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

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Summary

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 space-time 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 lecture one, asserts that there are situations involving two separate experiments, one performed in each of two space-like-separated space-time 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 three percent in each of the four alternative pairs of experiments. In other words, 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 the four sets of results in S agrees with the statistical predictions of quantum theory to within three percent, and 2) within S the results in each region are independent of which experiment is performed in the other region. This conclusion is not essentially different from that of Bell, but it is stated in a way that

avoids the apparent 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 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 macroscopically observable quantities themselves. It makes no "hidden variable" assumption, and consequently places conditions on all theories in which the macroscopic observables are well defined. These conditions will be examined in lecture four, after the Whitehead-Heisenberg theory is described.

In lecture two 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 lecture three the general features of the Whitehead-Heisenberg theory are described. Special attention is paid to the space-time 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's theorem. An alternative space-time structure is therefore proposed.

In lecture four the generalized Bell's theorem is examined in more detail, in order to determine what conditions it imposes on possible theoretical models of the world. It is argued that any such theory must be of either 1) the pragmatic type, in which the question "what determines what happens" is ignored, or 2) the many-worlds type, in which nothing determines what happens because everything happens, or 3) the one-world type, in which the effective freedom of variables subject to the control of experimenters is denied; or 4) the non-local type in which what happens in some space-time regions must depend on variables subject to the control of experimenters in space-like-separated regions. The Whitehead theory does not belong to any of the first three categories.

In lecture five 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 ~~signal~~ 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.

1. Generalized Bell's Theorem

J. S. Bell[1] proved in 1964 that the statistical predictions of quantum theory could not be reproduced by any local hidden variable theory. The present lecture describes a generalization of Bell's result that makes no reference to hidden variables. It is formulated instead directly in terms of observable quantities. This latter result is this[2]:

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

The property of local causes is formulated directly in terms of observable quantities. It asserts that if R_1 and R_2 are two space-like separated space-time regions then what happens macroscopically in R_1 is independent of variables subject to the control of experimenters in R_2.

By what happens macroscopically in R is meant the occurrence or non-occurrence in R of a macroscopic event such as the firing of some particle-detection device. By a variable subject to the control of an experimenter in R is meant the position in R of some macroscopic object that can be controlled either by an experimenter acting within R, or by a mechanism acting within R that is controlled by some random number generated within R.

To make the discussion specific consider an experimental arrangement in which a pair of particles is produced in some space-time region R_0, and one of the two particles of the pair proceeds to each of the two 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' of 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 relative to the axis D_1 fires, and is -1 if the particle detector corresponding to downward 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 space-time 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 space-like-separated 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, labelled 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 j th 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

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

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 equation (1) are

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

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

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

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

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 inhomogenous 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 space-like separated regions commute[3]. 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 that the individual events in R_1 should likewise be independent o made in R_2 between D_2' and D_2''. This expectation is reinforce that the information about the decision between D_2' and D_2'' doe get to R_1 unless it travels faster than the velocity of light 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

$$\frac{1}{N}\sum r_{1j}' \; r_{2j}' = -1 \tag{3a}$$

$$\frac{1}{N}\sum r_{1j}'' \; r_{2j}' = 0 \tag{3b}$$

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

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

From (3a) one obtains

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

which inserted into (3b) gives

$$\frac{1}{N}\sum r_{1j}'' \; r_{1j}' = 0 \tag{4b}$$

Subtracting (3d) from (3c) gives

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

which can be written as

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

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

$$\frac{1}{N}\sum | \; r_{1j}' \; r_{1j}'' - 1) \; r_{1j}'' \; r_{2j}'' \; | \geq \sqrt{2} \tag{4e}$$

which gives

$$\frac{1}{N}\sum | r_{1j}{}' r_{1j}{}'' - 1) | | r_{1j}{}'' r_{2j}{}'' | \geq \sqrt{2} \tag{4f}$$

which gives

$$\frac{1}{N}\sum | (r_{1j}{}' r_{1j}{}'' - 1) | \geq \sqrt{2} \tag{4g}$$

which gives

$$\frac{1}{N}\sum (1 - r_{1j}{}' r_{1j}{}'') \geq \sqrt{2} \tag{4h}$$

which gives

$$1 \geq \sqrt{2} + \frac{1}{N}\sum r_{1j}{}' r_{1j}{}'' \tag{4i}$$

which, together with (4b), gives

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

This equation is false. Thus the equations (1) and (2) are incompatible. Small error terms can be added to the equations (2) without upsetting the argument. This proves that within the set of conceivable results that agree with quantum theory to within (say) three percent either the results in R_1 must depend on the choice of experiment performed in R_2 or the results in R_2 must depend on the choice of experiment performed in R_1. This is the precise statement of the generalized Bell's Theorem.

The implications of this theorem will be discussed in a later lecture. The apparent implication is that information must travel faster-than-light, under the experimental conditions considered in the proof of the theorem.

2. 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[1,2] 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.

