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Quantum Ontologies

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Quantum Ontologies [*]

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Abstract

Quantum ontologies are conceptions of the constitution of the universe that are compatible with quantum theory. The ontological orientation is contrasted to the pragmatic orientation of science, and reasons are given for considering quantum ontologies both within science, and in broader contexts. The principal quantum ontologies are described and evaluated.

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DISCLAIMER

Introduction

Isaac Newton,[1] being unable to explain the cause of gravity, drew an important distinction between Science and Natural Philosophy: Science, according to Newton, deals with mathematical relationships between results of observations, whereas Natural Philosophy is concerned also with underlying essences. Einstein[2] adopted the same stance in his formulation of the special theory of relativity, when he analyzed spacetime relations in terms of mathematical connections between observations. The founders of quantum theory also adhered to this conception of science when they affirmed, in the words of Bohr,[3] that "strictly speaking, the mathematical formalism of quantum theory ... merely rs rules of calculation for the deduction of expectations about observations obtained under well–defined experimental conditions specified by classical physical concepts".

In view of this strong and successful tradition in science, which, in fact, is almost a characterization of what science actually is, any suggestion that scientists should attempt to peer behind the mathematical connections between observations and speak about underlying essences should be approached with caution.

Each of the three scientists cited above was also a Natural Philosopher, holding a deep interest not only in science, but also in the implications of scientific discoveries upon our ideas about the nature of the world in which we live. Indeed, the whole scientific attitude mandates that, in our search for an understanding of the nature of the universe, and our role in it, we extract as much information as possible from our successful scientific theories, construed as repositories of empirical findings.

In this broader context it becomes interesting and important to formulate conceptions of Nature that are at least compatible with our principal scientific theories. This task is not a trivial one, for the constraints imposed by quantum theory are not easily satisfied. One is forced into conceptions of the universe that are radically different from the ones suggested by the physical theories that prevailed at the beginning of this century. Those classical ideas about the nature of the universe, and of man's role in it, had a profound effect upon our institutions and upon the conceptual environment that controls every aspect of our lives. The ideas immanent in quantum theory can be expected to have an even greater impact.

Quantum ontologies are conceptions of the constitution of the universe that are compatible with quantum theory. Their study may be useful also within science itself: such a conception might provide the foundation for a generalization of quantum theory that evades certain limitations in scope that are inherent in the contemporary orthodox Copenhagen formulation of quantum theory. To spell out the nature of these limitations, and provide also stark contrast to the ontological descriptions to be given later, it will be useful to begin with a brief account of the orthodox Copenhagen formulation.

According to Bohr[4], "The essentially new feature in the analysis of quantum phenomena is ... the introduction of a fundamental distinction between the measuring apparatus and the objects under investigation. This is a direct consequence of the necessity of accounting for the functions of the measuring instruments in purely classical terms, excluding in principle any regard to the quantum of action."

The format for the application of quantum theory is this: Let A be a set of specifications, expressed in terms of classical concepts, of the dispositions of the instruments that prepare a quantum system. Let B be a set of specifications, expressed in terms of classical concepts, of the dispositions of the instruments that detect this quantum system, and of the dispositions that characterize a particular possible response. Then, according to quantum theory, there are mappings $A \rightarrow \rho_A$ and $B \rightarrow e_B$ of the classically described specifications into operators in an appropriate Hilbert space such that the probability that a response meeting specifications B will occur under conditions meeting specifications A is $tr\rho_A e_B$.

An essential feature of this format is that the quantum system does not "evolve" in accordance with equations of motion from the prepared state characterized by ρ_A into the detected state characterized by e_B. The possible result B represented by e_B is specified by an experimenter that stands outside the quantum system. He is free to select the particular set of specifications B in an infinitude of different ways; e.g., the pointer on a device, constructed in accordance with some specifications that he draws up, is required to lie, at a certain time that he specifies, in a certain interval that he specifies. It is the finiteness of the intervals within which the various observable parameters are constrained to lie that allows the probability for this result to be finite. These finite intervals, which are needed to characterize the discrete yes–no question B, are manufactured by the experimenter, not by the quantum system.

