Marchildon’s (favorable) assessment (quant-ph/0303170, to appear in Found. Phys.) of the Pondicherry interpretation of quantum mechanics raises several issues, which are addressed. Proceeding from the assumption that quantum mechanics is fundamentally a probability algorithm, this interpretation determines the nature of a world that is irreducibly described by this probability algorithm. Such a world features an objective fuzziness, which implies that its spatiotemporal differentiation does not “go all the way down”. This result is inconsistent with the existence of an evolving instantaneous state, quantum or otherwise.

1 INTRODUCTION

Louis Marchildon [1] has undertaken a difficult task: to make sense of my published attempts to make sense of quantum mechanics. (To minimize the use of “I” and “my” I will refer to them collectively as the “Pondicherry interpretation of quantum mechanics”, PIQM [2].) On the whole he has succeeded admirably, notwithstanding the difficulty of the task, which is compounded by the fact that our neurobiology militates not only against attempts to make sense of the quantum world [3, 4, 5] but also against attempts to communicate the way that, according to the PIQM, the world is. Here I respond to some of the issues raised by Marchildon’s assessment of the PIQM.

Marchildon mentions two approaches to the so-called “pointer problem”—decoherence theories [6, 7] and modal interpretations [8, 9, 10]—and states that the PIQM “does not seem to bring any additional insight to the issue”. I think it does. By his own admission, his “critical examination of a number of assertions” made by the PIQM does “not cover all aspects of the interpretation, which partakes of a wide-ranging system that reaches well into metaphysical ontology”. It appears to me that Marchildon has missed an aspect of the PIQM that is both metaphysical and relevant to the pointer problem. This aspect,
explained in Sec. 2, is the limited (or finite) spatiotemporal differentiation of the physical world, which follows from the relative and contingent reality of the spatial distinctions that we make, and which is inconsistent with the existence of an evolving instantaneous state. Its bearing on the pointer problem is discussed in Sec. 3.

According to the PIQM, value-indicating events (“measurements”) are uncaused. Marchildon considers this conclusion epistemologically “risky”. Section 4 assesses the risk. Section 5 examines two “good” reasons adduced by Marchildon for viewing the state vector as specifying an evolving (instantaneous) state, and offers further reasons for not doing so. Section 6 addresses a couple of specific questions raised by Marchildon and clears up an ambiguity concerning the “time of measurement”. In Sec. 7 the following question is addressed: What changes in our concepts of “state” and “evolution” are needed so as to make them applicable to a world that is fundamentally and irreducibly described by the probability distributions of QM? In the concluding section I show how the PIQM reconciles two apparently conflicting statements: According to Marchildon, the PIQM “takes quantum mechanics to be fundamental and complete, and it requires the validity of classical mechanics for its formulation”.

2 THE FINITE SPATIOTEMPORAL DIFFERENTIATION OF THE PHYSICAL WORLD

The PIQM assumes that QM is fundamentally exactly what somehow or other it obviously is—a probability algorithm. It seeks to determine the nature of a world that is fundamentally and irreducibly described by this probability algorithm. This must be confusing to many. Have we not been told time and again that if QM is nothing but a probability algorithm then it is an epistemic theory concerned with “states of knowledge” rather than “states of nature”, and if it is an ontological theory then the quantum state represents an evolving instantaneous state and not just a probability measure?

There are no sufficient grounds for either conclusion. If our fundamental physical theory is an algorithm for assigning probabilities to the possible outcomes of possible measurements on the basis of actual outcomes, or (what comes to the same) if it encapsulates correlations between value-indicating events (VIEs), then these correlations are descriptive of an objective fuzziness.¹ As a result of this fuzziness, the spatiotemporal differentiation of the physical world is finite; it does not “go all the way down”. But if the world is not infinitely differentiated timewise, there is no such thing as an evolving instantaneous state. Or so I will argue in this section.

Consider the probability distribution \( |\psi(x)|^2 \) associated with the position of the electron relative to the nucleus in a stationary state of atomic hydrogen. Imagine a small

¹ “Uncertainty” mistranslates the German original “Unschärfe”, the literal meaning of which is “fuzziness”.

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region $V$ for which $\int_V |\psi(x)|^2 dx$ differs from both 0 and 1. While the atom is in this state, 
the electron is neither inside $V$ nor outside $V$. (If the electron were inside, the probability 
of finding it outside would be 0, and vice versa.) But being inside $V$ and being outside $V$ 
are the only relations that can possibly hold between the electron and $V$. (An unextended 
object cannot have a part inside $V$ and another part outside $V$, nor is the position of an 
object the kind of thing that can have parts.) If neither of the possible relations between 
the electron and the (imagined) region $V$ hold, this region simply does not exist for the 
electron. It has no reality as far as the electron is concerned.

Conceiving of a region $V$ is tantamount to making the distinction between “inside $V$” 
and “outside $V$”. Hence instead of saying that $V$ does not exist for the electron, we may 
say that the distinction we make between “inside $V$” and “outside $V” is a distinction 
that the electron does not make. Or we may say that the distinction we make between 
“the electron is inside $V$” and “the electron is outside $V$” is a distinction that Nature 
does not make. It corresponds to nothing in the physical world.

Suppose, again, that the observables $A$, $B$, and $C$ are consecutively measured, the 
result of the first measurement being $a$. In the simplest case in which the Hamiltonian 
is 0, the probability of finding $c$ after the intermediate measurement of $B$ is

$$p(c|a, B) = \sum_i |\langle c|b_i\rangle \langle b_i|a\rangle|^2.$$ (1)

If the Hamiltonian is not 0, the brackets are transition amplitudes. Formula (1) applies 
whenever information concerning the value of $B$ is in principle available, however hard it 
may be for us to obtain it. If such information is strictly unavailable, the probability of 
finding $c$ is

$$p(c|a) = |\langle c|a\rangle|^2 = \left| \sum_i \langle c|b_i\rangle \langle b_i|a\rangle \right|^2.$$ (2)

Thus if the intermediate measurement is made, we add the probabilities associated with 
the alternatives defined by the results of the intermediate measurement. Otherwise we 
add the amplitudes $\langle c|b_i\rangle \langle b_i|a\rangle$ associated with these alternatives. Why?

