Quantum Nonlocality Explained

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Abstract

Quantum theory's violation of remote outcome independence is explained in the context of a novel interpretation of the theory, in which the unavoidable distinction between the classical and quantum domains is understood as a distinction between the manifested world and its manifestation.

1 Preliminaries

There are at least nine formulations of quantum mechanics [1], among them Heisenberg's matrix formulation, Schrödinger's wave-function formulation, Feynman's path-integral formulation, Wigner's phase-space formulation, and the density-matrix formulation. The idiosyncracies of these formations have much in common with the inertial reference frames of relativistic physics: anything that is not invariant under Lorentz transformations is a feature of whichever *language* we use to describe the physical world rather than an objective feature of the physical world. By the same token, anything that depends on the particular formulation of quantum mechanics is a feature of whichever *mathematical tool* we use to calculate the values of observables or the probabilities of measurement outcomes rather than an objective feature of the physical world.

That said, when it comes to addressing specific questions, some formulations are obviously more suitable than others. As Styer *et al.* [1] wrote,

> The ever-popular *wavefunction formulation* is standard for problem solving, but leaves the conceptual misimpression that [the] wavefunction is a physical entity rather than a mathematical tool. The *path integral formulation* is physically appealing and

> generalizes readily beyond the domain of nonrelativistic quantum mechanics, but is laborious in most standard applications.

When it comes to the problem of interpretation, of making physical sense of the theory, of giving some account of the nature of the physical world and/or our epistemological relation to it that serves to explain how it is that the statistical regularities predicted by the theory come out the way they do, or the problem of establishing the theory's semantic consistency, Feynman's path-integral formulation [2] far surpasses the wave-function formulation.

The term "semantic consistency" was introduced by von Weizsäcker. By the semantic consistency of a theory he meant "that its preconceptions, how we interpret the mathematical structure physically, will themselves obey the laws of the theory" [3, p. 260]. In the context of the wave-function formulation, the challenge of establishing the semantic consistency of quantum mechanics is formidable. What needs to be shown is that the correlations predicted by the theory are consistent with the existence of their correlata. While the existence of measurement outcomes is presupposed by the theory and for this reason cannot be accounted for by it, it obviously has to be consistent with it, and this does not seem to be the case. The stumbling block is the so-called eigenvalue-eigenstate link, which postulates that probability 1 is sufficient for factuality. Here is how this interpretive principle was formulated by Dirac [4, pp. 46–47]:

> The expression that an observable "has a particular value" for a particular state is permissible ... in the special case when a measurement of the observable is certain to lead to the particular value, so that the state is an eigenstate of the observable.

The wave-function formulation presents us not only with the challenge to explain why the unitary evolution is disrupted by the occasional collapse, which only results in the assignment of probability 1 to a particular outcome, but also with the challenge to explain the factuality of that outcome [5]. That this cannot be done is the gist of insolubility proofs of the so-called objectification problem due to Mittelstaedt [6, Sect. 4.3b] and Busch *et al.* [7, Sect. III.6.2]. If one tries to turn this problem into a postulate by adopting the eigenvalue–eigenstate link, inconsistency results, as was pointed out by Bub [8]:

> The basic question is whether it is consistent with the unitary dynamics to take the macroscopic measurement "pointer" or, in general, the macroworld as definite. The answer is "no," if we

> accept an interpretative principle sometimes referred to as the "eigenvalue-eigenstate link."[1]

Since we have no reason to doubt either the validity of the correlations that quantum mechanics predicts or the existence of their correlata, it must be possible to demonstrate the consistency of the correlations with their correlata, but for this one has to relinquish the eigenvalue–eigenstate link. The demonstration then proceeds in two steps. The first step is to show that the physical world cannot be spatially differentiated (or partitioned) "all the way down." The spatial differentiation of the physical world is incomplete. Physical space (as distinct from a calculational tool) cannot be modeled as an actually existing manifold of points. This invalidates the insolubility proofs of the objectification problem, inasmuch as these implicitly assume that the spatial differentiation of the physical world is complete. But if physical space cannot be modeled as an actually existing manifold of points labeled by triplets of real numbers, then physical time cannot be represented by an actually existing set of instants labeled by real numbers, and this means that the wave function's dependence on time cannot be the continuous time-dependence of an evolving physical state. The t in $\psi(t)$ can only refer to the time of the measurement to the possible outcomes of which $\psi(t)$ serves to assign probabilities. Bohr was right: what happens between a system preparation and a measurement is a holistic phenomenon, which cannot be decomposed into the unitary evolution of a quantum state and a subsequent "collapse" of the same:

> all unambiguous interpretation of the quantum mechanical formalism involves the fixation of the external conditions, defining the initial state of the atomic system concerned and the character of the possible predictions as regards subsequent observable properties of that system. Any measurement in quantum theory can in fact only refer either to a fixation of the initial state or to the test of such predictions, and it is first the combination

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[1] Bub claims that the unitary "dynamics" can be made consistent with the existence of measurement outcomes by stipulating that "the decoherence 'pointer' selected by environmental decoherence" is always definite. Decoherence then "guarantees the continued definiteness or persistent objectivity of the macroworld." Decoherence, however, merely displaces the coherence of the system composed of apparatus and object system into the degrees of freedom of the environment, causing the objectification problem to reappear as a statement about the system composed of environment, apparatus, and object system. Since the mixture obtained by tracing out the environment does not admit an ignorance interpretation, it can resolve the problem only FAPP (Bell's universally adopted abbreviation of "for all practical purposes").

> of measurements of both kinds which constitutes a well-defined phenomenon. [9]

This renders the wave-function formulation unsuitable for addressing the problem of interpretation.

The second step of the demonstration of the semantic consistency of quantum mechanics is to deduce from the incompleteness of the spatiotemporal differentiation of the physical world the existence of a non-empty class of objects whose positions are “smeared out” only relative to an imaginary spatiotemporal background that is more differentiated than the physical world. The two steps in outline [5, 10, 11, 12, 13]:

Step 1. While quantum mechanics can tell us that the probability of finding a particle in a *given* region of space is 1, it is incapable of *giving* us a region of space. For this a detector is needed. A detector is needed not only to indicate the presence of a particle in a region but also—and in the first place—to realize a region, so as to make it possible to attribute to a particle the property of being inside. Speaking more generally, a macroscopic apparatus is needed not only to indicate the possession of a property by a quantum system but also—and in the first place—to realize a set of properties so as to make them available for attribution to the system. (In addition a macroscopic clock is needed to realize attributable times.) But if detectors are needed to realize regions of space, space cannot be intrinsically partitioned. If at all we conceive of it as partitioned, we can do so only as far as regions of space can be realized—i.e., to the extent that the requisite detectors are physically realizable. Because this extent is limited by the indeterminacy principle, the spatial differentiation of the physical world is incomplete; it does not go “all the way down.”

Step 2. In an incompletely differentiated world, there will be objects whose position distributions are and remain so narrow that there are no detectors with narrower position distributions. If anything truly deserves the label “macroscopic,” it is these objects. While decoherence arguments can solve the objectification problem only FAPP, they quantitatively support the existence of macroscopic positions—positions whose indefiniteness is never revealed in the only way it could be revealed, i.e., through a departure from what the classical laws predict. The testable correlations between the outcomes of measurements of macroscopic positions are therefore consistent with *both* the classical *and* the quantum laws. This makes it possible to attribute to macroscopic positions a measurement-independent reality, and that makes it possible for macroscopic positions to define the obtainable values of observables and to indicate the outcomes of measurements.

2 Beyond semantic consistency

Trigger terms like “measurement apparatus,” “macroscopic object,” and “Bohr” are likely to elicit charges of instrumentalism, Copenhagenism, or some such. Common or garden instrumentalism, however, leaves the meaning of “macroscopic” up for grabs. What has been accomplished so far is a consistent definition of “macroscopic” in the theory’s own terms. And that’s only the beginning.

To be able to go beyond establishing semantic consistency, to give some account of the nature of the physical world and/or our epistemological relation to it that serves to explain how it is that the statistical regularities predicted by the theory come out the way they do, we need to replace the untenable eigenvalue–eigenstate link by a different interpretive principle, and we need a different formulation of the theory to do this, namely Feynman’s [2].

