Whiteheadian Approach to Quantum Theory and the Generalized Bell's Theorem[1]

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The model of the world proposed by Whitehead provides a natural theoretical framework in which to imbed quantum theory. This model accords with the ontological ideas of Heisenberg, and also with Einstein's view that physical theories should refer nominally to the objective physical situation, rather than our knowledge of that system. Whitehead imposed on his model the relativistic requirement that what happens in any given spacetime region be determined only by what has happened in its absolute past, i.e., in the backward light-cone drawn from that region. This requirement must be modified, for it is inconsistent with the implications of quantum theory expressed by a generalized version of Bell's theorem. Revamping the causal spacetime structure of the Whitehead–Heisenberg ontology to bring it into accord with the generalized Bell's theorem creates the possibility of a nonlocal causal covariant theory that accords with the statistical prediction of quantum theory.

1. INTRODUCTION

The model of the world proposed by Whitehead provides a natural theoretical framework in which to imbed quantum theory. This model accords with the ontological ideas of Heisenberg, and also with Einstein's view that physical theories should refer nominally to the objective physical situation, rather than our knowledge of that system.

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Whitehead imposed on his model the relativistic requirement that what happens in any given spacetime region be determined only by what has happened in its absolute past, i.e., in the backward light-cone drawn from that region. This requirement must be modified, for it is inconsistent with the implications of quantum theory expressed by a generalized version of Bell's theorem. This generalized version, which is proved in Section 2, asserts that there are situations involving two separate experiments, one performed in each of two spacelike-separated spacetime regions R_1 and R_2, in which either the macroscopic results of the experiment performed in R_1 must depend on which of two alternative experiments is performed in R_2, or the macroscopic results of the experiment performed in R_2 must depend on which of two alternative experiments is performed in R_1. This necessary connection follows directly from the demand that the statistical predictions of quantum theory be satisfied to within 3 % in each of the four alternative pairs of experiments. More precisely, if S is any set consisting of one conceivable set of results for each of the four alternative pairs of experiments, then there is no set S such that (1) each of the four sets of results in S agrees with the statistical predictions of quantum theory to within 3 %, and (2) within S the results in each region are independent of which experiment is performed in the other region. This conclusion is essentially different from that of Bell, because it is stated in a way that avoids the dependence of Bell's arguments on the requirement that the results of the various experiments be functions of a set of variables $w \equiv (e_1, e_2, w')$, where e_λ specifies which experiment is performed in R_λ, and w' is some set of "hidden variables" that can be held fixed as e_1 and e_2 are changed. Since quantum phenomena indicate that the experimental devices must be regarded as integral parts of the whole experimental situation, not separable from the system being studied, there is no reason to expect that there should be any quantities that can be held fixed as the experiments are changed. Thus the "hidden variable" assumption in Bell's formulation of his theorem severely limits the significance of his result: The most natural conclusion to draw from that formulation is simply that there are no such "hidden variables." This conclusion is not unexpected; it is completely in line with the canonical views of Bohr, and with the opinions of most quantum physicists. Moreover, it does not directly conflict with the Whitehead–Heisenberg model since in that model the events e_1 and e_2 are conditioned by events in their common past, and hence there is no clean separation of variables $w \equiv (e_1, e_2, w')$.

The generalized version of Bell's theorem is formulated directly in terms of the observable quantities of quantum theory. It makes no "hidden variable" assumption, and consequently places conditions on all theories in which the quantum theoretical observables are well defined, and the predictions regarding these observables agree with those of quantum theory.

In Section 3 it is pointed out that the pragmatically interpreted quantum theory is inherently limited in scope because the observer-scientists that are using the theory must stand outside the quantum system they are describing. This requirement entails that the pragmatically interpreted quantum theory can apply only in special idealized situations, namely those in which the quantum system is essentially isolated from the surrounding classically described world. This limitation in the scope of quantum theory creates the need for a more comprehensive theoretical structure that encompasses in one unified framework the domains of classical and quantum theory. Several other attempts to provide such a structure are briefly reviewed.

In Section 4 the general features of the Whitehead–Heisenberg theory are described. Special attention is paid to the spacetime conditions imposed by Whitehead to make his theory conform to the demands of relativity theory. It is argued that these conditions are unnecessary, and that they moreover disrupt the unity of description Whitehead sought to achieve. Furthermore, these conditions are apparently incompatible with the generalized Bell theorem. An alternative spacetime structure is therefore proposed.

In Section 5 the relationship between the views of Heisenberg and those of Whitehead is discussed. It is pointed out that Heisenberg's thinking about quantum theory has two levels: the pragmatic and the ontological. On the one hand, he agrees with Bohr that the mathematical formalism must be interpreted pragmatically, as a set of rules dealing with the knowledge of the community of observer-scientists. On the other hand, he suggests that what "happens" at the physical level can be understood in terms of the White-headian type of model, where the existing world creates "potentia" or tendencies for events that constitute the transition from the possible to the actual. This ontological level of description is not tied in any precise way to the mathematical formalism of quantum theory, which refers rather to our observations, and hence to our knowledge, rather than to features of the strongly objective (i.e., ontological) model of the physical world. The problem thus posed is to elevate the nonlocal Whitehead–Heisenberg ontology into a mathematical structure capable of providing a unified objective description of the classical and quantum domains of physical experience.

2. GENERALIZED BELL'S THEOREM

Bell[1] proved in 1965 that the statistical predictions of quantum theory could not be reproduced by any local hidden variable theory. The present section describes a generalization of Bell's result[2] that makes no reference to hidden variables. It is formulated instead directly in terms of the observable quantities of quantum theory.

To make the discussion specific, consider an experimental arrangement in which a pair of particles is produced in some spacetime region R_0, and one of the two particles of the pair proceeds to each of two spacelike-separated regions R_1 and R_2. Thereupon each particle enters a Stern–Gerlach device, where it is deflected either up or down relative to some axis of the device. Then it passes through one or the other of two detection devices according to whether it is deflected up or down. In this specific case the variables subject to the control of the experimenters are the axes of the devices in the regions R_1 and R_2. And what happens macroscopically in R_1 or R_2 is the firing of one or the other of the two particle detectors in that region.

It is sufficient for our purpose to consider a situation in which the direction D_1 of the axis in R_1 can be set at one of two positions $D_1{}'$ or $D_1{}''$, and the direction D_2 of the axis in R_2 can be set in one of two positions $D_2{}'$ or $D_2{}''$. Let the result in R_1 be described by the number r_1, which is $+1$ if the particle detector corresponding to upward deflection fires. Similarly, let the result in R_2 be described by the number r_2, which is $+1$ or -1 according to whether the event that occurs corresponds to the upward or downward deflection relative to the axis D_2.