Because in one case the distinctions we make between the alternatives have counter-
parts in the physical world, and in the other case they don’t. To cite a familiar example, 
in one case the electron ($e$) goes through either the left slit ($L$) or the right slit ($R$). 
The propositions “$e$ went through $L$” and “$e$ went through $R$” possess truth values; one 
of them is true, the other false. In the other case, these propositions lack truth values; 
they are neither true nor false but meaningless. (So, therefore, is the proposition “$e$ went 
through both slits”, since the conjunction of two meaningless proposition is another mean-
ingless proposition.) Nor does an electron (or the position of a C$_{60}$ molecule, for that matter [11]) have parts that go through different slits. The electron goes through $L&R$, 
the region defined by the slits considered as a whole, but it goes neither through $L$ nor
through $R$ because the distinction involved is a distinction that Nature does not make in this case.

Whenever QM requires us to add amplitudes, the distinctions we make between the corresponding alternatives are distinctions that Nature does not make. They correspond to nothing in the physical world. Hence the reality of spatial distinctions is relative and contingent—"relative" because the distinction we make between the inside and the outside of a region may be real for a given object at a given time, and it may have no reality for a different object at the same time or for the same object at a different time; and "contingent" because the existence of a given region $V$ for a given object $O$ at a given time $t$ depends on whether the proposition "$O$ is in $V$ at the time $t$" has a truth value.

Does this proposition have a truth value if none is indicated (that is, if none can be inferred from an actual event or state of affairs)? Here is a related question: Suppose that $W$ is a region disjoint from $V$, and that $O$'s presence in $V$ is indicated. Isn’t $O$’s absence from $W$ indicated at the same time? Are we not entitled to infer that the proposition “$O$ is in $W$” has a truth value (namely, “false”)? Because the reality of spatial distinctions is relative and contingent, the answer is negative. Regions of space do not exist by themselves. The distinction we make between “inside $W$” and “outside $W$” has no physical reality per se. If $W$ is not realized (made real) by some means, it does not exist. But if it does not exist, the proposition “$O$ is in $W$” cannot have a truth value. All we can infer from $O$’s indicated presence in $V$ is the truth of a counterfactual: if $W$ were the sensitive region of a detector $D$, $O$ would not be detected by $D$. Probability 1 is not sufficient for “is” or “has”.

It follows that a detector$^2$ performs two necessary functions: it indicates the truth value of a proposition of the form “$O$ is in $W$”, and by realizing $W$ (or the distinction between “inside $W$” and “outside $W$”) it makes the predicates “inside $W$” and “outside $W$” available for attribution to $O$. The apparatus that is presupposed by every quantum-mechanical probability assignment is needed not only for the purpose of indicating the possession, by a material object, of a particular property (or the possession, by an observable, of a particular value) but also for the purpose of realizing a set of properties or values, which thereby become available for attribution.$^3$

Now let $IR^3(O)$ be the set of unpossessed and purely imaginary exact positions relative to an object $O$. Since no material object ever has a sharp position, we can conceive of a partition of $IR^3(O)$ into finite regions that are so small that none of them is the sensitive region of an actually existing detector. Hence we can conceive of a partition of $IR^3(O)$

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$^2$A perfect detector, to be precise. If $D$ is less than 100 percent efficient, the absence of a click does not warrant the falsity of “$O$ is in $W$”.

$^3$This does not mean that QM is restricted “to be exclusively about piddling laboratory operations” [12]. Any event from which either the truth or the falsity of a proposition of the form “system $S$ has property $P$” can be inferred, qualifies as a measurement.
into sufficiently small but finite regions $V_i$ of which the following is true: there is no object $Q$ and no region $V_i$ such that the proposition “$Q$ is inside $V_i$” has a truth value. In other words, there is no object $Q$ and no region $V_i$ such that $V_i$ exists for $Q$. But a region of space that does not exist for any material object, does not exist—period. The regions $V_i$ represent spatial distinctions that Nature does not make. They correspond to nothing in the physical world. The bottom line: The world is not infinitely differentiated spacewise. Its spatial differentiation is finite—it doesn’t go all the way down.

While positions are indicated by (macroscopic) detectors, times are indicated by (macroscopic) clocks. (“Macroscopic” is defined in the following section.) Since clocks indicate times by the positions of their hands, and since exact positions do not exist, neither do exact times. What is true of the positions of objects is therefore equally true of the times of events: they have values only to the extent that values are indicated.

As the world is differentiated spacewise by the spatial relations (or relative positions) that exist in it, so it is differentiated timewise by the temporal relations (or relative times) that exist in it. While relative positions exist only as relations between material objects, relative times exist only as relations between actual events. The argument by which the world’s finite spatial differentiation has just been deduced from the nonexistence of exact positions, can therefore be repeated almost verbatim to deduce the world’s finite temporal differentiation from the nonexistence of exact times. But if the world is not infinitely differentiated timewise, there can be no such thing as an evolving instantaneous state.

3 THE POINTER PROBLEM

A fundamental physical theory that is essentially an algorithm for assigning probabilities to VIEs on the basis of other VIEs presupposes the occurrence of VIEs, and the challenge is to establish the internal consistency of such a theory. For this reason one of the more frequent worries of measurement theorists is to explain how possibilities—or worse, probabilities [14]—become facts, how properties emerge [8], or why events occur [15]. Yet it isn’t the task of a probability theory to account for the occurrence of the events to which, and on the basis of which, it assigns probabilities. While VIEs are causally linked to the future (inasmuch as they create traces or records, which is necessary for their being VIEs), they are causally decoupled from the past, and this not just for the trivial reason that the result of a successful measurement is generally not necessitated by an antecedent cause. Every quantum-mechanical probability assignment presupposes the occurrence of a VIE, and therefore QM (qua probability algorithm) cannot supply

4Digital clocks indicate times by transitions from one reading to another, without hands. The uncertainty principle for energy and time implies that this transition cannot occur at an exact time, except in the limit of infinite mean energy [13].
sufficient conditions for the occurrence of a VIE. If QM (qua probability algorithm) is
fundamental and complete, it follows that VIEs are uncaused.