Both the wave-function formulation and Feynman’s feature a pair of dynamical principles. In the former they are unitary evolution and collapse, in the latter they are summation over amplitudes (followed by taking the absolute square of the sum) and summation over probabilities (preceded by taking the absolute square of each amplitude). In the context of the wave-function formulation, unitary evolution seems “normal”; what calls for explanation is collapse. In the context of Feynman’s formulation, adding probabilities seems “normal” as it is what classical probability theory leads us to expect; what calls for explanation is why we have to add amplitudes. What is at issue, therefore, is not what causes the wave function to collapse but why we have to add amplitudes whenever quantum mechanics requires us to do so. To answer this question I have proposed the following interpretive principle:

(I) Whenever quantum mechanics requires us to add amplitudes, the distinctions we make between the alternatives correspond to nothing in the physical world.

This is a statement about the structure or constitution of the physical world, not a statement merely of our practical or conceptual limitations.

While the wave-function formulation stumps us with the dual problem of collapse and objectification, Feynman’s formulation presents us with a question to which there is a straightforward answer: the reason quantum mechanics requires us to add amplitudes is that the distinctions we make between the alternatives cannot be objectified (represented as real). We know why

> Any determination of the alternative taken by a process capable of following more than one alternative destroys the interference between alternatives [2].

By stating the indeterminacy principle in this way, Feynman does not mean to imply that the "destruction" is brought about by a physical process.

Armed with a new interpretive principle, we set out to apply it to two paradigmatic setups, one concerning distinctions between *regions* of space (or spacetime), the other concerning distinctions between *things*. Applied to a two-way interferometer experiment, (I) tells us that the distinction we make between "the particle went through the left arm" and "the particle went through the right arm" corresponds to nothing in the physical world. Since this distinction rests on *spatial* differences between the alternatives, it follows that space cannot be an intrinsically differentiated expanse. Its so-called parts need to be physically realized by the sensitive regions of detectors (defined in terms of macroscopic positions), and we have seen that the indeterminacy principle prevents them from being realized "all the way down."

Applied to an elastic scattering event involving two particles of the same type (say, two incoming particles N and S, two outgoing particles E and W), (I) tells us that the distinction we make between the alternative identifications

$$N = E, S = W \quad \text{and} \quad N = W, S = E$$

corresponds to nothing in the physical world. There is no answer to the question: "Which outgoing particle is identical with which incoming particle?" Now why would that be so? Here too there is a straightforward answer: because the incoming particles (and therefore the outgoing ones as well) are *one and the same entity.* What's more, there is no compelling reason to believe that this identity ceases when it ceases to have observable consequences owing to the presence of individuating properties. We are free to take the view that *intrinsically* each particle is numerically identical with every other particle. What presents itself here and now with these properties and what presents itself there and then with those properties is one and the same entity.[2] In what follows I shall call it "Being." If you prefer any other name, be my guest.

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[2] According to French [14], quantum mechanics is "compatible with two distinct metaphysical 'packages,' one in which the particles are regarded as individuals and one in which they are not." Esfeld [15] begs to differ: it is not "a serious option to regard quantum objects as possessing a primitive thisness (haecceity) so that permuting these objects amounts to a real difference."

3 Manifestation

Perhaps the main reason it is so hard to make sense of the quantum theory is that it answers a question we are not in the habit of asking. Instead of asking what the ultimate constituents of matter are and how they interact and combine, we should ask: *how are forms manifested?* This question, too, has a straightforward answer [5, 12]: *The shapes of things are manifested with the help of reflexive spatial relations.* By entering into reflexive spatial relations, Being gives rise to (i) what *looks like* a multiplicity of relata if the reflexive quality of the relations is ignored and (ii) what *looks like* a substantial expanse if the spatial quality of the relations is reified. As Leibniz said, *omnibus ex nihilo ducendis sufficit unum*—one is enough to create everything from nothing. A single self-existent entity is enough to create both the relata we call particles and the expanse we call space.

The following brief reflection leads to the same conclusion. While the non-relativistic theory allows us to conceive of a physical system as being composed of a definite number of parts, and to conceive of its form as being composed of a definite number of spatial relations (to which values can be attributed only if and when they are measured), the relativistic theory requires us to treat the number of a system's parts as just another quantum observable, which has a definite value only if and when it is measured. There is therefore a clear sense in which a quantum system is always one, the number of its parts being just one of its properties and having a definite value only if and when measured.

