-symmetric relation in quantum physics between measurements and probability assignments.

Born probability. The probability $P_B(a_i) = |\langle \Psi | P_{A=a_i} | \Psi \rangle|$ with which a measurement of the observable $A$ on a system $S$ performed after the so-called “preparation” of the state $|\Psi\rangle$ yields the result $a_i$. The operator $P_{A=a_i}$ projects on the subspace corresponding to the eigenvalue $a_i$ of $A$. Born probabilities are based only on past matters of fact about the properties of $S$.

Causal primary. An event or state of affairs the occurrence or existence of which is not necessitated by any cause, antecedent or otherwise.

Classical domain. A collective name for the positions of macroscopic objects.

Classical language. Quantum mechanics presupposes not only the existence of facts but also the possibility of describing facts in the classical language of persistent objects and causally
connected properties. Despite the extrinsic nature of all contingent properties, the use of classical language is consistent with quantum mechanics. Macroscopic objects are adequately described in this language – if one keeps in mind that the causal terminology is warranted by predictability rather than by nomological necessity.

**Conditional.** A hypothetical statement; a compound statement of the form “If \( p \) then \( q \).” Component \( p \) is called the antecedent.

**Contingent property.** A property that a system \( S \) may, but does not necessarily, possess. Being inside a given region of space and having a spin component of \(+\hbar/2\) along a given axis are contingent properties of electrons.

**Contrary-to-fact conditional.** A conditional that presupposes the falsity of its antecedent.

**Correlata.** The statistically correlated possible results of possible measurements performed either on the same system at different times or on different systems (see Measurement).

**Counterfactual.** A contrary-to-fact conditional.

**Dangle.** Extrinsic properties “dangle” from what happens or is the case in the rest of the world \( W − S \) in the sense that they are defined in terms of the goings-on in \( W − S \). They depend for their existence on some actual event or state of affairs that can be described without reference to \( S \) but has implications concerning the possessed properties of \( S \). Another way of saying this is that the possessed properties of \( S \) are supervenient on the goings-on in \( W − S \).

**Diachronic correlations.** Correlations between the results of local measurements performed on the same system at different times.

**Distributed.** Saying that \( O \)’s position is distributed over a set of mutually disjoint regions \( \{ R_i | i = 1, \ldots, n \} \), is the same as saying that the probability of finding \( O \) in \( R_i \) is positive for several or all values of \( i \). If the probabilities are subjective, what is distributed (in the literal statistical sense) is an ensemble of identically “prepared” systems. If the probabilities are objective, \( O \)’s position is not actually but counterfactually distributed (that is, it is distributed over contrary-to-fact conditionals).

**EPR correlations.** Correlations between the results of local measurements performed on different systems in spacelike separation.

**Event.** Something that happens, e.g., the deflection of a pointer needle or the click of a detector. Quantum mechanics presupposes actual events or states of affairs but does not account for their occurrence or existence. Nor can it tell us wherein the actuality of an actual event consists.

**Extrinsic property.** A contingent property of \( S \) that is undefined, and hence not attributable to \( S \), unless its being possessed by \( S \) can be inferred from what happens or is the case in the rest of the world \( W − S \). If \( p \) is an extrinsic property, the proposition \( p = “S \text{ is } p” \) is meaningless just in case neither its truth nor its falsity can be inferred from the goings-on in \( W − S \).

**Factually warranted.** Warranted by a (matter of) fact.

**Fuzzy.** Indefinite.

**Indefinite.** The value of an observable \( A \) (with a specific range of possible values \( a_i \)) is said to be indefinite if there isn’t any matter of fact from which the actually possessed value can be inferred, and if none of the values \( a_i \) has an objective probability equal to 1.
**Instantaneous state.** The state of a system at an exact time, supposed to be evolving in time and to represent not only actually possessed properties but also everything of the past that remains causally relevant to the future. According to the PIQM, there is no such thing.

**Intrinsic property.** A property $p$ of $S$ for which the proposition $p = "S is p"$ is “of itself” (that is, unconditionally) either true or false at any time; neither the truth nor the meaning of $p$ depends on the goings-on in the rest of the world $\mathbb{W} - S$.

**Local action (or local causality).** The fallacious notion that local matters of fact at a space-time point $P$ depend only on local matters of fact in the infinitesimal neighborhood of $P$.