To further fix ideas, suppose that R_1 and R_2 are two well-separated spacetime regions, and that within each there is a mechanism that sets the axis of the device in that region at one or the other of the two alternative settings. The choice between these two settings can be controlled, for example, by the precise times of decay of some radioactive nuclei. Because the two regions are spacelike-separated· it is not possible for the information about which choice is made in R_1 to get to R_2. Similarly, it is not possible for the information about which choice of axis is made in R_2 to get to R_1.

There are two possible settings of D_1 and two possible settings of D_2. Thus altogether there are four possible combinations of settings. Quantum theory makes statistical predictions about the results r_1 and r_2 in all four cases. In particular, if the two particles of the pair are both spin-$\frac{1}{2}$ particles and if they are produced in a spin-zero state, which can be achieved, for example, by producing them in a low-energy collision, and if one considers a large number N of such pairs, labeled by the index j, which runs from 1 to N, then quantum theory predicts that the following result will hold approximately for sufficiently large N:

$$\frac{1}{N} \sum_{j=1}^{N} r_{1j}(D_1, D_2)\, r_{2j}(D_1, D_2) = -\cos\theta(D_1, D_2) \tag{1}$$

Here $r_{\lambda j}(D_1, D_2) = \pm 1$ specifies the result in region R_λ for the jth pair of particles if the settings of the two devices are D_1 and D_2. The angle $\theta(D_1, D_2)$ is the angle between the directions D_1 and D_2 of the two axes, as measured

in the center-of-mass frame of the pair. These two directions are both taken to be perpendicular to the common line of flight of the particles, in this frame.

If the directions of D_1 and D_2, measured, say, by the clockwise angle of rotation from some arbitrary vertical line, are given by

$$\theta(D_1') = 0°, \qquad \theta(D_1'') = 90°, \qquad \theta(D_2') = 0°, \qquad \theta(D_2'') = 135°$$

then the angles $\theta(D_1, D_2) = \theta(D_1) - \theta(D_2)$ in the four cases will be fixed and the four cases of Eq. (1) are

$$(1/N) \sum_{j=1}^{N} r_{1j}(D_1', D_2') \, r_{2j}(D_1', D_2') = -1 \tag{1a}$$

$$(1/N) \sum_{j=1}^{N} r_{1j}(D_1'', D_2') \, r_{2j}(D_1'', D_2') = 0 \tag{1b}$$

$$(1/N) \sum_{j=1}^{N} r_{1j}(D_1', D_2'') \, r_{2j}(D_1', D_2'') = 1/\sqrt{2} \tag{1c}$$

$$(1/N) \sum_{j=1}^{N} r_{1j}(D_1'', D_2'') \, r_{2j}(D_1'', D_2'') = -1/\sqrt{2} \tag{1d}$$

The above equations are the standard statistical predictions of quantum theory. The locality property is expressed by the equations

$$r_{1j}(D_1', D_2') = r_{1j}(D_1', D_2'') = r_{1j}' \tag{2a}$$

$$r_{1j}(D_1'', D_2') = r_{1j}(D_1'', D_2'') = r_{1j}'' \tag{2b}$$

$$r_{2j}(D_1', D_2') = r_{2j}(D_1'', D_2') = r_{2j}' \tag{2c}$$

$$r_{2j}(D_1', D_2'') = r_{2j}(D_1'', D_2'') = r_{2j}'' \tag{2d}$$

The first of these equations, for example, says that the result in R_1 does not depend on which of the two settings D_2' or D_2'' is chosen in R_2.

Equation (1a) implies that the result $r_{1j}(D_1', D_2')$ depends on (is correlated to) the result $r_{2j}(D_1', D_2')$. In fact, there is an exact correlation: If $r_{1j}(D_1', D_2')$ is $+1$, then $r_{2j}(D_1', D_2')$ is -1, and vice versa. This correlation is demanded by quantum theory, and is expected also on the basis of classical ideas: The spins of the two particles are opposite in a spin-zero state and hence it is natural that their deflections (in inhomogeneous magnetic fields) should be opposite. On the other hand, quantum theory asserts that the expectations or probabilities regarding the behavior of the particle in R_1 do not depend upon

what the experimenter in R_2 decides to do. This is closely connected with the fact that the operators associated with the two spacelike-separated regions commute. Indeed, if the expectations or probabilities did not have this independence property, then signals could be sent faster than the speed of light.

Since the expectations or probabilities regarding the events in R_1 are independent of the choice made in R_2 between D_2' and D_2'', it is natural to expect that the individual events in R_1 should likewise be independent of the choice made in R_2 between D_2' and D_2''. This expectation is reinforced by the consideration that the information about the decision between D_2' and D_2'' does not have time to get to R_1 unless it travels faster than the velocity of light. This expected property is embodied in (2a). Equations (2b), (2c), and (2d) embody analogous expectations. However, the four equations (2) are mathematically incompatible with the four equations (1).

To exhibit this incompatibility, let (2) be inserted into (1). This gives

$$(1/N) \sum r_{1j}' r_{2j}' = -1 \tag{3a}$$

$$(1/N) \sum r_{1j}'' r_{2j}' = 0 \tag{3b}$$

$$(1/N) \sum r_{1j}' r_{2j}'' = 1/\sqrt{2} \tag{3c}$$

$$(1/N) \sum r_{1j}'' r_{2j}'' = -1/\sqrt{2} \tag{3d}$$

From (3a) one obtains

$$r_{1j}' = -r_{2j}' \tag{4a}$$

which inserted into (3b) gives

$$(1/N) \sum r_{1j}'' r_{1j}' = 0 \tag{4b}$$

Subtracting (3d) from (3c) gives

$$(1/N) \sum (r_{1j}' - r_{1j}'') r_{2j}'' = \sqrt{2} \tag{4c}$$

which can be written as

$$(1/N) \sum (r_{1j}' r_{1j}'' - 1) r_{1j}'' r_{2j}'' = \sqrt{2} \tag{4d}$$

since $r_{1j}'' r_{1j}'' = 1$ for all j.

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The absolute value of a sum is less than or equal to the sum of the absolute values of the terms. Thus (4d) yields the inequality

$$(1/N) \sum |(r'_{1j}r''_{1j} - 1)r''_{1j}r''_{2j}| \geqslant \sqrt{2} \tag{4e}$$

which gives

$$(1/N) \sum |(r'_{1j}r''_{1j} - 1)| \, |r''_{1j}r''_{2j}| \geqslant \sqrt{2} \tag{4f}$$

which gives

$$(1/N) \sum |(r'_{1j}r''_{1j} - 1)| \geqslant \sqrt{2} \tag{4g}$$

which gives

$$(1/N) \sum (1 - r'_{1j}r''_{1j}) \geqslant \sqrt{2} \tag{4h}$$

which gives

$$1 \geqslant \sqrt{2} + (1/N) \sum r'_{1j}r''_{1j} \tag{4i}$$

which, together with (4b), gives

$$1 \geqslant \sqrt{2} \tag{4j}$$

This equation is false. Thus Eqs. (1) and (2) are incompatible. Small error terms can be added to Eqs. (2) without upsetting the argument.

