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Nonlocal Character of Quantum Theory *

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Abstract

According to a common conception of causality, the truth of a statement that refers only to phenomena confined to an earlier time cannot depend upon which measurement an experimenter will freely choose to perform at a later time. According to a common idea of the theory of relativity this causality condition should be valid in all Lorentz frames. It is shown here that this concept of relativistic causality is incompatible with some simple predictions of quantum theory.

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1. Introduction

It widely believed by physicists that the work of Einstein, Podolsky, and Rosen[1], John Bell[2], and others[3] has demonstrated a conflict between quantum mechanics and the theory of relativity. This conflict is suppose to be a logical incompatibility between some elementary predictions of quantum theory and the idea that causal influences can propagate only into the forward light cone.

This belief, though widespread, is far from universal. A principal cause of dissent is this: the simplest demonstrations of the supposed conflict merely prove a conflict between quantum mechanics and a property called "local realism". As this phrase indicates, these proofs demonstrate no direct conflict between quantum mechanics and relativity, for there is the added assumption of "realism". This latter assumption can take various forms. It is essentially an assumption of the existence of hidden variables of a kind banned by quantum philosophy. Or perhaps it is an assumption of the existence of "elements of reality" of the kind proposed by Einstein, Podolsky, and Rosen, but rejected by Bohr. Alternatively, there might be an assumption akin to determinism, which likewise is rejected by quantum philosophy.

The aim of this paper is to give a new proof of a logical conflict between some prediction of quantum mechanics and the idea that no causal influence can propagate faster than light. This new proof is perhaps simpler than ones I have given before[4,5], and has some added technical virtues that I shall describe later.

To speak clearly about causal influences one must identify some "causes". The basic assumption in all Einstein-Podolsky-Rosen-Bell-type arguments is that the choices to be made by experimenters concerning which measurement they will eventually perform on some individual quantum system can be regarded as unconstrained, or free: these choices are assumed to be sufficiently uncontrolled, and independent of the quantum system under consideration, to be treated as free variables, within the context of the analysis. Indeed, Bohr repeatedly emphasized the freedom of experimenters to examine either one aspect or another of an individual quantum system.

The word "local" refers here to a putative causality condition that claims that no free choice can influence observable phenomena lying outside its forward light cone: if a statement S refers only to choices between possible experiments and their possible observable outcomes that are all localized in a spacetime region lying earlier than some time T then the truth of this statement S cannot depend upon which experiment is freely chosen and performed in a spatially separated region at a time later than T. Statement S cannot be true if one choice is made at the later time, but false if another choice is made at the later time. The crucial locality assertion, suggested by the theory of relativity, is that any Lorentz frame can be use to determine what it earlier and what is later: the non-dependence of the earlier upon the later should hold in all frames.

The argument to be used here depends on the idea that a choice to be made by an experimenter at a later time can be regarded as a free variable, and that the possible consequences of making different choices can be compared. Thus the argument involves a certain weak form of counterfactual reasoning. This fact is sometimes taken as a sufficient reason to discard wholesale all EPR-Bell-type arguments. That tactic is not rational.

Imagine in classical mechanics an electron of unknown velocity entering an apparatus having, say, various crossed electric and magnetic fields, so that if the electron is observed to land at a certain point then one knows from the theory what its incoming velocity was, and hence where it "would have landed" if the experimenter had used in the experiment a second apparatus, "instead of" the first one.

This example illustrates the fact that theoretical assumptions often allow one to say with certainty, on the basis of the outcome of a certain experiment, what "would have happened" if an alternative possible apparatus had been used. If logical arguments of this kind—that follow directly from certain theoretical assumptions—lead to a contradiction, then one must, if rational, accept the fact that at least one of the explicit or implicit theoretical assumptions is incorrect.

Logicians have developed a symbolic way of expressing conditionals of this kind, which abound in physics. It will be useful to adopt their notation.

The experiment to be examined here, from a theoretical perspective, involves two space-like separated space-time regions, **R** and **L**. There is initially one single physical system that is subjected in each region to a bivalent free choice between just two alternative possible measurements. The chosen measurement will then immediately be performed in that region.

Suppose $R1$ and $R2$ represent the two alternative possible measurements that might be performed in the space-time region **R**. The symbolic statement

$$(X \wedge R2) \Longrightarrow [R1\Box \rightarrow Y]$$

asserts that the truth of conditions X and $R2$ entails that if measurement $R1$ were to be chosen, *instead of* $R2$, then condition Y *would hold.* The notation is suppose to signify that the other free choice (i.e., the one in **L**) is left unchanged.

