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Einstein-Podolsky-Rosen Paradox

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By 1935 the conceptual understanding of the quantum theory was dominated by Bohr's ideas concerning complementarities. Those ideas centered on observation and measurement in the quantum domain. According to Bohr's views at that time, observing a quantum object involves a physical interaction with a classical measuring device that results in an uncontrollable disturbance of both systems. The picture here is of a tiny object banging into a big apparatus. The disturbance this produces on the measuring instrument is what issues in the measurement "result" which, because it is uncontrollable, can only be predicted statistically. The disturbance experienced by the quantum object restricts those quantities that can be co-measured with precision. According to complementarities when we observe the position of an object, we disturb its momentum uncontrollably. Thus we cannot determine precisely both position and momentum. A similar situation arises for the simultaneous determination of energy and time. Thus complementarities involve a doctrine of uncontrollable physical disturbance that, according to Bohr, underwrites the Heisenberg uncertainty relations and is also the source of the statistical character of the quantum theory.

Initially Einstein was enthusiastic about the quantum theory. By 1935, however, his enthusiasm for the theory had been replaced by a sense of disappointment. His reservations were twofold. Firstly, he felt the theory had resigned the historical task of natural science to provide knowledge of, or at least justified belief in, significant aspects of nature that were independent of observers or their observations. Instead the fundamental understanding of the wave in quantum theory was that it provided probabilities only for "results" if appropriate measurements were made (the Born Rule). The theory was simply silent about what, if anything was likely to be true in the absence of observation. In this sense it was unrealistic. Secondly, the quantum theory was essentially statistical. The probabilities built into the state function were fundamental and, unlike the situation in classical statistical mechanics, they were not understood as arising from ignorance of fine details. Einstein began to probe how strongly the quantum theory was tied to unrealism and indeterminism.

He wondered whether it was possible, at least in principle, to credit certain properties to a quantum system in the absence of measurement. Einstein began to ask whether the quantum mechanical description of reality was complete. Since Bohr's pairings provided strong support both for unrealism and indeterminism and since it played such a dominant role in shaping the widespread attitude toward quantum theory, the pairings became Einstein's first target. In particular, Einstein had reservations about the scope and uncontrollable effects of the physical disturbances invoked by Bohr and about their role in fixing the interpretation of the wave function. EPR was intended to support those reservations in a particularly dramatic way.

Max Jammer describes the EPR paper as originating with Einstein's reflections on a thought experiment he planned in the 1930 Solvay conference. That experiment concerns a box that contains a clock that appears able to time precisely the release of a photon with a determinate energy. If this were feasible, it would appear to challenge the unrestricted validity of the Heisenberg uncertainty relation that sets a lower bound on the simultaneous uncertainty of energy and time (Uncertainty Principle). The uncertainty relations, understood not just as a prohibition on what is co-measurable, but on what is simultaneously real, were a central component in the unrealistic interpretation of the wave function. Jammer describes how Einstein's thinking about this experiment, and

Bohr's objections to it, evolved into a different photon-in-a-box experiment, one that allows an observer to determine either the momentum or the position of the photon indirectly, while remaining outside, sitting on the box. Jammer associates this with the distant determination of either momentum or position that is at the heart of the EPR paper. Carsten Held cites a related correspondence with Paul Ehrenfest from 1932 in which Einstein described an arrangement for the indirect measurement of a particle of mass *m* using correlations with a photon established through Compton scattering. Einstein's reflections here foreshadow the argument of EPR, along with noting some of its difficulties.

Whatever their precursors, the ideas that found their way into EPR were worked out in a series of meetings with Einstein and his two assistants, Podolsky and Rosen. The actual text, however, was written by Podolsky and, apparently, Einstein did not see the final draft before Podolsky submitted the paper to *Physical Review* in March of 1935, where it was accepted for publication without changes. Right after it was published Einstein complained that his central concerns were obscured by the overly technical nature of Podolsky's development of the argument. Thus in discussing the argument of EPR one should consider both the argument in Podolsky's text and the argument that Einstein intended to offer. Consider an argument presented in Bohr's reply to EPR, which is possibly the best known version, although it differs significantly from the others.