To my mind, the most fruitful way to understand the indispensable distinction between the classical or macroscopic domain (containing measurement-independent properties) and the non-classical or quantum domain (whose properties exist only if, when, and to the extent that they are measured) is that it is essentially a distinction between the *manifested world* and its *manifestation.*

There is a curious mutual dependence between the two domains, which was alluded to by Landau and Lifshitz [16, p. 3] when they wrote that "quantum mechanics ... contains classical mechanics as a limiting case, yet at the same time it requires this limiting case for its own formulation".[3] It was also pointed out by Redhead [18] as a salient feature of the Copenhagen interpretation: "In a sense the reduction instead of descending linearly towards the elementary particles, moves in a circle, linking the reductive basis

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[3] To be precise, what quantum mechanics requires for its formulation is the *language* of classical physics rather than classical physics itself [17].

back to the higher levels".[4] But it does not seem to have been properly understood.

The manifestation of the world is a transition from an intrinsically undifferentiated (and therefore unqualifiable) Being—a condition of complete indefiniteness and indistinguishability—to a condition of complete or maximal definiteness and distinguishability, and what occurs in the course of this transition—what is not completely definite or distinguishable—can only be described in terms of probability distributions over what is completely definite and distinguishable.[5] What is instrumental in the manifestation of the world can only be described in terms of its result, the manifested world.

We live in a world that allows itself to be understood in terms of interacting objects and causally connected events. Quantum mechanics allows us to describe this world as emergent, not from some mystical domain of potentiality, nor by a dynamical process, nor through environmental decoherence, but by a transition from unity to multiplicity, across a dimension that is neither temporal nor spatial. The fact that quantum theory's "explanatory arrow" point from unity to multiplicity is certainly one of the principal reasons it is so hard to develop a convincing interpretation the theory, for our inveterate tendency is to explain in the opposite direction, i.e., to explain unity (wholes) in terms of multiplicity (their parts and internal relations).

The least differentiated stage of the transition from complete indefiniteness and indistinguishability to complete or maximal definiteness and distinguishability, which is probed by high-energy physics, is known to us through correlations between the counterfactual clicks of non-existent detectors, i.e., in terms of transition probabilities between in-states and out-states. At energies low enough for atoms to be stable, it becomes possible to conceive of objects with fixed numbers of components, and these we describe in terms of correlations between the possible outcomes of unperformed measurements. Molecules, arising at the next stage, are the first objects with forms that

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[4] While the manifested world can be described in terms of interacting objects and causally connected events, its manifestation cannot be described in these terms. It can only be described in terms of correlations between in-states and out-states, or between object preparations and measurement outcomes, which *can* be described in the classical language of interacting objects and causally connected events.

[5] This, in fact, is why the formal apparatus of quantum mechanics is a calculus of correlations, whose correlata are measurement outcomes. It is also worth stressing that the indeterminism of quantum mechanics is rooted in this underlying indeterminacy. Instead of consisting *fundamentally* in the existence of unpredictable changes disrupting a predictable evolution, it is a consequence of indeterminacies that *evince* themselves through unpredictable transitions in the values of outcome-indicating positions (Bub's "decoherence pointers").

can be visualized—their atomic configurations. But it is only the finished product—the manifested world, which allows itself to be understood in terms of interacting objects and causally connected events—that gives us the actual detector clicks and the actual measurement outcomes which allow us to study the correlations in terms of which quantum mechanics describes the various stages of the process of manifestation.

Quantum mechanics thus presents us with a so far unrecognized kind of causality—unrecognized, I believe, within the scientific literature albeit well-known to metaphysics, for the general philosophical pattern of a single world-essence manifesting itself as a multiplicity of physical individuals is found throughout the world.[6] This causality is associated with the atemporal process of manifestation. It must be distinguished from its more familiar temporal cousin, which links states or events across time or spacetime. The latter causality plays no role in the manifestation. Being part of the world drama, it does not take part in setting the stage for it.[7]

While an atemporal causality does not, of course, involve a temporal sequence, it does entail a sequence of stages. Although the stages of the transition from complete indefiniteness and indistinguishability to complete or maximal definiteness and distinguishability—from numerically identical particles via non-visualizable atoms and partly visualizable molecules to macroscopic objects—coexist, it makes sense to think of the more differentiated stages as emergent from the less differentiated ones, despite the difficulty we face in conceiving of this emergence without recourse to temporal notions—a difficulty not unlike the one we face in *not* conceiving of temporal succession in analogy with spatial extension. There is a causal arrow that makes it legitimate to speak of "stages," in the sense that the multiplicity exists *because* of the spatial relations that Being entertains with itself.