In the following proof the "locality" condition is asserted in three forms. They all express the idea that the truth of a statement pertaining to (macroscopic) phenomena confined to one region is independent of which measurement will be freely chosen and performed in the other region at a later time.

In the experiment to be considered here each of the possible measurements has two possible outcomes. Let the two possible outcome of $R1$ be called $R1+$ and $R1-$, etc..

Symbolically stated, the first locality condition is this:

$$LOC1 : (L2 \wedge R2 \wedge L2+) \Longrightarrow [R1\Box \rightarrow (L2 \wedge R1 \wedge L2+)].$$

It asserts that if under the condition that the choices were $L2$ and $R2$ the outcome in **L** at some earlier time were $L2+$, then if the (later) choice in **R** were to be $R1$, instead of $R2$, but the free choice in **L** were to remain unchanged, then the outcome $L2+$ in **L** would likewise remain unchanged. This assumption is an expression of the theoretical idea that the present facts are independent of which free choice will be made later.

The second locality condition is called $LOC2$. Suppose the measurement made in **L** is performed *before* the measurement performed in **R** is chosen. And suppose that under the condition that the measurement made in **L** is $L2$ one can prove (using $LOC1$) the truth of the following statement SR:

$$[(R2 \wedge R2+) \Longrightarrow (R1\Box \rightarrow R1-)].$$

Notice that everthing mentioned in SR is an observable phenomena in region **R**. This statement has the same form as the one from classical mechanics that

I used as an illustration. The assumption in $LOC2$ is that statement SR has been proved under the condition that $L2$ was performed in the far-away region **L** at an earlier time. Now special relativity comes in. According to the ideas of special relativity it should not matter which frame is used to specify "earlier" and "later". So let's use a frame in which the choice to perform $L2$ in region **L** is made *later* than all the phenomena referred to in SR. But a statement about what would happen in **R**, under certain condition defined there, that is known to be true under the condition that the later free choice in **L** is $L2$, cannot be rendered false by changing that later free choice, provided the idea is upheld that observable effects can propagate only into the future (light-cone). So $LOC2$ asserts this: "If SR is proved to be true under the condition that $L2$ is freely chosen in **L** then SR must be true also under the condition that $L1$ is freely chosen there instead."

The final locality condition, $LOC3$, asserts the commutability of $L1- \Longrightarrow$ and $R1\Box \rightarrow$. This result follows from the fact that, according to the putative locality property, the truth of $L1-$ is unaffected by changing the choice in **R** from $R2$ to $R1$: $L1-$ is the same condition whether asserted under condition $R2$ or $R1$.

These three locality conditions will be used in the context of an analysis of a Hardy-type experiment.

2. Hardy-type Experiment

The important features of a Hardy-type experiment are shown in Figure 1, along with the four pertinent predictions of quantum theory.

For example, the solid line from b to g represents the prediction that:
"If $L1$ is performed in **L** and the outcome there is b, then if $R2$ is performed in **R** the outcome there will be g."

This prediction can be written symbolically as:

$$(L1 \wedge b) \Longrightarrow (R2 \Longrightarrow g),$$

where $\Longrightarrow$ stands for *implies*, the strict conditional, and $\wedge$ stands for conjunction. Equivalently, this prediction can be written in the form of line 8 of the proof.

Informally, the general line of argument goes as follows. Suppose we consider a frame in which the measurement in region **L** is chosen and performed earlier than the measurement in region **R**. Suppose experiment L2 is chosen in **L**. Then the LOC condition that the outcome at the earlier time cannot be one outcome if the later choice in **R** is to perform experiment R2, but a different outcome if the later choice is to perform experiment R1, combined with the two QM predictions $g \rightarrow c$ and $c \rightarrow f$, allows one to conclude, under this condition that the earlier measurement is L2, that $g \rightarrow f$. Following the symbolic conventions of modal logic we express this conclusion in the following way:

$$(L2 \wedge R2 \wedge g) \Longrightarrow [R1 \Box \rightarrow (L2 \wedge R1 \wedge f)],$$

which is line 4 of the proof. It says that: "If L2 and R2 are performed and the result g=$R2+$ appears in **R** then if R1 had been performed there, instead of R2, then the outcome f=$R1-$ would have appeared."

