IS THERE ONTOLOGY AFTER BELL'S THEOREM?

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By

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I feel that it’s unfair to use a title containing a generally unfamiliar term, in this case "Bell's Theorem," without promptly giving some explanation. It happens that logic demands a rather lengthy lead-in, so let me quote here, as a sort of "jacket blurb" introduction, the abstract of the excellent review article on Bell's Theorem, by John Clauser and Abner Shimony.

> Bell's Theorem represents a significant advance in understanding the conceptual foundations of quantum mechanics. The theorem shows that essentially all local theories of natural phenomena that are formulated within the framework of realism may be tested using a single experimental arrangement. Moreover, the predictions by these theories must significantly differ from those by quantum mechanics. Experimental results evidently refute the theorem's predictions for these theories and favour those of quantum mechanics. The conclusions are philosophically startling: either one must totally abandon the realistic philosophy of most working scientists, or dramatically revise our concept of space-time.

If I were permitted to edit this statement, I would just add the words "or both" to the final sentence.

Ontology is a branch of metaphysics dealing with theories of reality or being. Almost all scientists, past and present, have embraced without reservation the theory called realism, which holds that external reality exists and possesses definite properties, altogether independently of whether or not those properties are observed by someone.

Of Course this point of view is not special to scientists - it's hard to imagine how any person, or for that matter, how even a mouse or a cockroach, could make his way in the world without tacitly assuming in every situation that realism is valid. But from its earliest introduction quantum mechanics has troubled physicists and philosophers who believe that ontological considerations are important, for it implies very directly that observation must necessarily alter the properties of that which is being observed. For most physicists this seemed only to acknowledge the fact that our means of observation are limited in their delicacy, and so naturally observation will disturb systems that are themselves very delicate.

But several of those who had participated in the development of quantum mechanics, notably Einstein, Bohr, Heisenberg, Schrodinger and Born, clearly understood that the theory seems to imply that the properties of real systems must be considered to be indefinite until observations are made. Furthermore, it seemed inescapable that the results of observation were inherently probabilistic: the indefiniteness of the properties of a system can be resolved by observation but the actual result can only be predicted in the sense that the probabilities for the various possible outcomes can be calculated.

Einstein particularly found this situation to be intolerable and endeavored to discover a way to salvage the theory of realism. That there was no possibility of an outright rejection of quantum mechanics, Einstein, as one of its founders, knew perfectly well. But it occurred to him that perhaps one could conceive of some abstract set of properties, which came later to be called “hidden variables,” that were always and in every situation definite, and which obeyed deterministic laws, even though the variables themselves might remain hidden, utterly beyond our capability of measurement. In 1935 Einstein, in collaboration with Boris Podolsky and Nathan Rosen, published a paper which he believed would convince everyone that quantum mechanics, while correct, was nevertheless incomplete. In a brilliant application of his favorite technique, the “gedankenexperiment,” (thought experiment) Einstein assuming that quantum mechanics is correct and assuming the validity of a principle that later came to be called locality, was able to show that the indefiniteness of properties was not inherent.

Specifically, he showed Heisenberg's uncertainty principle (according to which certain pairs of "complementary" quantities, such as the position and momentum of a particle, cannot be both be known simultaneously with arbitrarily high precision) must be considered to represent only a practical fact and should not be interpreted as implying that these properties cannot simultaneously exist, each with some exact value.

Before discussing the reception which this paper received, I should briefly describe what is meant by the idea of locality, which, as mentioned, was an assumption underlying the result of the Einstein-Podolsky-Rosen (EPR) gedanken. Locality is a refinement of the idea of causality and asserts that an event occurring at a certain time and place can be influenced by another event, only if a signal could be sent from the latter to the former. Locality thus outlaws so-called "action-at-a-distance," and hence conforms to the modern ideas of field theory, and, with signal velocities limited by the speed of light, to the requirements of relativity. Locality thus may be said to be the logical foundation of relativistic field theories, a category which includes the general theory of relativity and quantum electrodynamics, two spectacularly successful theories, which must appear near the top of any listing of great human achievements.