**Local realism.** The fallacious notion that physical properties are either locally instantiated (that is, they are properties of space-time points) or supervenient on locally instantiated properties. It entails the equally fallacious notion that space and time (or space-time) are adequately described as point sets.

**Macroscopic object.** An object whose position is not manifestly indefinite.

**Manifestly indefinite.** The distinction between objects whose positions are manifestly indefinite, and objects whose positions are not manifestly indefinite, is central to the PIQM. It defines a quantum/classical divide without positing ad hoc limits to the validity of quantum mechanics, and without compromising on the extrinsic nature of all contingent properties. An object $O$ has a manifestly indefinite position if the indefiniteness of its position is (counterfactually) evidenced by the existence of unpredictable matters of fact about its position. The position of a macroscopic object $M$ is not manifestly indefinite: Nothing ever indicates that $M$ has a position different from what is predictable on the basis of the pertinent classical laws and earlier position-indicating matters of fact.

**(Matter of) fact.** An actual event or an actual state of affairs.

**Measurement.** The existence of a matter of fact (or the occurrence of an actual event, or the coming into existence of an actual state of affairs) that warrants attributing a specific property to a physical system.

**Measurement result.** A matter of fact about the possessed properties of a physical system $S$; an actual state of affairs from which the possession by $S$ of a specific property can be inferred; a property the possession of which is factually warranted.

**Nomologically possible.** Consistent with the laws of physics.

**Nomological necessity.** The idea that the regularities displayed by empirical data are necessitated by causal laws; that things behave the way they do because of some invisible causal links. Since all empirical regularities are essentially statistical, this idea is an unwarranted anthropocentric projection deriving from our self-perception as agents in a successively experienced world.

**Numerical identity.** Identity proper, to be distinguished from exact similarity.

**Objective probability.** A probability assigned to a counterfactual (or to a possible result of a not actually performed measurement) on the basis of a complete set of relevant facts. Objective probabilities have nothing to do with ignorance – there is nothing to be ignorant of.

**Perfect detector.** Between a real detector and a perfect detector there exists a qualitative difference that no technological advance can bridge. The quantum-mechanical probability associated with finding $O$ in $R_i, i = 1, \ldots, n$, is conditional on the existence of a matter of fact.
about the region containing $O$. Perfect detectors are so defined as to eliminate this conditionality. What is a conditional probability for a real detector is an absolute probability for a perfect detector.

**Positional indefiniteness.** The indefiniteness of a position. The positional indefiniteness of a macroscopic object exists only in our minds. Nothing in the actual world corresponds to it because it exists only in relation to a background space that is more differentiated than the real thing, physical space.

**Preparation.** A bad word. It suggests that a measurement prepares an evolving actual state of affairs. In reality all that is “prepared” by a measurement is a set of probability assignments.

**Real detector.** The quantum-mechanical probability associated with finding $O$ in $R_i$, $i = 1, 2$, is conditional on the existence of a matter of fact about the region containing $O$. If the quantum-mechanical probability associated with finding $O$ in $R_1$ is $1/2$, a perfect detector with sensitive region $R_1$ clicks in 50% of all runs of the experiment, while a real detector $D'_1$ with the same sensitive region clicks in 50% of all runs of the experiment in which either detector clicks. The efficiency of a real detector (that is, its likelihood to click when the corresponding Born probability is 1) can be measured, but it cannot be calculated from “first principles,” for the same reason that the occurrence of a causal primary cannot be predicted.

**Retrocausation.** Backward-in-time causation.

**Retroparation, retropare.** The time reverse of “preparation” and “prepare.”

**Separability.** Based on the fallacious notion that space-time is adequately described as a point set, the equally fallacious notion that events or states of affairs in spacelike separation are independent not only causally but also statistically.

**Sharp.** Definite. No position is completely sharp. Some positions are sharper than others. Some objects (called “macroscopic”) have the sharpest positions in existence; their positional indefiniteness exists only in our minds.

**State.** The worst word in the vocabulary of quantum mechanics. Legitimately, a state is a collection of actually possessed properties. A quantum state, instead, is a collection of (Born) probability assignments. (A ket, like the corresponding projection operator, represents a property. If the possession of this property is factually warranted at a given time, the ket may be thought of as representing this factually warranted property. But the same ket unitarily propagated to other times is nothing but a rule for assigning probabilities. To keep clear of a potent source of confusion, it is better never to think of a ket as representing an actually possessed property.)

