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Reply to "On Stapp's 'Nonlocal Character of Quantum Theory' " *

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Abstract

The question raised by Shimony and Stein is examined and used to explain in more detail a key point of my proof that any theory that conforms to certain general ideas of orthodox relativistic quantum field theory must permit transfers of information over spacelike intervals. It is also explained why this result is not a problem for relativistic quantum theory, but, on the contrary, opens the door to a satisfactory realistic relativistic quantum theory based on the ideas of Tomonaga, Schwinger, and von Neumann.

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Shimony and Stein[1] have raised a question about an essential claim made in my 1997 paper[2]. I begin by explaining the claim, and the question they raised.

Lines 1 through 5 of my proof[2] show that under certain explicitly stated conditions the statement

$$L2 \Rightarrow [(R2 \wedge R2+) \rightarrow (R1\Box\!\!\rightarrow R1-)] \tag{1}$$

is true, while lines 6 through 14 of that proof show that under these same conditions the statement

$$L1 \Rightarrow [(R2 \wedge R2+) \rightarrow (R1\Box\!\!\rightarrow R1-)] \tag{2}$$

is false. Shimony and Stein arrive at the same conclusion—namely that (1) is true and (2) is false—under similar conditions. I then claim that this fact, that (1) is true and (2) is false, entails that information must sometimes be transferred over space-like intervals. Shimony and Stein question this claim, and suggest that one must make a hidden-variable assumption, as was done in Bell's theorems [3,4], in order to arrive at this strong conclusion.

This issue is important, because all the assumptions used my proof are elements of orthodox quantum philosophy, and hence my claim, if valid, means that the precepts of orthodox quantum philosophy entail that information must sometimes be transferred over spacelike intervals. That conclusion is far stronger than what is proved by Bell's theorem[3], and its usual generalizations[4,5], and it seems to have profound implications for development of relativistic quantum theory.

To provide an adequate foundation for the discussion I need to explain the meanings of (1) and (2), the assumptions that go into my proof that (1) is true and (2) is false, and the technical differences between my assumptions and those of Shimony and Stein.

The conditions under which I prove that (1) is true and (2) is false are these:

A. The choices made by the experimenters in each of the two regions **R** and **L** about which experiment will be performed in that region can be treated as *free choices*, or *free variables.*

B. There is at least one Lorentz frame of reference, call it LF, such that if in that frame every point of the spacetime region **L** is earlier than every point in the spacetime region **R** then for any experiment freely chosen and performed in the earlier region **L** the outcome that appears to observers in that region can be taken to be independent of which experiment will be freely chosen and performed later in the region **R**: the universe can be regarded as evolving forward in time in LF and, in particular, there is no action of a free choice made *later* in **R** upon an outcome that has *already appeared earlier* in **L**. This assumption is called LOC1.

C. No matter which experiments are freely chosen and performed, the predictions of quantum theory will be satisfied.

These assumptions are, I believe, compatible with the precepts of orthodox quantum thinking, and are, in a broad sense, entailed by them.

Notice that the truth of certain very special contrary-to-fact assertions is entailed by these assumptions. In particular, if the set of possible worlds is limited by conditions A, B, and C then,

SF: For any possible world W, the following statement is true:
If the situation in W is such that
1. The Hardy experimental conditions are satisfied,
2. Experiment L2 is freely chosen and performed in **L**,
3. Experiment R2 is freely chosen and performed in **R**, and
4. The outcome $L2+$ appears in **L**,

then in any possible world W' that is the same as world W except for possible consequences of choosing and performing in region **R** the experiment R1, instead of the experiment chosen and performed in **R** in world W, the outcome in the earlier region **L** is $L2+$.

The result asserted by SF is immediately entailed by the stated assumptions, actually just A and B, and it is expressed symbolically as

$$(L2 \wedge R2 \wedge L2+) \Rightarrow (R1 \Box\!\!\rightarrow L2+). \tag{3}$$

This statement asserts, in brief, that if the theoretical conditions A, B, and C are satified then freely choosing and performing R1, instead of R2, in the later region **R**, leaves the earlier outcome in **L** undisturbed.