To see what has been proved, we review the logical structure of the proof.

The logical structure is this: For each pair of particles j one introduces a set of eight numbers $r_{1j}(D_1', D_2')$, $r_{2j}(D_1', D_2')$, $r_{1j}(D_1'', D_2')$,..., $r_{2j}(D_1'', D_2'')$, where j runs from 1 to N. This set S of $8N$ numbers is a set of conceivable results for each of the four alternative experiments under consideration. The collection C is the collection of all conceivable sets S, and Q is the subset of C that consists of those sets S such that the statistical predictions of quantum theory are satisfied to within, say, 3 % for each of the four sets of conceivable results. If the number N is very large, then the results occurring in nature will, according to quantum theory, almost surely fall within this quantum-limited collect Q. The proof consists in a demonstration that within this quantum-limited collection Q there is not even a single set S of conceivable results for the four alternative experiments that conform to the requirement that what happens in one region be independent of the choice of experimental arrangement made in the other region. In other words, if L (for local) is the subset of C that consists of those sets S in which the result in each region is independent of which experiment is performed in the other region, then the intersection of L and Q is empty: $L \cap Q = \varnothing$.

The generalized theorem can now be stated formally: Let C be the collection of all sets S of conceivable results of the four experiments. Let Q be the subset of C such that the results of each experiment satisfy the predictions of quantum theory to within 3 %. Then there is no set S of conceivable results in Q such that what happens in each region is independent of which of the two alternative possible experiments is performed in the other region.

This nonlocality property of quantum theory entails[2] that no deterministic or probabilistic local hidden-variable theory (as defined by Bell and by Clauser and Horne) can agree with quantum theory. But it is a much stronger result. In the local hidden-variable theories *every* theoretically considered possibility must be a member of a quartet within which either the individual-event locality condition given above or an equivalent probabilistic locality condition is satisfied. These quartets are labeled by the hidden variable λ, and the theory demands an exact cataloging of all the theoretically allowed possibilities into separate quartets labeled by λ, with the locality condition satisfied within each quartet. But the nonlocality property proved above says that if one excludes a set of possibilities whose total probability can be made arbitrarily small by taking N sufficiently large, then there is not even one single quartet within which the locality condition is satisfied: the theory must maintain an almost rigid nonlocal connection.

In a general local causal theory, where each attribute of the world is localized and is determined jointly by those other attributes of the world that are localized roughly in its backward light-cone together with stochastic variables that represent the element of chance, this almost rigid connection can be maintained only by means of constraints on the settings. However, the experiment can be designed so that each setting is mechanically determined by whimsically chosen numbers that pertain to systems that are not represented in the calculation that leads to the rigid connection, for example, the temperature in Chicago, or the calorie count of the experimenter's wife's breakfast. Discarding the scientifically unreasonable possibility that the almost rigid connection is maintained by means of constraints on such whimsically chosen numbers, or consequently by constraints on the settings mechanically determined by these numbers, we are left with no possibility of maintaining the necessary connection within the framework of local causal theories.

Within the more general framework of causal theories, where each attribute is determined jointly by "prior" attributes together with stochastic variables that represent the element of chance, there is a natural way to maintain the necessary connection: Allow either the results in R_1 to depend causally on the setting in R_2 or the results in R_2 to depend causally on the setting in R_1. This possibility requires a revision of the traditional ideas of the connection between causality and spacetime. This revision is discussed in

Section 4. First the reasons for seeking a causal theory of the world are discussed.

3. PRAGMATIC AND ONTOLOGICAL INTERPRETATIONS OF QUANTUM THEORY

There are many interpretations of quantum theory, and I shall not try to summarize them here. However, I wish to distinguish two opposing lines of approach: the pragmatic and the ontological.

According to the pragmatic approach[3,4] quantum theory should be viewed as merely a set of rules for calculating correlations among observations. The basic format is this: The preparation of the quantum system, described in terms of a set of operational specifications A, is mapped by empirically determined procedures onto a density matrix ρ_A. The subsequent observation of the system, described in terms of operational specifications B, is similarly mapped onto a density (or efficiency) matrix ρ_B. A unitarity transformation U, which generates the dynamical development from the time of preparation to the time of observation, is constructed and

$$P(A, B) = \mathrm{Tr}\ U\rho_A U^{-1}\rho_B$$

is the probability that an observation that meets specifications B will occur if the preparation meets specifications A.

According to the pragmatic viewpoint the physical meaning of quantum theory is exhausted by this set of predictions: One should refrain from making ontological assumptions about the nature of the world that "lies behind" the observations. The observations themselves, together with their connections and correlations, are what is real for us. The construction of ontologies (theories of what exists) lies outside the scope of science. There is no scientific or logical reason why the mind of man, presumably created to cope with the problems of survival, should be able to grasp the ultimate essences of nature.

This pragmatic viewpoint has successfully guided the development of quantum theory for half a century. No attempt to develop an ontology compatible with quantum theory has led to anything of practical value.

The main objection to the pragmatic view is that it contains within itself no definitive criterion of completeness: It gives no way of knowing when further theorizing is useless. However, there are two guiding principles: The final theory should be comprehensive and unified.

Quantum theory is not a comprehensive, unified theory of nature: The completeness claimed by Bohr was of a limited kind. Bohr stressed that

quantum theory rests on an apparent contradiction between the demands that the quantum system must interact with the surrounding environment (i.e., with the measuring devices) to be prepared and observed, but must be isolated from the environment to be defined. That is, the quantum nature of the interactions between the quantum system and the measuring system makes it impossible to consider the quantum system as a separately existing system: It must be regarded as an integral part of the whole experimental arrangement. On the other hand, in order to represent the quantum system by a wave function, governed by the Schrödinger equation, this system must be idealized as a separate system. And for this idealization to work, the quantum system must be effectively isolated from quantum interactions with the surrounding environment.

To resolve these conflicting demands, quantum theory must in principle be applied to situations that conform to the format shown in Fig. 1. The spacetime region R_A of the preparation is separated from the spacetime region R_B of the observation. The gap between them is bridged by the quantum system, which must be effectively isolated from the environment during the passage from R_A to R_B. If the quantum system were not effectively isolated from the environment during this interval, then it could not be idealized as a separate system, and its quantum theoretical description in terms of a wave function that develops in time according to the Schrödinger equation appropriate to that system would lose its validity: The intrusion of the environment would cause quantum jumps.