According to Bohr[5], "... the definition of the state of a physical system, as ordinarily understood, claims the elimination of all external disturbances. But in that case, according to the quantum postulate, any observation will be impossible ...". These words of Bohr point to the fact that a condition for applicability of the theory is that the quantum system not act upon the environment during the interval between its preparation and detection, because if it does then there will be a loss of phase information, and the unitary law of evolution will fail, as it in fact does when the system acts upon the detection device. The whole framework rests, therefore, on an idealization, namely that the universe can be separated into two parts, the quantum system and the rest of the universe, with the latter including the measuring devices and observers, in such a way that the action of the quantum system upon the rest of the universe can be effectively ignored during the interval between preparation and detection. This idealization fails in the case of a (mesoscopic) system that is large enough to act essentially continuously upon its environment, but that does not act strongly enough to be described classically. The idealization fails also for the universe as a whole, which is not prepared and detected by outside devices and observers.

This brief account of the orthodox interpretation provides background for a discussion of quantum ontologies.

There are three principal quantum ontologies: the pilot–wave ontology of Bohm[6] and DeBroglie[7]; the many–worlds ontology of Everett[8]; and the actual-event ontology. The last of these I shall tie to the words of Heisenberg,[9] although earlier suggestions along similar lines were made by Bohm,[10] and by Whitehead.[11]

Space limitations mandate brevity in my descriptions of these alternatives. Still, I would like to include, and even to focus upon, evaluations. Of course, the ultimate test of these ideas in science will be their utility. So far none has proved useful in any practical context. Indeed, Einstein has warned that the path to a more complete theory of quantum phenomena will be lengthy and difficult.[12] So at this early stage we must be guided in part by considerations that are more aesthetic than mathematically decisive.

The Pilot–Wave Ontology

The simplest quantum ontology is the pilot–wave model. I can confine my description here to essential features, because the model has been described in the contribution to this conference of Bohm and Hiley.

According to this model a nonrelativistic universe containing n particles is described, in part, by two scalar functions $P(\vec{x}_1, \vec{x}_2 \cdots, \vec{x}_n; t)$ and $\varphi(\vec{x}_1, \cdots, \vec{x}_n; t)$, where P is the square of the absolute value of the configuration–space wave function, and φ is its phase. A velocity field is then defined by the gradient operator $\vec{\nabla}_i$ acting on φ:

$$\vec{v}_i(\vec{x}_1, \cdots, \vec{x}_n; t) = \frac{1}{m_i}\vec{\nabla}_i\varphi(\vec{x}_1, \cdots, \vec{x}_n; t) \quad i = 1, \cdots, n.$$

In addition to these functions there is a world trajectory consisting of a set of n single–particle trajectories $\vec{x}_i(t)$, where i runs from 1 to n. They satisfy the following equation of motion: for each i the velocity $d\vec{x}_i(t)/dt$ is $\vec{v}_i(\vec{x}_1(t), \cdots, \vec{x}_n(t); t)$.

For fixed P and φ these equations of motion generate from a set $(\vec{x}_1, \vec{x}_2, \cdots, \vec{x}_n)$ of possible positions of the n particles at a given time t_0 a possible world history, or trajectory. Taking all possible sets $(\vec{x}_1, \cdots \vec{x}_n)$ one obtains an infinite ensemble of possible world histories. If at any time t the statistical weighting of the different elements of this ensemble agrees with the probability function $P(\vec{x}_1, \cdots, \vec{x}_n; t)$ then this agreement will, by virtue of the equation of motion, be maintained for all time.

This model is important because it is a conceptually simple realistic model that reproduces the predictions of quantum theory. It belies the idea, seemingly suggested by the founders of quantum theory, that no reconciliation is possible, in the study of atomic phenomena, between the demands of spacetime description and causality. For, in this description the world history is represented by a set of classical spacetime trajectories, yet the model is completely deterministic.

This model has, in principle, greater scope than orthodox quantum theory. For it involves no separation of the world into one part described by quantum concepts and another part described by classical concepts. Hence it covers, in principle, situations in which the action of the observed system upon the environment is never weak enough to allow it to be idealized as an isolated system.