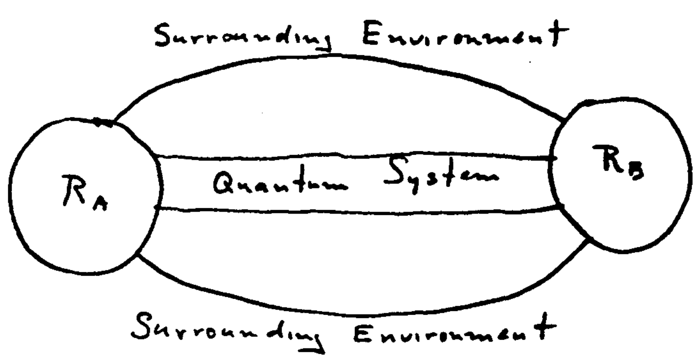
According to the pragmatic viewpoint the physical meaning of quantum theory is exhausted by this set of predictions: One should refrain from making ontological assumptions about the nature of the world that "lies behind" the observations. The observations themselves, together with their connections and 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 view point 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 Schroedinger 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 following format:



The space-time region R_A of the preparation is separated from the space-time 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 Schroedinger 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 involves 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, 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 independently 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 there 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 independently 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[3]. 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 $u_1{}^1 v_1 + u_2{}^1 v_2$. 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 set-up) 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[4] 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 Schroedinger equation generates the multifold world of possibilities, then consciousness actualizes one. Thus the world develops step-wise 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[5] has lent his support to this idea.

One objection to this view is that it seems excessively anthropocentric, at least of 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 lands and some observer in Dallas views his T.V. 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 pyschological 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 imcompatible 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 space-time fall-off property of the interactions that govern the dynamic development, via the Schroedinger 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[6], is often called the many-worlds interpretation[7].

Three objections can be raised against the many-world 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

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

(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

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

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

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

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

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

$$w_A\ (p^i;\ x^i)\ \ S\ (p^i;\ x^i\ :\ p^f;\ x^f)$$

$$e_B\ (p^f;\ x^f)$$

(The times $t_j = x_j^o$ 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

$$w_A\ (p,\ x) \equiv \int\ \rho_A\ (Mv - \tfrac{1}{2}\, q;\ Mv + \tfrac{1}{2}\, q)\ e^{-iqx}$$

$$(\tfrac{M}{m})^{1/2}\ \ 2\pi\ \delta(q\cdot v)\ \frac{d^4q}{(2\pi)^4}$$

where $v \equiv p/m$, and $M \equiv M\ (q) \equiv [m^2 - \frac{1}{4}\ q^2]^{1/2}$,
and defines $e_B\ (p,\ x)$ and $S\ (p^i;\ x^i;\ p^f;\ x^f)$ by analogous formulas (see ref. 8 for details) then one obtains exactly the properties a) through 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 though 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-world interpretation is that it relies on the notion of time development via the Schroedinger 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 Schroedinger 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 Schroedinger 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 Schroedinger 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 space-time view, in which one deals directly with the relationships between space-time events.

Thus a retension of the Schroedinger equation in relativistic quantum theory would run directly counter to the classical (non-quantum) situation, since the Schroedinger equation deals precisely with the temporal development of the quantum world. On the other hand, S-matrix theory adheres the overall space-time point of view and deals directly with relationships between the space-time events.

[S-matrix theory, though sometimes presented as an asymptotic theory, actually deals with statistical relationships between measurements performed in finite space-time regions. It constructs theoretical connections between these space-time 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 lecture 3 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.

Two final remarks should be added.

The focus in this lecture has been on the contrast between the pragmatic and ontological approaches. However, many works on the interpretation of quantum theory have centered on an alternative that lies between these two. In these works, which stem from von Neumann's analysis of the process of measurement, no attempt is made to describe the underlying real world. One deals only with the statistical functions of quantum theory. However, an attempt is made to give these statistical functions a "objective" significance that goes beyond the empirical significance that resides in the formula

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

Specifically, in these works it is assumed that if $\rho_A' \equiv U\ \rho_A\ U^{-1}$ represents a system in which some macroscopic instrument variable is confined to a set of macroscopically distinct and well-separated intervals $\ell_1, \ell_2, \ldots, \ell_n$ then ρ_A' is physically equivalent to $\rho_A'' = \rho_{A1}'' + \rho_{A2}'' + \ldots + \rho_{An}''$, where the instrument variable is confined to ℓ_i in the ensemble represented by ρ_{Ai}''. This extra "macroscopic requirement" arises from the idea that statistical functions should have some sort of "objective" meaning, and hence should reflect the fact that the observed macroscopic objects have well-defined macroscopic locations.

The rationale for imposing this macroscopic requirement is very obscure. Why should the statistical functions, which represents ensembles, have the localization properties of the observed systems? Of course, ρ_B, which represents the later observation on the system, will reflect the fact the observed macroscopic object will be in one place or another. But $u\rho_A u^{-1}$ is a theoretical construct that corresponds to probabilities or potentialities. Hence, there is no reason to require it to satisfy the macroscopic requirement.

Efforts to impose this macroscopic requirement have encountered great difficulties. An account of these difficulties can be found in the recent book of d'Espagnat[9].

Bohr's interpretation of the quantum theoretical formalism was completely pragmatic. However, in justifying his position that scientists should be satisfied with a theory that is acknowledged to be merely a set of rules for calculating correlations among observations he went beyond the usual pragmatic arguments and introduced his idea of complementarity. This idea of complementarity is not an ontology, but is nevertheless a commentary on the nature of the world, and on the limits consequently imposed on our ability to understand the world in terms of the classical ontologies, which integrate causual description with local space-time description. His arguments have no force against the radical ontology described in the next section.

