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Author
Stapp, Henry P.

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Henry P. Stapp

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Henry P. Stapp

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

The noncausal structure events demanded by Bell's theorem is shown to follow naturally from a theory of events similar to Whitehead's. In spite of this noncausal structure on the level of individual events the macroscopic causality structure observed in nature at the statistical level holds. Quantum theory itself emerges naturally, along with the basic analyticity properties of the S matrix.

1. Science and Quantum Theory

Science can be pragmatic or fundamentalistic. The aim of pragmatic science is to make predictions about what will be observed in different situations. The aim of fundamentalistic science is to understand the fundamental nature of things. The choice between these aims is a matter of taste and interest.

The adequacy of quantum theory depends on which view of science is adopted: Pragmatically it is an adequate theory of atomic phenomena, but it eschews description of underlying realities and is hence fundamentalistically inadequate. In view of quantum theory's

silence regarding underlying entities the Copenhagen claim of completeness must be interpreted as a claim of pragmatic completeness (1).

Pragmatic science and fundamentalistic science have different aims, but are mutually supportive. The former, through its study of detail, yields facts the latter must fit. The latter, through its search for unity, yields concepts the former can use. Thus each is justified by the standards of the other.

The basic problem in fundamentalistic science is to find a unified model of reality that is consistent with relativistic quantum theory. The aim of the present work is to adduce support for a model of reality similar to Whitehead's from an examination of the constraints imposed by Bell's theorem.

2. Bell's Theorem

Bell's theorem (2) is the most profound discovery of science. It shows that if the statistical predictions of quantum theory are approximately correct then, in certain cases, the principle of local causes must fail. This principle asserts that events in one region are approximately independent of variables subject to the control of experimenters in distant contemporary regions. The statistical predictions of relativistic quantum theory conform to this principle, but their character is such that the principle cannot hold for the individual events themselves. The particular predictions of quantum theory upon which this conclusion rests follow directly from the most basic principles of quantum theory, independently of the detailed dynamics. And they have been experimentally tested and confirmed (3).

Bell's theorem imposes a severe condition on models of reality, for it demands that an adequate model account simultaneously for the observed causal structure on the statistical level, and the noncausual structure on the individual event level. An adequate model of reality must, moreover, provide for a unified understanding of all of nature.

3. Theory of Events

Whitehead (4) has developed a model of reality that weaves the physical and psychical aspects of nature into a coherent, unified whole, thereby avoiding the aesthetic and logical difficulties inherent in materialistic, idealistic, and dualistic theories. A model similar to Whitehead's is now described.

The only realities are events, which have the following properties:

1. Events occur in a definite sequence. An event is prior to those it precedes in this sequence, and subsequence to those it follows.

2. Events are not contained space-time, which has no separate existence. However, each event has aspects that defines an associated region in a four-dimensional mathematical space. This space is called the space-time continuum, and the region associated with an event is called its location.

3. Each event is associated with a definite set of prior events, called its antecedents. An event is a successor to each of its antecedents.

4. Each event is a process that involves an assessment of the possible events, and a decision that determines both the location

of the event and the identities of its antecedents. This process can be regarded as psychical.

5. The possible events are limited by the following conditions: There is a timelike geodesic (straight line) extending forward in time from the location of the antecedent to the location of the event. Each such geodesic has a characteristic mass-value, which is a member of a set M of discrete non-negative numbers. A flow of momentum-energy along a geodesic is defined in accordance with relativistic particle dynamics: ($p = mv$). The total momentum-energy carried into the location of any event by the geodesics from its antecedents is greater than the sum of the momentum-energies carried out to any subset of its successors by a vector lying in the closed forward light-cone.

6. The process that determines which event shall occur is such that probabilities are determined by local conditions: i.e., under suitable conditions of isolation and definition the statistical behavior of ensembles prepared according to local specifications will not depend on the space-time location, orientation, or velocity of the isolated system.