Every physical theory has to name those of its ingredients that correspond to reality
or represent what is. The entire theoretical structure of QM—consisting of its formal
structure and the ontological structures described by it—must contain a particular sub-
structure that can consistently be regarded as factual per se, and that is capable, therefore,
of accommodating the VIEs presupposed by QM. Our task as measurement theorists is
not to account for the occurrence of VIEs, let alone for the realization of possibilities
unaided by VIEs, but to identify this substructure.

Here is how the PIQM carries out this task. The departure of an object $O$ from a
precise trajectory can be indicated only if there are detectors that can probe the region
over which $O$’s fuzzy position extends. This calls for detectors whose position probability
distributions are narrower than $O$’s. Such detectors do not exist for all objects. Some
objects have the sharpest positions in existence. For these objects the probability of a
position-indicating event (PIE) that is inconsistent with a precise trajectory, is necessarily
very low. Hence among these objects there are objects of which the following is true: every
one of their indicated positions is consistent with (i) every prediction that is based on
their previous indicated positions and (ii) a classical law of motion. Such objects deserve
to be called “macroscopic”. To enable a macroscopic object to play the role of a pointer,
one exception has to be made: its position may change unpredictably if and when it
serves to indicate a measurement outcome.

Since the indicated positions of macroscopic objects are consistent with classical tra-
jectories, we can think of the positions of macroscopic objects (“macroscopic positions”,
for short) as forming a system of causally connected properties that are effectively de-
tached from the events by which they are indicated. We can ignore their dependence on
PIEs because their effectively deterministic correlations permit us to think of them as a
self-contained and self-existent causal nexus (interspersed with unpredictable changes in
outcome-indicating positions).

The cogency of these conclusions hinges on the meaning of “effectively detached”.
Macroscopic positions are not really detached from the events by which they are indicated.
No position is possessed unless its possession is indicated. Even the Moon is where
it is only because of the (myriad of) events that betoken its whereabouts. Macroscopic
positions are possessed (to the extent that they are) because they are indicated by macro-
scopic positions (to the extent that they are). This mutual dependence, however, does
not affect the independent existence of the entire system of macroscopic positions (the
“macroworld”). While ontologically it would be wrong to consider a single macroscopic

5 This definition does not require that the probability of finding a macroscopic object where classically
it could not be, is strictly zero. What it requires is that there be no PIE that is inconsistent with
predictions based on a classical law of motion and earlier PIEs.
position as factual *per se*, nothing stands in the way of considering the entire system as factual *per se*.

Moreover, for all *quantitative* purposes (FAQP) it is perfectly legitimate to ignore the mutual dependence of macroscopic positions and to treat them as *individually* self-indicating. The existence of truth-value-lacking propositions of the form “*Q* has the value *q*” is a consequence of the fuzziness of physical variables. Such propositions call for a criterion for the existence of a truth value, and this consists in the occurrence of a VIE (indicating both the truth value of a proposition and the value of an observable). The fuzziness of physical variables thus implies the supervenience of possessed values on VIEs. The fuzziness of a macroscopic position, on the other hand, never evinces itself through unpredictable PIEs. (Macroscopic objects, recall, are defined that way.) It only exists in relation to an imaginary spatial background that is more differentiated than the physical world. It therefore is as unreal physically as the intrinsically and infinitely differentiated spatial background of classical theories. This is why it is perfectly legitimate FAQP (rather than merely FAPP) to ignore the supervenience of macroscopic positions on PIEs.

The structure that represents what exists, and that contains the VIEs presupposed by QM, thus turns out to be what every experimental physicist takes it to be: the system of macroscopic positions. It is a substructure in two senses: it is part of the entire theoretical structure of QM, and it is the self-existent foundation on which all indicated values supervene. It contains the VIEs as unpredictable transitions of value-indicating positions. (Since such a position belongs to the self-existent macroworld both before and after a value-indicating transition, the transition partakes of the factuality of the macroworld.) What makes this structure the sole candidate for the predicate “factual *per se*” is the physical unreality of its own fuzziness, existing as it does solely in relation to a nonexistent “manifold”. Thus even though there is no hermitian “factuality operator” (one cannot measure factuality), QM (qua probability algorithm) uniquely determines what is factual *per se*.

What light does this shed on the following “transition”?

\[ |s\rangle \otimes |m_0\rangle = \sum_i c_i |q_i\rangle \otimes |m_0\rangle \rightarrow \sum_i c_i |q_i\rangle \otimes |m_i\rangle. \]  

(3)

\( m_i \) is the property whose possession, by an apparatus \( \mathcal{A} \), indicates that a system \( \mathcal{S} \) has the property (or an observable \( Q \) has the value) \( q_i \), and \( m_0 \) is the apparatus-property of being in the neutral state. As it stands, \( (3) \) is not a physical transition but either a conditional probability measure or a substitution of one probability measure for another reflecting a change in the time of the possible measurements to the possible results of which probabilities are assigned. Assuming that the possession of \( s \) by \( \mathcal{S} \) and that of \( m_0 \) by \( \mathcal{A} \) at the initial time are indicated, the final probability measure tells us (among other things) that the probability of finding both \( m_i \) and \( q_k \) at the final time (given that the
appropriate measurements are successfully made) is $|c_i|^2$ if $k = i$ and 0 otherwise. If the initial possession of $s$ and $m_0$ is not indicated, the initial “state” is itself a probability measure based on earlier VIEs, assigning probability 1 to the joint detection of $s$ and $m_0$ (given that the appropriate measurements are successfully made).

Let us now take into account that $m_0$ stands for the neutral position of a macroscopic pointer, and that the possession by $\mathcal{A}$ of one of the properties $m_i$ indicates the result of a measurement. This means that the initial possession of $m_0$ and the final possession of one of the $m_i$ are embedded and recorded in the self-existent system of effectively sharp positions that make up the macroworld. In this case the transition of $\mathcal{A}$ from having the property $m_0$ to having one of the properties $m_i$ is a physical transition, indicating that $\mathcal{S}$ has the corresponding property $q_i$ at the time of the transition.

