THEORY OF REALITY*

Henry Pierce Stapp

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

Bell's theorem is used to guide the formulation of a unified theory of reality that incorporates the basic principles of relativistic quantum theory.

I. INTRODUCTION

Quantum theory is a theory of observations; the realities it deals with are certain observations of scientists who use the theory. These observations are only a small part of reality. Consequently quantum theory, considered as a theory of reality, is incomplete. Prevailing opinion holds, in fact, that no complete theory of reality can adequately describe quantum phenomena. This opinion stems from the long history of failures of attempts to achieve this end.

It is not clear, however, whether these failures arise from an inadequacy of the reality concept, or merely from a breakdown of the classical idea of causal space-time development. Bohr often emphasized the breakdown of this classical idea in the realm of quantum phenomena, and his point has now been strikingly verified and clarified by the work of J. S. Bell.(1)

Bell's work was originally formulated in the restricted framework of hidden-variable theory. However, it was soon realized(2)

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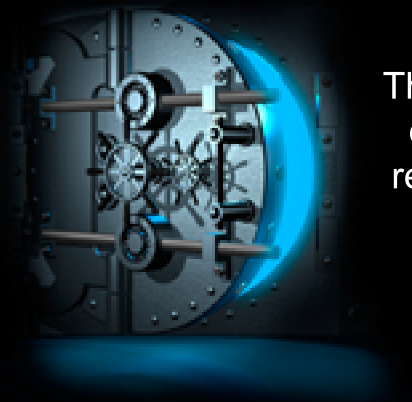

that what Bell had established was the following profound result:

The statistical predictions of quantum theory are incompatible with the principle of local causes.

The principle of local causes asserts that what happens in one space-time region is approximately independent of variables subject to the control of an experimenter in a far-away space-like-separated region. This principle holds in relativistic quantum theory at the level of statistical predictions. However, the character of these predictions is such that the principle must fail at the level of the individual events. The statistical predictions from which this result follow come directly from the basic principles of quantum theory, not from the detailed dynamics, and they have been experimentally tested and confirmed.(3)

Bell's theorem shows that no theory of reality compatible with quantum theory can allow the spatially separated parts of reality to be independent: These parts must be related some way that goes beyond the familiar idea that causal connections propagate only into the forward light-cone. This conclusion will guide our thoughts.

The first task of any general theory of reality is to formulate the connection between the experiential or psychic aspects of reality and the material or space-time aspects. The debate between Bohr and Einstein(4) pointed to the importance of this question, for Einstein appealed finally to the need for a comprehensible understanding of space-time relations, whereas Bohr appealed ultimately to the primacy of experiential relations. A unified theory of reality must bring these two aspects of reality into one coherent scheme.

A unified theory of reality has been formulated by Alfred North Whitehead.(5) According to this theory reality consists of discrete events. Each event has a location, which is a finite space-time region. It also has certain experiential characteristics.

To support the idea that experience comes in discrete units Whitehead cites the authority of William James, who writes:(6)

"Either your experience is of no content, of no change, or it is of a perceptible amount of content or change. Your acquaintance with reality grows literally by buds or drops of perception. Intellectually and on reflection you can divide these into components, but as immediately given they come totally or not at all."

To support the idea that physical processes consist of discrete events one may cite the authority of Niels Bohr:(7)

"(The essence of quantum theory) may be expressed in the so-called quantum postulate, which attributes to any atomic process an essential discontinuity, or rather individuality, completely foreign to the classical theories and symbolized by Planck's quantum of action."

A reality consisting of discrete events seems hopelessly fragmented and pluralistic. Yet Whitehead's reality is unified. This unity is achieved by considering each event to be a process in which all prior events are brought together, or "prehended", in a new pattern. Reality thus becomes the process of creation, in discrete individual steps, of an ever-growing web of relations between things that are parts of this same process. Mental events are a part of this general world process, and they afford an illustration of how events can be processes that bring together prior events in new patterns.

Each event in the world process prehends in some particular way every prior event, and hence contains within itself, in a certain sense, the whole of creation.

Whitehead chose a model that did not attain the full unity just described. He believed that relativity theory required space-like-separated events to be causally independent, and hence decreed that each event prehend, not all of creation, but only those events whose locations lay in its backward light-cone. This mutilation of the model destroys its natural unity and logical simplicity. Moreover, it is incompatible with quantum theory, by virture of Bell's theorem. Thus it must be undone. The result is a philosophically attractive unified model of reality that provides a natural setting for relativistic quantum theory.

