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The Pondicherry interpretation of quantum mechanics: An overview

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Abstract. An overview of the Pondicherry interpretation of quantum mechanics is presented. This interpretation proceeds from the recognition that the fundamental theoretical framework of physics is a probability algorithm, which serves to describe an objective fuzziness (the literal meaning of Heisenberg's term 'Unschärfe', usually mistranslated as 'uncertainty') by assigning objective probabilities to the possible outcomes of unperformed measurements. Although it rejects attempts to construe quantum states as evolving ontological states, it arrives at an objective description of the quantum world that owes nothing to observers or the goings-on in physics laboratories. In fact, unless such attempts are rejected, quantum theory's true ontological implications cannot be seen. Among these are the radically relational nature of space, the numerical identity of the corresponding relata, the incomplete spatio-temporal differentiation of the physical world, and the consequent top-down structure of reality, which defies attempts to model it from the bottom up, whether on the basis of an intrinsically differentiated space-time manifold or out of a multitude of individual building blocks.

Keywords. Interpretation of quantum mechanics; Pondicherry interpretation; objective probabilities; fuzziness; space; time.

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1. Introduction

Over the past five years, a new interpretation of quantum mechanics has emerged. After a series of publications that have focused on various aspects of the evolving 'Pondicherry interpretation' [1–11], it is time for an overview.

Does quantum theory need an interpretation? In a wide-circulation opinion piece, Fuchs and Peres [12] have claimed that it does not. Their actual claims, however, are that "quantum theory does *not* describe physical reality" (original emphasis), and that "[t]he compendium of probabilities represented by the 'quantum state' ρ captures everything that can meaningfully be said about a physical system". I am in full agreement with these authors when they insist that a quantum state (including the 'two-state' introduced by Aharonov and Vaidman [13]) is nothing but a compendium of probabilities. The objective fuzziness of relative positions and momenta is essential for the stability of matter. An objective fuzziness requires objective probabilities for its description. And a quantum state is an algorithm for calculating objective probabilities. In fact, the mathematical structure of quantum theory follows directly from this characterization of quantum states [7].

However, I disagree with Fuchs and Peres when they claim that quantum theory fails to describe physical reality, and that the density operator captures everything that can meaningfully be said about a physical system. I sympathize with their revulsion against realistic construals of quantum states. The transmogrification of a probability algorithm into an evolving ontological state cannot fail to generate pseudoproblems and invite gratuitous solutions. But the claim that from the quantal probability assignments we cannot 'distill a model of a free-standing *reality* independent of our interventions' is a *non-sequitur* and a cop-out. I therefore also sympathize with those who carry on the search for such a model.

Physical science owes its immense success in large measure to its powerful 'sustaining myth' [14] – the belief that we can find out how things *really* are. Neither the ultraviolet catastrophe nor the spectacular failure of Rutherford's atomic model made physicists question their faith in what they can achieve. Instead, Planck and Bohr went on to discover the quantization of energy and angular momentum. If today we seem to have reason to question our sustaining myth, it ought to be taken as a sign that we are once again making the wrong assumptions, and it ought to spur us on to ferret them out. The Pondicherry interpretation does just that.

2. Quantum mechanics, probabilities, and measurements

Quantum mechanics, the fundamental theoretical framework of contemporary physics, is a probability algorithm. This serves to assign, on the basis of outcomes of measurements that have been made, probabilities to the possible outcomes of measurements that may be made. The inevitable reference to 'measurement' in all standard axiomatizations of unadulterated quantum mechanics was famously criticized by John Bell [15]: "To restrict quantum mechanics to be exclusively about piddling laboratory operations is to betray the great enterprise." The search for more respectable ways of thinking about measurements began early. Since the discovery of special relativity in 1905, physicists had become used to calling them 'observations', and in 1939 London and Bauer [16] were the first to speak of 'the essential role played by the consciousness of the observer'.

Over the years, this red herring has taken many forms. To a few (e.g. [17]), it meant that the mind of the observer actively intervenes in the goings-on in the physical world, to some (e.g. [18,19]), it meant that science concerns our perceptions rather than the goings-on 'out there', while to most (e.g. [12,20,21]), it meant that quantum mechanics concerns knowledge or information about the physical world, rather than the physical world itself.