If the so-called “measurement problem” is the problem of how a particular element of some decomposition of the final algorithm comes to represent (or to appear to represent) what exists, the so-called “pointer problem” is the problem of why it is an element of this decomposition rather than another. As pointed out at the beginning of the present section, the first problem is spurious. All that needs to be established is the consistency of the spontaneous occurrence of uncaused VIEs with the quantum-mechanical correlations between VIEs, and this has just been done, at least in a qualitative or heuristic fashion. To render the argument quantitative, it suffices to invoke the results of decoherence investigations.

These investigations generally begin by dividing the world into a “collective system” (system + apparatus) and its “environment”. What they demonstrate is that, for a large class of models if not in complete generality [16], the reduced density operator of the collective system, obtained by a partial trace on the environment, becomes virtually diagonal with respect to a privileged basis in a very short time, and that it stays that way for a very long time. Because all known interaction Hamiltonians contain $\delta$-functions of the distances between particles, the privileged basis is that defined by the collective position variables.

This quantitatively underpins (i) the existence of objects for which the probability of a PIE that is inconsistent with a precise trajectory is very low, (ii) the conclusion that there are macroscopic objects in the specific sense spelled out above, and (iii) the consistency of the correlations encapsulated by QM with the assignment of independent existence to the system of macroscopic positions. The PIQM thus solves the pointer problem by availing itself of the tools of decoherence theories. At the same time it avoids the self-defeating philosophy espoused by decoherence theorists; for these take an encapsulation of correlations between VIEs, transmogrify it into an evolving state of affairs, and as a consequence are forced to deny the objective reality of VIEs: “While decoherence transforms the formal ‘plus’ of a superposition into an effective ‘and’ (an apparent ensemble of new wave functions), this ‘and’ becomes an ‘or’ only with respect
to a subjective observer” [17]. (The reason why the “and” is only “effective” is that the reduced density operator never becomes completely diagonal: decoherent histories exist only FAPP.)

What decoherence investigations demonstrate is that decoherence makes the environment a more accurate monitor of macroscopic positions than any individual apparatus could be. Individual measurements of macroscopic positions reveal pre-existent properties, in the sense that they indicate properties that are already indicated by the environment. Note that while this general result doesn’t make much sense in the context of the aforesaid philosophy, it makes good sense if one takes account of the supervenience of possessed values on VIEs, which follows from the fuzziness of physical variables.

Modal interpretations “solve” the problem of how the “and” becomes an “or” by turning it into a postulate: whenever a two-component system has a unique biorthogonal decomposition—this is the case in the event that all $c_i$ have different norms—one term of this decomposition represents the actual state of the system. There remains the problem of how an effective “or” becomes a bona fide “or”. To arrive at a bona fide “or” within the modal scheme one has to establish the exact biorthogonality of the decomposition of the final state in (3), now interpreted as a state of the collective system and the environment. The fact that the reduced density operator of the collective system,

$$\sum_{ij} c_i c_j^* \langle m_j | m_i \rangle |q_i\rangle \langle q_j|,$$

is diagonal (regardless of the values of the $c_i$) only if the environment kets $|m_i\rangle$ are orthogonal, suggests that modal interpretations and decoherence theories are equally incapable of establishing a genuine “or”. In addition it can be held against modal interpretations that (i) they consider an ever so small quantitative difference sufficient for a considerable conceptual difference, namely the difference between the existence and the nonexistence of a value [5], and (ii) they feature a superfluous postulate. As has been shown, QM (qua probability algorithm) is perfectly capable of a unique and consistent reality assignment, without extraneous postulates.

In summary, I believe that, contrary to Marchildon’s assessment, the PIQM does bring additional insight to bear on the pointer problem—additional to what is achieved by decoherence theories and modal interpretations.

4 RISK ASSESSMENT

According to the PIQM, VIEs are uncaused. Marchildon considers this conclusion epistemologically “risky”. He believes that classical mechanics explains everything except the initial conditions: “the totality of the world at one instant is unexplained, but the totality of the world at all other instants is explained”. He goes on to say that, according to the PIQM,
all the facts that constantly betoken positions of macroscopic objects should be taken as unexplainable. It seems that the unexplained here far exceeds what it is in classical mechanics. Inevitably, people will look for regularities in the occurrence of facts. . . . In a sense, spontaneous localization theory may be viewed as doing just that. . . . any theory that would correctly account for the occurrence of facts would, other things being equal, have a head start over one that does not.

Let us examine these claims. To begin with, the quantum-mechanical correlations between macroscopic objects are deterministic, in the sense that every indicated macroscopic position is consistent with every prediction that is based on previous indicated macroscopic positions and a classical law of motion. This makes it possible to think of them as correlations between causes and effects, rather than as correlations between VIEs or values indicated by VIEs, and to forget about the supervenience of macroscopic positions on VIEs, at least FAQP. It would be delusional, however, to believe that the deterministic correlations of classical mechanics are thereby explained.

Take classical electrodynamics. It is an algorithm for calculating, in two steps, the effects that electrically charged objects have on electrically charged objects. Given the distribution and motion of charges, we calculate four or six functions of spacetime coordinates, the components of either the 4-vector potential or the electromagnetic field. Given these functions, we calculate the effect that those charges have on other charges (or would have if other charges were present). If there is an underlying process or mechanism by which charges act on charges, we know nothing of it. The transmogrification of an algorithm for calculating effects into a process or mechanism by which these effects are produced is but a sleight of hand. Besides, the notion that the electromagnetic field is a physical entity in its own right, which is locally acted on by charges, locally acts on charges, and locally acts on itself, still doesn’t explain how the field is locally acted on by charges, how it locally acts on charges, and how it locally acts on itself.6

Again, classical mechanics cannot account for the stability of matter—the existence of objects that are composed of finite numbers of particles, that “occupy” finite regions of space, and that do neither collapse nor explode as soon as they are created. QM does. The stability of matter hinges on the fuzziness of the internal relative positions and momenta of composite objects, which finds its quantitative expression in the statistical correlations of QM. Does this justify the claim that (according to the PIQM) the unexplained “far exceeds what it is in classical mechanics”? I don’t think so.