Argument in EPR Text

The EPR text is concerned, in the first instance, with the logical connections between two assertions. One asserts that quantum mechanics is incomplete. The other asserts that incompatible quantities cannot have simultaneously real values. The authors assert as a premise, later to be justified, that one or another of these must hold. It follows that if quantum mechanics were complete then the second option, that incompatible quantities cannot have simultaneously real values, would hold. However they also take as a second premise that if quantum mechanics were complete, then incompatible quantities could indeed have simultaneous, real values. They conclude that quantum mechanics is incomplete. The conclusion certainly follows since one would have a contradiction. Nevertheless the argument is highly abstract and formulaic and even at this point in its development one can readily appreciate Einstein's disappointment with it.

EPR now proceeds to establish the two premises, beginning with a discussion of the idea of a complete theory. Here they offer only a necessary condition; namely, that for a complete theory "every element of the physical reality must have a counterpart in the physical theory." Although they do not specify just what an "element of physical reality" is they use that expression when referring to the values of physical quantities.

With these terms in place it is easy to show that if, say, the values of position and momentum for a quantum system were elements of reality then the description provided by the wave function of the system would be incomplete, since no wave function contains counterparts for both elements. They establish the first premise: either quantum theory is incomplete or there can be no simultaneously real values for incompatible quantities. They now need to show that if quantum mechanics were complete, then incompatible quantities could have simultaneous real values, which is the second premise. This, however, is not easily established. Instead of assuming completeness and on that basis obtaining incompatible quantities can have simultaneously real values; they simply set out to develop the concluding assertion without any completeness assumption at all. This turns out to be the heart of the paper and its most controversial part. It attempts to show that in certain circumstances a quantum system can have simultaneous values for incompatible quantities for position and momentum, where these values are elements of reality.

They proceed by sketching a thought experiment. In the experiment two quantum systems interact in such a way that two conservation laws hold. One is the conservation of relative position. If one imagines the systems located along the x-axis, then if one of the systems (we can call it John’s) were found at position q along the axis at a certain time, the other system (call it Kat’s) would be found then a fixed distance d away, say at $q'=q-d$, where we may suppose that the distance d between q and q' is substantial. The other conservation law is that the total linear momentum (along that same axis) is always zero. So when the momentum of John's system along the x-axis is determined to be p, the momentum of Kat’s system would be found to be $-p$. The paper constructs an explicit wave function for the combined system that satisfies both conservation principles. Although commentators later raised questions about the authenticity of this wave function, it does appear to satisfy the two conservation principles at least for a moment (Jammer 1974). In any case, one can model the same conceptual situation in other cases that are clearly well defined quantum mechanically.

At this point of the argument EPR make two critical assumptions, although they do not call special attention to them. The first assumption is that at the time when measurements will be performed on John's system there is some reality that pertains to Kat’s system alone. In effect, they assume that Kat’s system maintains its separate identity even though it is linked with John's. They need this assumption to make sense of another. The second assumption is that of location. This supposes that no real change can take place in Kat’s system as a consequence of a measurement made on John’s system. They commentary this by saying, "at the time of measurement the two systems no longer interact." On the basis of these two assumptions they conclude that Kat’s system can have real values for both position and momentum simultaneously. There is no detailed argument for this in the text. Instead they use these two assumptions to show how one could be led to assign both a position and a momentum to Kat's system, from which the simultaneous acknowledgment of elements of reality is supposed to follow. Since this is the central and most controversial part of the paper, it pays to go slowly here in trying to reconstruct an argument on their behalf.