Statements of this general kind are commonplace in physics: theory often allows one to deduce from the outcome of certain measurements on a system what the outcome of some alternative possible measurement would necessarily be. That is why modal logic really had to be developed: to cope with the fact that statements of this general kind are endemic in science.

The conclusion obtained above can be formulated as a statement that if measurement L2 is performed then $g \rightarrow f$, where the consequence is a statement referring only observables in region **R**. [See line 5 of the proof for the complete statement.]

Now the truth of this statement cannot depend on how we select the frame of reference, which is merely a notational convention. So let us shift to another frame, where the measurements in region **L** are chosen and performed later. The statement $g \rightarrow f$ must still be true. But the truth of this statement, which refers only to observables in **R**, cannot, according to the putative locality principle LOC, depend on whether measurement L2 or L1 is chosen to be performed at the later time. Yet if this implication $g \rightarrow f$ holds also under the condition that L1 is performed in **L** then we can combine that implication with $b \rightarrow g$ to get $b \rightarrow f$, which contradicts the prediction of QM that b entails e some nonzero fraction of the time.

3. The Proof

1. LOC1: $(L2 \wedge R2 \wedge c) \Longrightarrow [R1\Box \rightarrow (L2 \wedge R1 \wedge c)]$.
2. QM: $(L2 \wedge R2 \wedge g) \Longrightarrow (L2 \wedge R2 \wedge c)$.
3. QM: $(L2 \wedge R1 \wedge c) \Longrightarrow (L2 \wedge R1 \wedge f)$.
4. LOGIC: $(L2 \wedge R2 \wedge g) \Longrightarrow [R1\Box \rightarrow (L2 \wedge R1 \wedge f)]$. [From1, 2, 3.]
5. LOGIC: $(L2) \Longrightarrow [(R2 \wedge g) \Longrightarrow (R1\Box \rightarrow f)]$. [Logically equivalent to 4.]
6. LOC2: $(L1) \Longrightarrow [(R2 \wedge g) \Longrightarrow (R1\Box \rightarrow f)]$.
7. LOGIC: $(L1 \wedge R2) \Longrightarrow [g \Longrightarrow (R1\Box \rightarrow f)]$. [Equivalent to 6.]
8. QM: $(L1 \wedge R2) \Longrightarrow [b \Longrightarrow g]$.
9. LOGIC: $(L1 \wedge R2) \Longrightarrow [b \Longrightarrow (R1\Box \rightarrow f)]$. [From 7 and 8.]
10. LOC3: $(L1 \wedge R2) \Longrightarrow [R1\Box \rightarrow (b \Longrightarrow f)]$.
11. LOGIC: $R2 \Longrightarrow [L1 \Longrightarrow [R1\Box \rightarrow (b \Longrightarrow f)]]$. [Equivalent to 10.]
12. QM: $L1 \Longrightarrow [R1 \Longrightarrow \neg(b \Longrightarrow f)]$.
13. LOGIC: $L1 \Longrightarrow [R1\Box \rightarrow \neg(b \Longrightarrow f)]$. [Entailed by 12.]
14. LOGIC: $R2 \Longrightarrow [L1 \Longrightarrow [R1\Box \rightarrow \neg(b \Longrightarrow f)]]$. [Entailed by 13.]

The symbol $\neg$ is negates the proposition that follows it.

The conjunction of 11 and 14 contradicts the assumption that the experimenters in regions **R** and **L** are free to choose which experiments they will perform. Thus the incompatibility of the assumptions of the proof is established.

4. Conclusion

A contradiction has been obtained. Thus some assumption of the proof must be false. The only assumptions were: (1) the validity of some simple predictions of quantum theory, (2) the explicitly stated locality conditions, (3) the general idea that physical theories can cover a variety of special instances that can be imagined to be created by free choices of experimenters, and (4) the *general* principles of modal logic, which merely formalize what we mean by modal language. The latter two assumptions do not contravene the principles of quantum mechanics as they are normally understood: Bohr often emphasized that the freedom of experimenters to examine one aspect or another of a quantum system is in no way compromised by quantum theory: indeed his idea of complementarity rested on the idea that we enjoy that freedom. And he embraced the use of ordinary language and logic to describe the observable aspects of things.

An advantage of the present proof over those of references 4 and 5 is that there is no appeal here to any special technical assumption or to any of the special rules of "closeness of worlds" that philosophers have introduced to extend the meaning of modal language beyond what is strictly entailed by the strict laws of nature and other conditions, such as our locality conditions, that allow conclusions to be drawn simply from the basic meanings of the words, as formalized by the *general* principles of modal logic.