It is unsettling then, to put it mildly, to discover that it is exactly this principal of locality that is undermined by the experimental results relating to Bell's Theorem.

Returning to the EPR gedanken, the response by the physics community must have surprised and disappointed Einstein. Neils Bohr, leader of the Copenhagen school which initiated and championed the probability interpretation of quantum mechanics, responded immediately. His criticism was directed to a rather fine point of the EPR gedanken. Einstein had established at a certain stage of the experiment that one could predict with unlimited precision <u>either</u> the position <u>or</u> the momentum of a particle without (and here is where locality enters) in any way disturbing that particle, by making an appropriate measurement on a second particle. Einstein believed that since one was free to choose either measurement, and since that measurement could not, according to the principles of locality, have any influence upon the particle in question, that both properties of that particle, each quite definite, must be "elements of reality." Bohr simply refused to accept this argument, insisting that any prediction must actually be carried out. This would require that <u>both</u> measurements be made on the second particle, and this, according to Heisenberg's uncertainty principle, cannot be done with unlimited precision.

Many physicists accepted Bohr's argument and agreed with his opinion that the whole realistic point of view is untenable, at least in the realm of atomic phenomena. Many others felt that since no difference in observable phenomena was involved, the issue was an unimportant matter of taste.

Others, a very tiny minority among physicists, were encouraged by the EPR gedanken to elaborate theories involving hidden variables, in spite of Bohr's argument, and in spite of putative proofs by John von Neumann in 1932 and by A.M. Gleason in 1957, that hidden variable theories could not be consistent with quantum mechanics. Among those attempting hidden variable theories, I will mention only three, Louis de Broglie, David Bohm, and John S. Bell, the author of Bell's Theorem.

De Broglie was one of the earliest contributors to the development of quantum mechanics. It was he who first suggested the existence of "matter waves," and he proposed at a very early stage (1926) an interpretation which differed sharply with the probability interpretation of Born and Bohr, and which, it was eventually realized, was in fact a deterministic, hidden variables theory.

David Bohm took his BS at Penn State, his PhD at Cal Berkeley, and began his working career at Cal's famous Radiation Laboratory. Following short stays at Princeton, Sao Paulo, the Technion, and Bristol, he settled (1961) in Birkbeck College, University of London. He is now a British subject and is presently involved in the development and promotion of a radically new theory of physical reality which posits the existence of an underlying “implicate order,” which bears the same relation to the “explicate order” (that is, the familiar universe of objects moving in space) as a hologram bears to its corresponding image. In 1952 Bohm published a paper in which he developed a hidden variables theory constructed so as to reproduce the results predicted by quantum mechanics for a system of the EPR type. Bohm also showed that deBroglie’s theory, which was also consistent with quantum mechanics, shared a peculiar feature with his own: both required the non-local interaction of particles. The study of this paper by Bell in the mid 60s was important to his first formulation of the theorem that bears his name.

Bohm made another crucial contribution relevant to Bell’s theorem. In 1951 he formulated a variant (indicated by the letters EPRB) of the EPR gedanken that is at once conceptually much clearer and, more importantly, realizable as an actual experiment. Bohm’s system relates to a system of particles that have been prepared in a state of zero spin (here spin refers to intrinsic angular momentum, a discrete variable, one of the so-called quantum numbers peculiar to quantum mechanics). In the framework of the EPR gedanken, a prediction of the measurement of the spin of one particle of the pair is made in terms of the measuring the spin of its mate. In experiments testing Bell’s theorem, one is concerned with the correlation between measurements of the spin of each of the particles of the pair.