This isolation requirement limits in principle the scope of quantum theory. For example, it precludes, in principle, a quantum-theoretical analysis of systems that are being continuously observed. And it excludes in principle also a unified description of phenomena such as those occurring in the field of molecular biology, where the phenomena under investigation involve essentially the exchange of matter between the system and the surrounding environment.

This isolation requirement, and the consequent limitation on the scope of quantum theory, arises from the need, within the pragmatic framework, to treat the measuring devices and the surrounding environment classically,
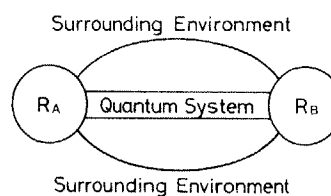

Fig. 1

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i.e., in terms of operational specifications. This need arises, in turn, from the fact that the measuring devices and surrounding environment are dynamically linked to the observer-scientists who use the theory. Thus these measuring devices, etc., can be treated quantum mechanically only if the quantum system is taken to include also these observer-scientists. However, the inclusion of the observer-scientists in the system they are studying is not possible within the pragmatic framework.

One immediate apparent difficulty with the inclusion of the observer-scientists in the system they are studying is this: The observer-scientists can apparently invalidate any quantum-theoretical predictions they make about their own behaviors simply by acting contrary to those predictions.

A closely related problem is this: Consider an observer-scientist who is observing the instruments that record his own brain patterns. Suppose his observation of instrument-result A generates a brain pattern that produces an instrument-result B. And suppose his observation of instrument-result B generates a brain pattern that produces instrument-result A. Then the observation of either state will replace it by the other.

This example illustrates the fact that the observer-scientists cannot obtain detailed knowledge about the states of their own brains without altering those states. Thus situations in which the observer-scientists are included in the quantum system they are studying are logically different from those in which they stand outside that system.

Because of this logical difference, together with insuperable practical difficulties, the pragmatically interpreted quantum theory can in principle be applied only to those special situations in which operationally describable measuring devices are interacting via a system that is effectively isolated from its environment.

This isolation requirement, and the consequent limitation in the scope of quantum theory, applies equally well to classical theory, insofar as it is regarded as a pragmatic statistical theory. However, the classical theory provides, in addition to the pragmatic statistical description, also a purported description of the world itself as it exists independent of the observer-scientists. In this second description the observer-scientists play no special role, and the description is consequently applicable in principle to all situations, rather than only those special situations that involve operationally described instruments interacting via an isolated intermediate system. This second (ontological) description can therefore provide some basis for understanding those situations in which the idealizations needed for the applicability of the pragmatic statistical description are not fulfilled.

This limitation in the scope of quantum theory means that basic physical theory is now in a fragmented state. For example, in the field of molecular biology the scientist must switch back and forth between classical theory

and quantum theory, since theee is no way to consistently treat quantum systems that are continually interacting with the surrounding environment. This fragmented character of contemporary physical theory is an aspect of the exclusion—often mentioned by Bohr—of living systems from the domain of phenomena adequately treated by quantum theory.

Within a pragmatic philosophy it is possible to accept a fragmented basic theory of nature: There is no logical reason why the mind of man must necessarily be able to comprehend all of nature within the confines of a single theoretical construct. This point of view would suggest that scientists should be satisfied with sets of rules each convering only a limited domain of knowledge. On the other hand, major scientific advances have historically come from the search for unity of physical description. The development of physics is impressive witness to the fact that the nature of the world is such that ever broader domains of experience can come under the sway of the inventive powers of man's mind. And even within the pragmatic philosophy the search for unity is justified by the fact that only by seeking can one find what is possible, and by the expectation that a unified theory, if constructable, should provide a better understanding of phenomena that lie at the interface of the existing fragments.

The most compelling argument for the completeness of quantum theory is the apparent futility of all efforts made over the past fifty years to construct a better theory. However, the situation has recently changed in one important respect: Bell's theorem has focused attention on the possibility, not seriously considered before, that superluminal connections occur at the level of individual events, but disappear at the statistical level. The central mystery of quantum theory has always been the puzzling way that information gets around. Thus the new information provided by Bell's theorem seems to be exceedingly pertinent, and points to areas of research not seriously considered before.

The most natural way to get a unified theory of nature is to construct an ontology that is consistent with quantum theory; i.e., to construct a model or picture of what exists—i.e., a model of the world itself—that is compatible with the quantum facts. This is the ontological approach.

One conceivable way to picture the world itself is to regard the wave function not merely as a tool for calculating correlations among observations, but rather as the appropriate mental representation of the world itself, as it presumably exists independent of our knowledge or awareness of it. This approach, which will be called the absolute-ψ approach, arises naturally from a misinterpretation of Bohr's claim that quantum theory is complete. Bohr's claim was that quantum theory provides a pragmatically complete description of atomic phenomena: All empirical correlations among observations in the field of atomic physics can be understood within the general quantum-

theoretical framework. This claim of pragmatic completeness is altogether different from the claim that quantum theory is ontologically complete.

The notion that quantum theory is ontologically complete leads immediately to the idea that the world itself can be represented by a wave function.

The central problem encountered by this "absolute-ψ" interpretation of quantum theory is illustrated by the following example: Suppose a particle is known to have passed through one of two slits, and to be represented by a wave function u_1 or u_2, where u_1 represents the case in which it has passed through slit one, and u_2 represents the case in which it has passed through slit two. Suppose a particle counter is placed behind each slit, and that at some initial time t_0, before the particle reaches either counter the wave function of the pair of counters is v_0, which corresponds to neither counter having fired. Suppose the time development to time t_1 carries the product wave function $u_1 v_0$ into $u_1{}^1 v_1$, where v_1 represents the situation in which the first counter has fired and the second counter has not fired. And suppose the time development to time t_1 carries $u_2 v_0$ into $u_2{}^1 v_2$, where v_2 represents the situation in which the second counter has fired and the first counter has not fired. The above suppositions correspond to what would be expected in a simple measurement situation, according to von Neumann's theory of measurement[5]. In particular, the situation described corresponds to a good measurement because if the particle has passed through slit one, then at t_1 the first counter will have fired but the second will not have fired, whereas if the particle has passed through the second slit, then the second counter will have fired but the first will not have fired. Thus by noting which counter has fired an observer may determine through which slit the particle has passed.