4 The EPR-Bohm scenario

The core principle of Feynman's formulation of quantum mechanics—add amplitudes if nothing "destroys" the interference between the alternatives—

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[6] Some of its representatives in the Western hemisphere are the Neoplatonists, John Scottus Eriugena, and the German idealists. The quintessential Eastern example is the original (pre-illusionist) Vedanta of the Upanishads [19, 20, 21].

[7] Ladyman and Ross [22, pp. 258, 280] concur: "the idea of causation has similar status to those of cohesion, forces, and [individual] things. It is a concept that structures the notional worlds of observers. . . . There is no justification for the neo-scholastic projection of causation all the way down to fundamental physics and metaphysics."

covers not only the two-slit experiment with electrons, which according to Feynman [23, Sect. 1–1] "has in it the heart of quantum mechanics," and the "miraculous identity of particles of the same type," which according to Misner *et al.* [24, p. 1215] "must be regarded, not as a triviality, but as a central mystery of physics," but also the entanglement of systems in spacelike relation, which for Schrödinger [25] was "not … one but rather *the* characteristic trait of quantum mechanics." In our elastic scattering experiment with particles of the same type, initially moving northward and southward, respectively, the final probability of finding one particle moving eastward and one moving westward takes the form

$$|\langle EW|NS\rangle \pm \langle WE|NS\rangle|^2, \tag{1}$$

where the sign depends on whether the particles are bosons or fermions. This result can also be obtained by using the Born rule with the following initial and final states:

$$|\psi_i\rangle = \frac{1}{\sqrt{2}}\big(|NS\rangle \pm |SN\rangle\big), \quad |\psi_f\rangle = \frac{1}{\sqrt{2}}\big(|EW\rangle \pm |WE\rangle\big). \tag{2}$$

It is now readily seen why the evolving-states formulation of quantum mechanics requires the use of (anti)symmetrized particle states. If we were to use $|AB\rangle$ instead of the (anti)symmetrized product, we would introduce, in addition to the physically warranted distinction between "the particle in A" and "the particle in B," the physically unwarranted distinction between the "first" or "left" particle and the "second" or "right" particle (in the expression $|AB\rangle$). This would be justified if the particles carried "identity tags" corresponding to "left" and "right," in which case we would be required to add probabilities, not amplitudes. If the distinction between "the particle in A" and "the particle in B" is the only physically warranted distinction, the distinction between the "left" particle and the "right" particle must be eliminated, and this is achieved by (anti)symmetrization.

To apply the core principle of Feynman's formulation to a pair of entangled systems in spacelike relation, we need to take account of the fact that Born probabilities are time-symmetric. The Born rule can be used to assign probabilities to the possible outcomes of an earlier measurement on the basis of the actual outcome of a later measurement as well as vice versa. (This is one more reason why quantum states should not be thought of as evolving states.) Let us begin with a more formal outline of Feynman's formulation ([10, Sect. 11] or [13, Sect. 5.1]):

Premise 1. Quantum mechanics provides us with algorithms for assigning probabilities to possible measurement outcomes on the basis of actual outcomes. Probabilities are calculated by summing over alternatives. Alternatives are possible sequences of measurement outcomes.[8] Associated with each alternative is a complex number called "amplitude."

Premise 2. To calculate the probability of a particular outcome of a measurement M_2, given the actual outcome of a measurement M_1, choose a sequence of intermediate measurements, and apply the appropriate rule.[9]

Rule C. If the intermediate measurements are made (or if it the setup makes it possible to infer from other measurements what their outcomes would have been if they had been made), first square the absolute values of the amplitudes associated with the alternatives and then add the results.

Rule Q. If the intermediate measurements are not made (and if the setup does not make it possible to infer from other measurements what their outcomes would have been), first add the amplitudes associated with the alternatives and then square the absolute value of the result.