Similarly, the symbolic statement (1) asserts that, under the three conditions A, B, and C, if experiment L2 is freely chosen and performed in the earlier region **L** then a certain statement SR is true, whereas statement (2) makes the same claim under condition L1. Thus the conjunction of the facts that (1) is true and (2) is false implies that the truth of statement SR depends nontrivially on which of the two alternative possible experiments, L1 or L2, is freely chosen and performed in the space-time region **L**.

The statement SR just mentioned is represented symbolically by

$$[(R2 \wedge R2+) \rightarrow (R1 \Box\!\!\rightarrow R1-)] \tag{4}$$

It is an assertion about a possible world W, and it states

SR: If in the possible world W the experimenter in the space-time region **R** freely chooses and performs experiment R2 and gets the outcome $R2+$, then in any possible world W' that is the same as world W except for the possible consequences of choosing in the region **R** the experiment R1, instead of whatever was chosen in W (namely R2), the outcome in **R** is $R1-$.

In reference [2] I justified each step in the proof that statement (1) is true and statement (2) is false by using the machinery of David Lewis's rules of reasoning with counterfactual statements. The Lewis machinery is reasonable and orthodox, but was created in the climate where the ideas of deterministic classical physics prevailed, and in the end it is merely a set of conventions designed to cope in a deterministic setting with the idea that something other than what actually happens 'could have happened'. The conventions are designed to mesh with our intuitions about the proper use of contrary-to-fact statements, but there are other contending rules, and the whole situation is somewhat controversial. But as I have emphasized, and Shimony and Stein have agreed, the quantum situation permits a more direct approach, which avoids leaning on the basically conventional features of the classical approach. Instead, one can exploit the fact the concept of a 'free choice' is compatible with quantum theory, due to its basically indeterministic character. This allows one to stay with ordinary logic plus a natural specified meaning for the needed counterfactual assertion.

In order to have a common ground for dealing with the concerns of Shimony and Stein I shall, in this paper, adopt this alternative approach, which is strictly in line with quantum thinking, rather than relying on Lewis's classical rules. However, apart from this technical change, I shall adhere to the logical form of the argument that I used in reference [2]. In particular, I shall retain the following natural meaning of the statement $(E\Box \rightarrow O)$:

$(E\Box \rightarrow O)$ is, by definition, true in a possible world W if and only if outcome O occurs in any possible world W' that is the same as world W except for the possible consequences of freely choosing and performing experiment E instead of the alternative experiment freely chosen and performed in W. The set of possible worlds is limited by the specified conditions A, B, and C.

To use this definition one must limit "the possible consequences of ..." This is always done by using LOC1. Since this definition is toothless without this condition LOC1, or some such condition, and since LOC1 is used only in connection with this definition, it is not unreasonable to incorporate LOC1 into the definition of the counterfactual statement. Shimony and Stein have done essentially that. However, they did not do *exactly* that. My condition LOC1 excludes from the effects of changing a free choice *only* effects on outcomes that have already appeared *earlier*, in the special Lorentz frame LF. But Shimony and Stein exclude all effects that lie outside the forward light-cone of the region in which the change in the free choice occurs.

I use the weaker assumption LOC1 because the truth of LOC1 is certainly compatible with the principles of relativistic quantum field theory, and is in fact entailed by them, whereas the stronger form used by Shimony and Stein is incompatible those principles. It is much clearer to argue directly from assumptions that are true, in the sense of being consequences of orthodox quantum theory, rather that making an assumption that is incompatible with relativistic quantum theory.

The fact that LOC1 is entailed in orthodox relativistic quantum field theory is proved by noting that the possibility of defining *one* such frame LF follows from the Tomonaga-Schwinger [6,7] formulation of relativistic quantum field theory, in which advancing space-like surfaces are the analogs of the advancing constant-time surfaces of the non-relativistic formulation of von Neumann [8]. Of course, an infinitude of *alternative* possible choices for LF can be found: *any* frame will do. But the required property follows for *only one frame* **or** *another*, not for any two or more together.

With the stage thus set, I can turn to the central question of whether the conjunction of the truth of (1) and the falsity of (2) can be reconciled, as Shimony and Stein appear to suggest, with the idea that *no* information about the choice made in region **L** can get to region **R**, which is situated spacelike relative to **L**.