3. Whitehead's Theory

Alfred North Whitehead[1] has 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 potentialities inhering in the set of prior events. This model of nature accords with Heisenberg's[2] 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[3] 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[4] view 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 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 pre-existing 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 pre-existing world. For example, interference effects in optical experiments pose no problem in principle if the event of photon absorbtion by a particular grain in the photographic plate has a potentia to occur that is conditioned by the entire experimental set-up.

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 lectures is not exactly the one proposed by Whitehead. In the first place it ignores the mental aspects, and concentrates instead on the space-time and momentum-energy aspects, in order to bring the theory into contact with theoretical physics. However, this concentration on the non-mental 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, Whithhead'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 space-time structure. This change is discussed below.

The following postulates[5] define an ontology that is similar to that of Whitehead:

1. <u>The creative process</u>. There is a creative process that consists of a well-ordered sequency of individual creative acts called events.

<u>Remark 1</u>. 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.

<u>Remark 2</u>. 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 space-time continuum: Existence is logically prior to space-time.

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

Remark 1. Space-time has no independent existence in this theory. Rather each event has characterisitics 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 pre-existing space-time 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 space-time 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 space-time 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 pre-relativity physics temporal ordering is considered to define the order in which things come into existence. But in relativity theory the temporal order of two space-like-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 space-like-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 space-time standpoint.

An alternative point of view is that the space-time coodinates of an event merely label its position in the space-time 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 space-time 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 space-time 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 4° K background radiation defines an empirically preferred frame of reference that can be used to define an absolute order of coming into existence.

3) Kurt Gödel[6] has remarked that all cosmological solutions of the Einstein

gravitational equations have preferred systems of space-like 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 lead 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 space-time stand-point. This concept entangles existence with space-time and is much more complex than the absolute one, if indeed it can be understood at all (See Gödels remark).

One argument in support of the relative concept of existence is that one should refrain from introducing into the basic theoretical structure any non-covariant 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 pre-relativistic 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 indepedent 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 space-like-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. This question of faster-than-light signals is discussed in the next section.

4. The Implications of the Generalized Bell's Theorem

The theoretical implications of Bell's original theorem are clear: if the statistical predictions of quantum theory are correct in certain correlation experiments then local hidden-variable theories cannot explain the facts. This conclusion is quite interesting, but is in complete harmony with the canonical views of Bohr.

The mathematical relations that lead to these results have, however, further implications, which are contained in the generalized version of Bell's theorem proved in lecture one. This generalized version asserts that the statistical predictions of quantum theory are incompatable with the property of local causes.

Local causes asserts that if R_1 and R_2 are two space-like-separated space-time regions then the macroscopic results of experiments in R_1 are independent of variables subject to the control of experimenters in R_2.

The failure of local causes is unexpected. This property was assumed by Einstein, Podolsky, and Rosen[1] in their famous argument against the completeness of quantum theory, and this assumption was not challenged by Bohr.[2] In fact, it was accepted by Bohr, who consequently had to resort to a subtle epistemological counter-argument.

The property of local causes is formulated directly in terms of macroscopic observables, rather than in terms of an assumed theoretical substructure. This makes the generalized theorem more physical and more general, but leaves its theoretical implications non-explicit. The aim of this lecture is to spell out these theoretical implications.

The statement of the generalized theorem given above is physical, rather than formal, since the terms in it have not been formally defined. To see what has been proved formally it is necessary to 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

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, three percent 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 of 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: $L \cap Q = \phi$.

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 three percent. 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.

A set S consists of a set of results for each of the four alternative possible experiments. Only one of the four alternative possible experiments can actually be performed. Thus the numbers that represent the conceivable results of the other three experiments are in principle unknowable. The assumption that it is theoretically permissible to represent the conceivable results of the unperformed experiments by definite (unknown) numbers is called the assumption of contrafactual definiteness.

The need to make this assumption could be the basis for a claim that the theorem is meaningless because it is based on a consideration of numbers that are unknowable in principle. However, the strong positivistic criterion of meaning that rejects as meaningless all theoretical considerations that are based on quantities that might have been measured but were not, and hence are unknowable in principle, is now recognized by philosophers to be unacceptable because it rejects constructions that are useful in science[3]. For example, the theory of the propagation of electromagnetic waves in a vacuum is based on the theoretical idea of the fields E and H. But these fields cannot be measured in a vacuum: one would have to insert a test body, which would destroy the vacuum. Thus one is using here theoretical quantities that represent what would have been measured if one had performed an experiment that one did not in fact perform.

The immediate rejection of the theorem simply because it introduces (unknown) numbers to represent the conceivable results of the unperformed experiments is therefore unjustified. The proper function of a criterion of meaning is not to mask embarrassing ignorance, but to exclude that which is necessarily useless, and theoretical considerations of alternative possibilities have been exceeding useful to man, both in science and in everyday life.