It is not hard to account for the relative popularity of the slogan 'quantum states are states of knowledge' [22]. The fundamental theory of the physical world is a probability algorithm, and there is a notion that probabilities are *inherently* subjective. Subjective probabilities are ignorance probabilities: they enter the picture when relevant facts are ignored. Because we lack the information needed to predict

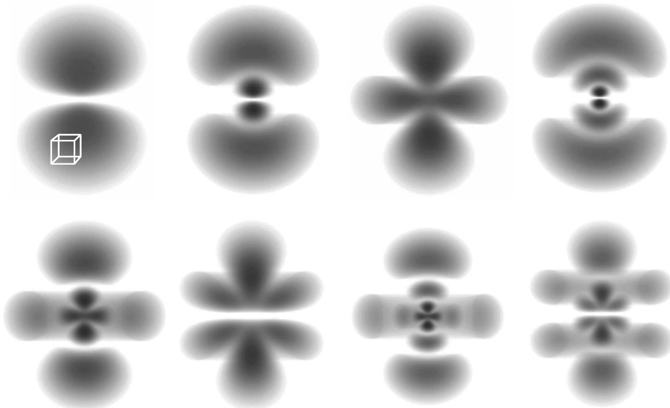

Figure 1. The fuzzy position of the electron relative to the proton in various stationary states of atomic hydrogen.

on which side a coin will fall, we assign a probability to each possibility. Subjective probabilities disappear when all relevant facts are taken into account (which in many cases is *practically* impossible).

The notion that probabilities are inherently subjective is a wholly classical idea. The very fact that our fundamental physical theory is a probability algorithm tells us that the probabilities it serves to assign are *objective*. The existence of objective probabilities (not to be confused with relative frequencies) is due to the fact that even the totality of previous measurement outcomes is insufficient for predicting subsequent measurement outcomes with certainty. The 'uncertainty principle' (the literal meaning of Heisenberg's original term, *fuzziness principle*, is more to the point), guarantees that, unlike subjective probabilities, quantum mechanical probabilities cannot be made to disappear. If the relevant facts are sufficient to predict a position with certainty, there are no facts that would allow us to predict the corresponding momentum. What matters are facts, not what we can know about them.

Again, the very stability of matter hinges on the fuzziness principle. Ordinary objects have spatial extent, are composed of a (large but) finite number of objects without spatial extent, and neither collapse nor explode the moment they are created. The existence of such objects is made possible by the *objective fuzziness* of their internal relative positions and momenta [23], not by our subjective uncertainty about the values of these 'observables'.

What is the proper (i.e., mathematically rigorous and philosophically sound) way of describing the objective fuzziness of the quantum world? It is to assign *objective probabilities* to the possible outcomes of *measurements*. Take the familiar cloud-like images in figure 1. Each image represents the fuzzy position of the electron relative to the proton in a particular state of atomic hydrogen. Neither the electron nor the proton is shown. All we see is a fuzzy position. Or rather, all we see is a cloud of varying density, representing a continuous probability distribution: integrate the density of the cloud over a region like the box inserted in the first image, and get the probability of finding the electron inside if the appropriate measurement is made.

Now imagine that this measurement is actually made. It is an elementary measurement, in the sense that it answers a single yes/no question: is the electron inside that region? Before the measurement, the electron is neither inside nor outside, for if it were inside, the probability of finding it outside would be zero, as would the density of the cloud outside, and if it were outside, the probability of finding it inside would be zero, as would the density of the cloud inside. After the measurement, the electron is either inside or outside. In other words, the measurement creates a new state of affairs. If we want to describe a fuzzy state of affairs *as it is*, without messing with it, we must describe it counterfactually, by assigning probabilities to the possible outcomes of *unperformed* measurements. Clearly, quantum theory's inevitable reference to 'measurement' has little to do with 'piddling laboratory operations'.

While the notion that probabilities are inherently subjective has induced many physicists to believe that quantum mechanics is an epistemic theory, the falsity of the notion that quantum mechanics is an epistemic theory has induced many other physicists to deny that the mathematical formalism of quantum mechanics is fundamentally and irreducibly a probability algorithm. This, too, is a *non-sequitur* arising from the classical notion that probabilities are necessarily subjective. At present the physics community can be divided into three factions:

The first – the majority – does not care what (if anything) quantum mechanics is trying to tell us.

The second embraces agnosticism. It asserts that we cannot describe the quantum world as it is by itself; its features are forever beyond our ken. All we can usefully talk about is the statistical correlations between measurement outcomes (synchronic correlations between outcomes of measurements performed on different systems in space-like relation as well as diachronic correlations between outcomes of measurements performed on the same system at different times).