One attempt might go as follows. Suppose that we measure, say, the position of John’s system. The reduction of the state function for the combined systems then yields a position Eigen state for John’s system. The Eigen state applies to the reality there and that Eigen state enables us to predict a determinate position for Kat’s system with probability one. Since that prediction only depends on a measurement made on John's system, locality implies that the prediction of the position of Kat’s system does not involve any change in the reality of Kat’s system. If we interpret this as meaning that the prediction does not disturb Kat’s system, all the pieces are in place to apply The Criterion of Reality. It certifies that the predicted position value, corresponding to the position Eigen state, is an element of the reality that pertains to Kat’s system. One could argue similarly with respect to momentum.

This line of argument, however, is deceptive and contains a serious confusion. It occurs right after one applies locality to conclude that the measurement made on Albert's system does not affect the reality pertaining to Kat's system. For, recall one has not yet determined whether the position inferred for Kat's system is indeed an element of that reality. Hence it is still possible that the measurement of John's system while not disturbing the reality pertaining to Kat's system, does disturb its position.

The unreasonableness to which EPR alludes in making the reality on the second system depend upon the process of measurement carried out on the first system, which does not in any way disturb the second system is just the unreasonableness that would be involved in renouncing locality itself. For it is locality that enables one to overcome the incompatibility of position and momentum measurements of Albert's system by requiring their joint consequences for Kat's system to be incorporated in a single, stable reality there. If one recalls Einstein's acknowledgment to Ehrenfest that getting simultaneous position and momentum was necessary, one can see how EPR responds by making it become necessary once locality is assumed.

The EPR experiment with interacting systems accomplishes a form of indirect measurement. The direct measurement of John's system yields information about Kat's system. But it does this at a distance, without any further physical interaction taking place between the two systems. Thus the thought experiment at the heart of EPR undercuts the picture of measurement as necessarily involving a tiny object banging into a large measuring instrument. If one looks back at Einstein's reservations about similarity, one can appreciate that by focusing on a non-disturbing kind of measurement the EPR argument targets Bohr's program for explaining central conceptual features of the quantum theory. For that program relied on uncontrollable disturbances as a necessary feature of any measurement in the quantum domain. Nevertheless the cumbersome machinery employed in the EPR paper makes it difficult to see what is central. It distracts from rather than focuses on the issues. That was Einstein's complaint about Podolsky's text in his June 19, 1935 letter to Schrödinger. Schrödinger responded on July 13 reporting reactions to EPR that vindicate Einstein's concerns.

Einstein's versions of the argument

Einstein set about almost immediately to provide a clearer and more focused version of the argument. He began that process just a few weeks after EPR was published, in the June 19 letter to Schrödinger, and continued it in an article published the following year. He returned to these ideas some years later in a few other publications. Although his various expositions differ from one another they all employ composite systems as a way of implementing non-disturbing measurements at a distance. None of Einstein's own accounts contains the tortured EPR argument over when values of a quantity can be regarded as elements of reality. Nor does Einstein engage in calculations, like those of Podolsky, about the explicit form of the total wave function for the composite system. Moreover, as early as June 19, 1935 Einstein makes it plain that he is not especially interested in the question of simultaneous values for incompatible quantities like position and momentum. The concern that he expresses to Schrödinger is with the question of completeness, given the resources of the quantum theory, in describing the situation concerning a single variable. With respect to the treatment of an incompatible pair he tells Schrödinger "ist mir wurst" — literally, it's sausage to me; i.e., he couldn't care less (Fine). In his writings subsequent to EPR, Einstein probes an incompatibility between affirming locality and separability, on the one hand, and completeness in the description of individual systems by means of state functions, on the other. His argument is that one can have at most one of these but never both. He frequently refers to this dilemma as a "paradox".

In the letter to Schrödinger of June 19, Einstein sketches a simple argument for the dilemma, roughly as follows. Consider an interaction between the John and Kat systems that conserves their relative positions. Consider the evolved wave function for the total system. Now assume a principle of locality-separability (Einstein calls it a *Trennungsprinzip* — separation principle): Whether a physical property holds for Kat's system does not depend on what measurements are made locally on John's system. If we measure the position of John's system, the conservation of relative position implies that one can immediately infer the position of John's. By locality-separability it follows that Kat's system must already have had a determinate position just before John began that measurement. At that time, however, Kat's system has no independent state function. There is only a state function for the combined system and that total state function does not predict with certainty the position one would find for Kat's system. Thus the description of Kat's system afforded by the quantum state function is incomplete. In this formulation of the argument it is clear that locality-separability conflicts with the Eigen value Eigen state link, which holds that a quantity of a system has an Eigen value if and only if the state of the system is an eigenstate of that quantity with that Eigen value. The only if part of the link would need to be weakened in order to interpret quantum state functions as complete descriptions.