To see the apparent conflict one can consider the consequence of the fact that (1) is true and (2) is false in the context of the orthodox idea that "nature chooses the outcome" of the experiment chosen by the experimenter. In this context the consequence of the truth of (1) and falsity of (2) is that SR asserts the existence of a definite theoretical connection between the outcomes that nature delivers under the two alternative possible conditions, and that this theoretically necessary condition on what nature can do in **R** depends nontrivially on which experiment is freely chosen and performed by the experimenter in L.

But how can *any* theoretical model—hidden-variable or not— fulfill conditions on Nature's choices in region **R** that depend nontrivially on which free choice is made in **L** if no information about this choice made in **L** can be present in **R**?

This apparent result, that any theoretical model that conforms to the conditions A, B, and C must accomodate transfers of information over a spacelike intervals, does not conflict with the requirements of the theory of relativity, *in the context of quantum theory*: it conflicts only with a certain prejudice generated by uncritically extending to indeterministic quantum theory a feature of its deterministic classical approximation. This prejudice has, in fact, been the barrier that has blocked for many years the creation of a satisfactory realistic formulation of relativistic quantum theory. In a quantum context the Lorentz requirements of relativity theory pertain exclusively to relationships among observables, not to the reality that lies behind the phenomena. Thus the obvious realistic, relativistic quantum theory is just relativistic quantum field theory with a preferred sequence of advancing Tomonaga-Schwinger [6,7] spacelike surfaces defining the successive instants "now".

This entails, of course, a reversion to the pre-relativity Newtonian idea of an absolute time, or something similar to it, at the underlying ontological level. But the founders of quantum theory strongly stressed the fact that this theory, as they conceived it, was only about relationships between observations, not about properties of the underlying reality. The Tomonage-Schwinger theory maintains all the observable requirements of the theory of relativity, no matter how the preferred sequence of advancing spacelike surfaces is chosen. Hence the only thing actually blocking acceptance of this theory as the relativistic quantum theory of reality is the prejudicial assumption that the reality itself, like the connections between observations, can have no transfer of information over spacelike intervals. But the fact that this condition can be maintained in the *deterministic* classical limit, where the entire history of the universe is determined by the initial conditions, and can immediately be laid out on a space-time background, with no free choices allowed, does not entail that it can be maintained in the full indeterministic theory with free choices allowed.

The analysis of the Hardy case supports the view that the reality behind the indeterministic quantum rules cannot maintain this constraint. That observation immediately elevates John von Neumann's [8] formulation of quantum theory, applied to Tomonaga-Schwinger relativistic quantum field theory, to prime candidacy as the paradigm relativistic quantum theory of reality.

Shimony and Stein allege that this apparent result—that the information about whether L1 or L2 was freely chosen and performed in region **L** must be available in region **R** of—is incorrect. They base their argument on the assertion that *the semantical truth conditions for the counterfactual in question refer explicitly to the entire exterior of the extended future light-cone of* **R**.

That claim about the *entire* exterior is not exactly true in my version of the proof. The statement SR combine with LOC1 says:

SR-LOC1: "If in the possible world W the experiment R2 is freely chosen and performed in **R** and the outcome there is $R2+$ then if W' is a possible world that is the same as W in **L**, but in which R1 is freely chosen and performed in **R**, instead of R2, the outcome in **R** in world W' is $R1-$.

In spite of the difference between the light-cone version of the causality condition used by Shimony and Stein and the condition LOC1 used by me, this combined statement SR-LOC1 exhibits the feature pointed to by Shimony and Stein: a reference to the region **L**, which lies outside the forward light cone of the region **R**. It is this implicit reference of SR to **L** that Shimony and Stein are concerned about. The question is whether this reference to **L** upsets my essential claim that the conjunction of the truth of (1) and the falsity of (2) requires the information about whether L1 or L2 is performed in **L** to be present in **R**.

Let me begin my answer by explaining the question in more detail.

The statement SR involves the words "instead of". We have a clear idea of what we mean here by "instead of". In the real situation the experimenter in **R** makes the choice R2. But we have assumed that, just at the moment of choosing, the other choice R1 could have popped out instead of R2. But the central idea is that everything *prior to that moment of choosing* is exactly what it is in the actual world: there is just *one* evolving quantum world, which could go either way at the moment of choice.