The third insists that there must be a way of talking about the quantum world as it is by itself, independent of measurements. This faction is split into numerous sects, each declaring to see the light, the ultimate light. Go to any conference on quantum foundations, and you will find their priests pitted in holy war. (My thanks to Fuchs [24] for this observation.)

The agnostics and the priests both have a point and both are wrong. The agnostics have a point in that nothing of relevance can be said without reference to measurements. They are wrong in their belief that the features of the quantum world are beyond our ken. The priests have a point in that it is indeed possible to describe the features of the quantum world. They are wrong in their belief that these features can be described without reference to measurements. The objective fuzziness of the quantum world requires for its description assignments of probabilities to the possible outcomes of unperformed measurements.

3. Ontological implications

Consider again the unperformed elementary measurement designed to ascertain the electron's presence in, or absence from, the small box-like region inside the first 'cloud'. Before the measurement, the electron is neither inside nor outside this region. Yet being inside and being outside are the only relations that can hold between an electron and a given region. If neither relation holds, this region simply does not exist as far as the electron is concerned. But conceiving of a region R is tantamount to making the distinction between 'inside R' and 'outside R'. Hence we may say that the distinction we make between 'inside R' and 'outside R' is a distinction that the electron does not make. Or we may say that the distinction we make between 'the electron is inside R' and 'the electron is outside R' is a distinction that Nature does not make. It corresponds to nothing in the physical world. It exists solely in our heads.

This illustrates a general feature of the quantum world. It imposes limits on the distinctions that are physically warranted, not only spatial distinctions (between inside and outside) but also substantial distinctions (between this object and that object). Probabilities are calculated by summing over alternatives. Each alternative contributes an amplitude. In some cases we first square the amplitudes and then add the results. In all other cases we first add the amplitudes and then square the result. Whenever we add amplitudes first, the distinctions we make between the corresponding alternatives have no counterparts in the physical world.

Because of the limits that quantum mechanics imposes on the objectification of spatial distinctions, spatial distinctions are relative and contingent: *relative* because the difference between 'inside R' and 'outside R' can be real for a given object at a given time and not have any reality for a different object at the same time or for the same object at a different time; and *contingent* because the reality of that difference (for a given object at a given time) depends on whether a relation (inside or outside) exists between this object and that region. Since no material object ever has an exact position, this in turn implies that the spatial differentiation of the physical world is incomplete. It does not go all the way down. If we mentally partition the world into smaller and smaller regions, there comes a point when there is no material object left for which these regions, or the corresponding distinctions, exist. And this again implies that a model of the quantum world cannot be built from the bottom up, on an intrinsically and completely differentiated space-time manifold.

It is odd that for three quarters of a century, the ontological and/or epistemological status of the quantum mechanical wave function Ψ has been the focus of a lively controversy, while the ontological status of the points and instants on which Ψ depends, has hardly ever been called into question. Virtually every published paper concerning the ontology of relativistic quantum mechanics (a.k.a. 'quantum field theory') begins by postulating the existence of an intrinsically and completely differentiated space-time manifold, despite the fact that quantum mechanics tells us that these points and instants exist solely in our heads. As long as the objective existence of such a manifold is postulated, it is safe to say that our attempts to beat sense into quantum mechanics are doomed.

The consequences of the limits that quantum mechanics imposes on our substantial distinctions, are not less drastic. We are allowed to distinguish between *this* particle and *that* particle only to the extent that particles have properties by which they can be distinguished, and they have such properties only to the extent that the possession of such properties can be inferred from the facts. As an illustration, consider an elastic scattering event involving two particles lacking properties that could serve as identity tags. Which outgoing particle is identical with which incoming particle? Quantum statistics implies that the question is meaningless. The challenge is to learn to think about the quantum world in ways that do not lead to meaningless questions. If we say that initially there are two incoming particles, one moving northward and one moving southward (say), and in the end there are two outgoing particles, one moving eastward and one moving westward (say), we cannot help asking that meaningless question. If, on the other hand, we say that initially there is one thing moving both northward and southward, and in the end there is one thing moving both eastward and westward, the meaningless question – which is which? – cannot be asked.

In a more philosophical language, what I am saying is that, in the quantum world, the concept of 'substance' betokens existence but it never betokens individuality. Individuality is strictly a matter of properties. If here you have a particle with these properties and there you have a particle with those properties, what you have is not two substances each with a set of properties but one substance with two sets of properties. This leads to the following conclusions:

(i) Considered by themselves (out of relation to each other, out of relation to measurements, and out of relation to the laws that correlate measurement outcomes), the structureless constituents of matter are identical not merely in the weak sense of exact similarity but in the strong sense of *numerical* identity. (The evening star and the morning star are identical in this way.)