However, if the initial wave function at t_0 is $u v_0$, with $u = u_1 + u_2$, then, by virtue of the basic linearity property of quantum theory, the wave function at t_1 must be $u_1{}^1 v_1 + u_2{}^1 v_2$. Thus the wave function *at the macroscopic level* would be a superposition of two terms. The first term corresponds to the particle's having gone through the first slit, not the second, and the first counter's having fired but not the second. The second term corresponds to the particle's having gone through the second slit, not the first, and the second counter's having fired but not the first. Both terms are present at the macroscopic level, and there is no way to arrange matters (by complicating the setup) so that the measuring procedure will lead to a wave function corresponding to only one or the other of the two macroscopic situations. On the other hand, our experience in such a situation would correspond either to the first counter's having fired and not the second, or to the second counter's having fired and not the first. It does not correspond to a "superposition" of these two classically incompatible possibilities.

The natural explanation of this apparent discrepancy between theory and

experience is simple: The wave function represents probabilities, rather than the world itself. It is completely natural that the probabilities in the stated circumstances should have one part corresponding to the particle's having gone through the first slit and another part corresponding to the particle's having gone through the second slit. Moreover, these two parts should correspond, under the experimental conditions described above, to two mutually incompatible macroscopic situations, each with nonzero weight.

Thus the wave functions naturally represent probabilities, rather than the world itself. In the pragmatic interpretation these probabilities are the probabilities that observations that meet certain specifications will occur under conditions that meet certain specifications.

In spite of its apparent character as a probability function, one can try to maintain that the wave function ψ represents also the world itself. Three alternative strategies can be considered:

1. *Collapse of macroscopic level.* In this approach one assumes that the linearity property of quantum theory breaks down at the macroscopic level, in such a way that the wave function collapses into either $u_1^1 v_1$ or $u_2^1 v_2$. Ludwig[6] has espoused a similar view.

2. *Collapse when consciousness enters.* In this approach one assumes that the linearity property breaks down when consciousness enters. This approach is attractive because it provides consciousness with an important dynamic role in nature; the Schrödinger equation generates the multifold world of possibilities, then consciousness actualizes one. Thus the world develops stepwise by a dynamic interplay between the material aspect of the world, represented by the lawful, continuous development of possibilities and probabilities, and the mental aspect, represented by the choice between these possibilities. Wigner[7] has lent his support to this idea.

One objection to this view is that it seems excessively anthropocentric, at least if consciousness is reserved for human beings and higher creatures: Before the appearance of such creatures the world would be synthesizing endless superposed possibilities, with nothing actual or real, waiting for the first conscious creature to occur among the possibilities. Then a gigantic collapse would occur. Similarly, the Martian landscape would be nothing but superimposed possibilities until Mariner landed and some observer in Houston viewed his TV screen. Then suddenly the rocks and boulders would all snap into their observed places. This view seems to assign a role to such observers that is out of proportion to their place in the world they create.

A second objection is that there would be a gross physical dissymmetry between two observers of a quantum event. One would cause the event; the other would merely watch what the first has done. But there is no great psychological dissymmetry between the two observers.

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3. *No collapse.* In this view one assumes that the linearity property of quantum theory is never violated: Quantum theory is accepted as true universally. Then the world, as represented by the wave function, will develop into the form $u_1{}^1v_1 + u_2{}^1v_2$, which corresponds to a superposition of two apparently incompatible macroscopic situations; one in which counter one fires but counter two does not fire, and the other in which counter two fires but counter one does not fire. If now an observer, who has decided to run upstairs if he sees that counter one has fired and counter two has not fired, but to run downstairs if he sees that counter two has fired and counter one has not fired, looks at the counters and acts in accordance with his decision, then the world, as represented by the wave function, will develop into a form $u_1{}^1v_1{}^1w_1 + u_2{}^1v_2{}^1w_2$, where w_1 represents the observer running upstairs and w_2 represents the observer running downstairs. A world consisting of such a superposition of two macroscopically incompatible parts might at first seem incompatible with experience. However, two facts should be noted. First, it will be virtually impossible ever to bring the two parts of the wave function back into a situation where they interfere with each other. Two terms of a multiparticle wave function can interfere only if they overlap simultaneously (in both x and p space, and every other space) in every degree of freedom. When the two parts of the wave function correspond to two macroscopically different motions of macroscopic objects, then the degrees of freedom involved are all those in the forward light-cones from the regions where the two motions are taking place. It seems manifestly impossible to arrange, in practice, ever to get all the $\sim 10^{23}$ degrees of freedom of the macroscopic objects back into simultaneous overlap, particularly if this must be done without inducing nonoverlaps in the degrees of freedom of the surrounding environment.

The second fact to be noted is that the observer's memory is associated, by assumption, to the state of his brain, and in particular to patterns in the brain that can direct subsequent action. Because of the spacetime falloff property of the interactions that govern the dynamic development, via the Schrödinger equations, of the wave function of brains, it seems certain that the memory of the observer, in our example, would necessarily break into two separate parts that are independent in the sense that neither would be able to affect the other: The brain patterns that represent the memory of one part will be unable to affect the actions or brain patterns of the other part. The synaptic structure of brains would also probably allow the discrete aspects of our experiences (things either happen or do not happen) to be derived from the basically continuous underlying quantum structure. Consequently, there appears to be no obvious need to invoke a breakdown of the basic linearity property of quantum theory in order to reconcile the familar aspects of human experience with the assumption that the wave function represents the world itself, rather than merely probabilities. Personal human

experience would merely be associated with the individual branches of the many-branched world.

This interpretation of quantum theory, which was first described in the literature by Everett,[8] is often called the many-worlds interpretation.[9]

Three objections can be raised against the many-worlds interpretation. The first is that the mathematical properties of the wave function, and the way it is used in practice, make it closely analogous to the probability function of classical statistical mechanics. Let me expand upon this point. In classical statistical mechanics a statistical ensemble of freely moving particles defined by set of operational specifications A can be represented by a density function $w_A(p, x)$ that has the following properties:

(a) $w_A(p, x)$ is real.

(b) For any real τ

$$w_A(p, x) = w_A(p, x + \tau v), \qquad v = p/m$$

(this asserts that the particles with momentum p have velocity $v = p/m$).

(c) If $e_B(p, x)$ is the detection efficiency function associated with an observation conforming to specifications B, then the probability that an observation that meets specifications B will occur if the system is prepared in accordance with specifications A is

$$P(A, B) = \int \frac{d^3p}{(2\pi)^3} \int d^3x \; w_A(p, x) \, e_B(p, x)$$

(d) In a scattering experiment suppose that $(p^i; x^i) \equiv (p_1^i,..., p_n^i; x_1^i,..., x_n^i)$ are the variables of the initial particles, that

$$(p^f; x^f) \equiv (p_1^f,..., p_m^f; x_1^f,..., x_m^f)$$

are the variables of the final particles, and that $S(p^i; x^i: p^f; x^f)$ is the probability that a set of initial particles with variables $(p^i; x^i)$ will emerge as a set of final particles with variables $(p^f; x^f)$. Then the probability of occurrence of an observation on the final particles meeting the (multiparticle) specifications B when the initial particles are prepared in accordance with the (multiparticle) specifications A is

$$P(A, B) = \int \frac{d^{3n}p^f}{(2\pi)^{3n}} \, d^{3n}x^f \, \frac{d^{3m}p^i}{(2\pi)^{3m}} \, d^{3n}x^i$$

$$\times w_A(p^i; x^i) \, S(p^i; x^i; p^f; x^f) \, e_B(p^f; x^f)$$

[The times $t_j = x_j^0$ can be chosen arbitrarily because of (b).]