Another possible general objection to the theorem is that it violates the quantum-theoretical injunction against considering in one theoretical analysis the contemplated results of several incompatible experiments. This objection is based on a misunderstanding of thatinjunction. Bohr emphasized that the experimenter is free to decide which of the alternative experiments he will perform, and that the alternative results have to be considered as complementary in the sense that they represent equally essential knowledge about the quantum system, and together exhaust this knowledge. What he rejected is the attempt to combine this knowledge into a single classical-type picture of the system. Thus he says, for example, "within the scope of classical physics all characteristic properties of a given object can in principle be ascertained by a single experimental arrangement. . .and can be combined into a consistent picture of the object under investigation. In quantum physics, however, evidence about atomic objects obtained by different experimental arrangements exhibit a novel kind of complementary relationship. Indeed, it must be recognized that such evidence which appears contradictory when combination into a single picture is attempted, exhausts all conceivable knowledge about the object." Elsewhere he says, "A most conspicuouscharacteristic of atomic physics is the novel relationship between phenomena observed under experimental conditions demanding different elementary concepts for their description. Indeed, however contrasting such experiences might be when attempting to picture a course of atomic processes along classical lines, they have to be considered as complementary in the sense that they represent equally essential knowledge about atomic systems and together exhaust this knowledge."[5]

Thus Bohr issued no blanket injunction against the simultaneous theoretical contemplation of results of incompatible experiments. In fact he endorsed it. He rejected, rather, the idea that incompatible experiments should be considered to be simultaneously performable, and the attempt to combine the imagined information from such experiments into a single classical-type picture of the object.

In our theoretical discussion the conceivable results from the alternative possible experiments are treated precisely as conceivable results from alternative possible expeiments. It is neither suggested nor implied that both alternatives could be performed. Quite the opposite: the notion of dependence used in the proof is based on the idea that the alternative experiments are alternatives, only one of which can be performed. No attempt is made to combine the imagined information from both experiments into one picture of some object.

The two objections cited above can be cast in the form of the following question: How can one learn anything about what exists by considering alternatives that cannot exist? The answer is that in thinking about the world we must necessarily think in terms of our theories about the world. Theories about the world generally deal with the actual world as one of a collection of possible worlds. This is true of classical physical theory, where the arbitrariness of the initial conditions allow for an infinite set of possible worlds. It is also true of quantum theory where, in the words of Bohr, "The freedom of experimentation presupposed in classical physics is of course retained and corresponds to the free choice of experimental arrangement for which the mathematical structure of quantum theory offers the appropriate latitude."[6] Also in the Whitehead theory there is, explicitly, a world of possibilities from which the actual world is chosen.

The general line of argument here will be first to consider a very general theoretical realm that embraces all conceivable results of all conceivable experiments, and then to examine the theoretical constraints imposed by the assumed validity of the statistical predications of quantum theory.

Among the theoretical possibilities that will accomodate these constraints are those in which the general theoretical conditions specify the world completely and uniquely: no accidents are allowed. This is the "one-world" possibility, which is certainly not ruled out by the quantum theoretical limitations. In this case there would be no need for superluminal information transfer: the whole universe would be some monolithic structure all parts of which would be rigidly fixed, and the idea of information transfer would not be appropriate. A similar theoretical possibility is the "highly constrained world" in which the universe is not uniquely fixed by the general theoretical conditions, but in which there is, nevertheless, no theoretical possibility of performing all four alternative experiments. These theories are contained in the more general theoretical framework in which all conceivable results of all four experiments are initially admitted. Hence they fall within the scope of the ensuing theoretical discussion.

In order to determine the theoretical implications of the generalized Bell's theorem, and to dispel in particular the cloud connected with the use of the notion of dependence based on the assumption of contrafactual definiteness, it will be useful to present the proof in a way that displays more clearly its essential logical elements. This will be done by formulating as clearly as possible six assumptions that cannot all be satisfied:

Assumption 0. Theories.

The subject under discussion is not the world itself, but possible theories about the world.

Remark 0.1. This is not really an assumption. It is just an explicit statement of the fact that the aim of the analysis is to determine conditions on possible theoretical models or pictures of the world. The ensuing assumptions are to be understood as assumptions on some theoretical model of the world.

Before stating these assumptions it will be useful to fix ideas by describing a special class of experimental arrangements. Suppose in each of the two regions R_1 and R_2 of the Bell experiment there is a telescope directed away from the other region and at a distant galaxy, and that the choice between the two possible experiments in this region is controlled, mechanically, by the arrival time measured in microseconds of the first photon in some frequency range that comes down the telescope after some initial starting time. Thus the choice of the experiment performed will be controlled by the arrival time of a photon that probably originates in a distant galaxy.

This particular galaxy is to be picked by the experimenter by means of a complex routine that uses as inputs a set of whimsically chosen numbers such as the number of calories in his wife's breakfast, the noon temperature in Chicago, and the evening Dow-Jones average. Thus the choices of experiments are determined by a set of irrationally chosen numbers, combined in an arbitrary way with the arrival times of photons from distant galaxies.

Suppose an experiment is performed that involves $N = 10^6$ pairs of particles that are produced, deflected by the Stern-Gerlach device, and counted in the counters. Quantum theory predicts that the observed results will almost surely agree with the predicted averages to within three percent.

Assumption 1. Conceivable alternative experiments and results.

The experiment actually performed is one experiment from the set E of four conceivable experiments

$$E \equiv \{(e_1,e_2);\ e_1 = +1 \text{ or } -1,\ e_2 = +1 \text{ or } -1\}$$

The result actually obtained is one result from the set R of 4^N conceivable results

$$R \equiv \{r_{1i},r_{2i},\ \ldots,r_{1N},r_{2N});\ r_{1i} = +1 \text{ or } -1,\ r_{2i} = +1 \text{ or } -1,\quad i = 1,\ \ldots,N\}$$

The experiment and result that actually occur is one element from the set $E \otimes R$ of 4×4^N conceivable experiments and results.