**State of affairs.** Something that is actually the case, e.g., the needle’s pointing left. Quantum mechanics presupposes actual events or states of affairs but does not account for their occurrence or existence. Nor can it tell us wherein the actuality of an actual state of affairs consists.

**Subjective probability.** A probability assigned on the basis of an incomplete set of relevant facts. If a measurement is actually performed, the probabilities associated with the possible results are based on an incomplete set of facts; they take no account of the actual result; they therefore express our (subjective) ignorance of the actual result.

**Supervenient.** See Dangle.
Temporal referent. The temporal referent of something X is the time at which X happens or obtains. The temporal referent of motion is a set of factually warranted moments that is not dense in time.

Trivial probability. A probability of either 0 or 1.

Truth value. True or false. A proposition lacks a truth value if it is neither true nor false (and therefore meaningless).

Ultimate detector. A detector whose position and boundary are too sharp to be manifestly indefinite.

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3. I cannot at this point define what I mean by a “matter of fact about the value of an observable,” except by saying that it is an actual event or state of affairs from which that value can be inferred. The question of how to define “(matter of) fact,” “event,” “state of affairs,” and similar expressions will be addressed below.

4. Yakir Aharonov, Peter G. Bergmann, and Joel L. Lebowitz, “Time symmetry in the quantum process of measurement,” Phys. Rev. 134B, 1410-1416 (1964); reprinted in Quantum Theory and Measurement, edited by John Archibald Wheeler and Wojciech Hubert Zurek (Princeton University Press, Princeton, NJ, 1983), pp. 680-686.

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8. If the measurement at \( t_m \) had yielded \( \downarrow y \), the final measurement could not have yielded \( \uparrow y \).

9. This point has been forcefully made by Huw Price (Time’s Arrow & Archimedes’ Point, Oxford University Press, New York, 1996).

10. Professional soccer players and neuroscientists alike may contest this account, but that’s besides the point.

11. Ulrich Mohrhoff, “Objectivity, retrocausation, and the experiment of Englert, Scully and Walther,” Am. J. Phys. 67, 330-335 (1999).

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15. In this context Mermin considers it possible that my now is two weeks behind or fifteen minutes ahead of his now. This peculiar notion does not bear scrutiny. Temporal relations exist between objective events and/or objective states of affairs, not between nows. The use of “now” in the plural is at best bad English. My experiential now – the special moment at which the world has the technicolor reality it has in my consciousness – is coextensive with my wordline, and so is Mermin’s with his wordline. Every event that I have been or will be aware of, has had or will have this miraculous kind of reality. Assigning a temporal relation to the experiential nows of different persons therefore makes as much sense as assigning a temporal relation to two parallel worldlines. If I point at a spot $(t_1, x_1)$ on my wordline and a spot $(t_2, x_2)$ on your wordline and say, “When my now is here, yours is there,” I actually say “When my clock shows $t_1$, your clock shows $t_2$.” But this is a statement that makes sense only if it concerns the relation between two coordinate systems. As a statement about different times relative to the same coordinate system it is a self-contradictory statement about synchronized clocks.

16. A. Peres and W.H. Zurek, “Is quantum theory universally valid?,” Am. J. Phys. 50, 807-810 (1982).

17. Where real detectors are concerned, we must distinguish between two kinds of probability: the probability that a detector will respond (no matter which) and the probability that a specific detector will respond given that any one detector will respond. The latter (conditional) probability is the one that quantum mechanics is concerned with. The former (absolute) probability can be measured (for instance, by using similar detector in series), but it cannot be calculated using the quantum formalism (nor, presumably, any other formalism). One can 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. The efficiency of a real detector cannot be calculated from “first principles.” And since the efficiency of a real detector is determined by at least one fundamental coupling constant such as the fine structure constant, this also implies that a fundamental coupling constant cannot be calculated; it can only be gleaned from the experimental data.

18. Michael Redhead, Incompleteness, Non locality and Realism (Clarendon, Oxford, 1987), p. 72.

19. An anonymous referee (of a different paper and a different journal) claims that standard quantum mechanics rejects Redhead’s sufficiency condition but endorses the “eigenstate-eigenvalue link,” according to which an element of reality corresponding to an eigenvalue of an observable exists at time $t$ if and only if the system at $t$ is “in the corresponding eigenstate of this observable.” It is obvious that the PIQM rejects this claim, since it rejects the very notion that quantum states warrant inferences to actualities.