Because Born probabilities are time-symmetric, the intermediate measurements need not be intermediate *in time.* In an EPR-Bohm setup [28, pp. 614–622], M_1 might be a spin measurement on particle 1 with respect to axis A, M_2 might be a spin measurement on particle 2 with respect to axis B, and the intermediate measurement might be a spin measurement on particle 1 with respect to any axis, which could have been made (but was not) right after the time of the molecule's dissociation into two particles of spin 1/2. Adding the two amplitudes and taking the absolute square of the result yields the conditional probability $p(b|a)$:

$$\big|\langle b|u\rangle\langle d|a\rangle^* - \langle b|d\rangle\langle u|a\rangle^*\big|^2 = \big|\langle b|u\rangle\langle a|d\rangle - \langle b|d\rangle\langle a|u\rangle\big|^2. \tag{3}$$

The left-hand side reflects the logical order (as usual, from right to left): the ket $|a\rangle$ ("up" with respect to axis a) represents the outcome on the basis of which the probability $p(b|a)$ is assigned, the ket $|b\rangle$ ("up" with respect to axis b) represents the outcome to which the probability $p(b|a)$ is assigned, and the kets $|u\rangle$ and $|d\rangle$ represent the possible outcomes of the (logically)

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[8] It deserves to be stressed that alternatives are defined in terms of measurement outcomes. The only referents needed to formulate the laws of quantum mechanics are property-indicating events.

[9] The parenthetical phrases take care of "quantum eraser" setups like that discussed by Englert, Scully, and Walther [26, 27].

intermediate measurement on particle 1, which is not actually made. If this measurement were to yield u, then particle 2 would start out "in" the state $|d\rangle$, and if it were to yield d, then particle 2 would start out "in" the state $|u\rangle$. The negative sign appears because the two amplitudes differ by an exchange of fermions. The complex conjugate amplitudes are used where the logical order is the reverse of the temporal order, which is restored on the right-hand side. If we simplify the right-hand side to

$$p(b|a) = |\langle ba|ud\rangle - \langle ba|du\rangle|^2, \tag{4}$$

the analogy with Eq. (1) becomes obvious. In the evolving-states formulation one obtains the same conditional probability by calculating the joint probability $|\langle ba|S\rangle|^2$, where $|S\rangle$ stands for the singlet state $(|ud\rangle - |du\rangle)/\sqrt{2}$, and dividing it by the marginal probability of finding "up" with respect to axis A. It is worth noting, though, that in order to do the Feynmanesque calculation we do not need to know how to write the singlet state. All we need to know is that the two spins are anti-correlated, as required for the conservation of angular momentum.

Equation (3) is not meant to suggest that some kind of backward causation is involved. The view put forth here is, rather, that no kind of *spatiotemporal* causation is involved, whether forward or backward or sideways. To be quite clear about this, suppose that we measure the spin of an electron twice, once at the time t_1 with respect to an axis A_1, and again at the time t_2 with respect to an axis A_2. If the measurement at t_1 yields *up*, we can predict that the measurement at t_2 will yield *up* with probability $\cos^2(\alpha/2)$, where α is the angle between the two axes. But if the measurement at t_2 yields *up*, we can equally *postdict* (on the basis of *this* outcome) that the measurement at t_1 must have yielded *up* with the same probability. To experimentally verify the prediction, we use a preselected ensemble: we select those pairs of measurements that yield *up* at t_1 and measure the relative frequencies with which *up* is obtained at t_2 for different orientations of A_2. To experimentally verify the postdiction, we use a postselected ensemble: we select those pairs of measurements that yield *up* at t_2 and measure the relative frequencies with which *up* is obtained at t_1 for different orientations of A_1. As far as the mathematics is concerned, the situation is time-symmetric.

The story found in most textbooks is not. If both measurements yield *up* with respect to their respective axes, that story goes like this: (i) the electron's spin is *up* with respect to A_1 not only at t_1 but also during the entire interval between t_1 and t_2; (ii) at t_2 it changes from being *up* with respect to A_1 to being *up* with respect to A_2. If this story were actually supported by quantum mechanics, then so would be the following story: (i) the electron's spin is *up* with respect to A_2 not only at t_2 but also during the entire interval between t_1 and t_2; (ii) at t_1 it changes from being *up* with respect to A_1 to being *up* with respect to A_2. According to the first story, the reason why the electron's spin is *up* with respect to A_1 between t_1 and t_2 is that it is found to be *up* with respect to A_1 at t_1. According to the second story, the reason why the electron's spin is *up* with respect to A_2 during the same interval is that it is found to be *up* with respect to A_2 at t_2. If the second is not a credible story, then neither is the first. If the measurement outcome at t_2 does not cause the electron's spin to have been *up* with respect to A_2, then the measurement outcome at t_1 does not cause the electron's spin to be subsequently *up* with respect to A_1. All there is is statistical correlations between what the spin of the electron turns out to be when measured, and these correlations are time-symmetric.