John Stewart Bell, FRS 1972, grew up in Belfast where he attended high school and Queen’s College. He took his PhD at the University of Birmingham in 1949, and joined AERE Harwell. Since 1960 he has been working with CERN in Switzerland. His work on hidden variables includes the construction of a model appropriate for the description of the spin of particles, which, by yielding results consistent with quantum mechanics, demonstrates that the arguments made by von Neumann are unnecessarily restrictive, vitiating the latter’s “proof” that quantum mechanics was complete as is. Bell has also presented arguments to the same effect regarding Gleason’s corollary, which applies to the descriptions that embrace more aspects of reality than merely spin.

These studies are very deep indeed, and the issue of the possibility of a hidden variables theory that is consistent with quantum mechanics is by no means settled. But for our concerns, the important thing is that these studies led Bell to a detailed examination of Bohm's work, and so to pose the question as to whether the peculiar non-locality exhibited by the models of Bohm and of de Broglie was a necessary feature of all hidden variable theories that agree with quantum mechanics. In 1965 Bell proved that the answer is positive, provided that certain idealizations of apparatus and systems are allowed. Subsequently, Bell and others were able to show that all realistic theories satisfying the demand of locality impose constraints on the results of real, non-ideal experiments. It was finally appreciated that the issues of hidden variables and of determinism generally, are not directly involved, but rather that non-locality is a property of quantum mechanics itself. This theoretical work of analysis and generalization was carried out by a growing number of workers, led by Bell himself and including H.P. Stapp, John Clauser, M.A. Horne, Abner Shimony, and R.A. Holt, among others.

Nowadays, Bell's Theorem is a term applied to any restriction, usually stated in the form of an inequality limiting experimental correlations that may be deduced on the basis of assuming the validity of the principle of locality.

All of the many forms of Bell's Theorem ultimately derive from the simple fact that locality demands that the probability of observing a result with apparatus A cannot depend upon what sort of measurement may have been made (or not made) with another instrument B in a situation where no real signal could have traveled from B to A. Under these circumstances, the probability for a certain pair of measurements, say α at A, and β at B, can we written as the product of two simpler probabilities:

$$P_{\alpha\beta} (A, B) = P_{\alpha} (A) P_{\beta} (B)$$

But the predictions of quantum mechanics do not allow for this sort of factorization, and thus it is clear that quantum mechanics must be a non-local theory. In hindsight it all seems quite simple. And yet discussion of the logical foundations of Bell's Theorem has continued for nearly two decades to the present.

The first actual experiment was carried out by Freedman and Clauser in 1972. The experiment dealt with pairs of photons emitted by excited calcium atoms. The results were in good agreement with the predictions of quantum mechanics and violated the constraint imposed by Bell's Theorem. Similar experiments by Clauser (and by Fry and Thompson) using mercury atoms produced similar results. Kasday, Ullman and WU in 1975 performed experiments employing high-energy photons produced in positron-electron annihilation events. Their results were also in good agreement with quantum mechanics. In 1976, Lamehi-Rachti and Mittig carried out experiments using protons and again the results favored quantum mechanics over local realistic theories.

Without doubt, the most definitive experiments to date are those carried out by Alain Aspect and his French co-workers. Their paper of 1981 shows the largest discrepancy between the predictions of local realistic theories and quantum mechanics. But that experiment, like all those preceding it, was a static one, so that the possibility of some kind of signal propagating from one measuring event to the other was not ruled out. A year later however, Aspect's team reported the results of an experiment incorporating a switching arrangement that ruled out any communication at sub-luminal speed between the two measuring events. Again, the predictions of quantum mechanics were found to be in excellent agreement with the experimental results, while the constraints implied by local realism via Bell's Theorem were certainly violated.

Thus, it has been definitely established that Nature, at least in the quantum realm, behaves in ways that are inconsistent with the principle of locality, that relativistic, field-theoretic extension of causality which had seemed such a solid foundation stone of modern physics.