This argument does not even depend on the reduction of the total state function for the combined system. Although this simple argument concentrates on what Einstein saw as the essentials, stripping away most technical details and distractions, he had another slightly more complex argument that he was also fond of producing. This second argument focuses clearly on the interpretation of quantum state functions and not on any issues about simultaneous values for incompatible quantities.

Suppose, as in EPR, that the interaction between the two systems preserves both relative position and zero total momentum and that the systems are far apart. As before, one can measure either the position or momentum of John's system and, in either case, one can infer the position or momentum for Kat's system. It follows from the reduction of the total state function that, depending on whether we measure the position or momentum of John's system, Kat's system will be left either in a position Eigen state or in a momentum Eigen state. Suppose too that separability holds for Kat; that is, that Kat's system has some real physical state of affairs. If locality holds as well, then the measurement of John's system does not disturb the assumed reality for Kat's system. However, that reality appears to be represented by quite different state functions, depending on which measurement of John's system one chooses to carry out. If one understands a complete description to rule out that one and the same physical state can be described by state functions with distinct physical suggestions, then one can conclude that the quantum mechanical description is incomplete. Here again one confronts a dilemma between separability-locality and completeness.

As seen in framing his own EPR-like arguments for the incompleteness of quantum theory, Einstein makes use of separability and locality, which are also tacitly assumed in the EPR paper. He provides a clear statement of his ideas here in a letter to Max Born,

> *It is … characteristic of … physical objects that they are thought of as arranged in a space-time continuum. An essential aspect of this arrangement … is that they objects "are situated in different parts of space". … The following idea characterizes the relative independence of objects (A and B) far apart in space: external influence on A has no direct influence on B.* (Born, 1971, pp. 170-71)

In the course of his correspondence with Schrödinger, however, Einstein realized that assumptions about separability and locality were not necessary in order to get the incompleteness conclusion that he was after. Separability supposes that there is a real state of affairs and locality suppose that one cannot directly influence it by acting at a distance. What Einstein realized was that these two suppositions were already part of the ordinary conception of a macroscopic object. Hence if one looks at the interaction of a macro-system with a micro-system there would be no need to frame additional assumptions in order to conclude that the quantum description of the whole was incomplete with respect to its macroscopic part. Writing to Schrödinger on August 8, 1935 Einstein says that he will show this by means of a "crude macroscopic example".

> *The system is a substance in chemically unstable equilibrium, perhaps a charge of gunpowder that, by means of intrinsic forces, can spontaneously combust, and where the average life span of the whole setup is a year. In principle this can quite easily be represented quantum-mechanically. In the beginning the psi-function characterizes a reasonably well-defined macroscopic state. But, according to your equation* [i.e., the Schrödinger equation], *after the course of a year this is no longer the case. Rather, the psi-function then describes a sort of blend of not-yet and already-exploded systems. Through no art of interpretation can this psi-function be turned into an adequate description of a real state of affairs; in reality there is just no intermediary between exploded and not-exploded.* (Fine 1996, p. 78)

Bohr's Response to Argument

The literature surrounding EPR contains yet another version of the argument, a popular version that — unlike any of Einstein's — features the Criterion of Reality.

Assume again an interaction between our two systems that preserves both relative position and zero total momentum and suppose that the systems are far apart. If one measures the position of John's system, one can infer that Kat's system has a corresponding position. One can also predict it with certainty, given the result of the position measurement of John's system. Hence, according to the Criterion of Reality, the position of Kat's system constitutes an element of reality. Similarly, if one measures the momentum of John's system, one can conclude that the momentum of Kat's system is an element of reality. The argument now concludes that since one can choose freely to measure either position or momentum, it follows that both must be elements of reality simultaneously.