II. THEORY OF EVENTS

In this section a physical theory of events is erected on the model of reality described above. This theory incorporates the basic principles of relativistic quantum theory. The theory is set forth in eight assumptions or postulates, which have physical, metaphysical, and mathematical aspects. The guiding principle is maximal simplicity: The aim is to use the simplest and most economical metaphysical and mathematical structures consistent with what we know from experience.

The postulates are as follows:

1. The creative process. There is a creative process that consists of a well-ordered sequence of individual creative acts called events.

Remark This assumption affirms that there is actual creation, i.e., a real coming into being, or a coming into existence, and that the process of creation can be decomposed into a sequence of individual acts. Whatever is created exists, and nothing else exists. Nothing passes out of existence. At the end of each creative act the whole of creation is settled and definite: all that exists is unambiguously fixed.

This simple logical structure can be contrasted with ones in which all of creation, past, present, and future exists, and is fixed, and change is some sort of illusion. It may also be contrasted with ones in which the creative process is not a single linear process but rather a multiple process that proceeds somehow independently in different space-time regions, sothat what exists is not globally well-defined but depends on the space-time point from which the determination of what exists is made. (These models bifurcate nature: they posit either changing experiences of a pre-existing world or a changing world in pre-existing space-time.)

2. Space-time location. Each event has characteristics that define an associated region in a four-dimensional mathematical space. This mathematical space is called the space-time continuum, and the region in this space associated with an event is called its location.
Remark Space-time has no independent existence in this theory. Rather each event has characteristics that can be interpreted as a region in a certain mathematical space. For physical applications this metaphysical distinction is unimportant, and one may imagine a pre-existing space-time continuum with the events scattered through it.
Definition An event is prior to another if it occurs earlier in the sequence of creative acts described in (1). It is subsequent if it occurs later in this sequence.

3. Conservation of momentum-energy. Among the events prior to a given event are some events called its antecedents. Any event is

a successor to each of its antecedents. The location of each event is connected to the location of each of its antecedents by a directed geodesic (a directed straight line in space-time) that runs from the location of the antecedent to the location of the successor. Each geodesic is associated with a real mass-value m, and also with a momentum-energy vector p = mv, where v is the four-velocity defined by the direction of the geodesic. The sum of the momentum-energy vectors associated with the geodesics coming into the location of a given event from the locations of its antecedents is equal to the sum of the energies associated with the geodesics going out from the location of the event to the locations of its successors.

Remark This physical assumption, like those that follow, is holistic rather than mechanistic; it is formulated as a mathematical condition on the overall space-time structure of what emerges from the process of creation, not as a dynamical law that governs the detailed way in which reality unfolds.

Definition A system is a local space-time pattern of events.

4. Lorentz Invariance. Probabilities are determined by local conditions: under suitable conditions of isolation the statistical behavior of ensembles of systems defined by local specifications do not depend on the Lorentz frame used to relate the local specifications to global space-time.

Remark The isolation condition requires a local system to be isolated in the sense that outside sources of energy are negligible. The assumption is that under this condition of isolation ensembles of subsystems defined by local specifications exhibit the type of behavior characterized by probability functions. Moreover these probability functions are invariant under Lorentz transformations.

Thus if A represents the local specifications that characterize an initial ensemble and B represents the local specifications that define a final ensemble and $P[A; B]$ is the probability that B holds under conditions A, then $P[A; B]$ is independent of the Lorentz frame used to relate the space-time coordinates occurring in the local specifications A and B to physical space-time points.

5. Scattering formalism. The statistical results of scattering experiments can be described by the formalism of classical relativistic statistical mechanics, with the geodesics identified with the trajectories of classical point particles.

<u>Remark</u> In the classical description each beam of initial particles is described by a probability or weight function $w(p,x)$ and the detection system for each of the final particles is described by an efficiency function $e(p,x)$. The expression

$$\int d^3p \; d^3x \; w(p,x) \; e(p,x) \Big|_{x^0=t} = P[w,e] \qquad (1)$$

gives the probability that a particle in the beam described by w will be detected by the system described by e. (The time t can be chosen arbitrarily.) For a scattering of m particles into n particles the expression

$$P\left[w_1,w_2,\cdots,w_m;\ e_1,e_2,\cdots,e_n\right] \equiv \int \prod_{i=1}^{m} d^3p_i\ d^3x_i\ w_i(p_i,x_i)$$

$$\times \prod_{j=1}^{n} d^3p_j\ d^3x_j\ e_j(p_j',x_j')$$

$$\times\ S(p_1,x_1,\cdots,p_m,x_m;\ p_1',x_1',\cdots,p_n',x_n')\Big|_{\substack{x_i^{o}=t_i \\ x_j^{o\prime}=t_j}} \tag{2}$$

gives the probability that if the initial beams are described by the weight functions $w_1,\cdots,w_m$ and the final-particle detection systems are described by the efficiency functions $e_1,\cdots,e_n$ then all n final particles will be detected. (The times t_i and t_j can be chosen arbitrarily.)