In quantum theory one represents the initial preparation by a density matrix

$$\rho_A(p'; p'') = \sum_i \psi_{Ai}^*(p') \, w_{Ai} \psi_{Ai}(\phi'')$$

where the p's are on-mass-shell four-vectors: $p^2 = m^2$. If one defines

$$w_A(p, x) = \int \rho_A \left(Mv - \frac{1}{2} q; \, Mv + \frac{1}{2} q \right) e^{-iqx} \left(\frac{M}{m} \right)^{1/2} 2\pi \, \delta(q \cdot v) \frac{d^4q}{(2\pi)^4}$$

where $v = p/m$, and $M = M(q) \equiv (m^2 - \frac{1}{4}q^2)^{1/2}$, and defines $e_B(p, x)$ and $S(p^i; x^i: p^f; x^f)$ by analogous formulas (see Ref. 10 for details), then one obtains exactly the properties (a)–(d). Thus the mathematical properties of the wave functions, when transcribed into the forms $w_A(p, x)$ and $e_B(p, x)$, are closely analogous to the functions of classical statistical mechanics represented by these symbols. Moreover, the physical interpretation of the two theories, via the correspondence through the formulas for $P(A, B)$, is exact.

The key insight upon which the pragmatic interpretation is based is the recognition that experimental uncertainties force one even in classical physics to use a statistical formulation to calculate correlations among observations. Thus if one knows the laws that govern the dynamical development of the statistical functions, it is superfluous, at the practical level, to have a model of the underlying reality: One can have a complete theory at the practical level without describing the underlying reality. The claim of pragmatic completeness rests on this simple fact. This argument uses the tight logical and mathematical connection between the statistical functions of classical statistical mechanics and the corresponding functions of quantum theory.

A second objection to the many-worlds interpretation is that it relies on the notion of time development via the Schrödinger equation. This equation is a basic ingredient of nonrelativistic quantum theory, but it is doubtful whether it can be carried into the relativistic domain. In the S-matrix formulation of relativistic quantum theory the Schrödinger equation emerges only in the nonrelativistic limit. On the other hand, the field-theoretic efforts to build a relativistic quantum theory on the idea of the Schrödinger equation has encountered severe mathematical difficulties. Thus the many-worlds interpretation is based not on quantum theory as it exists today, but rather on a conjecture that, in spite of many contrary mathematical indications, the notion of the Schrödinger equation can be extended into the domain of relativistic quantum theory.

In this connection it is worth noting that in classical (non-quantum) physics the essential change wrought by relativity theory was precisely the rejection of the view of the world as a system developing in time, in favor of

the overall spacetime view, in which one deals directly with the relationships between spacetime events.

Thus a retension of the Schrödinger equation in relativistic quantum theory would run directly counter to the classical (non-quantum) situation, since the Schrödinger equation deals precisely with the temporal development of the quantum world. On the other hand, *S*-matrix theory adheres to the overall spacetime point of view and deals directly with relationships between the spacetime events. (*S*-matrix theory, though sometimes presented as an asymptotic theory, actually deals with statistical relationships between measurements performed in *finite* spacetime regions. It constructs theoretical connections between these spacetime events without introducing, explicitly or implicitly, the notion of the time development of the world as a whole. Thus the *S*-matrix approach to relativistic quantum theory is completely in line with the change wrought by relativity theory at the classical level.)

The third objection to the many-worlds interpretation is that it pushes the basic problem of quantum theory, which is to reconcile the formalism with the character of human experience, onto the problem of the connection between mind and body, which it leaves unresolved.

In Section 4 another ontological approach to quantum theory is described. It is based on the ideas of Whitehead, and is in general accord with those of Heisenberg.

4. WHITEHEAD'S THEORY

Alfred North Whitehead[11] proposed a theory of reality that provides a natural ontological basis for quantum theory. The basic elements of his theory are events that actualize, or bring into existence, certain definite relationships from among a realm of possibilities or potentalities inhering in the set of prior events. This model of nature accords with Heisenberg's[12] idea that each quantum event actualizes a definite result from among a realm of possibilities, and that the wave function describes the probabilities, or "potentia," for the occurrence of the various possible results. Whitehead's events have certain characteristics of mental events, and hence his theory accords, to some extent, with Wigner's[7] suggestion that the actualizing of definite results is associated with mind or consciousness. However, Whitehead's events are not confined to higher life forms, but constitute all of nature. Hence Whitehead's theory accords also with Heisenberg's view (Ref. 12, p. 54) that in the observation of atomic phenomena the critical quantum event that actualizes one result, rather than a macroscopically different alternative, occurs already at the level of the experimental devices

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that detect the atomic disturbance, rather than at the level of the perceiving human observer.

It is fundamental to Whitehead's theory that the potentia of each event is conditioned by the entire preexisting world. This feature corresponds to the fact, often stressed by Bohr, that in describing quantum phenomena, the whole experimental arrangement must be taken into account. Indeed, the basic conceptual problems of quantum theory disappear once it is admitted that the potentia for each event is conditioned by the entire preexisting world. For example, interference effects in optical experiments pose no problem in principle if the event of photon absorption by a particular grain in the photographic plate has a potentia to occur that is conditioned by the entire experimental setup.

No detailed dynamics of event generation was worked out by Whitehead, but the general ontological framework is broad enough to cope with the quantum facts.

The theory developed in these sections is not exactly the one proposed by Whitehead. In the first place it ignores the mental aspects, and concentrates instead on the spacetime and momentum–energy aspects, in order to bring the theory into contact with theoretical physics. However, this concentration on the nonmental aspects is not meant to deny that any theory claiming to be an ontological description of reality should have the potentiality of dealing adequately with the mind–body problem. Indeed, Whitehead's detailed analysis of the mind–body problem in the framework of his theory constitutes a significant factor in the overall credibility of theories of this general kind. A second departure from Whitehead concerns a change in the spacetime structure. This change is discussed below.

The following postulates[13] define an ontology that is similar to that of Whitehead:

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

Remark 1.   This assumption affirms that there is a real coming into being, or coming into existence, and that the process of creation can be decomposed into a well-ordered sequence of individual creative acts. Whatever is created exists, and nothing else exists. Nothing passes out of existence, and at the end of each creative act the whole of creation is settled and definite: All that exists is unambiguously fixed.