This condition of *sameness prior to the moment of choice* is the condition that limits the changes permitted by the phrase "except for the possible consequences of the change in the free choice": no possible consequence of a changed choice can lie earlier than the moment of choice.

The point raised by Shimony and Stein, as applied to my argument, is that this implicit reference to the (unchanged) state of affairs (in **L**) prior to the moment of the choice between R1 and R2 is an essential element of the very idea of "instead of" that appears in the statement SR. Hence there is in SR an essential implicit reference to region **L**, even though all the symbols explicitly appearing in SR pertain to possible events in **R**.

Their concern about this implicit reference to **L** stems from the fact that in my 1997 paper I based my argument—for the claim that the conjunction of the truth of (1) and falsity of (2) entails a violation of the idea that "observable effects can propagate only into the future (light-cone)"—on the fact that "everything mentioned in SR is an observable phenomenon in region **R**." Their concern is that the essential implicit reference of SR to the region **L** might upset my argument.

This essential implicit reference of SR to **L** does not affect my argument. To understand why it does not, one must note that the steps in a logical argument are like a series of black boxes, each of which displays explicitly only certain of the variables of the system. These explicitly displayed variables are like inputs and outputs: certain connections between these variables are exhibited, but the reasons why these connections hold are not shown. However, all of the relevant effects pertaining to the inner workings must be controlled by the displayed variables.

In the statement (1),

$$L2 \Rightarrow [(R2 \wedge R2+) \to (R1 \Box\!\!\to R1-)],$$

the only displayed variables are $L2, R2, R2+, R1$, and $R1-$. The input conditions are $L2, R2, R2+$, and $R1$, and the output is $R1-$. The statement asserts that if the input variables $L2, R2, R2+$, and $R1$ are put into a certain logical expression, the output must be $R1-$, never $R1+$, But the falseness of (2) says that if the inputs are changed only by changing L2 to L1, then the output is no longer restricted to $R1-$: it is now allowed to be $R1+$. So changing the input variable from L2 to L1 has affected the output variable $R1+/R1-$. There can be all sorts of dependence on all sorts of inner variables, but whatever these dependences are they *must*, to the extent that they are relevant to the output conclusion, be controlled by the input variables, if the statement is indeed logically correct. So, in this case at hand, changing the input variable L1/L2 affects nontrivially the output variable $R1+/R1-$. But then the information about whether L1 or L2 is chosen in **L** must get to the region **R** where the value of the output variable $R1+/R1-$ is displayed.

Reply to Part II.

In their part II Shimony and Stein say that they prefer their covariant form of the locality condition "because of its relativistic invariance, which is *demanded* by relativity theory and hence should be respected in an investigation of the compatibility of quantum mechanics and that theory."

First of all, I must emphasize that I am not arguing that "quantum mechanics implies a nonlocality that is inconsistent with the locality of relativity theory" as Shimony and Stein assert in their abstract. My intent is rather to provide support for a reconciliation of quantum theory with relativity theory, a reconciliation that de-mystifies the "mysterious actions at a distance". The nonlocality that I claim to exhibit is completely compatible with the locality properties of relativity theory, which, in a quantum context, pertain only to features of *our observations*, not to features of a putative underlying reality.

I adopted the weaker locality condition, which involves a preferred set of spacelike surfaces, in order to have a condition that is *provably compatible* with relativistic quantum field theory. One can prove this compatibility from an examination of the Tomonaga-Schwinger formulation of quantum theory, which is built on the fact that even in a fully relativistic quantum field theory the quantum state of the system is defined as the state associated with a spacelike surface. In Schwinger's words:

"The problem of constructing a complete set of commuting operators, that is, of simultaneously measureable physical quantities, necessarily involves specific properties of the fields. Nevertheless, as a general principle associated with relativistic requirements, we must expect such mutually commuting operators to be formed from field quantities at physically independent space-time points, that is, points which cannot be connected even by light signals. A continuous set of such points form a spacelike surface, which is a geometric concept independent of the coordinate system. Therefore, a base vector system $\Psi(\zeta', \sigma)$ will be specified by a spacelike surface σ and by the eigenvalues ζ' of a complete set of commuting operators constructed from field operators attached to that surface. A change of representation will correspond, in general, to the introduction of another set of commuting operators on a different spacelike surface. ... A description of the temporal development of a system is evidently accomplished by stating the relationship between the eigenvectors associated with different spacelike surfaces, or, in other words, by exhibiting the tranformation function (2.5)."