Remark 1.1. This assumption is also not a real assumption. It is just a definition of the sets E and R. But the assumption 1 asserts that we can introduce these definitions. This is certainly within the range of our theoretical capabilities.

Assumption 2. Decisions.

The general theoretical structure admits a set $\mathfrak{T}$ of theoretical worlds w. The actual world is pick-out from the set $\mathfrak{T}$ by a set of decisions. These decisions can be deterministic, stochastic, or at any other kind.

The particular subset of $\mathfrak{T}$ that is relavant to this discussion is the set $\mathfrak{P}$ of possible worlds defined next.

Definition. A subset $\mathcal{P}$ of $\mathcal{T}$ is defined by the following two conditions:

a) for each w of $\mathcal{P}$ the initial conditions of the experiments here under discussion are satisfied,

b) for each w of $\mathcal{P}$ one element (e(w), (r(w)) of E $\otimes$ R is picked out as the experiment and set of results that occur in the possible world w.

Remark. The initial conditions referred to in requirement a) are the conditions that define those initial portions of the experiment in which the N pairs of particles are produced, and are sent to the regions R_1 and R_2, where the experimental equipment is waiting to be placed in one of the four alternative possible settings in accordance with the imminent arrival times of the photons.

Assumption 3. Variables.

Each of the four experiments $e \equiv (e_1,e_2)$ of E occurs for at least one w in $\mathcal{P}$.

Remark 3.1. In a theory in which quantum effects are controlled by stochastic elements it should be easy to satisfy assumption 3. For example, if the time of absorbtion of the photon coming down the telescope is controlled in part by a stochastic element (i. e. by a random variable) then a different choice of this element could cause the photon to arrive a microsecond later, which would alter the choice of (e_1,e_2) without appreciably altering the initial conditions.

Remark 3.2. In a deterministic theory in which one is free to fix the boundary conditions on any chosen space-like surface, and in which no faster-than-light propagations occur, it should again be easy to satisfy assumption 3. One could choose some space-like surface lying just before the initial preparation, and change nothing in a certain neighborhood $\mathcal{n}$ of the experiment that extends out to the two key photons coming in from the distance galaxies. One or both of these photons could be retarded by a microsecond, which would cause an alteration in the choice of one or both elements of the pair (e_1,e_2), without altering the initial conditions.

Remark 3.3. Consider a theory in which it is necessary to set the initial conditions in a random way at time $t=-\infty$, in order to obtain the proper statistical results. In such a theory it might be impossible to change anything in the universe without changing various contemporary things all over the universe. Assumption 3 could be satisfied in such a theory provided some contemporary things could be left approximately intact. What is required is only that there be a set of (at least four) theoretical worlds in which each of the four possible experiments $e \equiv (e_1, e_2)$ is performed, and that in each of these theoretical worlds w some particular set of results r(w) occurs.

Remark 3.4. The prime examples of theories that fail to satisfy assumption 3 are the one-world theories described earlier. In such theories the general theoretical conditions fix everything uniquely: there are no theoretical variables.

Remark 3.5. The set of possible worlds entailed by assumption 3 allows a clear meaning to be given to the notion of "variables" occurring in the statement of the generalized Bell's theorem: within the realm of possible worlds the choices of experiments performed in R_1 and R_2 become theoretical variables. The one actual world no longer plays a distinguished role; all of the possible worlds have equal status. The ill-defined idea of "what would have happened if the other experiment had been performed" does not enter: there could be many possible worlds corresponding to each element (e_1, e_2) of E.

Definition. Let $\mathcal{P}_Q$ be the subset of $\mathcal{P}$ that consists of those w such that the set of the results r(w) agrees with the predictions of quantum theory to within three percent.

The experiments and results that occur in the set of possible worlds $\mathcal{P}$ is a subset of the set of conceivable experiments and results. Thus the earlier result $L \cap Q = \phi$ implies that there is no quartet of possible worlds {w(+1,+1), w(+1,-1), w(-1,+1), w(-1,-1)} such that for all (e_1, e_2) in E and all j in {1,...,N} the following five conditions are satisfied:

a) $e_1(w(e_1,e_2)) = e_1$, (4.1a)

b) $e_2(w(e_1,e_2)) = e_2$, (4.1b)

c) $r_{1j}(w(e_1,+1)) = r_{1j}(w(e_1,-1))$, (4.1c)

d) $r_{2j}(w(+1,e_2)) = r_{2j}(w(-1,e_2))$, (4.1d)

and

e) $w(e_1,e_2)$ is in $\mathcal{P}_Q$. ~~for all four (e_1,e_2) in E~~ (4.1e)

This result imposes an absolutely rigid constraint on the set $\mathcal{P}_Q$: it says that it is not possible to find within the set $\mathcal{P}_Q$ even a single set of four possible worlds, one for each e in E, such that changing the experiment performed in R_1 leaves the results that occur in R_2 unchanged and changing the experiment performed in R_2 leaves the results that occur in R_1 unchanged: within $\mathcal{P}_Q$ the results in one of the two regions must depend on the choice of experiment performed in the other.