5 Quantum nonlocality

> *For those interested in the fundamental structure of the physical world, the experimental verification of violations of Bell's inequality constitutes the most significant event of the past half-century. In some way our basic picture of space, time, and physical reality must change. These results, and the mysteries they engender, should be the common property of all who contemplate with wonder the universe we inhabit.* — Tim Maudlin [29, p. 4]

In his seminal paper of 1964, Bell [30] used the EPR-Bohm scenario to show that the principle of local causes (also called Einstein locality) was incompatible with quantum mechanics—a result that was hailed by Stapp [31] as "the most profound discovery of science." The principle asserts that events occurring in a given spacetime region are independent of parameters that can be controlled, at the same moment, by an agent located in a distant spacetime region. If it did hold, Alice, having measured a spin component of particle 1, would not be in a position to assign probabilities other than 1/2 to the outcomes that can be obtained by Bob, who measures a spin component of particle 2. In actual fact, Alice can even use her outcome to predict with certainty the outcome obtained by Bob whenever he measures the same spin component as Alice. Schrödinger, in his famous "cat" paper [32], observed that "Measurements on separated systems cannot directly influence each other—that would be magic." Bell's work has shown that the magic is real. Bell's conclusion was that

> In a theory in which parameters are added to quantum mechanics to determine the results of individual measurements, without changing the statistical predictions, there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote. [30]

The reason Bell examined deterministic theories, in which parameters are added to quantum mechanics, was not that he was averse to indeterminism but that deterministic theories were the only hope for retaining locality, a hope that he dashed for good. While in a deterministic theory locality is doomed by Bell's inequality, in an indeterministic theory it is doomed by perfect correlations. No matter whether measurement outcomes are determined by hidden variables or stochastic, there must be a causal connection between the setting of one apparatus and the reading of another. And since this connection cannot be accounted for by a common cause in the intersection of the past light cones of the measurement events, the causal connection must be superluminal in case the spatiotemporal relation between the events is spacelike.

The causality associated with the atemporal process of manifestation casts a new light on the magic. The causality responsible for quantum theory's violation of remote outcome independence [33] need not be of the familiar spatiotemporal kind. Local explanations involve either a common cause *in the intersection of the past light cones of the measurement events* or a superluminal causal connection *across spacetime.* The reason they do not work could be the same as the reason why the manifestation of the spatiotemporal world cannot be explained by processes that connect events *within* the spacetime arena.

The manifestation of the world is the nonlocal event *par excellence.* Instead of being an event *in* spacetime, it is, depending on one's point of view, either "outside" of spacetime (i.e., not localized at all) or coextensive with spacetime (i.e., completely delocalized). It is the process by which Being enters into reflexive relations and matter and space come into being as a result. It is the transition by which Being acquires both the aspect of a multiplicity of relata (if the reflexive quality of the relations is ignored) and the aspect of a substantial expanse (if the spatial quality of the relations is reified). The atemporal causality of this transition supports the folk causality that connects objects across space and events across spacetime, which helps us make sense of the manifested world as well as of the cognate world of classical physics, but which throws no light on the process of manifestation nor on the quantum correlations that are instrumental in the process.

It may be instructive to contrast the manifestation of the macroworld with the classical philosophical concept of the emergence of the Many from a One. In classical metaphysics, this emergence was conceived as running parallel to predication: an immaterial essence or predicable universal becomes instantiated as an impredicable material individual. This instantiation, moreover, was conceived in the framework of a Platonic–Aristotelian dualism, which postulates an instantiating medium (matter and/or space) in or by which the essences or universals get instantiated. The manifestation of the macroworld, on the other hand, requires no separate medium and implies no dualism. All that is required is the realization of spatial relations. Being may be said to manifest the macroworld *within* itself—after all, the macroworld is manifested with the help of *reflexive* relations—rather than in something other than itself.

The view that space consists of reflexive spatial relations[10] goes farther in relationism—the doctrine that space and time are a family of spatial and temporal relations holding among the material constituents of the universe—in that it also affirms that the ultimate material constituents are *formless*.[11] The shapes of things, on this account, resolve themselves into sets of spatial relations between formless relata. The truism that the universe lacks a position because it lacks *external* spatial relations thus has a fitting complement: a fundamental particle lacks a form because it lacks *internal* spatial relations.