Remark 2.   This set of discrete events appears highly pluralistic. However, each event is assumed to "prehend" all prior events in the sequence. In particular, each event embodies within itself all of prior creation, and establishes a new set of relationships among the previously existing parts.

Thus each event embraces all of creation and endows it with a new unity.

Remark 3. The sequence of creative events is well-ordered. One event is "prior" to another if it precedes it in this primordial sequence. This primordial sequence, which contains all that exists, is defined without reference to the spacetime continuum: Existence is logically prior to spacetime.

2. *Spacetime position.* Each event has characteristics that define an associated region in a four-dimensional space. This mathematical space is called the spacetime continuum. The region in this space associated with an event is called its location.

Remark 1. Spacetime has no independent existence in this theory. Rather, each event has characteristics that can be interpreted, theoretically, as a region in a four-dimensional mathematical space. For physical applications this metaphysical distinction is unimportant, and one can imagine the events to appear at a well-ordered sequence of locations in a preexisting spacetime continuum. The order of occurrence of events need not coincide with any particular temporal order.

Remark 2. The positions (i.e., centers) of the actual events are nowhere dense in the spacetime continuum. Thus the actual events atomize space. However, the possible position of any event, before it is actualized, ranges over a continuum. Thus, as regards potentiality, spacetime is continuous.

Whitehead's ontology differs from the one described above in two important respects: (1) Whitehead does not specify that the set of events forms a well-ordered sequence. (2) Each of his events prehends (and is dependent upon) not all prior events, but only the events of its own "actual world." The actual world of a given event is the set of all actual events whose locations lie in the backward light-cone of its own location.

These differences between Whitehead's ontology and the one proposed here originate in Whitehead's attempt to bring his ontology into conformity with the demands of relativity theory. These demands are discussed next.

In prerelativity physics temporal ordering is considered to define the order in which things come into existence. But in relativity theory the temporal order of two spacelike-separated events depends on the frame of reference, and hence it is not well-defined, in an absolute sense. Thus if one tries to retain in relativity theory the notion that temporal order specifies order of coming into existence, then the order in which two spacelike-separated events come into existence is not well-defined in an absolute sense. This line of thought leads to a relative concept of existence in which what exists depends on spacetime standpoint.

An alternative point of view is that the spacetime coordinates of an

event merely label its position in the spacetime continuum; they do not specify or determine the order in which events come into existence.

This second point of view allows one to retain the absolute concept of existence, in which what exists does not depend on spacetime standpoint.

Whitehead's use of the concept of "actual world" suggests his acceptance of the relative concept of existence. In opposition to this relative concept the following points can be raised:

1. The observations dealt with by physicists depend, as far as we know, on the relative spacetime positions of events, but not on the order in which they come into existence. Thus in pragmatic science the question of order of coming into existence is irrelevant: Ontological questions need be answered only if one demands an ontology. Thus the theory of relativity, considered as a theory of physical phenomena, says nothing about the issue in question.

2. The 2.7 K background radiation defines an empirically preferred frame of reference that can be used to define an absolute order of coming into existence.

3. Gödel[14] has remarked that all cosmological solutions of the Einstein gravitational equations have preferred systems of spacelike surfaces that can be used to define an absolute order of coming into existence.

4. One of Whitehead's chief aims was to fulfil the philosophical demand for unity of the world. This unity is destroyed if each event prehends, not all of creation, but only its own actual world. Thus Whitehead's general philosophy should have led him to embrace the absolute concept of existence.

5. Bell's theorem apparently requires some events to depend on events whose positions lie outside their backward light-cones. This would be contrary to Whitehead's scheme.

6. A simple concept, if adequate, is preferable to a complex one. The relative concept of existence makes existence dependent on something else, namely spacetime standpoint. This concept entangles existence with spacetime and is much more complex than the absolute one, if indeed it can be understood at all (see Gödel's remark).

One argument in support of the relative concept of existence is that one should refrain from introducing into the basic theoretical structure any noncovariant feature, because it will then be difficult to recover in a natural way the general covariance of the physical laws.

This argument has no force against the ontology proposed here because that ontology does not specify any one frame as preferred over any other, at the level of general principle. Of course, the actually existing world will be described in a particular way in a particular frame of reference, but we can

(and shall) assume that the positions of the events are relational constructs that have significance only relative to one another.

A second argument for the relative concept of existence rests on the claim (1) that what exists for an event consists precisely of that upon which it depends and the claim (2) that an event depends precisely on the events in its backward light-cone. Claim (1) goes far beyond usual ideas, which allow an event to depend only on a small part of what exists. Claim (2) seems to be contradicted by Bell's theorem.

A third argument for the relative concept of existence rests on the fact that in prerelativistic thinking temporal order defines simultaneity, which in turn specifies order of coming into existence. The claim that this linkage should be maintained in relativity theory has no rational justification. For temporal ordering depends on arbitrary labeling conventions, whereas existence should be independent of arbitrary conventions. The natural way to deal with this disparity is simply to decouple temporal order from order of coming into existence.

The essential change wrought by the ontology proposed here is to make the process of creation manifestly global: The entire universe is regarded as an organic whole. This conceptualization is entirely in line with Whitehead's general aims and ideas. However, Whitehead chose to reconcile his philosophic aims with the empirical facts by imposing special ad hoc conditions on his basic ontology, rather than allowing the empirical facts to follow from his philosophic principles. These ad hoc conditions are complicated, unnecessary, and apparently incompatible with the quantum facts represented by Bell's theorem.

For these reasons the ontology of Whitehead has been modified here to bring it into accord with his own general principles. The modifications entail a dependence of events on spacelike-separated events, in accordance with the apparent implications of Bell's theorem. However, no violation of the general principles of relativity theory is entailed by this change: The general covariance of physical laws can be maintained, along with the prohibition against faster-than-light signals.

For other discussions of Whitehead's ideas in quantum physics see Burgers[15] and Shimony.[16]

5. HEISENBERG AND WHITEHEAD

Heisenberg's views on quantum theory can be separated into two parts. Regarding the interpretation of the mathematical formalism of quantum theory he was in essential agreement with the pragmatic position of Bohr, according to which the quantum-theoretic formalism is a set of rules that

scientists use to expand and order their experiences in the domain of atomic physics. The reality dealt-with by the theory consists of that portion of the knowledge of the community of communicating observer-scientists that pertains to their observations of atomic phenomena. Heisenberg is completely in line with this viewpoint when he says:

> "We are finally led to believe that the laws of nature which we formulate mathematically in quantum theory deal no longer with the particles themselves but with our knowledge of the elementary particles ... The conception of the object-ive reality of the elementary particles has thus evaporated in a curious way, not into the fog of some new, obscure, or not yet understood reality concept, but into the transparent clarity of a mathematics that represents no longer the behavior of the elementary particles but rather our knowledge of this behavior."[7]

Heisenberg is also in accord with this pragmatic position concerning the mathematical formalism when he says "... the theoretical interpretation of an experiment requires three distinct steps: (1) the translation of the initial experimental situation into a wave function; (2) the following up of this function in the course of time; (3) the statement of a new measurement to be made on the system, the result of which can then be calculated from the probability function (Ref. 12, p. 46).