(ii) Quantum mechanics is inconsistent with any attempt to construct a model of reality by assembling a multitude of distinct substances.

The quantum world thus can be built neither on the foundation of an intrinsically differentiated space-time manifold nor out of a pre-existent multitude of individual substances. Any adequate model of the quantum world has to be constructed *from the top down*. What ultimately exists is *one*. Call it whatever you like. Matter and space both come into being when this enters into (more or less fuzzy) spatial relations with itself, for physical space is the totality of existing spatial relations (relative positions and relative orientations), while matter is the corresponding apparent multitude of relata – *apparent* because the relations are *self*-relations. This is about the simplest creation story that can be told, and it is a straightforward consequence of our fundamental theory of matter.

4. The importance of measurements

The existence of fuzzy variables calls for a criterion for the possession of a property (by a system), of a value (by a variable), or of a truth value ('true' or 'false', by a proposition such as 'the electron is in R at the time t'). There is a notion that probability 1 is sufficient for 'is' or 'has'. To see that this notion is wrong, let us ask why the probability of finding a given particle in the union C of two disjoint regions A and B, calculated according to the standard Born rule, is equal to the probability of finding the particle in A plus the probability of finding the particle in B: $p(C) = p(A)+p(B)$. The answer would be self-evident if the particle's position were not fuzzy. In that case the particle would be either in A or in B whenever it is in C, and the probabilities we calculate with the help of the quantum formalism would be subjective. To see that the answer is *not* self-evident, imagine two perfect (100% efficient) detectors $D(A)$ and $D(B)$ each monitoring one of those regions. If both $p(A)$ and $p(B)$ are greater than 0 (and therefore less than 1), it is not certain that $D(A)$ will click and it is not certain that $D(B)$ will click. Yet if $p(C) = 1$ then it *is* certain that either $D(A)$ or $D(B)$ will click. How come?

The answer lies in the fact that quantum mechanical probability assignments are invariably made on the (tacit) *assumption* that a measurement is successfully made: there is an outcome. The existence of an outcome means that either detector clicks. So there is no mystery here, but the upshot is that quantum mechanics gives us probabilities with which this or that outcome is obtained in a successful measurement, *not* probabilities with which this or that property, value, or truth value is possessed. Probability 1 is not sufficient for 'is' or 'has'.

If probability 1 is not sufficient for 'is' or 'has', then what is? As far as unadulterated, standard quantum mechanics is concerned – no surreal particle trajectories *à la* Bohm [25], no non-linear modifications of the Schrödinger equation *à la* Ghirardi *et al* [26] or Pearle [27], no extraneous axioms like the traditional eigenstate–eigenvalue link [28] or the modal semantical rule [29] – the only condition available is to be measured. To paraphrase a well-known dictum due to Wheeler [30], no property (or value) is a possessed property unless it is an indicated property – unless, that is, its possession can be inferred from property-indicating events or states of affairs (a.k.a. 'measurements'). In other words, in the quantum world, properties and values are *extrinsic* rather than *intrinsic* (the latter word signifying 'possessed regardless of whether their possession is indicated').

The fact that measurements *create* their outcomes was most forcefully brought home to us by Greenberger, Horne, and Zeilinger (GHZ) [31], who discovered a state of three entangled spin-1/2 particles that is an eigenstate of the following variables: the product $\sigma_x^1\sigma_x^2\sigma_x^3$ of the x components of the three spins, and the products $\sigma_x^1\sigma_y^2\sigma_y^3$, $\sigma_y^1\sigma_x^2\sigma_y^3$, and $\sigma_y^1\sigma_y^2\sigma_x^3$ of the x component of one spin and the y components of the two other spins. The corresponding possessed eigenvalues are -1 for $\sigma_x^1\sigma_x^2\sigma_x^3$ and $+1$ for the remaining three products. If the individual spin components were in possession of either of their possible values ($+1$ or -1) regardless of measurements, the following equations would hold for their possessed values:

$$s_x^1 s_y^2 s_y^3 = 1, \quad s_y^1 s_x^2 s_y^3 = 1, \quad s_y^1 s_y^2 s_x^3 = 1, \quad s_x^1 s_x^2 s_x^3 = -1. \tag{1}$$

Multiply the left-hand sides of the first three equations to find that it equals $s_x^1 s_x^2 s_x^3$. The product of the right-hand sides equals 1, implying that $s_x^1 s_x^2 s_x^3 = 1$, in direct contradiction to the fourth equation. So unless a (compatible) set of spin components are actually measured, no values can be attributed to them.