The model is important also because it illustrates in concrete terms how one can have faster–than–light influences without faster–than–light control (or signalling). For, in the field–theoretical version relativistic covariance is maintained and faster–than–light control (or signalling) is excluded, yet faster–than–light–influences are present. These arise from the fact that the velocity at time t of the ith particle, namely $\vec{v}_i(\vec{x}_1(t), \vec{x}_2(t), \cdots, \vec{x}_n(t); t)$, depends, in principle, on the positions of all the particles at time t. Thus if the quantum universe is imagined to be imbedded in a classical electromagnetic field, controlled by an outside agent, then the choice of this field in one spacetime region will influence directly the motions of the particles in that region, and the resulting change in the positions of these particles will then immediately influence the velocities of the far–away particles. This nonlocal dynamical influence is precisely what causes, in this model, the breakdown in the EPR–Bohm experiment of the EPR idea of locality.

The pilot wave model is therefore important and instructive at the philosophical level: it shows, in particular, that one is not necessarily forced to abandon all hope for a description of Nature more complete than the one provided by the orthodox interpretation. However, it has, from an aesthetic point of view, certain deficiencies.

The first of these involves the "empty branches". If a measurement is performed then the Schroedinger wave function separates into several disjoint parts, or branches, with respect to certain (pointer) variables. The equation of motion then forces the world–trajectory into one of these branches, namely the one that corresponds to the observed result of the measurement. The other branches of the wave function then turn out to have essentially no influence at all on the subsequent motion of the world: they can be ignored or discarded.

In Bohm's words the role of the wave function is to in–form (put form into) the motion of the world. Because the empty branches do not perform this function, they have no status as carriers of information. Yet, according to the basic ontology, Nature must, nevertheless, continue to generate, endlessly, the evolution of all of these ineffectual branches. This seems to be a highly uneconomical way for Nature to operate.

A second point pertains to initial conditions. Within a purely pragmatic context there is nothing wrong with having undetermined initial conditions: one can try to determine these conditions from presently available information . But within an ontological context the tremendous freedom available in the choice of both the initial wave function, and the initial positions of all of the particles, entails a fundamental incompleteness: an external "creator" is required to get a whole system going, and to specify with infinite precision, right at the outset, a continuum of variables. Thus the most important part of the ontology left out. This omission may have been acceptable, and even desirable, at the time of Newton. But today it would be more satisfactory to be able to deal with the question of initial conditions in a less arbitrary way, without invoking something that is not an integral part of the ontology.

The Many–Worlds Ontology

These problems are partly resolved by the many–worlds interpretation, to which I now turn.

The many–worlds interpretation appears, initially at least, to be more economical than the pilot–wave model: the universe is represented simply by the wave function alone, and nothing else, except for an epiphenomenal consciousness associated with brains.

The immediate problem for this ontology is Schroedinger's cat, or the equivalent problem pertaining to a pointer that specifies the result of a quantum measurement. According to quantum principles, such a pointer will, in certain cases, be in a superposition of a state in which the pointer has swung to the right and a state in which the pointer has swung to the left. However, any observation will show that the pointer has swung either to the right or to the left, not both.

This apparent discrepancy between the ontology and observation is actually no problem. This is because quantum theory entails that when the observer looks at the pointer, to see which way it has swung, his wave function, like that of the pointer, will divide into a superposition of two parts. In one part his brain, with its physical memory structure, will correspond to his having seen the pointer pointing to the right; in the other part his brain structure will correspond to his having seen the pointer pointing to the left. These two parts of the wave function will evolve separately, with the physical memory structure of each part having no effect upon the actions of the observer in the other part. It is therefore natural to suppose, in this situation, that the epiphenomenal eriences associated with the two parts of the wave function of the brain will be separate and distinct: a physical observer should naturally "see" the pointer in one position or the other, even though both outcomes are present on the basic ontological level.

This many-worlds (i.e., many-minds) ontology resolves the problem of the empty branches: all branches are ontologically equivalent It also resolves, at least in part, the initial-condition problem: no classical world-trajectory is picked out from all the others. The initial wave function still plays a role. But it is a small additional step to the supposition that the full universe is a mixture of all possible ones: then no initial condition at all is arbitrarily picked out. This model is economical also in the sense that all possible worlds are actually realized: there is no discarding, or wasting, of any possibility. The model might, therefore, be explanatory of the fact that conscious life exists, in spite of the apparent unlikelihood for such a thing. For, according to this model, if something can occur then it will occur.