6 Conclusion

Why is it so hard to make sense of the quantum theory? The philosopher of science Dennis Dieks [34] has given the following explanation:

> First, the rigorous results which have been achieved preponderantly have a negative character: they are "no-go theorems." No-

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[10] The previous conclusion that physical space cannot be an intrinsically differentiated or partitioned expanse could be taken to imply that it is an intrinsically undifferentiated expanse, one without intrinsic parts. But physical space is not an expanse that exists or can be conceived out of relation to its material content. It appears to be such an expanse only if the reflexive character of the relations is reified.

[11] A particle lacking internal structure is often said to be pointlike. The absence of internal structure can be inferred from the scale-invariance of a particle's effective cross-section(s) in scattering experiments with probe particles that are themselves pointlike in this sense. But since such scale-invariance is unobservable below the de Broglie wavelength of the probe particles, no scattering experiment can furnish evidence of absence of internal structure, let alone evidence of a literally pointlike form. For further reasons why fundamental particles ought to be conceived as formless see Sect. 9 of Ref. [12].

> go theorems show the impossibility of certain interpretations, but do not themselves provide a new interpretation. For example, Bells theorem demonstrates that a “local” theory in which physical objects possess well-defined properties is not possible. More generally, the outcome of foundational work in the last couple of decades has been that interpretations which try to accommodate classical intuitions are impossible, on the grounds that theories that incorporate such intuitions necessarily lead to empirical predictions which are at variance with the quantum mechanical predictions. However, this is a negative result that only provides us with a starting-point for what really has to be done: something conceptually new has to be found, different from what we are familiar with. It is clear that this constructive task is a particularly difficult one, in which huge barriers (partly of a psychological nature) have to be overcome. Apart from finding a general and consistent interpretational scheme, there is the difficulty of “getting a feeling” for it; to attain a position in which one understands the interpretation.

As Dieks so aptly points out, not only there are huge barriers (partly of a psychological nature) to be overcome but also there is the difficulty of getting a feeling for an interpretation. Some of the psychological (and neurological barriers) are discussed in Refs. [35, 36]. As to getting a feeling for the interpretation attempted here, the difficulty is that it requires exercising our “metaphysical muscles,” which appears to be quite different from exercising our mathematical ones. Since mathematics doesn’t have much to say about the events to which, and on the basis of which, probabilities are assigned, the predominantly mathematically trained will focus their interpretive efforts on the quantum-mechanical probability algorithms themselves, such as wave functions, state vectors, or density operators. They will tend to attribute to them an undue concreteness and ignore that, as Falkenburg [37, p. 340] has stressed,

> to our present knowledge subatomic reality is not a micro-world on its own but a part of empirical reality that exists relative to the macroscopic world, in given experimental arrangements and well-defined physical contexts outside the laboratory.

To arrive at an adequate understanding of the quantum domain, we need to plumb the synergetic implications of the quantum-mechanical correlation laws *and* well-defined macroscopic contexts, as was done in Sects. 2 and 3.

To paraphrase Kant's famous statement that "Thoughts without content are empty, intuitions without concepts are blind" [38, p. 193]: without measurements the formal apparatus of quantum mechanics is empty, measurements without the formal apparatus of quantum mechanics are blind.

To get a feeling for the interpretation attempted here is to get a feeling for the process by which Being enters into reflexive relations and matter and space come into being as a result—a transition from unity to multiplicity, from a condition of complete indefiniteness and indistinguishability to a condition of complete or maximal definiteness and distinguishability, via emergent stages populated by numerically identical particles, non-visualizable atoms, and partly visualizable molecules. While this transition is neither temporal nor spatial, we cannot help conceive it in temporal terms, just as we cannot help conceive temporal relations in spatial terms, as aspects of a 4-dimensional continuum, since, as the philosopher Colin McGinn [39] has pointed out,

> We are, cognitively speaking as well as physically, spatial beings par excellence: our entire conceptual scheme is shot through with spatial notions, these providing the skeleton of our thought in general. Experience itself, the underpinning of thought, is spatial to its core.

Although the spatialization of time fails to do justice to the qualitative aspects of our experience of time (change and succession), we would be hard pressed to deal with the relativistic interdependence of distances and durations without conceiving of time as if it were another spatial dimension. My contention is that quantum mechanics presents us with a similar Catch-22: although by temporalizing the transition from complete indefiniteness and indistinguishability to complete or maximal definiteness and distinguishability we fail to do justice to the transition, we would be hard pressed to envision it without temporalizing it.

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