20. Asher Peres, “Can we undo quantum measurements?,” Phys. Rev. D 22, 879-883 (1980); reprinted in Wheeler and Zurek (Ref. 4), pp. 692-696.

21. Thus the characterization of a measurement as an “irreversible act of amplification” is inadequate. 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 property-indicating event or state of affairs has happened or come into existence, it is logically impossible to reverse this. For the relevant fact is not that the needle deflects to the left (which could be reversed by returning the needle to the neutral position); the relevant fact is that 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.

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35. Ian C. Percival, “Primary state diffusion,” Proc. R. Soc. Lond. A **447**, 189-209 (1994).
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38. Philip Pearle, “True collapse and false collapse,” in *Quantum Classical Correspondence*, edited by Da Hsuan Feng and Bei Lok Hu (International Press, Cambridge, MA, 1997), pp. 51-68.
39. Jorge Luis Borges, “The Garden of Forking Paths,” *Ficciones* (Everyman’s Library, Knopf / Random House, New York, 1993).

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42. Werner Heisenberg, *Physics and Philosophy* (Harper and Row, New York, 1958), Chap. 3.

43. Karl R. Popper, *Quantum Theory and the Schism in Physics*, edited by W.W. Bartley, III (Rowan & Littlefield, Totowa, NJ, 1982).

44. The “collapse” of an inference basis is *necessarily* unpredictable: if it could be predicted, the inference basis would remain unchanged.

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47. It is often said that the “motion” of the now or the “flow” of time are purely subjective (Ref. 11, Sec. V). I wouldn’t go so far. I prefer to think that objective reality encompasses more than “objective” science can handle. Science knows nothing of the singular and the individual. It deals with classes and types and the patterns or regularities that define membership in a class. It deals with greylags but not with the greylag goose Martina. It deals with lawfulness but not with what instantiated the lawfulness. It deals with the laws of physics but not with what it is that obeys the laws of physics. It classifies fundamental particles but keeps mum on what a fundamental particle intrinsically is. From this it does not follow that, objectively, there is no such thing as a fundamental particle. By the same token, from the fact that physics can deal only with the quantitative features of time, it does not follow that the qualitative features of time are not objective.

48. “...there is no interpolating wave function giving the ‘state of the system’ between measurements” – Asher Peres, “What is a state vector?”, *Am. J. Phys.* **52**, 644-650 (1984).

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53. Another way to see this is to recall from note 17 that no theoretical account can be given of the efficiency of a real detector – its likelihood to click when the corresponding Born probability is 1. *A fortiori*, no theoretical account can be given of why or when a detector is certain to click. It never is.

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59. Because these conditions can be stated in classical language, causal terms do have a domain of application. More about this in Sec. X.
60. See Carl Friedrich von Weizsäcker, The Unity of Nature (Farrar, Straus, Giroux, New York, 1980), Sec. IV.4.
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65. Departures from the classically predicted positions are necessarily random, or unpredictable. A predictable departure would reveal a classical law not previously taken into account; it would not be a departure from the classically predicted position.
66. “...even when phenomena transcend the scope of classical physical theories, the account of the experimental arrangement... must be given in plain language, suitably supplemented by technical physical terminology. This is a clear logical demand, since the very word ‘experiment’ refers to a situation where we can tell others what we have done and what we have learned.” – Niels Bohr, Atomic Physics and Human Knowledge (Wiley, New York, 1958), p. 72.
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70. The denial of nomological necessity in physics (sometimes referred to as “causal nihilism”) does not entail that our self-perception as causal agents is a delusion. See Ulrich Mohrhoff, “Interactionism, energy conservation, and the violation of physical laws,” Physics Essays 10, 651-665 (1997); “The physics of interactionism,” Journal of Consciousness Studies 6, No. 8/9, 165-184 (1999).
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how it can be like that." – Richard P. Feynman, *The Character of Physical Law* (MIT Press, Cambridge, MA, 1967), p. 129.

72. David K. Lewis, *Philosophical Papers, Volume II* (Oxford University Press, New York, 1986), p. x.

73. Reference 58, p. 126.

74. For a summary see, for instance, Ref. 18, pp. 49-51; Barry Loewer, “Copenhagen versus Bohmian interpretations of quantum theory,” *Brit. J. Phil. Sci.* 49, 317-328 (1998).

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