6One is left to wonder why we tend to stop worrying once we have transformed the mystery of action at a distance into the mystery of local action. Perhaps it is because “physicists are, at bottom, a naive breed, forever trying to come to terms with the ‘world out there’ by methods which, however imaginative and refined, involve in essence the same element of contact as a well-placed kick” [8].
Next, to say that “all the facts that constantly betoken positions of macroscopic objects should be taken as unexplainable” is to overstate the lack of sufficient conditions for the occurrence of a VIE. Many aspects of the click of a counter or the deflection of a pointer can be understood in terms of the deterministic correlations that structure the macroworld. As Marchildon correctly points out, “properties of facts may be subject to experimental investigation and, therefore, call for theoretical analysis”. Theoretical analysis is an analysis of types and causal relations. The absence of causally sufficient conditions for the occurrence of an event of type X does not preclude a detailed theoretical analysis of events of type X. To say that facts are irreducible, as Marchildon does, is therefore incorrect. What is irreducible is only the factuality of facts and the occurrence of value-indicating facts.

As Marchildon’s allusion to spontaneous localization theory suggests, if the lack of causally sufficient conditions is a drawback, it is a drawback of standard QM (unadulterated by spontaneous localizations or such) rather than a drawback of the PIQM. But is it a drawback? One thing is certain: The inability to formulate sufficient conditions for VIEs does not imply that QM is incomplete, for it could be the physical world that is “incomplete”. If QM is fundamentally a probability algorithm quantifying (among other things) the fuzzy spatial relations that contribute to “fluff out” matter, this is indeed the case: the physical world does not contain all the spatiotemporal distinctions that we tend to make, and its spatiotemporal differentiation does not go all the way down. If QM’s being fundamentally a probability algorithm entails the impossibility of formulating sufficient conditions for VIEs, this is a small price to pay for a significant insight into the spatiotemporal structure of the physical world. Moreover, the nonexistence of causally sufficient conditions for VIEs is itself (a direct consequence of) another significant insight: The applicability of causal concepts is confined to the macroworld. Causal “explanations” are causal interpretations of statistical correlations, and such interpretations are possible only in the limiting case in which the correlations become deterministic in the sense just spelled out (that is, only within the system of macroscopic positions, which evolves deterministically except for the value-indicating transitions that occur in it).

It may be true that “any theory that would correctly account for the occurrence of facts would, other things being equal, have a head start over one that does not”, only there is no such theory. There are always relevant “other things” that are not equal. As

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7It seems to me that it would take a far more substantial overhaul of QM than a nonlinear or stochastic modification of the dependence of probability assignments on the times of VIEs, in order to arrive at a theory featuring causally sufficient conditions for VIEs. The efficiency of any actually existing detector is related to the value of at least one coupling constant. This contributes to determine the probability of detection in the event that the (Born or ABL) probability of detection is 1. By building large redundancies into our detectors (which is possible only for large detectors) we can make this probability close to 1, but we cannot make it exactly 1. And if it is not exactly 1, the detection event, if it occurs, cannot be said to have been necessitated (caused).
d’Espagnat has argued at length and convincingly [19, 20, 21], one has either to accept a modified “dynamics” or content oneself with a theory that is objective only in a weak, intersubjective sense, inasmuch as it countenances a conceptual fuzziness that allows “≈” to do duty for “=” [5]. The PIQM has to do neither because it does not share the assumption on which d’Espagnat’s conclusion rests. By rejecting the assumption that a quantum state is an evolving (instantaneous) state of affairs of some sort, as well as the intrinsically and infinitely differentiated background time/spacetime that this assumption entails in a nonrelativistic/relativistic context, the PIQM avoids the conceptual fuzziness of statements that are true only FAPP. It features, instead, an objective fuzziness and statements that are true FAQP.

5 THE PSYCHOLOGY OF QUANTUM STATE EVOLUTION

Marchildon adduces a couple of “good” (albeit not compelling) reasons to view the state vector as specifying an evolving (instantaneous) state. The first is this: Almost everybody agrees that a complete measurement performed on a system $S$ at a time $t_1$ warrants the inference that at this time $S$ possesses a property (or a set of properties) that can be represented by a one-dimensional projector $P(t_1)$. Knowing this property as well as the system’s Hamiltonian, we can predict that the appropriate measurement, if successfully performed at a time $t_2 > t_1$, will warrant (or would warrant) the inference that $S$ possesses the property represented by $P(t_2)$ at the time $t_2$. This is usually considered sufficient ground for the belief that $S$ possesses $P(t_2)$ at $t_2$ even if it is not the outcome of an actually performed measurement. “This possibility of correctly predicting the value of a time-dependent dynamical variable motivates the association of the state vector with an actual state of affairs” [1].

It is, however, equally possible to correctly retrodict the value of a time-dependent variable. Knowing $P(t_1)$ and the system’s Hamiltonian, we can retrodict that the appropriate measurement, if successfully performed at a time $t_2 < t_1$, did warrant (or would have warranted) the inference that $S$ possesses $P(t_2)$ at $t_2$. But this means that Marchildon’s first “good” reason is a good reason not to view the state vector as specifying an (instantaneous) state that evolves (toward the future). All quantum-mechanical probability assignments are time symmetric. Born probabilities can be assigned on the basis of either past or future VIEs, and ABL probabilities [22] are by nature time-symmetric, whereas the notion of an evolving state of affairs is anything but time-symmetric.