It should be emphasized that no conflict has been established here between quantum theory and the general causal principle that the present facts are independent of free choices to be made at later times. The contradiction arises only when one tries to extend this principle by asserting the relativistic notion that the principle can be assumed to hold in all Lorentz frames. There is no difficulty with the assumption that this causality condition holds in some single preferred frame of the universe, such as the cosmic black-body radiation rest frame.

5. Concluding Comment

The theory of relativity was created within the context of deterministic physical theories. In deterministic theories the entire course of the history of the universe is determined by the initial conditions, or by early conditions. Thus an account of the actual process of the physical unfolding of this history is not really essential to the physical theory. That was Einstein's point. The data that scientists use are what can be written down in a log book that lists what was observed. Some observations may include the reading on some clock when the observation was made. But this latter reading is just part of the observation. This log-book sort of information is timeless, even though the observations do include readings on clocks. There is no remnant in this data of the order in which the data from different regions "came into being", beyond the logged-in evidence itself. But the log-book sort of physical data is fixed by a deterministic theory without mentioning any process of the "coming into beingness" of reality: one can simply adopt an overall spacetime point of view.

In quantum theory the evolution of the state in accordance with the Schroedinger equation is deterministic. But that is only half of the dynamical story. There is, in practice, also a second process, represented by the collapse of the wave function. This second process is, within contemporary theory, not deterministic: at any point in the development of reality the future is not yet fixed by the deterministic part of the dynamics, but depends on what the yet-to-be-determined future collapses will select as the actual.

The original "Copenhagen" interpretation was epistemological in character, and the collapse of the wave function was construed to be a consequence of the increased knowledge of the observer/scientist. As such it could not be considered to cause any actual transfer of information faster than light. The system should, therefore, inherit from the Schroedinger equation (in its local field theory form) the property that causal influences propagate only into the forward light cone.

This Copenhagen strategy of bringing the observer and his knowledge into the physical theory was opposed by Einstein and others in the early days, and it seems again to be troubling physicists. Einstein believed that the future theory would not only remove the observer and his knowledge from center stage, but would also save the relativistic principle that causal influences propagate no faster than light. Saving this principle has been shown here to be impossible. However, it is still possible to save the relativistic principles that there is no preferred frame of reference, and no propagation of influence backward in time, where "backward" now means into the (closed) backward light-cone

In an effort to remove "the observer" from physical theory I proposed many years ago a "theory of events"[10]. A similar idea has recently been proposed independently by Rudolf Haag[11]. Without going into details let me only say that the basic idea is to postulate that there are real events associated with finite regions in spacetime, and with real (objective) collapses of the (objective) wave function. If, as a special case, one takes these regions to be confined to the (open) backward light-cones from spacetime points, then one obtains a picture of the process of generating reality as a succession of steps each of which augments the "past" by adding the backward lightcone from some new spacetime point, and moves forward the three-dimensional manifold "now" that separates the past from the unfixed future. Each new event is associated with a collapse of the wave function that defines the state on the new surface "now". No special frame is singled out as preferred. The surface "now" advances always into the future, in finite steps. Each event influences, immediately, only things at points spacelike separated from itself, in the sense that each old point of the new surface "now" is spacelike separated from every point in the region associated with the new event. Although each quantum event can, therefore, influence things at spacelike separated points, the model is otherwise in line with the ideas of the theory of relativity.

The apparent violation established in this paper of the putative relativistic causality condition lends support to an an objective evolutionary picture of this general sort, in which the collapses are real actual events that can influence the objective propensities for subsequent (to "now") spacelike separated events.

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References

1. A. Einstein, B. Podolsky, and N. Rosen, "Can Quantum Mechanical Description of Physical Reality be Complete?" *Physical Review 47*, 777-780 (1935).

2. J.S. Bell, "On the Einstein-Podoksky-Rosen Paradox", *Physics 1*, 195-200 (1964).

3. J.F. Clauser and A. Shimony, Bell's theorem: experimental tests and implications, *Reports on Progress in Physics 41*, 1881-1927 (1978); D.M. Greenberger, M.A. Horne, A. Shimony, and A. Zeilinger, Bell's theorem without inequalities *American Journal of Physics 58*, 1131-1143 (1990); Lucien Hardy, Quantum mechanics, local realistic theories, and Lorentz-invariant realistic theories, *Physical Review Letters 68*, 2986-2984 (1992); Lucien Hardy, Nonlocality for two particles without inequalities for almost all entangled states, *Physical Review Letters 71*, 1665-1668 (1993); P.H. Eberhard and P. Rosselet, Bell's theorem based on a generalized EPR criterion of reality, *Foundations of Physics 25*, 91-111 (1995).