7. Certain conglomerates of events whose locations are confined to regions of limited spatial extent are self-sustaining or stable, in the sense if the region is isolated, in the sense that there is no outside source of momentum-energy available for events in the region, then no energy-momentum is lost: i.e., all the energy-momentum available from prior events of the conglomerate is absorbed by subsequent events of the conglomerate. Groups of events that approximately satisfy these conditions are also called conglomerates. Physical objects, such as experimental devices and experimenters, are conglomerates.

8. Under conditions appropriate to the study of scattering processes the geometric features appropriate to classical scattering processes emerge: i.e., conglomerates identified as production and detecting devices behave as if they were producing and detecting, with their own characteristic efficiencies, particles moving on classical trajectories, which can be identified with the geodesics between the locations of events in these conglomerates.

These general conditions on events are sufficient to ensure the macroscopic causality properties (5) and Lorentz invariance properties observed in nature. They also ensure the existence of a general scattering probability formalism that is equivalent to that of quantum theory (6). It is likely that the quantum theoretical representation of this formalism is, apart from equivalencies and degeneracies, unique, subject to very broad conditions of simplicity (7). If so, then the existence of the general S-matrix formalism follows from the general properties of events listed above, together in the demand for a simple mathematical representation of the scattering probability formalism.

From the general S-matrix formalism and macrocausality one can derive the Landau rules for the physical-region singularity surfaces (5), and also the formulas for the associated discontinuities (8). If the singularity surfaces away from physical points are generated by this physical-region structure (9), then one can probably reconstruct in principle (10,11) all of quantum theory, given a few basic constants. And these constants may themselves be determined by self-consistency requirements (12). Thus all of quantum theory, and hence all of physics, would follow, in principle, from little more than the general properties of events listed above. Not all the steps in this

derivation have been rigorously established, but from the mathematical viewpoint the unproved steps are not implausible.

4. Bell's Theorem and Theory of Events

The noncausal structure of events demanded by Bell's theorem is incomprehensible in the framework of ordinary ideas, but is a natural consequence of the theory of events, described above.

In the simplest cases involving Bell's phenomena there are three (scattering) events E_0, E_1, and E_2. Their locations L_0, L_1, and L_2 lie in three well-separated experimental areas A_0, A_1, and A_2. Experiment E_0 is an antecedent of both E_1 and E_2. Thus there is a geodesic from L_0 to L_1 and another from L_0 to L_2, as shown in Fig. 1. An experimenter in A_1 can choose to perform experiment E_{11} or experiment E_{12}. An experimenter in A_2 can choose to perform experiment E_{21} or experiment E_{22}. Suppose E_{1jk} is the event (result) that occurs in experiment E_{1j} if the experimenter in A_2 does experiment E_{2k}. Suppose E_{2jk} is the event (result) that occurs in E_{2j} if the experimenter in A_1 does experiment E_{1k} The ordinary idea of causality (i.e., the principle of local causes) demands that E_{ijk} should be independent of k. But Bell's work shows that this requirement is incompatible with the statistical predictions of quantum theory.

According to the theory of events one of the two events E_1 or E_2 is prior to the other. Suppose E_1 is the prior event. When it occurs the possibilities for events in A_2 are radically changed. For example, if the locations L_0, L_1, and L_2 are effectively points (compared to the large distances between them) then the two locations L_0 and L_1 determine the geodesic L_0L_1, and hence the energy-momentum

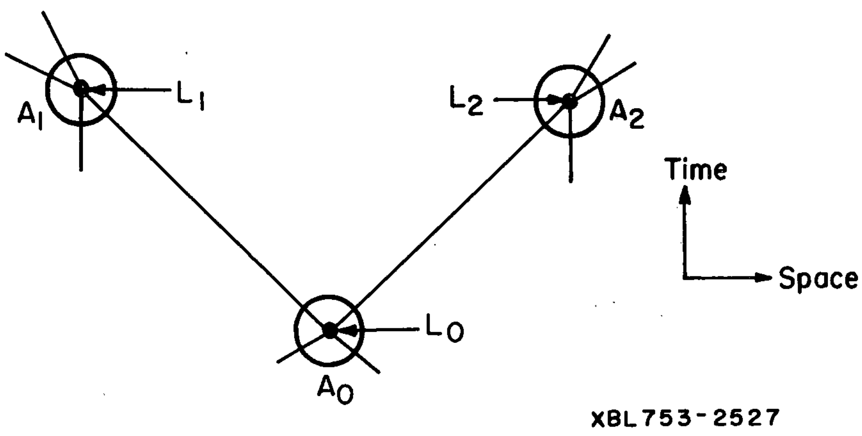

Fig. 1. Space-time picture of Bell's phenomena.