It is certainly ironic, and perhaps surprising at first glance, that quantum electrodynamics, which is itself a relativistic field theory, conforms beautifully with the results of experiments directed to test the restrictions of Bell's Theorem. This can be understood once it is realized that the fields with which quantum theories are concerned do not in themselves represent reality, but are rather only elements of a mathematical scheme by means of which the probabilities for the various possible outcomes may be calculated.

It is not only the principle of locality that is lost. Recall that the argument of EPRB gedanken was based upon the assumption of locality. So if locality falls, then so also does realism fall, at least if the EPRB gedanken represents the best defense of the theory of realism.

So where are we then? If reality is indeed a crutch, at what level may we lean upon it? A partial answer can inferred from the work of N.D. Mermin, who shows, for simple spin sys terns, that the range of angles over which Bell's inequalities are violated varies inversely with the spin quantum number, and so goes to zero in the classical limit. This gives assurance that violations of locality will not be seen in everyday macroscopic phenomena. So as a practical matter, we may all go on using the principle of causality, and continue to imagine that there is a real world out there.

But philosophy is not usually considered to be a practical, rule-of-thumb business. It is usually imagined to be concerned with truth. The philosopher is apt to view causality as an all-or-nothing affair, much as a fundamentalist preacher might view virginity. What can be said in this regard? To get some idea of how bad the situation is, consider the following two alternative suggestions by H.P. Stapp, by means of which one may avoid the need of including non-local influences in one's world view.

First, there is <u>superdeterminism</u>, in which the free choice of the experimenter is denied. In this scheme, in order to avoid the repellent notion of action-at-a-distance, the whole idea of actual causality is thrown out, to be replaced by a sham causality built into the pre-ordained choreography for the universe.

Stapp's second alternative is even worse, and relates to the "many-worlds" interpretation of quantum mechanics suggested about twenty years ago by Bryce DeWitt. In this truly mad vision of the world, everything that can happen does, so that at each juncture (i.e., each time some wave function ~s interrogated by an act of observation) the whole universe bifurcates (or tri-furcates, or n-furcates, depending upon the number of quantum states available) into a pair (or trio or n-ensemble) of separate and non-interacting universes: The idea, if I understand it, is that we are automatically prevented from seeing those outcomes which would be inconsistent with the predictions of quantum mechanics. I must admit that I have never been able to persuade myself that DeWitt was not making an elaborate joke.

Let me turn from philosophical considerations back to physics. An important question is whether or not the non-local interactions of quantum mechanics are consistent with relativity, which holds that the speed of light cannot be exceeded by massive objects or by signals. Two events are said to be connected by a space-like interval if they occur too far apart from one another and too close together in time to permit a light signal to be sent from one event to the other. As we have seen, quantum mechanics demands that in certain circumstances, events which are connected by a space-like interval must nevertheless be inter-dependent. It is natural to attempt an explanation in which one imagines that some sort of super-luminal signal goes from one event to the other.

Leaving aside the question as to whether such a model could be consistent with quantum mechanics and relativity, it is a very remarkable fact that it can be shown that it is quite impossible to make use of this effect to implement a faster-than-light system of communication. This result, at base, depends upon the fact that the individual observations made at each location are still probabilistic, even though they may be correlated more strongly than is consistent with local realistic theories. I should mention that at least one physicist, Jack Sarfatti, a director of an organization called the Physics/Consciousness Group, disagrees, and claims that super-luminal communication based upon a variant of the EPRB gedanken is feasible.

Accepting the majority view, then, it may be said that there is no gross violation of relativity. But there remains the question as to whether or not an explanation for the non-locality can be put together in a manner consistent with relativity. The answer appears to be yes, but again, it will certainly appear to some that the Cure is far worse than the ailment.