The second “good” reason is the belief, largely due to von Neumann [23], that a measurement is an interaction followed by a collapse. Marchildon considers a series of

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[8] Even spontaneous localization theories are not free from this kind of fuzziness, since the collapsed probability distributions have “tails”.
three measurements—of $A$ yielding $|a\rangle$ at $t_1$, of $B$ yielding $|b\rangle$ at a later time $t_2$, and of $C$ yielding $|c_i\rangle$ at an intermediate time $t$—and argues that

For the purpose of computing probabilities of measurement results at time $t$, state $|a\rangle$ and state $|b\rangle$ are equally useful. For the purpose of making ontological statements, however, it is more natural in the absence of a $C$ measurement to hold that $|a\rangle$, rather than $|b\rangle$, is the intermediate state, since $|b\rangle$ obtains only after an intervening interaction.

According to von Neumann, (i) $|b\rangle$ only obtains after an intervening interaction, and (ii) the state vector specifies an evolving (instantaneous) state of affairs. If one makes assumption (ii) then it is natural to attribute to the state vector two modes of evolution, a continuous one that (owing to some interaction between system and apparatus) leads to an entangled state according to formula (3), and a subsequent “collapse”. Evidently, $|b\rangle$ then obtains only after the collapse. Conversely, if one makes assumption (i)—that is, if one regards $|b\rangle$ as due to a collapse from an entangled state brought about by a prior interaction—then it is natural to look upon the state vector as an evolving (instantaneous) state of affairs. The two assumptions support each other. What is missing is a good reason that supports them both.

It is indeed “more natural” to hold that $|a\rangle$ is the intermediate state, but for reasons that are psychological rather than physical. We are accustomed to the idea that the redness of a ripe tomato exists in our minds, rather than in the physical world. We find it incomparably more difficult to accept that the same is true of the experiential now: it has no counterpart in the physical world. There simply is no objective way to characterize the present. And since the past and the future are defined relative to the present, they too cannot be defined in physical terms. The temporal modes past, present, and future can be characterized only by how they relate to us as conscious subjects: through memory, through the present-tense immediacy of qualia, or through anticipation. In the physical world, we may qualify events or states of affairs as past, present, or future relative to other events or states of affairs, but we cannot speak of the past, the present, or the future. The idea that some things exist not yet and others exist no longer is as true (psychologically speaking) and as false (physically speaking) as the idea that a ripe tomato is red.

If we conceive of temporal or spatiotemporal relations, we conceive of the corresponding relata simultaneously—they exist at the same time in our minds—even though they happen or obtain at different times in the physical world. Since we cannot help it, that has to be OK. But it is definitely not OK to think of the spatiotemporal whole as a simultaneous spatial whole that persists in time, and to imagine the present as advancing through it. There is only one time, the fourth dimension of the spatiotemporal whole. There is not another time in which this spatiotemporal whole persists as a spatial whole and in which the present advances. If the experiential now is anywhere in the spatiotemporal whole, it is trivially and vacuously everywhere—or, rather, everywhere.
In a world that has no room for an advancing now, time does not “flow” or “pass”. To philosophers, the perplexities and absurdities entailed by the notion of an advancing objective present or a flowing objective time are well known. (See, e.g., the illuminating entry on “time” in Ref. 24.) To physicists the nonexistence of an advancing present was brought home by the discovery of the relativity of simultaneity. This was Nature’s refutation of “presentism”, the view that only the present is real. The opposite view, that no time is “more real” than any other time, however, is so counterintuitive (given the distinctiveness of the experiential now), that few physicists can resist the fallacy of projecting an advancing now into the physical world.9

In the maximally differentiated world of classical physics this leads to the well-known folk tale according to which causal influences reach from the nonexistent past to the nonexistent future through persisting “imprints” on the present. If the past is unreal, it can influence the (equally unreal) future only through the mediation of something that persists. Causal influences reach from the past into the future by being “carried through time” by something that “stays in the present”. There is, accordingly, an evolving instantaneous state, and this includes not only all presently possessed properties but also traces of 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, 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). Classical electrodynamics is a case in point. What compels one to transmogrify this algorithm for calculating the effects that electrically charged objects have on electrically charged objects (Sec. 4) into a local mechanism or a continuous process by means of which effects are produced, is the attempt to foist an advancing now into the world of classical physics. The attempt to foist an advancing now into the quantum world compels one to seize instead on a probability algorithm and to transmogrify the same into an instantaneous state that plays a similar mediating role.

The are other reasons for not viewing the state vector as specifying an evolving (instantaneous) state. One is the relativity of simultaneity. Simultaneity is a feature of the language by which we describe the world, rather than a feature of the world. Delocalized evolving quantum states have the nasty habit of collapsing simultaneously, which means that collapses, too, are features of our language rather than features of the world. “Collapse is something that happens in our description of the system, not to the system itself” 26. A description that introduces features that correspond to nothing in the physical world may be convenient for certain purposes, but for making ontological statements a coordinate-free description is obviously superior. Since simultaneity does not feature in such a description, neither can collapses. It follows either that quantum states are not

9Those who can, tend to go to the other extreme of altogether denying the temporality of the physical world, e.g.: “The objective world simply is, it does not happen…” 25.
evolving instantaneous states, or that they are such states but never collapse, in which case we have a theory that reifies a mathematical encapsulation of correlations between events the reality of which it denies (Sec. 3).

Finally, if one takes one’s cue from the stability of matter, which hinges on the fuzziness of relative positions and momenta, and looks for an appropriate tool for dealing with fuzzy variables, one finds this to be a probability algorithm. Since the most direct consequence of the fuzziness of physical variables (apart from the very existence of stable objects) is the unpredictability of measurement outcomes, the obvious way to quantify a fuzzy variable is to assign nontrivial probabilities. What is more, the quantum formalism can be derived by a straightforward generalization of the classical probability algorithm [29], which represents possible outcomes by subsets and probability measures by points (Sec. 7). To make room for nontrivial probabilities, one represents probability measures by 1-dimensional rays instead of 0-dimensional points, and possible outcomes by subspaces instead of subsets. The rest follows via Gleason’s theorem.