4. H.P. Stapp, "Noise-induced reduction of wave packets and faster-than-light influences", *Physical Review 46 A*, 6860-6868 (1992).

5. H.P. Stapp, Reply to 'Stapp's algebraic argument for nonlocality', *Physical Review A49*, 4257-4260 (1994).

6. Lucien Hardy, "Quantum mechanics, local realistic theories, and Lorentz-invariant realistic theories", *Physical Review Letters 68*, 2981-2984 (1992); "A

quantum optical experiment to test local realism", *Physics Letters A 167*, 17-23 (1992).

7. P.H. Eberhard and P. Rosselet, "Bell's theorem based on a generalized EPR criterion of reality", *Foundations of Physics 25*, 91-111 (1995)

8. N. David Mermin, "Quantum mysteries revisited", *American Journal of Physics 58*, 880-887 (1994).

9. David Lewis, *Counterfactuals,* Blackwell Press, Oxford; *Philosophical Papers Vol II*, Oxford University Press, Oxford, 1986; D. Bedford and H.P. Stapp, "Bell's Theorem in an Indeterministic Universe", *Synthese 102*, 139-164 (1995).

10. Henry P. Stapp, "Bell's Theorem and World Process", Nuovo Cimento 29, 270-276 (1975); "Theory of Reality", Foundations of Physics 7, 313-323 (1977); "Whiteheadian Approach to Quantum theory and the Generalized Bell's Theorem", Foundations of Physics 9, 1-25 (1979).

11. Rudolph Haag, *Local Quantum Physics* Springer-Verlag, Berlin,1996, Second Edition, Chapter VII; "An Evolutionary Picture for Quantum Physics", Commun. Math. Phys. 180, 733-743 (1996).

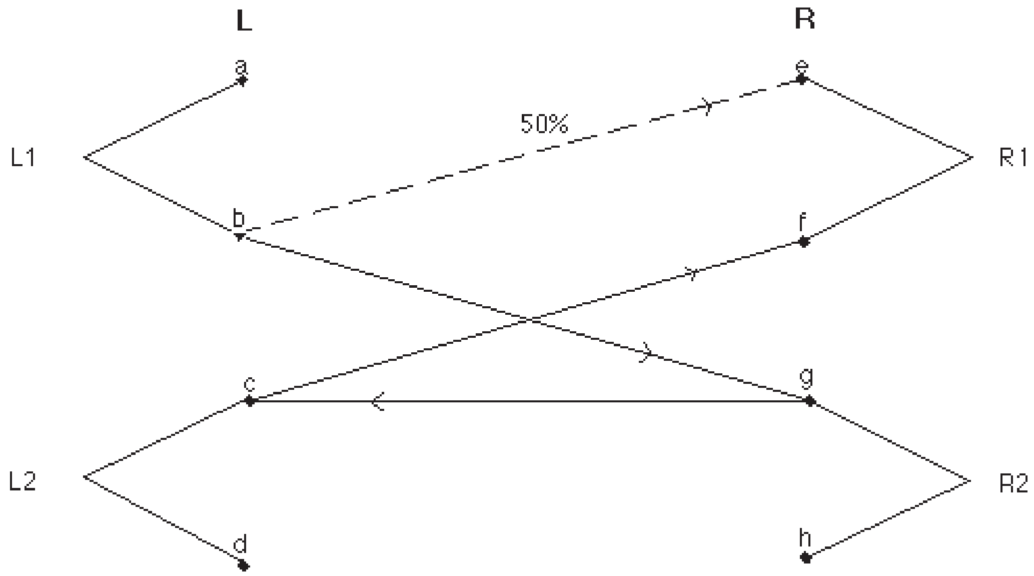

Figure 1: The logical structure of the Hardy experiment is represented, together with the four pertinent predictions of quantum theory. The three solid paths between pairs of labelled points represent predictions that have conditional probability equal to unity. The dashed line represents a connection that has conditional probabilty equal to 50%. (The 50% comes from the Eberhard/Rosselet version: Hardy's optical case gives 67%)