The principal problem for the many-worlds ontology is to explain how distinct experience can emerge from amorphous ontology. This problem is generally obscured by the fact that the many-worlds ontology is usually considered in connection with the measurement problem in quantum theory. In that context one is dealing with a physical system that has separated itself into several distinct branches, which we expect to be experienced in one of several distinct possible ways. The element of definiteness or discreteness is, in this case, already introduced by the character of the system being observed.

But one can consider instead, with Einstein,[13] a pen on a moving scroll, triggered to move by the decay of a radioactive nucleus. In this case the wave function evolves into a continuous superposition of macroscopic possibilities. Extrapolating from the smoothing effect in this simple case to the smoothing effects of all the radioactive decays since the birth of the universe, and to the smoothing effects of all scatterings of elementary particles, one is led to the conclusion that the brain of any individual will, in the many–worlds ontology, be an amorphous superposition of a continuum of different states, each with zero probability. But how, then, can one then understand the distinctness of experience?

To be more specific consider some particular combination $(\vec{x}_1, \vec{x}_2, \cdots, \quad)$ of the possible positions of the particles in some human brain. Suppose the wave function of the universe is $\psi(\vec{x}_1, \cdots, \vec{x}_m, \cdots \vec{x}_n; t)$. Is there supposed to be, at time t, some definite experience associated with this set of variables $(\vec{x}_1, \vec{x}_2, \cdots, \vec{x}_m)$?

It seems apparent that the content of the experience should depend not only the location of the particles in the brain but also on the way in which these particles are moving. In a universe defined by a fixed wave function the positions of the particles determine also their velocities, in the sense defined in the pilot–wave model. So one possibility would be to suppose that the content of the experience depends both on the locations of particles in the brain and also on the velocities of these particles, as defined by the gradient of the phase. This would, in accordance with the structure induced by the pilot–wave structure, make the experience of each person depend upon what was being done to his far–away acquaintances.

This way of trying to specify the connection of the wave function of the brain to the content of experience would convert the many–worlds universe into a superposition of pilot–wave universes. Some other way of understanding this connection might be possible. For example, the experience might be determined by the wave function of the brain taken as a whole. Of course, the wave function of a brain depends on the state of the rest of the universe: according to quantum principles each state of the rest of the universe corresponds, in principle, to a separate wave function of the brain. But even if one considers a general fixed state of the rest of the universe one must expect, lacking any proof to the contrary, that the corresponding wave function of the brain will be an amorphous superposition of components corresponding, in terms of their physical characteristics such as memory structure, to different experiences of the kind we know. Without some preferred basis of linearly independent "experiential states" into which the wave function of the brain is to be expanded there would be an unstructured continuum of ways in which a given brain wave function could be decomposed into components which, according to their physical characteristics, ought to correspond to different experiences: given any one decomposition there would be a continuum of others obtained by shifting slightly each of the basis es, and there would be other continuums induced by taking an over–complete set of basis states. This means that the relatively well–defined and simple idea that naturally arises in the consideration of a process of measurement, namely that there will be a splitting of the mental world into a collection of well–defined discrete mental states, with one such state for each of the discrete possible results of the quantum measurement, degenerates into a structureless morass if one considers, instead of a measurement–type process, rather the more normal diffusion type of evolution generally produced by the Schroedinger equation.

Quantum theory alone, because of this arbitrariness, induced by the superposition principle, gives, in the normal diffusion situation, no natural meaning to the idea that an amorphous wave function of the brain corresponds to some well–defined collection of discrete experience. Consequently the whole problem of the reconciliation of the general amorphousness of wave functions with the discreteness of observed results, which is *the* basic problem in the interpretation of quantum theory, is pushed onto the question of how discrete experiences emerge from the amorphous wave function of a brain. What are the principles of the integrative process that achieves this? Which discrete experiences emerge from some amorphous of wave function of the brain?

These are, presumably, questions for neurophysiology and psychology. But the important point is that once this question is admitted then the many–worlds ontology becomes incomplete. For the ontology rests, then, upon some unexplained process that generates, in a nontrivial way, distinct experiences from amorphous wave functions. The ontology pushes the central discreteness problem of quantum theory onto the mind–brain problem, which it leaves unresolved.