carried from L_0 to L_1. This fixes in turn the momentum-energy available for the geodesic from L_0 to L_2, which fixes this geodesic itself (assuming that the two geodesics exhaust the momentum-energy available from E_0). Thus after E_1 occurs the event in A_2 is required to lie on a fixed geodesic that is determined by the events E_1 and E_2.

At this stage only space-time and momentum-energy considerations have been introduced, and Bell's phenomena does not enter. The correlations between the events in A_1 and A_2 are just those expected from classical ideas: the course of events in A_2 is correlated to what is observed in A_1, but not to decisions made by the experimenter in A_1.

Though the results at this stage are similar to those of classical particle theory, the logical structure is different. In the classical theory what happens in A_2 is determined by what happens in

the earlier region A_0, whereas in the theory of events the possibilities for E_2 are limited jointly by the prior events E_1 and E_0. This logical difference becomes important in experiments involving spin, which are the ones in which Bell's phenomena occurs.

Suppose the geodesics L_0L_1 and L_0L_2 are associated with spin $\frac{1}{2}$ representations of the Lorentz group. Just as before the possibilities for E_2 are limited jointly by the prior events E_0 and E_1. Part of the information determined by E_0 and E_1 is represented by the momentum-energy four-vector associated with the geodesic L_0L_1. However, these two events E_0 and E_1 determine also another vector associated with the geodesic L_0L_1, namely a spin vector associated with the corresponding spin space.

The spin vector and the momentum-energy vector associated with L_0L_1 are both determined jointly by E_0 and E_1. Thus it would be unnatural, in the framework of the theory of events, to treat them differently. It is accordingly assumed that these two vectors should be treated in the same way.

Treating the spin and momentum-energy vectors in the same way leads to very different effects with respect to the ordinary idea of causality. This difference stems from the fact that the two experimenters can independently manipulate the directions of the two spin vectors, modulo signs, but cannot do this with the two momentum vectors, without disrupting the experiment. For the two momentum vectors are required by the conservation laws to be essentially parallel, whereas the two spin vectors, modulo signs, can be independently fixed by the two experimenters.

The spin vector associated with L_0L_1, like the momentum vector, is determined by events E_0 and E_1. But the experimenter in A_1 can, by choosing the experiment to be performed, fix this spin vector, up to a sign. Thus, in the theory of events, the event E_2 depends on what the experimenter in A_1 decides to do. This effect is contrary to the ordinary idea of causality, but conforms to the requirements imposed by Bell's theorem.

The theory of events contradicts the ordinary idea of causality. But it provides an alternative space-time picture of causality. This structure arises by regarding the geodesic associated with a spin-J representation of the Lorentz group as a conduit of spin-J information. This information flows from an event both forward to its potential successors and backward to its antecedents. For example, the determination in event E_1 of the spin vector associated with geodesic L_0L_1 is viewed as being instantly communicated along L_0L_1 to L_0, where it can be tapped by geodesic L_0L_2, in the assessment of a possible successor to E_0 having location L_2.

Bohr (13) has insistently maintained that quantum phenomena is incompatible with causal space-time description. The model of reality proposed here conforms to Bohr's dicta, insofar as classical causal space-time description is concerned, but circumvents it by introducing a nonclassical space-time structure of causal connection.

5. Conclusions

The proposed model of reality yields the basic mathematical features of relativistic quantum theory, and seems capable of providing a unified understanding of nature.

FOOTNOTES AND REFERENCES

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