Of course no such conclusion follows from one's freedom of choice. It is not sufficient to be able to choose at will which quantity to measure; for the conclusion to follow from the Criterion alone one would need to be able to measure both quantities at once. This is precisely the point that Einstein recognized in his 1932 letter to Ehrenfest and that EPR addresses by assuming locality and separability. What is striking about this version is that these principles, central to the original EPR argument and to the dilemma at the heart of Einstein's versions, disappear here. Instead, what one has is closer to a picture of the EPR paper than it is to a serious reconstruction. Unfortunately, perhaps due in part to the difficulties presented by Podolsky's text, this is the argument most commonly cited in the physics literature and attributed to EPR themselves. Podolsky, however, should not get all the blame. For this version of Podolsky's text has a prominent source in terms of which one can more readily understand its popularity among physicists. It is Niels Bohr himself.

By the time of the EPR paper many of the early interpretive battles over the quantum theory had been settled, at least to the satisfaction of working physicists. Bohr had emerged as the philosopher of the new theory and the community of quantum theorists, busy with the development and extension of the theory, were content to follow Bohr's leadership when it came to explaining and defending its conceptual underpinnings (Beller). Thus in 1935 the burden was on Bohr to explain what was wrong with the EPR paradox. The major article that he wrote in discharging this burden (Bohr) became the norm for how to respond to EPR. Unfortunately, Bohr's summary of EPR in that article, which is the version just above, also became the norm for what EPR contained by way of argument.

Bohr's response to EPR begins, as do many of his treatments of the conceptual issues raised by the quantum theory, with a discussion of limitations on the simultaneous determination of position and momentum. As usual, these are drawn from an analysis of the possibilities of measurement if one uses an apparatus consisting of a diaphragm connected to a rigid frame. Bohr emphasizes that the question is to what extent one can trace the interaction between the particle being measured and the measuring instrument. Following the summary of EPR, Bohr then focuses on the Criterion of Reality which, he says, "contains an ambiguity as regards the meaning of the expression ‘without in any way disturbing a system’"(Bohr). Bohr concedes that the indirect measurement of Kat’s system achieved when one makes a measurement of John’s system does not involve any "mechanical disturbance" of Kat’s system. Still, he claims that a measurement on John’s system does involve "an influence on the very conditions which define the possible types of predictions regarding the future behavior of [Kat’s] system." What Bohr may have had in mind is that when, for example, one measures the position of Kat's system and get a result one can predict the position of Kat's system with certainty. However, measuring the position of John's system does not allow a similarly certain prediction for the momentum of Kat's system. The opposite would be true had one measured the momentum of John's system. Thus depending on which variable one measures on John's system, one will be entitled to different predictions about the results of further measurements on Kat's system.

There are two important things to notice about this response. The first is this. In conceding that Einstein's indirect method for determining, say, the position of Kat's system does not mechanically disturb that system, Bohr here departs from his original program of similarity which was to base the uncertainty relations and the statistical character of quantum theory on uncontrollable physical disturbances in a system, disturbances that were supposed to arise inevitably in measuring some variable of the system. Instead Bohr now distinguishes between a physical disturbance and a disturbance in the information available for predicting the future behavior of a system. He emphasizes that only the second arises in the EPR situation.

The second important thing to notice is how Bohr's response needs to be implemented in order to block the type of arguments favored by Einstein, which pose a dilemma between principles of locality and completeness. In Einstein's arguments the locality principle makes explicit reference to the reality of the unmeasured system. Hence Bohr's pointing to an informational disturbance would not affect the argument at all unless one includes the information available for predicting the future behavior of the unmeasured system as part of the reality of that system. That would be implausible on two counts. Firstly, because the information about Kat's unmeasured system is available to those near John's system, which is someplace else, and to their contacts, wherever they may be. Secondly, because the very idea of information about Kat's system would make little sense if what one designate by Kat's system includes that very information. Nevertheless, this is the move that Bohr appears to make, maintaining that the "conditions constitute an inherent element of the description of any phenomena to which the term 'physical reality' can be properly attached" (Bohr) . To be sure, if one includes predictive information in the reality of the unmeasured system, then the locality principle fails to hold and so the EPR inference to the incompleteness of the quantum theory would be blocked. Thus this way out concedes the validity of the EPR argument and blocks its impact on the issue of completeness by expanding the concept of physical reality in such a way as to make the quantum theory highly nonlocal.