Each function $w_i(p,x)$ is a real function of the real mass-shell momentum-energy vector p and the real four-vector x. It satisfies, for any λ,

$$w_i(p,x) = w_i(p,x+\lambda p) . \tag{3}$$

This condition arises from the fact that all the particles of momentum p move in the direction defined by $p = mv$; i.e., along p.

Functions satisfying (3) can be constructed by specifying $w(p,x)$ at some time, say $x^o = t$, and then forming

$$w(p,x) = \int d^3x'\ d(\lambda p^o)\ w(p,x')\ \delta^4(x'-x-\lambda p)\Big|_{x^{o\prime}=t} . \tag{4}$$

Another way of constructing solutions to (3) is to write, for any complex function $\psi(p)$ and any real constant $\hbar$,

$$w(p,x) = \int \frac{d^4q}{(2\pi)^3}\, \psi\left(Mv - \frac{1}{2}q\right) \psi^*\left(Mv + \frac{1}{2}q\right) e^{-iqx/n}\, \delta(q\cdot v)\left(\frac{M}{m}\right)^{\frac{1}{2}} , \qquad (5)$$

where $v = p/m$ and $M = \left(m^2 - \frac{1}{4}q^2\right)^{\frac{1}{2}}$.

6. The quantum assumption. The functions $w(p,x)$ occurring in nature are sums of functions of the form (5), with different functions $\psi(p)$ but with the same constant $\hbar$. This constant is Planck's constant. The analogous formula holds for $e(p,x)$.

Remark This assumption allows the scattering formula (2) to be transcribed into quantum mechanical form.(8) The S-matrix $S(p_1,\cdots,p_m;\ p_1',\cdots,p_n')$ is then defined in terms of the function $S(p_1,\cdots,x_n')$ appearing in (5). Conservation of probability implies the unitarity of $S(p_1,\cdots,p_n')$.

7. Macrocausality.(9) Momentum-energy is transferred over macroscopic distances only by the stable systems: an event having an incoming geodesic not positive time-like or with mass not that of a stable system has a probability to occur that falls off exponentially under space-time dilation. The size of the location of an event has a finite bound that depends only on the incoming geodesics.

Remark This macrocausality condition entails that the S-matrix $S(p_1,\cdots,p_n')$ be an analytic function at all real points $(p_1,\cdots,p_n')$ except those lying on a set of well-defined surfaces called the positive-α Landau surfaces. The rule of continuation around each of these singularity surfaces is also determined.(9)

8. Maximal analyticity.(10) The analytic continuation of the S matrix to complex $(p_1,\cdots,p_n')$ has only those singularities that are required by the unitarity conditions.

Remark Maximal analyticity is a principle of economy; it asserts that the S matrix has no unnecessary singularities. Or it is a principle of simplicity; it asserts that the S matrix has the simplest possible analytic structure. Any useful physical theory must be based on some principle of economy or simplicity. There is no theoretical or experimental evidence for any singularity not required by unitarity.

It seems entirely possible that the general principles of Lorentz invariance, unitarity, macrocausality, and maximal analyticity may determine in principle a unique complete relativistic quantum theory of elementary particles.(10) A few constants may have to be determined empirically, at least in practice.

If this theory is carried over to the nonrelativistic limit, where particle-creation is excluded, then it yields(11) the Schroedinger equation, and hence the concept of equations of motion. And the Schroedinger form of quantum theory reduces, in appropriate contexts and limits, to classical physics. It thus appears that all of physics can emerge from the eight assumptions listed above, together, perhaps, with a few empirical constants.

III. 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 timelike 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 the E_{1jk} be independent of k. But Bell's work shows this requirement to be 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 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_0 and E_1.