The outcome of the work of Tomonaga and of Schwinger is a relativistic quantum theory that generalizes the nonrelativistic theory by replacing the advancing sequence of constant-time surfaces of the latter theory by an advancing sequence of spacelike surfaces σ, and the set of states $\Psi(\zeta', t)$ of the nonrelativistic theory by a set of states $\Psi(\zeta', \sigma)$. By imposing appropriate boundary conditions one can ensure an evolution of the state that leaves the past fixed but the future open, in the sense that the measurements can be freely chosen, and a von Neumann Process One applied at each measurement, with the consequent change of the state occurring on a spacelike surface σ rather than on a surface at constant time t. In the context of a quantum theory defined over a space-time manifold defined by general relativity it is natural to use as the preferred sequence of surfaces σ the constant-time surfaces of the Robertson-Walker metric. In a special-relativity context it is most natural to use the surfaces at constant times in the frame in which the cosmic background radiation is isotropic. But the key point, in the present context, is that one can ensure no backward action for any *one* sequence of advancing spacelike surfaces σ, but not in general for two different sequences simultaneously. I have defined my locality condition so that it is relativistic in the sense that it is compatible with relativistic quantum field theory, and in particular with the Tomonaga-Schwinger formulation of relativistic quantum field theory.

Shimony and Stein note that I have "abandoned the enterprise of justifying LOC2." That is correct. In my 1997 paper I tried to justify LOC2, and then prove that it was was false, in a reductio ad absurdum strategy. Although that form of argument is logically correct, it is needlessly complicated. In my reply to Shimony and Stein I have exploited the fact that they confirm that my claim that (1) is true and (2) is false follows from my premises. Proving that fact was the main focus of my 1997 paper. Given that basic result it is simpler to argue straightforwardly from premises that are compatible with relativistic quantum field theory, and that means jettisoning both LOC2 and the covariant formulation of the locality condition.

My argument was, and continues to be, based on the fact that "everything mentioned in SR is an observable in **R**". Shimony and Stein based their challenge on the fact that the statement SR has a certain potential *implicit* reference to region **L** built into it. In order to identify their concern I introduced in my reply a statement, SR-LOC, that explicitly exhibits the reference to region **L** that Shimony and Stein are concerned about. However, all that I use in my argument, or logically need, is the fact that the explicit condition for the truth of statement SR is that [for *any* (unnamed) free choice made in **L**] if the free choice in **R** is $R2$ and the outcome there is $R2+$, then in any conceivable allowed world in which $R1$ is freely choosen instead of $R2$, the outcome must be $R1-$. My input-output analysis makes the following point: the fact that (1), the truth or falsity of this statement SR is, for any fixed choice made by the experimenter in **L**, determined explicitly by whether or not a certain conceivable event, R1-, must occur in **R** under conditions defined in **R**, coupled with the agreed-upon fact that (2), the truth of SR depends upon which choice is made by the experimenter in **L**, means that whether or not this conceivable event in **R** must occur depends upon which choice is made by the experimenter in **L**. This dependence of whether or not a certain event must occur in **R** upon the free choice made in **L** is a necessary constraint on any theory or model that satisfies the assumptions of my non-hidden-variable theorem.

It is of course true that in order for the condition for the truth of SR to necessarily hold if $L2$ is freely chosen in **L**, and to necessarily not hold if $L1$ is chosen in **L**, there must be some logical linkage between what can occur in **R** and the free choice made in **L**. This linkage comes in via the various conditions of the theorem. The no-backward-in-time- influence condition specifies that the free choice made later in **R** can have no effect on which outcome appeared already earlier in **L**. This condition together with the quantum predictions impose a set of constraints that link the outcomes in **R** to the free choices made in **L** in the specified way: R1- must occur if $L2$ is freely chosen but need not occur if $L1$ is chosen.

