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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 $w = (e_1, e_2, w')$.

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 Whiteheadian 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

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

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

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

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

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

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

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.

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

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

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,

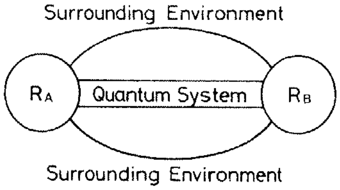

Fig. 1

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_1v_0 into $u_1{}^1v_1$, 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_2v_0 into $u_2{}^1v_2$, 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 uv_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 $u_1{}^1v_1 + u_2{}^1v_2$. 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 $u_1{}^1v_1$ or $u_2{}^1v_2$. 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.

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