At this stage only space-time and momentum-energy considerations have been introduced, and Bell's phenomena do not enter. The correlations between the events in A_1 and A_2 are just those

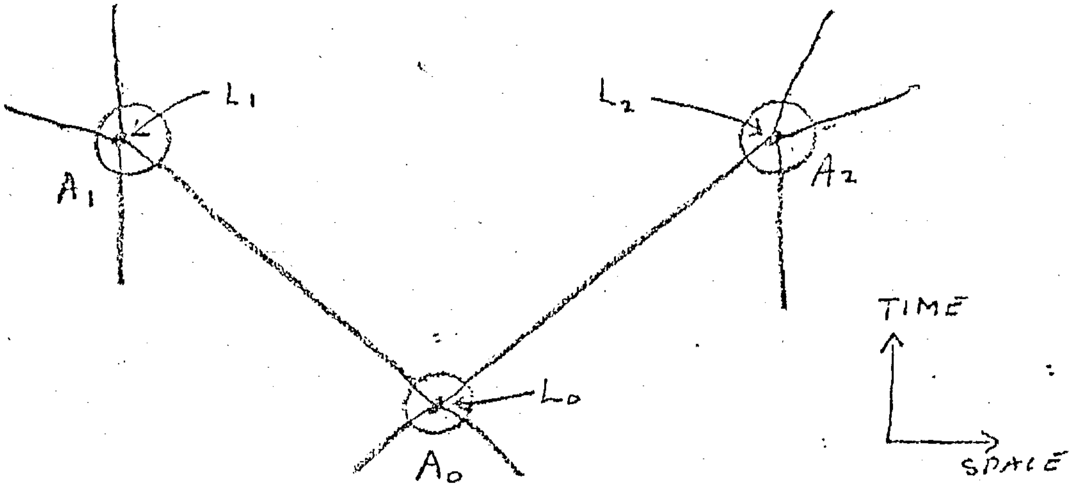

Fig. 1. Space-time picture of Bell's phenomena.

expected from classical ideas: the course of events in A_2 is correlated to what is <u>observed</u> in A_1, but not on 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 occur.

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 does not conform to the ordinary idea of causality. But it provides an alternative possible space-time picture of causality. This picture 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.

IV. CONCLUSIONS

The basic properties of relativistic quantum theory emerge in a natural way from a logically simple model of reality. In this model there is a fundamental creative process that proceeds by discrete steps. Each step is a creative act or event. Each event is associated with a definite space-time location. The fundamental process is not local in character, but it generates local space-time patterns that have mathematical forms amenable to scientific study.

This theory of reality reconciles the positions of Einstein and Bohr. It conforms to Einstein's view that the complete basic theory should be a complete theory of reality rather than a theory of observations; i.e., it should describe "any real (individual) situation (as it supposedly exists apart from any act of observation)."(12) The model described above attempts to do exactly that. In the model everything that exists is perfectly definite: Schroedinger's cat is either dead or alive, not both, independently of any act of observation, or of any choice of space-time perspective. On the other hand, the theory is probably useless in the realm of atomic physics, and for essentially the reasons advanced by Bohr, namely that, "The element of wholeness, symbolized by the quantum of action and completely foreign to classical physical principles,...makes recourse to a statistical mode of description imperative as regards to the expectations of the occurrence of individual quantum effects in one and the same experimental arrangement."(13)

This probable lack of utility of the model in the realm of atomic physics does not necessarily mean that the model has no uses at all. In the realm of elementary particle physics the quantum theoretical principles, though perhaps sufficient in principle, are difficult to apply, and the insight provided by a model of the underlying reality might be useful. More important would be the possible uses in those realms of science where the approximations essential to the applicability of quantum theory fail. Bohr often stressed that the wave function of a system has meaning only to the extent that the system can be regarded as isolated from the rest of the world,(14) i.e., only in those situations where the possible outside sources of energy-momentum can be ignored. When this idealization is inapplicable the wave function of the system is not definable, and even if it could be defined it would be undergoing continual quantum jumps, and no adequate theory of quantum jumps exists.

No system is completely isolated from the rest of the world, except the whole world, which cannot be treated by quantum theory since there is no outside "observer". And most systems of interest are not even approximately isolated from the rest of the world. One class of systems of special interest to man are living systems. These require interactions with their environments to sustain life, and consequently, as emphasized by Bohr,(15) they cannot be fully described by quantum theory.

Unity of understanding is a natural goal of thought. In attempting to unify the various branches of science and knowledge such as physics, biology, psychology, sociology, philosophy, etc., some overarching conceptual framework is required. It is reasonable to begin with the logically simplest model of reality that is consistent with all we know. The theory of events outlined above is a logically simple model of reality that is apparently consistent with all we know. Taken in conjunction with Whitehead's theory of process it is, as far as I know, the only existing model of all of reality that incorporates the basic principles of relativistic quantum theory.

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