Why is it that physical variables have values only if, and only to the extent that, values are indicated ('measured')? Take positions. Since spatial distinctions are relative and contingent, physical space is anything but an intrinsically differentiated expanse. Neither regions of space nor positions exist 'by themselves'. Philosophically speaking, positions are properties, not substances; they exist only if and when they are possessed. But properties are possessed only if their possession is indicated, and the possession of the property of being in a region R can only be indicated if R, or the distinction between inside R and outside R, is realized (made real) by a detector (in the broadest sense of the word: anything capable of indicating the presence of something somewhere). A detector, therefore, performs *two* necessary functions: to indicate the presence of an object in its sensitive region R, and to make the predicates 'inside R' and 'outside R' available for attribution. Much the same goes for any other measurement apparatus, not least because every measurement outcome is ultimately indicated by the position of something like a pointer: it serves to realize indicatable properties as well as to indicate them.

And why are certain variables incompatible? Because the corresponding properties cannot be simultaneously *realized*. This is particularly clear in the case of spin components. In the absence of an axis that is physically realized by a magnetic gradient, the values 'up' and 'down' are undefined. Since the superposition of two magnetic fields with different gradients yields a single magnetic field with a single gradient, only one axis can be realized at a time.

If the points and instants on which Ψ functionally depends have no counterparts in the physical world, what is the meaning of the spatial and temporal arguments of Ψ? The wave function is one of the quantum mechanical tools for calculating probabilities. It is the appropriate tool when we assign probabilities on the basis of an earlier outcome of a complete measurement. We provide two kinds of information: (i) the difference $t - t'$ between the *physically realized* time t of the measurement to the possible outcomes of which probabilities are assigned, and the *physically realized* time t' of the measurement on the basis of whose outcome probabilities are assigned; (ii) a *physically realized* region R (the small box-like region above, or any region of the system's configuration space). Without this information, the wave function is an empty shell devoid of physical significance.

Having plugged in this information, Ψ gives us the probability of finding the electron (or the system) in R *given that* the corresponding elementary test is successfully made at the time t. Once we have this probability for all conceivable regions, we can calculate the mean value, the variance, and the higher moments that characterize a fuzzy relative position. Using the Fourier transform of Ψ, we can similarly compute the various moments of the corresponding fuzzy momentum. And under certain conditions this gives us a complete description of a fuzzy state of affairs. (The complete description of the fuzzy state of affairs that obtains *between* successive measurements is given by the time-symmetric probability algorithm due to Aharonov *et al* [32], rather than by the Born rule, which bases probabilities on earlier *or* later outcomes [2].)

5. Explanations or delusions?

Consider once again three spin-1/2 particles in the GHZ state. By measuring the x components or the y components of two spins, we can predict with certainty the x component of the third spin. By measuring the x component of one spin and the y component of another spin, we can predict with certainty the y component of the third spin. And by measuring the z component of one spin, we can predict with certainty the z components of the two other spins. How is it possible to predict any spin component of any of the three particles after subjecting the other particles to the appropriate measurements, considering that (i) the GHZ correlations are independent of the distance between the three particles (in principle they can be light years apart) and (ii) these measurements do not reveal pre-existent values but *create* their outcomes?

Counter question: Why do the GHZ correlations *seem* impossible? If we believe, as Einstein did, that 'things claim an existence independent of one another' whenever they 'lie in different parts of space' [33], then such correlations are indeed impossible. Fact is that the three particles, irrespective of the distances between them, are *not* independent of one another. Fiction is that they lie in different parts of space. As we have seen, space has no parts. If we insist on thinking of space as a self-existent expanse, to which spatial relations owe their quality of spatial extension, quantum mechanics does not permit us to think of this expanse as being divided. The spatial multiplicity of the world rests on the existence of more or less fuzzy relations, rather than on the existence of spatial parts. One might say, paradoxically yet to the point, that, as far as 'space itself' is concerned, there is only one place, and this is everywhere. Instead of separating things, space (qua expanse) unites them by being devoid of any kind of multiplicity. However, since being extended and being undifferentiated makes a rather paradoxical combination of properties, it is much better to look on space, not as a self-existent expanse, but as the totality of spatial relations that hold between material objects. Then one cannot even conceive 'parts of space'.