Bohr and Heisenberg both recognized that the fact that the quantum-theoretic rules work says something about the nature of the world itself. Bohr's approach to this question was cautious. He emphasized that the character of quantum phenomena precludes any return to theories of the classical type, which fulfill simultaneously the joint requirements of causality and spacetime description. And he stressed the need for science to adopt new ways of thinking (eg., complementarity) in order to expand understanding into new realms of experience. However, he carefully refrained from indulging in ontological speculation.

Heisenberg, on the other hand, was willing to propose a rough picture of what "happens." He presented an ontological description of an objective world in which the world of our experience is imbedded. This description was in terms of the ideas of "potentia" and "actual." According to this picture the existing actual world creates a potentia, or tendency, for future events. Each occurring event signalizes a transition of the "possible" to the "actual." He says:

> "The word 'happens' ... applies to the physical, not the psychical act of ob-servation, and we may say that the transition from the 'possible' to the 'actual' takes place as soon as the interaction of the object with the measuring device, and thereby with the rest of the world, has come into play; it is not connected with the act of registration of the result by the mind of the observer. The discontinuous change in the probability function, however, takes place with the act of re-gistration, because it is the discontinuous change of our knowledge in the instant

of registration that has its image in the discontinuous change of the probability function" (Ref. 12, pp. 54–55).

The intermingling in Heisenberg's writings of the pragmatic and ontological levels of his thinking has created some confusion, particularly because the mathematical formalism is tied tightly to the observational level of description, and only very loosely to the ontological level. This situation is just the reverse of that in classical theory, where the precise mathematics pertains to the ontologically described objective world, while relations among observations are considered imprecise, due to the inherent fuzziness of observations. Yet in quantum theory it is the observations that are the subject of the precise mathematical formalism, and the ontological description of the objective world is left vague, ostensibly because it involves the complexities of the entire world, and hence is not amenable to precise mathematical description.

Any attempt to tie the mathematical formalism of quantum theory in a precise way to an ontological description of the imbedding objective world is contrary to the Copenhagen interpretation. However, the theoretical situation today differs in two important respects from the situation in the early days of quantum theory. In the first place, the generalized Bell's theorem now apparently makes it necessary to suppose that the process of event-generation is a global process in which events in one region depend on decisions associated with spacelike-separated regions. In the second place, the severe mathematical difficulties encountered by relativistic quantum field theory have undermined the notion that quantum theory is tied essentially to the idea of a true development according to a Schrödinger equation. Rather, the S matrix is emerging as the central quantity of quantum theory. But the S matrix is a function that merely determines probabilistic connections between events without describing any intermediate temporal development. The natural ontological framework in which to imbed the S matrix is precisely a framework in which the world develops in stages each consisting of a sequence of localized real events that determines the probabilities or propensities of the various possibilities of the next real event. Such a scheme would, if each event had also certain primitive aspects of consciousness, seem to provide a rational realistic basis for understanding all of nature.

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REFERENCES

1. J. S. Bell, *Physics* **1**, 195 (1964); and in *Foundations of Quantum Mechanics* (Proceedings of the Enrico Fermi International Summer School, Course IL) (Academic Press, New York).
2. H. P. Stapp, Correlation Experiments and the Nonvalidity of Ordinary Ideas About the Physical World, Berkeley Preprint 1968 and LBL-5333; *Phys. Rev. D* **3**, 1303 (1971); Are Superluminal Connections Necessary, *Nuovo Cimento* (1977), to be published; J. F. Clauser and M. A. Horne, *Phys. Rev. D* **10**, 526 (1974); N. Herbert, *Am. J. Phys.* **43**, 315 (1975); A. Aspect, *Phys. Rev.* **14D**, 1944 (1976); G. Lochak, *Found. Phys.* **6**, 173 (1976); P. H. Eberhard, *Nuovo Cimento* (1977), to be published; N. Herbert and J. Karush, Generalization of Bell's Theorem, *Found. Phys.*, to be published.
3. N. Bohr, *Atomic Theory and the Description of Nature* (Cambridge University Press, Cambridge, England, 1934); *Atomic Physics and Human Knowledge* (Wiley, New York, 1958); *Essays 1958/1962 on Atomic Physics and Human Knowledge* (Wiley, New York, 1963).
4. H. P. Stapp, *Am. J. Phys.* **40**, 1098 (1972); *Phys. Rev. D* **3**, 1303 (1971); The Pragmatic Interpretation of Quantum Theory, LBL 759 (App. A).
5. J. von Neumann, *Mathematical Foundation of Quantum Theory* (Princeton University Press, Princeton, N. J., 1955).
6. G. Ludwig, *Z. Phys.* **152**, 98 (1958); and in *Werner Heisenberg und die Physik unserer Zeit* (Braunschweig, Vieweg, 1961).
7. E. Wigner, in *The Scientist Speculates*, I. J. Good, ed., (W. Heinemann, London, 1961).
8. H. Everett III, *Rev. Mod. Phys.* **29**, 454 (1957).
9. H. Everett *et al.*, in *The Many-Worlds Interpretation of Quantum Theory*, B. DeWitt and N. Graham, eds. (Princeton University Press, Princeton, N.J., 1973).
10. H. P. Stapp, Foundations of S-Matrix Theory: Theory and Experiment, LBL 759 (Rev.); D. Iagolnitzer, *The S Matrix* (Holland Press, 1978).
11. A. N. Whitehead, *Process and Reality* (Macmillan, New York, 1929).
12. W. Heisenberg, *Physics and Philosophy* (Harper, New York, 1958).
13. H. P. Stapp, *Nuovo Cimento* **29**, 270 (1975); *Found. Phys.* **7**, **313** (1977).
14. K. Gödel, in *Albert Einstein, Philosopher–Physicist*, P. A. Schilpp, ed., (Tudor Publishing Co., New York, 1951).
15. J. M. Burgers, *Rev. Mod. Phys.* **35**, 145 (1963).
16. A. Shimony, in *Quantum Physics and the Philosophy of A. N. Whitehead* (Boston Studies in the Philosophy of Science, Vol. II), R. S. Cohen and M. Wartofsky, eds. (Humanities Press, New York, 1965).
17. W. Heisenberg, *Daedalus* **87**, 95 (1958), p. 99.