> *If one only imagines the possibility that without disturbing the phenomena one determines through which hole the electron passes, one would truly find oneself in irrational territory, for this would put one in a situation in which an electron, which might be said to pass through this hole, would be affected by the circumstance of whether this* [other] *hole was open or closed; but … it is completely incomprehensible that in its later course* [the electron] *should let itself be influenced by this hole down there being open or shut.* (Bohr)

Notice how close the language of disturbance here is to EPR. But here Bohr defends locality and regards the very contemplation of non-locality as "irrational" and "completely incomprehensible". Since "the circumstance of whether this [other] hole was open or closed" does affect the possible types of predictions regarding the electron's future behavior, if one expands the concept of the electron's "reality", as he appears to have suggested for EPR, by including such information, one does "disturb" the electron around one hole by opening or closing the other hole. That is, if one gives to "disturb" the same sense here that Bohr appears to give it when responding to EPR, then one is led to an "incomprehensible" non-locality, and into the territory of the irrational. There is another way of trying to understand Bohr's position. According to one common reading, after EPR Bohr embraced a relational account of property acknowledgment. On this account to speak of the position, say, of a system assumes that one already has already put in place an appropriate interaction involving an apparatus for measuring position. Thus the position of the system refers to a relation between the system and the measuring device. In the EPR context this would seem to imply that before one measures the position of John's system, talk of the position of Kat's system is out of place; whereas after one measures the position of John's system, talk of the position of Kat's system is appropriate and, indeed, one can say truly that Kat's system has a position. Similar considerations oversee momentum measurements. It follows, and then, that local manipulations carried out on John's system, in a place one may assume to be far removed from Kat's system, can directly affect what is linguistically meaningful as well as factually true of Kat's system. Similarly, in the double slit arrangement, it would follow that what can be said and said truly about the position of the electron around the top hole would depend on the context of whether the bottom hole is open or shut. One might suggest that such relational actions at a distance are harmless ones; like becoming the best when your only competitor fails. Still, they represent precisely the sort of non-locality already discussed with respect to "informational disturbance", and that Bohr seemed to dislike.

In the light of all this it is difficult to know just what response can be attributed to

Bohr reliably that would derail EPR. Bohr may well have been aware of the difficulty in framing the appropriate concepts clearly when, a few years after EPR, he wrote,

> *The unaccustomed features of the situation with which we are confronted in quantum theory necessitate the greatest caution as regard all questions of terminology. Speaking, as it is often done of disturbing a phenomenon by observation, or even of creating physical attributes to objects by measuring processes is liable to be confusing, since all such sentences imply a departure from conventions of basic language which even though it can be practical for the sake of brevity, can never be unambiguous* (Bohr).

The Bohm Argument of EPR

For about fifteen years following its publication, the EPR paradox was discussed at the level of a thought experiment whenever the conceptual difficulties of quantum theory became an issue. In 1951 David Bohm, then an untenured Assistant Professor at Princeton University and a protégé of Robert Oppenheimer, published a textbook on the quantum theory in which he took a close look at EPR in order to develop a response in the spirit of Bohr. Bohm showed how one could mirror the conceptual situation in the EPR thought experiment by looking at the dissociation of a diatomic molecule whose total spin angular momentum is zero; for instance, the dissociation of an excited hydrogen molecule into a pair of hydrogen atoms by means of a process that does not change an initially zero total angular momentum (Bohm).