We saw, moreover, that the quantum world has room for only one substance. Considered by themselves, the structureless constituents of matter are identical in the strong sense of numerical identity. All existing relations are self-relations. How then could things possibly 'claim an existence independent of one another'?

It is one thing to dispose of misconceptions that make the peculiar non-local behavior of quantum systems seem impossible. It is quite another to *explain* the quantum mechanical correlation laws. If these laws are indeed the fundamental laws of physics (and apart from our dogged insistence on explaining from the bottom up, we have no reason to believe that they are not), then they cannot be explained the way Kepler's laws of planetary motion can be explained by Newton's law of gravity. Only a law that is not fundamental can be so explained.

Can we interpret the quantum mechanical correlation laws as *descriptive* of a physical mechanism or process? Where the synchronic correlations are concerned, this notion is patently absurd. Alas, to many the absurdity of interpreting the diachronic correlation laws as descriptive of some physical process does not seem to be obvious, despite the preposterous consequences of doing so, such as wave function collapse or lack of relativistic covariance and of gauge invariance.

As an algorithm for assigning probabilities to possible measurement outcomes on the basis of actual measurement outcomes, Ψ has two obvious dependences. It depends continuously on the time of a measurement: if you change this time by a small amount, the probabilities assigned to the possible outcomes change by small amounts. And it depends discontinuously on the outcomes that constitute the assignment basis: if you take into account an outcome that was not previously taken into account, the assignment basis changes unpredictably as a matter of course. Transmogrify Ψ into the description of an evolving, instantaneous state of affairs, and you are faced with the mother of all quantum mechanical pseudoproblems: why are there two modes of evolution rather than one?

While the real trouble with von Neumann's formulation of quantum mechanics [34] is that it postulates two modes of evolution rather than *none*, many believe that the trouble with it is that it postulates two modes of evolution rather than *one*. Instead of addressing the root of the disease – the transmogrification of a probability algorithm into an evolving ontological state – they make matters worse by postulating a universal quantum state that evolves deterministically at all times.

This postulate is inconsistent with the ontological implications of the quantal probability algorithm. If the wave function represented something that evolves deterministically, it would evolve in a completely differentiated time. Unitary evolution implies that the world is infinitely differentiated time-wise, whereas the quantum mechanical correlation laws imply that the world is infinitely differentiated neither space-wise nor time-wise, as the following will show.

Like the properties or values themselves, the times at which properties or values are possessed must be indicated (measured) in order to exist. As detectors are needed not only to indicate but also to realize positions, so clocks are needed not only to indicate but also to make times available for attribution. Since clocks realize times by the positions of their hands, and since exact positions do not exist, neither do exact times. (Digital clocks indicate times by transitions from one reading to another, without hands, but the 'uncertainty' principle for energy and time implies that these transitions cannot occur at exact times [35].) Exact times therefore are not available for attribution. Like the existing spatial relations, the existing temporal relations are fuzzy. From this the incomplete temporal differentiation of the physical world follows in exactly the same way as its incomplete spatial differentiation follows from the fuzziness of positions.

There are several reasons, most of them psychological and none of them physically warranted, why we tend to believe in the existence of an evolving instantaneous physical state. And once we believe that there is such a state, it is obviously hard to avoid thinking of the wave function as representing such a state, and of the evolution of the wave function as a physical process.

For one, classical physics appears to be consistent with these notions. It therefore deserves to be pointed out that even the idea that a *classical* dynamical law describes (i) the evolution of a physical state and (ii) a physical *process*, rests on nothing but the physically unwarranted transmogrification of an algorithm for calculating the *effects* of interactions into a physical process. Take classical electrodynamics. It allows us to calculate the effects that charges have on charges. The calculation involves two steps. (i) Given the distribution and motion of charges, we calculate six functions, the components of the electromagnetic field. (ii) Given these six functions, we calculate the effect that those charges have on any other charge. And that is that. The rest is embroidery, including the belief that the unobservable electromagnetic field is a physical entity in its own right, that it is locally generated by charges, that it locally acts on charges, that it physically mediates interactions and propagates energy and momentum (which are construed as some localizable kind of stuff), and that this *explains* how charges act on charges. If we were honest, we would admit that all we have in classical physics is correlations that, being deterministic, can be thought of as correlations between causes and effects. We do not have the merest notion of how (through what mechanism or process) causes produce effects.