6 ON THE “TIME OF MEASUREMENT”

Marchildon asks, “Is a detector required to have some minimum mass to be able to work as a detector?” Much of the answer depends on what one means by a “detector”. What I mean is an object capable of indicating the presence of another object in a (more or less well-defined) region of space that exists by virtue of being defined in terms of self-existent macroscopic positions—the positions (say) of the macroscopic parts of the material boundary of the detector’s sensitive region. (The reason why this region is only more or less well defined is that its boundary is eventually made up of non-macroscopic objects with measurably fuzzy positions.) In addition, a detector must be capable of indicating the presence of another object in its sensitive region, and this requires a macroscopic pointer. Without a macroscopic pointer there is nothing that can indicate the possession of an attributable position, and without a region defined in terms of macroscopic positions, there is no attributable position (Sec. 2).

Given my definition of “macroscopic” (Sec. 3), an object with a large mass is very likely to be macroscopic, and an object with a small mass is unlikely to be so. There is therefore no precise mass limit at which an object ceases to be macroscopic. By the same token, there is no precise mass limit below which an object cannot function as a detector. Marchildon raises the question of whether an atom can work as a detector. Perhaps the

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10 And what about GHZ correlations [27]? The values of all three spin components of each of the three particles can be correctly predicted on the basis of measurements performed on the other two particles. Does the possibility of correctly predicting these values warrant the association of the state vector with an actual state of affairs? It certainly does not warrant the association of values with unmeasured spin components, for if one associates values with all $x$ and all $y$ components, the correlations imply that the product of the three $x$ components equals both $+1$ and $-1$ [28].
atomic tip of a scanning tunneling microscope can be regarded as a detector (for electrons with energies matching the potential between the tip and the sample), but only because it is attached to a macroscopic object and therefore in possession of a rather precise position, and only because a macroscopic pointer indicates the rate at which electrons are detected. Without the benefit of such macroscopic paraphernalia, no atom can work as a detector. Marchildon next considers a hydrogen atom in a 2\(p\) state, confined in a high vacuum.

In a split second the atom is very likely to emit a 1216 Å photon and fall to the ground state. Perhaps one will maintain that when the photon has gone far enough, a fact has occurred. But then the question is, When did the fact occur?...If it is agreed that the fact has already occurred at \(t = 1\) s..., it must have occurred at some instant between \(t = 0\) and \(t = 1\) s. That instant is defined as the one starting from which it is impossible to undo or erase.

To begin with, since even probability 1 is not sufficient for “is” or “has” (Sec. 2), the fact that the probability of finding the atom in its ground state is very close to 1 does not warrant the conclusion that the atom is in its ground state. Unless either the atom is found in its ground state or (what usually comes to the same) the photon is detected, no fact has occurred.

Next suppose that both the atom’s being in a 2\(p\) state at \(t = 0\) and its being in the ground state at \(t = 1\) are indicated. From this it does not follow that the transition has occurred at some instant between \(t = 0\) and \(t = 1\). If all that can be inferred from the goings-on in the macroworld is the atom’s respective states at these times then saying that the transition has occurred between \(t = 0\) and \(t = 1\) means no more than that the atom was in a 2\(p\) state at \(t = 0\) and in the ground state at \(t = 1\). In this case the state of affairs that obtains in the meantime is a temporally undifferentiated state of affairs (Sec. 7).

Marchildon defines the transition time as the earliest time after which it is impossible to undo or erase the fact by which the transition is indicated. In point of fact, there is no such time, for it is strictly impossible to undo or erase a VIE. In order to be a VIE, it must create a record, with the help of a value-indicating position that is embedded in the self-existent macroworld. Because the latter evolves deterministically, it retains information about the indicated value. Thus before there is a record, there is no VIE, and once there is a VIE, there is a record that can be erased only FAPP.\(^{11}\)

The notion that a VIE can be erased stands or falls with the notion that a quantum state has a kind of reality of its own, distinct from the reality of actual events and states of affairs (including measurements). One may see the quantum state as an evolving

\(^{11}\)The so-called “quantum erasure” of information \([30, 31, 32]\) is not an erasure of macroscopically recorded information but merely an “erasure” of the possibility of obtaining such information.
matrix of “propensities” or “potentialities”, or one may look upon it as the real reality, to be distinguished from the apparent reality experienced by information gathering and retaining system like us. In either case one searches the reality of one kind for criteria that warrant the other kind of reality. If one then believes that a particular kind of entanglement in the reality of the first kind (e.g., entanglement with a sufficiently massive object, or entanglement that is FAPP irreversible) warrants a reality assignment of the second kind, the possibility of reversing such a reality assignment exists. But only then.

Marchildon’s remarks nonetheless touch on an ambiguity concerning the time of a VIE that ought to be cleared up. A VIE lacks a causal precursor, and it leaves a trace that can be erased only FAPP. The paradigm example of a VIE—the deflection of a loudspeaker membrane or a pointer needle—satisfies the requirement of being embedded in the macroworld, but it does not seem to lack a causal precursor. After all, a detector does not click without (say) an initial ionization, and the paradigmatic click is no more than a convenient way to refer to the causal chain by which information is retained in the deterministically evolving macroworld. The converse, however, is equally true: without the click or record there would be no initial ionization. Like the measurement outcome indicated by the click, the initial ionization event supervenes on the goings-on in the macroworld.

This necessitates a distinction between the causality we mentally project into the macroworld, onto the deterministic correlations between macroscopic positions, and the causality by which we extend a record backward as far as counterfactuals permit. The first is an (imaginary) connection between events of which there are separate records. The second connects an individual record to the property or value that is indicated by the record and supervenes on it. There is no harm in regarding an initial ionization as causing the click (and an incoming particle as causing the ionization) on the strength of a counterfactual—without an incoming particle there would have been no ionization, and without ionization there would have been no click—as long as we remember the flip side: without the click or record there would have been no ionization, and without an ionization event, there would have been no incoming particle.

As we extend our story towards the past, it becomes less and less distinct. The question of which atom in the counter was the first to get ionized, for instance, involves distinctions that Nature does not make. Still less can be inferred regarding the incoming particle. If the setup warrants it, we can identify this particle with a particle detected earlier elsewhere, but even in this rather exceptional case the causal chain cannot be extended beyond the first ionization by the incoming particle. The particle’s indicated presence here and now is certainly not a consequence of the particle’s indicated presence there and then.