A rigid connection between the choice of experiment e_λ in region R_λ and the results $r_{\lambda'}$ that occur in the other region $R_{\lambda'}$ $(\lambda \neq \lambda')$ could conceivably be due to a causal dependence of e_λ and $r_{\lambda'}$ upon some common cause. However, the choice of experiment e_λ depends critically on several whimsically chosen numbers, such as the calorie count of the experimenter's wife's breadfast and the noon temperature in Chicago, etc. Thus a rigid connection between e_λ and $r_{\lambda'}$ would demand that the dependence of $r_{\lambda'}$ upon these whimsically chosen numbers stay exactly in step with the dependence of e_λ upon these numbers. Otherwise the e_λ could change without $r_{\lambda'}$ changing. This rigid connection must hold for all theoretical worlds in which similar experiments are performed. A rigid connection of this type in which a change in a variable e_λ that is controlled by an experimenter (in a whimsically chosen way) is necessarily accompanied by a change in $r_{\lambda'}$ is what we mean when we say that the result $r_{\lambda'}$ must depend on the choice e_λ.

Thus what has been proved here is that within the quantum-limited set $\mathcal{P}_Q$ either r_1 must depend on e_2 or r_2 must depend on e_1.

The result just stated is the generalized Bell's theorem, stated as a condition on physical theories.

To obtain the promised contradiction three more assumptions will be introduced.

Assumption 4. Causality I.

Let $r_d(w)$ represent the result or outcome of decision d in world w. Then

$$r_d(w) = \tilde{r}_d(I_d(w)), \tag{4.2}$$

where $I_d(w)$ is the information about the world w upon which decision d is based. This information does not include the information represented by $r_d(w)$ itself. Thus equation (4.2) asserts that $r_d(w)$ can be expressed as a function $\tilde{r}_d$ of other features of w. These other features are called the information $I_d(w)$ about w upon which decision d is based. It is not required that the set of decisions d be denumerable.

Assumption 5. Locality.

The information $I_d(w)$ can be considered to be localized in space-time and subject to the following conditions:

a) If a decision d determines what will happen in world w in a macroscopic space-time region R_d then $I_d(w)$ is confined to $V^-(R_d)$, which is the backward light-cone drawn from R_d.

b) If the disposition of an instrument in a macroscopic region R_λ is controlled by whimsically chosen elements brought together in R_λ from far-apart space-time regions and there combined in a whimsically chosen way to produce an essentially random number n_λ that is mechanically related to two possible choices of the disposition of the instrument by a relation $e_\lambda = (-1)^{n_\lambda}$ then the information represented by the choice of value of e_λ, insofar as it is usable as information upon which other decisions depend, is localized in $V^+(R_\lambda)$, which is the forward light-cone drawn from R_λ.

Remark 5.1. This locality requirement is suggested by relativity theory.

Remark 5.2. Assumptions 4 and 5 entail that in the Bell-theorem situation $\tilde{r}_1$ does not depend explicitly on e_2 and $\tilde{r}_2$ does depend explicitly on e_1.

Assumption 6. Free variables.

Any variables that are controlled by whimsically chosen numbers brought from distant regions and combined in whimsically chosen ways can be considered to be free variables in the sense that any necessary dependence of some quantity on such a variable can be represented as an explicit dependence of that quantity upon this variable, in the formula $\tilde{r}$.

Remark 6.1. If this assumption is rejected then a necessary connection of some quantity on such a variable would evidently require some systematic correlation between the quantity and the variable involving the features of the world-at-large that control the variable.

Since the necessary dependence of $r_{\lambda'}$ on e_λ was derived from the quantum theoretic analysis of a two-particle system, with no reference to the experimenter's wife's breakfast, etc., the rational approach is to try first to understand this connection in terms of the experimental systems that are directly involved, rather than in terms of constraints on the whimsically chosen experiments.

Remark 6.2. The six assumptions lead to a contradiction. The first three assumptions entail that within $\mathcal{P}_Q$ either r_1 must depend on e_2 or r_2 must depend on e_1. The last time three assumptions entail that both alternatives are false.

Remark 6.3. The essential difference between the present discussion and that of Bell is that the present discussion does not rely, implicitly or explicitly, on the requirement that the set of possible world can be parameterized in the form $w = w(w^1, e_1, e_2)$. If the natural variables of the theory were values of some initial parameters at t = -00, and the results of decisions referring to events extending back to t = -00, then the parameters e_1 and e_2 would be intimately connected with things all over the universe, and there would be no natural way of introducing some set of "hidden variables" w^1 such that the simple locality properties $r_\lambda(w^1,e_1,e_2) = r_\lambda(w^1,e_\lambda)$ would hold. Bell's original result rule out theories where such a parameterization exists. The generalized theorem places conditions on theories, such as those of the Whitehead type, where no such parameterization is introduced.

At least one of the five assumptions 2-~~5~~ 6 must be invalid. Assumption 2 asserts that nature must somehow decide what occurs. There are two ways to avoid this assumption. The first is to adopt a pragmatic attitude and simply refuse to consider the question "what determines what occurs". The second is adhere to the many-worlds view that everything occurs, and hence to deny that decisions are made.