Among the psychological reasons for our belief in an evolving instantaneous physical state and the ensuing misconceptions, the following deserves to be mentioned: while our successive experience of reality makes it natural for us to hold that only the present is real, or that it is somehow 'more real' than the future or the past, our self-experience as agents makes it natural for us to hold that the known or in principle knowable past is 'fixed and settled', and that only the unknown and apparently unknowable future is 'open'. None of this has anything to do with physics.

For one thing, it is impossible to consistently project the experiential Now into the physical world. To philosophers, the perplexities and absurdities entailed by the notion of a changing objective present or a flowing time are well-known [36]. To physicists, the subjectivity of a temporally unextended yet persistent and persistently changing present was brought home by the relativity of simultaneity. The same is implied by quantum mechanics, inasmuch as the incomplete differentiation of the quantum world rules out the existence of an (evolving) instantaneous state.

For another thing, the physical correlation laws (whether classical or quantum) know nothing of a preferred direction of causality. They are time-symmetric. They let us retrodict as well as predict. The figment of a causal arrow is a projection, into the physical world, of our sense of agency, our ability to know the past, and our inability to know the future. It leads to the well-known folk tale according to which causal influences reach from the non-existent past to the non-existent future through persisting 'imprints' on the present: If the past and the future are unreal, the past can influence the 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'. This evolving instantaneous state includes not only all presently possessed properties but also traces of everything in the past that is causally relevant to the future.

In classical physics, this is how we come to conceive 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). In quantum physics, this is how we come to seize on a probability algorithm that depends on the relative time between measurements and on the outcomes of earlier measurements, to transmogrify the same into an evolving instantaneous state, and to think of its evolution as a physical process.

The bottom line: we have no reason to mourn the loss of our ability to interpret the physical correlation laws as descriptive of a physical process (the evolution of a physical state), inasmuch as the idea that we once had this ability is a delusion. We have lost nothing. Instead, we have gained significant insights into the spatiotemporal and substantial aspects of our world.

6. Quantum mechanics and reality

The extrinsic nature of physical properties and values appears to entail a vicious regress. No value is a possessed value unless it is indicated, and a pointer position is no exception; it has a value only because, and only to the extent that, its value is indicated by other 'pointer positions'. How, then, can a detector (in the broadest sense) realize a region R (or the distinction between 'inside R' and 'outside R')? Is it possible to terminate this regress without invoking an extra-physical principle like consciousness? Indeed it is. As we shall see, this possibility crucially depends on the incomplete spatial differentiation of the physical world.

The possibility of obtaining evidence of the departure of an object O from its classically predictable position (given all relevant earlier position-indicating events) 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 obtaining such evidence is extremely low. Hence *among* these objects there are many 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 indicate an unpredictable value, one exception has to be made: its position may change unpredictably if and when it serves to indicate such a value.

Decoherence investigations [37–39] have shown for various reasonable definitions of 'macroscopic' that the probability of finding a macroscopic object where classically it could not be, is extremely low. This guarantees the existence of macroscopic objects according to our stricter definition, which are never actually found where classically they could not be. The correlations between the indicated positions of these objects are deterministic in the following sense: their fuzziness never evinces itself through outcomes that are inconsistent with predictions that are based on earlier outcomes and a classical law of motion. Macroscopic objects (including pointers) follow trajectories that are only counterfactually fuzzy. That is, they are fuzzy only in relation to an imaginary background that is more differentiated spacewise than is the actual world. In the physical world, there is nothing over which they are 'smeared out'. So we cannot say that they are fuzzy – nor can we say that they are sharp: 'not fuzzy' implies 'sharp' only if we postulate the intrinsically and completely differentiated background space that does not exist in the quantum world.

To terminate that seemingly vicious regress, we must be allowed to look upon the positions of macroscopic objects – macroscopic positions, for short – as intrinsic, as self-indicating, or as real *per se*. The reason why this is indeed legitimate, is that the extrinsic nature of the values of physical variables is a consequence of their fuzziness. If macroscopic positions are not manifestly fuzzy, we have every right to consider them intrinsic – notwithstanding that they are at the same time extrinsic, for even the Moon has a position only because of the myriad of 'pointer positions' that betoken its whereabouts. The reason why macroscopic positions can be both extrinsic and intrinsic is that they indicate each other so abundantly, so persistently, and so sharply that they are only counterfactually fuzzy.