The time of a position measurement, accordingly, is not the time of a click (which, after
all, just stands for an enduring record) but the time of the first event in a causal chain. As far as time is concerned, this chain begins (in our example) with the first ionization of an atom by an incoming particle. From an ontological point of view, however, the chain begins with an unpredictable change in the value of a macroscopic position. The earlier part of the chain supervenes on the later part of the chain.\textsuperscript{12}

### 7 HOW QUANTUM SYSTEMS EVOLVE

I concede to Marchildon that it is not logically inconsistent, as I have claimed \textsuperscript{37}, to interpret an algorithm for assigning probabilities to the possible outcomes of possible measurements (on the basis of actual measurement outcomes) as an evolving state of affairs. Classical mechanics does indeed provide a counterexample. Its probability measure, a point $P$ in a phase space, assigns trivial probabilities to all possible measurement outcomes, which are represented by subsets—probability 1 to subsets containing $P$, and probability 0 to subsets not containing $P$. Because the probability measure is trivial, it can be interpreted as an evolving state of affairs. If the only probabilities are 1 and 0, nothing stands in the way of interpreting probability 1 as “has” and probability 0 as “lacks” \textsuperscript{29}.

Let us then ask: What changes in our concepts of “state” and “evolution” are needed so as to make them applicable to a world that is fundamentally and irreducibly described by the probability distributions of QM? To begin with, there is no instantaneous state. There are states that obtain at the times of measurements, and then there are states that obtain between measurements. There are two reasons why the times of measurements are fuzzy. For one, they are indicated by fuzzy positions, notwithstanding that macroscopic positions are fuzzy only in relation to an imaginary spatiotemporal background that is more differentiated than the physical world. For another, the time of possession of an indicated property (or the time of the onset of a property-indicating causal chain) supervenes on macroscopic events in this chain (e.g., the click of a counter). In general the time of the click does not sharply determine the time of possession; this adds to the fuzziness.

At the time $t_a$ of a complete measurement, system $S$ possesses a property that is represented by a one-dimensional projector $P_a$. Let us assume that $S$ is not subjected to any further measurement. Then all we have to describe the state of affairs that obtains

\textsuperscript{12}This supervenience has significant implications for cosmology. As we approach the cosmological time $t = 0$ (from later times), we enter an era in which there is as yet no macroworld. About this era we can make two kinds of statements: statements that are true (or false) only because their truth values are indicated much later, and counterfactuals. If we assign a density operator to this era, it is an “advanced” or “retropared” density operator rather then a “retarded” or “prepared” one. It “evolves” from later VIEs toward the past in the same (spurious) sense in which a prepared density operator evolves from earlier VIEs futurewards \textsuperscript{36}. 
thereafter is $P_a$. This describes a fuzzy state of affairs in terms of probability distributions over the possible results of unperformed measurement.

If the Hamiltonian is not 0 then the probability distributions describing the subsequent fuzzy state of affairs depend on the times of unperformed measurements. This is not the same as saying that the subsequent fuzzy state of affairs changes with time, for the antecedents of these counterfactual probability assignments are false not only because they affirm that a measurement is made but also because they affirm that this is made at a particular time. Where $S$ is concerned, there is no particular time until another measurement is made. $S$ is temporally differentiated by its VIEs. Between actual measurements it is only counterfactually differentiated (by unperformed measurements).

If another measurement is subsequently made, the fuzzy state of affairs that obtains in the meantime (during which no measurement is made) is fully described only if all relevant information is taken into account. This includes the result of the subsequent measurement. (Probability assignments based on earlier and later measurement data are made according to the ABL rule [2, 22].) Thus if, instead of filling the unmeasured gaps between measurements with stories that are extraneous to QM (qua probability algorithm), we let QM (qua probability algorithm) say all that it is capable of saying, what obtains between measurements is what is appropriately described by counterfactual probability assignments, namely, fuzzy states of affairs. Like the probability algorithm that describes it, a fuzzy state of affairs is not something that evolves. It is not only fuzzy but also temporally undifferentiated. What may be said to evolve is quantum systems. The evolution of $S$ consists in an alternating succession of indicated states that obtain at the times of measurements and temporally undifferentiated fuzzy states that obtain between measurements. This is in sharp contrast with the manner in which macroscopic positions evolve, whose indicated values merge into continuous histories that are fuzzy only relative to a nonexistent spatiotemporal background. (For further discussion see [5].)

8 CONCLUSION

Perhaps the most unusual feature of the PIQM, given our tendency of explaining things by taking them to pieces, is the supervenience of the microscopic on the macroscopic. To be able to understand it, one must conceive of space as the totality of the more or less fuzzy spatial relations (relative positions and relative orientations) that hold between material objects, rather than as a self-existent and intrinsically differentiated expanse. Fuzzy positions have values only to the extent that values are indicated. Values (in this case, spatial regions) can be indicated only if they exist—as the sensitive regions of detectors. This, as well as the fact that every probability algorithm presupposes the events to which it assigns probabilities, suggests that Niels Bohr was right to insist that quantum physics presupposes classical physics. But how can the PIQM take QM “to
be fundamental and complete” and at the same time require “the validity of classical mechanics for its formulation”, as Marchildon affirms?

It is a question of finding the right reality assignment. The fuzziness of a position can evince itself only to the extent that less fuzzy positions exist. Since the fuzziness of the least fuzzy positions has no observable consequences, it can FAQP be ignored. This makes the system of macroscopic positions the only structure to which independent reality can be attributed consistently, and it permits us FAQP to treat each macroscopic position as factual per se (Sec. 3). If one wants to speak of an “emergence” of the “classical domain” from the “quantum domain”, this is it. It is, however, a purely theoretical emergence, for what emerges is what exists by itself. Instead of being a substrate from which the classical domain emerges, the quantum domain supervenes on the classical domain. This is how the PIQM fleshes out the mutual dependence of the quantum and classical domains that is sometimes invoked (e.g., [38]). It is also how the claim that QM is fundamental and complete can be reconciled with the dependence of the quantum domain on the macroworld.

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