At this point it is appropriate to review two episodes in the history of physics. The first is the heroic struggle of H.A. Lorentz to construct a complete theory of the electron, in particular, his attempt to account for the effect that an electron's radiation has upon its motion. Lorentz found that in order to get consistent results, he was forced to make use of a solution to Maxwell's equations which had always been considered to be a mathematical fiction and something of an embarrassment. This is the so-called "advanced solution," in which the electromagnetic potentials at a point 1n space are determined not by what the sources were doing in the past, with the time lapse just right to permit their effects to arrive, but by what those sources would be doing in the future:

The second episode is not really a single event but rather a series of interpretations introduced by Richard Feynman of Caltech. Most spectacular was his interpretation of antiparticles as ordinary particles "moving backward 1n time." Earlier, Feynman, working with his teacher, John Wheeler, had shown how the advanced solutions of electromagnetic theory should properly be interpreted as waves moving backwards in time. In this interpretation, both emitter and absorber give off advanced as well as retarded waves, but each at only half amplitude, and such that the waves given off by the absorber have their phase opposite to those of the emitter. It is then shown that the sum of these waves cancel for all times preceding the event of emission and also for all times after the act of absorption. Furthermore, in between these events, the two half waves combine to form the single whole wave corresponding to the perceived reality. Although the original work by Wheeler and Feynman was carried out in the idiom of classical electrodynamics, Davies has shown that the results carryover without essential alteration into the quantum electrodynamic (QED) description. All of this goes under the name "absorber theory.” It all works out very nicely, but it has to go very much against the grain of any mind steeped in naive realism, for it clearly holds that the whole transaction of emission and absorption involves a bizarre sort of negotiation carried out backwards and forwards in time between the emitter and absorber.

You’ll recall, hope, that we got into all of this in the hope of answering the question of whether the non-locality of quantum mechanics can be squared with the requirements of relativity. John G. Kramer of the University of Washington has developed a generalized absorber theory that treats the interaction of massive particles as well as the photons of QED.

In a 1980 paper, Cramer introduces two forms of the principle of causality. His strong-causality principle corresponds to what we have called locality, and may be stated as follows:

> A cause must always precede all of its effects, in every reference frame. Furthermore, no information can be transmitted over a space-like interval or over a negative time-like or negative light-like interval.

The statement of Cramer's weak-causality principle depends upon his introduction of a dichotomy for phenomena based upon the involvement or non-involvement of observers. For phenomena involving observers he uses the word macroscopic. Thus he says

> “By a macroscopic cause we mean a cause initiated by An observer, by a macroscopic effect we mean an effect which would allow an observer to receive information, and by macroscopic information we mean information which would allow one observer to communicate with another. Any other kinds of causes, effects, or information we consider to be microscopic.”

Cramer's weak-causality principle then is identical with the statement of the strong principle, except that the modifier "macroscopic" is inserted throughout.

He then goes on to show that paradoxes of the EPRB type can be resolved without conflict with the weak-causality principle. He also shows that there is no need to consider that even microscopic phenomena exchange information over space-like intervals, even though they do send information backward ~n time, that is, over negative time-like intervals. Thus relativity is saved, at least with respect to the issue upon which it made a pronouncement communication over space-like intervals. I think that it’s fair to say that relativity was silent on the issue of sending messages backward in time, because the idea would have been considered too absurd to even mention by Einstein and Lorentz - the originators of that theory.

Here we are presented with an interpretation that is very similar to Stapp’s superdeterminism. The Universe, working on its secret microscopic levels and negotiating back and forth between past and future, contrives to put together a world in which causality and free will seem to exist.

It seem. to me that this sort of realism is but a little better than solipsism, that negation of realism which holds that only the self exists and therefore that reality is subjective.

It's interesting to speculate as to what the originators of this dialog, Einstein and Bohr, might say if available for comment. My guess is that Bohr would be not at all surprised by the experimental results relating to Bell's Theorem, and might even be willing to express his pleasure in seeing quantum mechanics prevail, as it were, not only over naive realism, but also over causality, at least in its strong expression. On the other hand, I am afraid that Einstein might now retract his famous statement,

“Subtle is the Lord, but malicious He is not.”