Nothing therefore stands in the way of attributing to the entire system of macroscopic positions an independent reality, and nothing prevents us from considering the entire system of possessed relative positions or spatial relations (including the corresponding multitude of material relata) as self-contained. What the extrinsic nature of physical properties forbids us, is to attribute independent reality to an individual macroscopic position, and to model the physical world from the bottom up. We are not entitled to the belief that the macroworld is what it is because its constituents are what they are. The 'foundation' is the macroworld – the system of macroscopic positions, in which value-indicating events occur as unpredictable transitions in compliance with the quantum mechanical correlation laws. All other properties of the physical world (in particular the properties of the so-called 'quantum domain') exist solely because they are indicated by the goings-on in the macroworld (the so-called 'classical domain'). As philosophers would say, the properties of the quantum domain *supervene* on the goings-on in the classical domain.

A fundamental physical theory concerned with nothing but statistical correlations between value-indicating events, presupposes the occurrence of such events. The philosphically most challenging problem is to understand how such a theory can be complete – how it can at the same time encompass the value-indicating events. The solution of this problem calls for a judicious choice on our part: which substructure of the entire theoretical structure of quantum mechanics corresponds to what exists? Independent reality can be attributed consistently neither to an intrinsically divided 'manifold' nor to a multitude of microscopic constituents nor to an evolving instantaneous 'quantum state' but only to the macroworld.

The problem of making sense of quantum mechanics is often misconceived as the problem of how a classical domain emerges in a quantum world. Some feel called upon to explain how possibilities – or worse, probabilities [40] – become facts, some try to show how properties emerge [41], and some wish to tell us why events occur [42]. Since the quantum domain supervenes on the goings-on in the macroworld, and since independent reality can be consistently attributed only to the macroworld, there is no 'underlying reality' from which the macroworld could emerge. Saying in common language that a possibility becomes a fact is the same as saying that something that is possible – something that *can* be a fact – actually *is* a fact. This non-problem becomes a pseudoproblem if the common-language 'existence' of a possibility is construed as another kind of existence – a matrix of 'propensities' [43] or 'potentialities' [44,45] – that transforms into the genuine article (non-existence proper or existence proper) by way of measurement. (Pseudoproblems of this kind are bound to arise if one misconstrues a probability algorithm as an evolving, instantaneous physical state.) There is no such matrix.

Nor is it possible to explain why events occur. As we observed in §4, quantum mechanical probability assignments are made with the tacit assumption that a measurement is successfully made: there is an outcome. If quantum mechanics is our fundamental theoretical framework, and if every quantum mechanical probability assignment *presupposes* the (actual or counterfactual) success of a measurement (in the form of a value-indicating event), then quantum mechanics cannot possibly supply sufficient conditions for the occurrence of such an event. The events by which properties or values are indicated, are *uncaused*. (While this implies that perfect detectors are a fiction, it does not prevent us from invoking perfect detectors to assign probabilities to the possible outcomes of *unperformed* measurements.)

So does quantum mechanics encompass the system of macroscopic positions, in which value-indicating events occur as unpredictable transitions? It does. The fuzziness of all existing relative positions implies the incomplete spatial differentiation of the physical world, on account of which the least fuzzy positions in existence are at the same time sharp and the least fuzzy extrinsic properties are at the same time intrinsic. This makes the attribution of independent reality to the system of macroscopic positions both possible and inescapable.

Do the quantum mechanical correlation laws *account* for the correlata which they presuppose? Since value-indicating events are uncaused, they do not. This is no more a shortcoming of quantum physics than it is a shortcoming of classical physics that it cannot explain why there is anything, rather than nothing at all. Physics is concerned with laws, and hence with nomologically possible worlds – worlds consistent with the laws. It would be preposterous to expect from it an explanation of why the actual world exists. Quantum physics is concerned with correlation laws, and it would be preposterous to expect it to account for the existence of the correlata. We have done our utmost if we have demonstrated not only the consistency of the correlation laws with the existence of correlata (which is trivial) but also the *completeness* of the correlation laws: they can account for anything but the factuality of (value-indicating) facts. Many aspects of a value-indicating event can be understood in terms of the deterministic correlations that structure the macroworld, and everything else *but* the actual occurrence of such an event can be understood in terms of the statistical correlations that structure the (supervenient) microworld. The absence of causally sufficient conditions for the occurrence of an event of type X does not preclude a complete theoretical analysis of events of type X. As we have seen, our inability to formulate sufficient conditions for the occurrence of a value-indicating event does not imply the incompleteness of quantum mechanics but is instead a consequence of the incompleteness of the quantum world, in particular its incomplete spatio-temporal differentiation.

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