In the framework of the many-worlds interpretation one might try to identify the different "possible paths" in the many-worlds universe with the different "possible worlds" of the present discussion. This would be permissible if these paths were distinct and discrete like the water molecules in a branching stream. However, if this discrete-path view of the many-worlds interpretation is adopted then the many-worlds interpretation becomes essentially the same as the hidden-variable interpretation, since one can identify one path as the actual world, and discard the others as "unreal". Conversely, the (Bohm) hidden-variable theory could be converted into the discrete-path many worlds theory by introducing a dense set of paths, in place of the usual one unique path. Hence the many-worlds approach becomes significantly different from the hidden-variable approach only if the idea of a dense set of discrete paths is rigorously avoided. But if there are no discrete paths then the idea that a decision is made at each branching of paths no longer holds and assumption 2 is not satisfied. Theories in which there are no decisions will be called theories of the many-world type.

Assumption 3 and 6 are the assumptions that the choices of experiment can be considered free. A theory in which either of these two assumptions fails will be called a theory of the one-world type.

Assumption 4 and 5 are the assumptions that the decisions are based on localized information that travels no faster than light.

The possible ways out of the contradiction fall, therefore, into four categories: 1) the pragmatic category, in which the question "what determines what occurs" is rejected; 2) the many-world category, in which the idea that decisions pick-out what will occur is rejected; 3) the one-world category, in which the notion that the choice of experiment can be considered a free variable is rejected; or 4) the nonlocal category, in which the notion that the decisions are based on localizable information that travels no faster than light is rejected.

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 lead 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 objective 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"[1]. 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"[2].

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 space-time 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 a ontological description of an objective world in which the world of our experience is impedded. 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 observation, 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 registration, 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"[3].

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, for our purposes it will be useful to put Heisenberg's ontological ideas into a symbolic form. This can be done by revising assumption 4 of the preceeding lectures. The new form of this assumption is as follows:

Assumption 4 Causality

The result $r_d(w)$ of decision d in world w depends jointly on the information $I_d(w)$ about w available for making decision d, and on some random variables $V_d(w)$:

$$r_d(w) = \tilde{r}_d\ (I_d(w),\ V_d(w)). \qquad (5.1)$$

The decisions d can be ordered so that the information $I_d(w)$ does not include, either directly or indirectly via some chain of decisions, the result $r_d(w)$ of decision d itself. The sets of random variables V_d associated with different decisions need not be disjoint.

Remark 1. The ordering requirement in assumption 4 distinguishes causal theories from theories in which what happens is determined by implicit (or self-consistency) requirements, rather than by a direct causal chain. Implicit connections, if they exist, could perhaps be replaced by constraints, in order to convert a theory with some self-consistency requirements into a causal theory. Causal theories are allowed to be stochastic, since the decisions are permitted to depend on random variables.

Remark 2. The assumptions listed above provide a framework consistent with the ontological ideas of Heisenberg. The information $I_d(w)$ can represent the information that resides in the macroscopic world, and is describable in classical terms. The potentia, or tendencies, that determine the probabilities corresponding to the different possible outcomes or results of decision d can then be functions of $I_d(w)$. The outcome itself of decision d would be fixed by the information $I_d(w)$ plus a set of random variables $V_d(w)$ that would pick out from the set of possibilities the particular thing that occurs or happens in possible world w.

Remark 3. Within this framework the double-slit experiment presents no problem. The probabilities would be determined by the whole experimental arrangement. If one changed to a new experiment w' then the potentia would change to the one fixed by $I_d(w')$. The information provided by the results of experiments in the two different experimental situations, w and w', would not have to be understood in terms of a single picture of any object since they refer to different worlds. However, the information provided by the statistical results obtained in altered situations could be considered to represent complementary information about some idealized theoretical object. Thus the theoretical framework provided by the foregoing assumptions conforms to Bohr's central tenets.

Remark 4. The framework conforms also to Einstein's demands that the basic theory should nominally describe the objective situation, rather than features of the knowledge of the observers.

Remark 5. No locality requirement is imposed on the random variables $V_d(w)$. In fact, they must have a global or nonlocalized character. For if a particle is emitted from a localized source and its wave function spreads out in a spherical wave to distant parts of the universe, then the random variable must pick the place where detection occurs: If the detection occurs at one place then it cannot occur at another place. In this sense the variables V transcend space-time.

Remark 6. This framework is probably in general accord also with the intuitive idea of quantum theory held by many practical workers in the field.

Remark 7. Bohr would presumably maintain that any discussion of the process that picks out the particular result is useless. That is, he would presumably refuse to consider the question "what determines what happens". However, this question is a natural one to ask, and Bohr's arguments do not show, or even claim to show, that an examination of the question must forever be useless in every context. If, therefore, this question "what determines what happens" is faced, and the answer given is "chance", then the framework defined by the foregoing assumptions provides a natural mathematical setting for a further elaboration of this answer.

Remark 8. It is well known[4] that the probabilities or expectations in one region of the Bell experiment do not depend on the choice of experiment in the far-away region. This is reflected by the fact, which follows from assumptions 4 and 5, that $I_{1i}(w)$ does not depend explicitly on e_2 and $I_{2i}(w)$ does not explicitly on e_1. But the arguments codified in assumption 6 (of lecture 4), together with the generalized Bells theorem, imply that either the results $\tilde{r}_{1i}$ must depend explicitly on e_2 or the results $\tilde{r}_{2i}$ must depend explicitly on e_1. Therefore, either $V_{1i}(w)$ must depend explicitly on e_2 or $V_{2i}(w)$ must depend explicitly on e_1.