In the way that I have explicitly formulated things the statement SR refers *only* to conceivable possible events in **R**. Then the conditions of the theorem impose constraints that link the truth of SR to the free choice made in **L**, thus entailing that, under the conditions of the theorem, the information about the free choice made in region **L** must get to region **R**.

On the other hand one, could alter the logic slightly and incorporate the locality condition immediately into the definition of SR, so that the condition of doing $R1$ *instead of* $R2$ would already incorporate the condition that no *outcome* in **L** would be affected by this later change of the free choice made in **R**.

Shimony and Stein base their challenge on this alternative way of organizing the proof. However, this slight change in the order of introducing the constraints of the theorem should not affect the conclusion. The net effect is unchanged: the truth of a statement about a conceivable possible event in **R** is logically linked by the assumptions of the theorem to the free choice made in **L**.

Of course, the very fact that within the framework supplied by the assumptions of the theorem one can prove that the truth of a certain statement about what can occur in **R** depends on the free choice made in **L** means that the constraints imposed by the assumptions of the theorem *must* link these possible events. It is no valid objection to the conclusion to point to the occurrence of such a dependence. What is relevant is not the fact that such connections are introduced by the premises of the theorem, but rather the fact that in the context of the Hardy experiment the combination of these premises makes the linkage between these possible events so strong.

In short, I believe that by basing the proof directly in the proven truth of Eq. (1) and falseness of Eq. (2), as suggested by Shimony and Stein themselves, one evades their challenge, which is rooted in the inherent complication associated with justifying the false premise LOC2.

Shimony and Stein admit that "the choice between L1 and L2 does makes a difference of some kind," but they suggest that the proof does not demonstrate the need for the presence in region **R** of information about the choice made by the experimenter in **L**, because this dependence may be simply a "brute fact" about the structure of certain sets of possible worlds.

The argument of Shimony and Stein is perhaps not altogether clear at this point, but they are evidently asking for a proof of the claimed transfer of information within the formal framework of possible worlds, which we both have used to give precise meaning to the logical statements. So let me supply that proof.

The statement in question is;

$$SR : (R2 \wedge R2+) \rightarrow [R1\Box \rightarrow R1-]$$

The meaning of this statement SR in terms of possible worlds, as given in ref. 9, applied to the present case, is this:

SR is true in world W if and only if the conditions that $R2$ is performed and that the outcome $R2+$ occurs in W entail that for every world W' such that

(1) R1 is performed in W', and

(2) W' coincides with W for times earlier than σ (where σ is an element of the preferred advancing sequence of spacelike surfaces that separates "earlier" from "later", and **L** and **R** are, respectivly, earlier and later than σ)

the outcome $R1-$ occurs in region **R**.

The assumptions of the theorem have been shown to entail that this claim that $R1-$ occurs in region **R** is true provided the set of possible worlds W is restricted to those in which the choice made by the experimenter in **L** is L2, but is false if the set of possible worlds W is restricted to those in which the free choice made by the experimenter in **L** is L1.

Thus the analysis in terms of possible worlds asserts that the free choice in **L** is correlated (within a subset of pairs of worlds fixed by a condition of no backward-in-time influence) with what can occur in **R**:

If L2 is selected the outcome R1- must occur in W' but if L1 is selected the outcome R1- need not occur in W'.

So within the theoretical structure created by the assumptions of the theorem the information about which experiment is chosen in **L** in W appears in **R** as the truth or falsity of the assertion that $R1+$ cannot occur in the related world W'.

I say that this conclusion means that any theory that conforms to the assumptions of the theorem must allow the information about the choice made in **L** to get to **R**. But choice of wording is a matter of definition and terminology. What is important is the use to be made of the technical result. In this connection one must remember that the purpose in science of theorems of this kind is to place conditions on allowed theories and models. My theorem places a logical condition on a broad class of theories that do not satisfy the assumptions of the theorems about hidden-variable theories.

The theoretical result described above shows that theories that meet certain weak conditions that are fully compatible with ordinary relativistic quantum field theory, and which express the general idea that choices made by experimenters can be treated as free variables that do not affect outcomes that have already been observered, must permit, *within a logical framework built directly upon those assumptions themselves,* conditions on whether or not certain conceivable possible events can occur in the region **R** to depend upon which choice is made by experimenters in the region **L**, which is situated spacelike relative to **R**.