In the Bohm experiment the atomic fragments separate after interaction, flying off in different directions freely. Subsequently, measurements are made of their spin components, whose measured values would be anti-correlated after dissociation. In the so-called singlet state of the atomic pair, the state after dissociation, if one atom's spin is found to be positive with respect to the orientation of an axis at right angles to its flight path, the other atom would be found to have a negative spin with respect to an axis with the same orientation. Like the operators for position and momentum, spin operators for different orientations do not commute. Moreover, in the experiment outlined by Bohm, the atomic fragments can move far apart from one another and so become appropriate objects for assumptions that restrict the effects of purely local actions. Thus Bohm's experiment mirrors the entangled correlations in EPR for spatially separated systems, allowing for similar arguments and conclusions involving locality, separability, and completeness.

A subsequent paper, co-authored with Aharonov (Bohm and Aharonov) goes on to sketch the machinery for a plausible experiment in which these correlations could be verified. It has become customary to refer to experimental arrangements involving determinations of spin components for spatially separated systems, and to a variety of similar set-ups as "EPRB" experiments — "B" for Bohm. Because of technical difficulties in creating and monitoring the atomic fragments, however, there seem to have been no immediate attempts to perform a Bohm version of EPR.

Bell and beyond

That was to remain the situation for almost another fifteen years, until John Bell utilized the EPRB set-up to construct a stunning argument, at least as challenging as EPR, but to a different conclusion (Bell). Bell shows that, under a given set of assumptions, certain of the correlations that can be measured in runs of an EPRB experiment satisfy a particular set of constraints, known as the Bell inequalities. In these EPRB experiments, however, quantum theory predicts that the measured correlations violate the Bell inequalities, and by an experimentally significant amount. Thus Bell shows that quantum theory is inconsistent with the given assumptions. Prominent among these is an assumption of locality, similar to the locality assumption tacitly assumed in EPR and explicitly assumed in Einstein's versions. Thus Bell's theorem is often characterized as showing that quantum theory is nonlocal. However, since several other assumptions are needed in any derivation of the Bell inequalities, one should be cautious about singling out locality as necessarily in conflict with the quantum theory.

Bell's results were explored and deepened by various theoretical investigations and they have stimulated a number of increasingly sophisticated and delicate EPRB-type experiments designed to test whether the Bell inequalities hold where quantum theory predicts they should fail. With a few inconsistent exceptions, the experiments confirm the quantum violations of the inequalities. The confirmation is quantitatively impressive and, although there are still viable ways of reconciling the experimental results with frameworks that embody locality and separability (Szabo and Fine), many conjecture that as experiments are improved such frameworks will not stand the test of time. While the exact significance of these experimental tests of the Bell inequalities thus remains a matter of continued controversy, the techniques developed in the experiments, and related theoretical ideas for utilizing the entanglement associated with EPRB-type interactions, have become important in their own right. These techniques and ideas, stemming from EPR and the Bell theorem, have applications now being advanced in several relatively new fields of investigation — quantum cryptography, teleportation and computing.

To go back to the EPR dilemma between locality and completeness, it would appear from the Bell theorem that Einstein's strategy of maintaining locality, and thereby concluding that the quantum description is incomplete, may have fixed on the wrong horn. Even though the Bell theorem does not rule out locality conclusively, it should certainly make one wary of assuming it. On the other hand, since Einstein's exploding gunpowder argument supports incompleteness without assuming locality, one should be wary of adopting the other horn of the dilemma, affirming that the quantum state descriptions are complete and therefore that the theory is nonlocal. It may well turn out that both horns need to be rejected: that the state functions do not provide a complete description and that the theory is also nonlocal. There is at least one well-known approach to the quantum theory that makes a choice of this sort, the de Broglie-Bohm approach (Bohmian Mechanics). Of course it may also be possible to break the EPR argument for the dilemma plausibly by questioning some of its other assumptions. That would lead to the remaining option, to regard the theory as both local and complete. If made cogent, perhaps some version of the Everett Interpretation will come to occupy this branch of the interpretive tree.

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