Remark 9. The symmetrical way to allow either $V_{1i}(w)$ to depend on e_2 or $V_{2i}(w)$ to depend on e_1 is to allow both to depend on (e_1, e_2). For example, one could assume that the variables of V_{1i} are identical to the variables of

V_{2i} and are represented by a variable V_i whose weight is uniformly distributed over the ellipse in Fig. 5.1

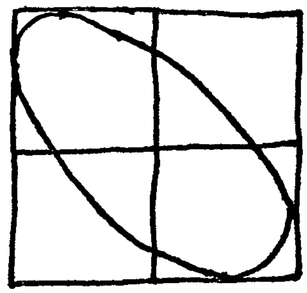


Fig. 5.1

The position of this point $V_i = V_i(w)$ in this ellipse determines the results $r_{1i}(w)$ and $r_{2i}(w)$ in accordance to the quadrant in which V_i lies. The shape of the ellipse would be determined jointly by $\vec{e}_1$ and $\vec{e}_2$. However, the formula for the shape of this ellipse in terms of the angle between the directions e_1 and e_2 of the axes of the two devices is neither simple nor aesthetically attractive.

Remark 10. There is a stronger reason to reject any such symmetric solution: Suppose the experiment at each end is set up so that each particle has a good chance to miss the detectors, but that those that miss are refocused and sent through a second Stern-Gerlach device that has the "other" choice of axis and that his process is repeated down a long chain of Stern-Gerlach devices with alternating choices of axes. Then the effective choice of e'_λ will be determined jointly by the free variable e_λ (the choice of axis of the first device) and the result r_λ: $e'_\lambda = e'_\lambda(e_\lambda, r_\lambda)$. But the causality requirement excludes the possibility that r_{1i} and r_{2i} both depend explicitly on each other. Thus if the theory is to be causal then the symmetrical solution in which both r_λ's depend on both e_λ's is excluded: One must go to the asymmetric solution where either r_1 depends explicitly on e_2 and r_2 does not depend explicitly on e_1 or r_2 depends explicitly on e_1 and r_1 does not depend explicitly on e_2.

Remark 11. The above result is this: If one accepts the six assumptions (and in particular accepts the idea of decisions based causally on localized information plus random variables, and accepts the condition that the choice of experiment in the stated circumstances can be regarded as free) then one must accept the fact that for one of the two values of λ the set $V_{\lambda i}(w)$ depends explicitly on e_{λ}', $\lambda' \neq \lambda$, while $V_{\lambda' i}(w)$ does not depend explicitly on e_{λ}. That is, the causal formulas must be asymmetric!

Remark 12. Once this asymmetry is accepted it is easy to understand the quantum results in a simple way. The possible spin states of each particle are represented by the points on a unit sphere. The restriction to the state of total spin zero imposes the condition that the points representing the two spins be located at relative anti-podes. The result of one the two experiments, say the one in R_{λ}, is the prior one upon which the other one depends. The result of this first experiment fixes the point that represents the spin of the particle that is present in its region R_{λ}, and hence also, by the spin-zero condition, the point that represents the spin of the second particle. The result of the second experiment is then determined by the usual rule that the probability $P(\vec{e}_a, \vec{e}_b)$ that a spin state represented by a point $\vec{e}_a$ on the unit sphere will generate a result corresponding to a point $\vec{e}_b$ on the unit sphere is $\frac{1}{2}(1 + \vec{e}_a \cdot \vec{e}_b)$. This description is, of course, nothing but the usual objective description used by practical workers in quantum theory. The point brought out by the generalized Bell's theorem is that any causal description (that satisfies our six assumptions) must share some basic features of the above description, namely that one of the two results must be picked out as the prior one, even though the two results occur in space-like-separated regions, and the information about the (free) choice of experiment corresponding to the prior result must be used in determining the other result. This conclusion is established in a very general framework that is essentially in accord with the ideas of Bohr, Heisenberg, and Einstein. Bohr might challenge the utility of trying to analyze the question "what determines what happens", but the general framework adopted here is otherwise in accord with his ideas.

Returning now to the general Heisenberg model we must ask: What is the nature of the actual world. It is the failure of quantum theory to give any answer to this question that is the reason why it must be interpreted pragmatically, if it is to be considered complete.

There are two natural candidates for models of the actual world. In the first model the actual world is a world that can be described classically. This is a very attractive possibility. However, no one has yet figured out how to make it work i.e., how to make the classical world generate potentialities which when combined with random variables determines the further development of the classical world. The other way is to accept the idea that nature makes discrete decisions. The occurrence of discrete decisions seems to be an essential feature of quantum theory. But if nature does make discrete decisions then the simplest possible ontology is the one in which the world consists of these decisions~~ and their actual results~~. This, in a nutshell, is the essence of the Whitehead ontology.

These decisions ~~and their results~~ may indeed be the substance of reality. But to do physics we must have a connection to space-time: The decisions must have images or consequences that can be described in space-time. Our problem, therefore, is to forge this connection. The first stage of an attempt to do this is described in ref. 5.

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