If one admits into the ontology a nontrivial integrative process that converts amorphous wave functions into discrete experiences then the question arises as to whether such a process, if it exists, should be purely epiphenomenal, and play *no role whatever in the evolution of the universe.* If Nature has equipped herself with some nontrivial process that extracts distinct experiences from amorphous wave functions then it would seem that this process should play some important role, rather than being a purely epiphenomenal appendage.

The Actual–Events Ontology

Both the pilot–wave and many–worlds ontologies appear to entail the existence of some process of selection or integration not explicitly represented in the description that they provide of physical reality. The actual–events ontology brings such a process explicitly into the physical description. The fundamental process of Nature is taken to be the formation of a sequence of discrete actual events. Each event transforms the potentialities created by the prior event into the potentialities for the next event.

According to Heisenberg[14] "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 in our knowledge at the instant registration that has its image in the discontinuous change of the probability function."

The final sentence in this quotation emphasizes the fact that according to the Copenhagen interpretation the wave function of quantum theory is a mental construction that represents our knowledge; it is to be used purely as a tool to make predictions about our observations. This point having been stressed it is useful, however, in the present ontological context, to consider the wave function of the quantum theorist to be a mental counterpart also of an "absolute wave function" that represents the potentialities and tendencies of the the Heisenberg ontology. Then each actual event is represented by a "quantum jump" in this absolute wave function.

Heisenberg did not need to specify the details of the transition from possible to actual, because orthodox quantum theory does not depend upon this ontological superstructure. What is under consideration here, however, is the use of Heisenberg's ontological ideas as the basis for a generalization of the orthodox quantum theory that will have greater scope. For this purpose the details of the transition from possible to actual must be spelled out.

The most recent attempts along this line are those of Ghirardi, Rimini, and Weber,[15] and of Philip Pearle.[16] These efforts are admittedly ad hoc and arbitrary. The former has been described and criticized in the contribution to this conference of D. Albert. That criticism is, however, not decisive: it merely points to the fact that the effects of the actual events (or quantum jumps) in the GRW ontology do not become large unless large numbers of particles acquire delocalized wave functions. The GRW mechanism seems, in spite of this, to be sufficient to keep all directly observable phenomena closely in line with our observations of them. For phenomena involving small numbers of quanta the associated transition to the actual might occur only at the level of the retina.

A more serious problem, I believe, is the use of constant-time slices. That concept is not in line with the theory of relativity. Moreover, the idea of a finite change occurring over a time span of zero duration is problematic.

In this connection it is probably important to recognize that relativistic quantum field theory actually involves two different kinds of time. One of these is the time that is joined to space to form the spacetime continuum of the theory of relativity. This time can be called Einstein time. The Lorentz covariance properties of the theory are expressed in terms of this spacetime structure, which demands a deterministic equation of motion to connect the different parts of the spacetime continuum. In the Heisenberg representation the field operators at various spacetime points are connected together by equations of motion in accordance with this covariance condition.

The second kind of time is connected with the actual changes that occur in connection with quantum jumps. In the Heisenberg representation the Heisenberg state vector is associated with all of spacetime, and the quantum jump, which consists of a change in this state vector, induces changes in expectation values of the field operators over all of spacetime.

The time associated with the quantum jump can be called "process" time. It is associated with actual change, whereas Einstein time, in quantum theory, is associated with the evolution of the potentialities.

Recognition of these two kinds of time eases the problem of maintaining compatability with the constraints of the theory of relativity: those constraints deal primarily with spacetime relations among potentialities that hold at each single stage in process time. The actual changes are, as regards spacetime, global in character, and hence do not involve any time slices in spacetime.

The set of potentialities that form, in this ontology, the basis for the selection of each actual event extend over all of spacetime. This means that the selection of a single "actual" from among the various possibilities need not be a "blind choice": the potentialities pertaining to the entire virtual future are, according to the ontology, laid out, and available for integration into the process of selection. Thus the actual–events ontology, in conjunction with the mathematical structure of quantum field theory, provides naturally for the possibility of future–directed action. This is the first requirement for a meaningful universe. Whether the actual–events interpretation of quantum theory can be developed in a way such that the idea of the emergence of a quality of meaningfulness can be given empirical support remains to be seen. On the answer to this question hinges the magnitude of the role that physics can play in the development of a comprehensive conception of the universe.

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