This result is essentially a development of the line of argument instigated by Einstein, Podolsky, and Rosen, but formulated now strictly within a relativistic quantum field theory framework. Once the need for *some kind* of spacelike transfer of information is recognized it becomes reasonable to consider a theory in which *some one* of the possible advancing sequences of Tomonaga-Schwinger surfaces σ defines the actual temporal evolution of the universe. The "mysterious actions at a distance" are immediately demystified by this theoretical move, in conjunction with von Neumann's theory of measurement, generalized by the replacement of the advancing sequence of constant-time surfaces in von Neumann's nonrelativistic formulation of quantum theory by *some particular* advancing sequence of spacelike surfaces σ.

Part III. Postscript

It is gratifying that all of the probing and discussion has boiled our differences down to this simple, easily stated point. We seem to be in essential agreement on almost everything. It is, of course, manifestly obvious that there must be some structure that makes SR true under the condition that $L2$ is performed in **L** but false under the condition that $L1$ is performed in **L**, or, equivalently, that ensures, under certain fixed conditions in **R**, that the outcome $R1-$, must occur if $L2$ is performed in **L**, but need not occur if $L1$ is performed there. This means that the difference in the free choice made in **L** between $L2$ and $L1$ entails, within the structure provided by the assumptions of the theorem, this difference in whether or not $R1-$ must occur in **R**.

One may wish to say that this fact that SR is true if the free choice in **L** is $L2$ but is false if the free choice in **L** is $L1$ means that the "specific meaning" of SR is different in the two cases. As Shimony and Stein assert, my statement that "X must occur" means "X is true in every one of a class of possible worlds that is picked out by a certain protocol." But the only difference in the two protocols is a difference in the free choice made in region **L**, whereas the resulting change in what "must occur" is a conceivable event located in region **R**. This is the transfer to **R** of information about the free choice made in **L** that I am talking about.

Shimony and Stein counter that this "conceivable event located on **R**" is not well identified, because it is connected to the protocol, which involves the free choice made in **L**. But that is exactly the point: the conceivable event in **R** identified by this protocol "must occur" when the free choice in **L** that enters into this protocol is $L2$, but need not occur when that free choice is $L1$, and this latter difference of the free choice made in **L** is the sole difference between the two protocols.

The bottom line, of course, is whether this theorem, whose assumptions are, unlike those of the hidden-variable theorem, compatible with the principles of quantum theory, rules out possible models of quantum reality. I have given an example that is ruled out, namely the model where nature chooses outcomes in each given region on the basis of information available in that region, with information about the free choices made in any region confined to the closed forward light-cone from that region.

Thus the theorem has interesting non trivial consequences.

Shimony and Stein suggest that I have made some "concession", which I, however, view as a simply a helpful observation.

Shimony and Stein assert that my reply contains a "surprising modification of his position in 1997." But a careful reading of my statements shows that this is not the case. When I asserted in this paper that "I am not arguing that 'quantum mechanics implies a nonlocality that inconsistent with the locality of relativity theory' " I was emphasizing that in quantum mechanics the locality of relativity theory pertains to *connections between observations,* and the nonlocality asserted by my theorem does not conflict with that locality.

Shimony and Stein do not see the connection between my main objective, which is to "de-mystify" the "mysterious actions at a distance", and my claimed strengthening of Bell's theorem.

The connection is this: The Tomonaga-Schwinger formulation of quantum theory, with some specified advancing sequence of spacelike surfaces would de-mystify the action at a distance, in the sense that it would provide a perfectly well defined specification of these actions. However, it has always seemed that the empirical equivalence of all the elements of the infinite set of possible choices of sequences renders all of them devoid of physical meaning, and the notion that there really is some instantaneous action at a distance a chimera, But if it is established, on the basis of reasonable assumptions, that there must be faster-than-light transfers of information, then it becomes much more sensible to accept the idea of a preferred set of Tomonaga-Schwinger spacelike surfaces along which these faster-than-light transfers act. Then the Tomonaga-Schwinger formulation constitutes an already-worked-out theory of the needed faster-than-light transfers, and it is a theory that is, in spite of all the interactions at a distance, known to be compatible with all the requirements of relativistic quantum field theory.

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