QUANTUM APPROACHES TO CONSCIOUSNESS.

1. Introduction.

Quantum approaches to consciousness are sometimes said to be motivated simply by the idea that quantum theory is a mystery and consciousness is a mystery, so perhaps the two are related. That opinion betrays a profound misunderstanding of the Nature of quantum mechanics, which consists fundamentally of a pragmatic scientific solution to the problem of the relationship between mind and matter.

The key philosophical and scientific achievement of the founders of quantum theory was to forge a rationally coherent and practically useful linkage between the two kinds of descriptions that jointly comprise the foundation of science. Descriptions of the first kind are accounts of psychologically experienced empirical findings, expressed in a language that allows us to communicate to our colleagues what we have done and what we have learned. Descriptions of the second kind are specifications of physical properties, which are expressed by assigning mathematical properties space-time points, and formulating laws that determine how these properties evolve over the course of time. Bohr, Heisenberg, Pauli, and their colleagues discovered a way to connect these two kinds of descriptions by causal laws, and their seminal discovery was extended by John von Neumann from the domain of atomic science to the realm of neuroscience, and in particular to the problem of understanding and describing the causal connections between the minds and the brains of human beings.

The magnitude of the difference between the quantum and classical conceptions of the connection between mind and brain can scarcely be exaggerated. All approaches to this problem based on the precepts of classical physics founder first on the problem of the lack of any need within classical mechanics for consciousness to exist at all, and second on the seemingly manifest impossibility of ever actually understanding how the experiential realities that form our streams of consciousness could ever be produced by, or naturally come to be associated with, the motions of the things that classical physics claims the physical world to be made of. The first problem is that, according to precepts of classical physics, the causal properties of the physical world suffice, by themselves, to completely specify all physical properties of the universe, including the activities of our bodies and brains, without ever acknowledging the existence of consciousness: everything would go on just the same if nothing but the physical properties were present. The second problem is that the differences-in-kind between the experiential and physical sorts of stuff is so great that it seems beyond the realm of possibility that a tight rational connection could exist between them. The fact that consciousness does exist thus enforces an awkward departure of science from a purely naturalistic stance; nonphysical entities such as conscious thoughts, ideas, and feelings must be added for no apparent naturalistic or physical reason!

All of this is completely changed by the switch to quantum physics. According to quantum physics, as it is both practiced and taught, our human choices play a key dynamical role in our scientific description of nature. This injection of observer/participants into the basic causal structure of physics was the radical revision in the conception of science ushered in by the founder's of quantum theory. The related problem of the huge disparity in classical physics between the experiential and physical kinds of stuff is resolved in quantum mechanics by altering the nature of the physical stuff: the physical world is transformed from a substance-based structure to a construct based on "events" that inject information into an information bearing quantum state. It is extremely important that this radical revamping at the foundational level is achieved without giving up, at the practical level, hardly anything from classical physics. Apart from making room for, and a need for, conscious choices, the profound changes introduced by quantum theory at the foundational level preserve at the pragmatic level almost all of classical physics.

I shall in the remainder of this introductory section sketch out the transition from the classical-physics conception of reality to the von Neumann application of the principles of quantum physics to our conscious brains. In succeeding sections I describe the most prominent of the many efforts being made by physicists to develop and extend von Neumann's work.

The quantum conception of the relationship between the psychologically and physically described components of scientific practice was achieved by abandoning the classical picture of the physical world that had ruled science since the time of Newton, Galileo, and Descartes. The building blocks of science were shifted from descriptions of the behaviors of tiny bits of mindless matter to accounts of *the actions that we take to acquire knowledge* and of the *knowledge that we thereby acquire*. Science was transformed from its seventeenth century form, which effectively excluded our conscious thoughts from any causal role in the mechanical workings of Nature, to its twentieth century form, which focuses on our active engagement with Nature, and on what we can learn by taking appropriate action.

Twentieth century developments have thus highlighted the fact that *science is a human activity* that involves us not as passive witnesses of a mechanically controlled universe, but as agents that can choose to perform causally efficacious actions. The basic laws of Nature, as they are now understood, not only fail to determine how we will act, but moreover inject our *choices about how to act* directly into the dynamical equations. Human choices, which are both empirically accessible and consciously controllable, become the essential input parameters, replacing classically conceived microscopic variables, which are both *empirically inaccessible* and in principle uncontrollable.

The altered role of conscious agents is poetically expressed by Bohr's famous dictum:

> "In the great drama of existence we ourselves are both actors and spectators." (Bohr, 1963, p. 15: 1958, p. 81)

It is more concretely expressed in statements such as:

> "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 the quantum mechanical formalism offers the appropriate latitude." (Bohr, 1958, p. 73}

The fact that quantum theory is formulated in terms of an *interaction* between the physically described world and conscious agents that are, within the causal structure defined by the known physical laws, *free to choose* which aspect of nature they will probe, is perhaps the most important innovation of quantum theory. It is the crack, or gap, in the mechanistic world view that opens the way to a radically new conception of nature and our place within it.

Another chief innovation pertains to the *nature* of the stuff of the physically/mathematically described universe. The switch is succinctly summarized in Heisenberg's famous assertion:

> "The conception of the objective reality of the elementary particles has thus evaporated not into the cloud of some obscure new reality concept, but into the transparent clarity of a mathematics that represents no longer the behavior of the particle but rather our knowledge of this behavior." (Heisenberg, 1958a)

What the mathematics describes in no longer the locations of tiny bits of substance, or matter: it describes instead a knowledge-bearing or information-bearing structure. This structure is abruptly altered by discrete "events" that inject new information into it. But the structure is not passive: it has an active quality. It acts in a mathematically well-defined way as a carrier of "objective tendencies" or "potentia" or "propensities" for new events. (Heisenberg, 1958b, p. 53). The surprising fact is that this radical revamping of the foundational structure preserves most of classical physics, in domains where it works well, while allowing deviations from classical determinism in situations influenced by our conscious free choices.

Comprehending this new conception of the relationship between the psychologically experienced empirical side and the mathematically described physical side of the scientific endeavor requires an appreciation of certain novelties in the logical structure of quantum theory. This conceptual re-organization can be understood without becoming enmeshed in technical mathematical details.

The Classical-Physics Approach.

To grasp the essential change one must know what came before.

Classical physics arose from the theoretical effort of Isaac Newton to account for the findings of Johannes Kepler and Galileo Galilei. Kepler discovered that the planets move in orbits that depend on the location of other physical objects - such as the sun - but not on the manner or the timings of our observations: minute-by-minute viewings have no more influence on a planetary orbit than daily, monthly, or annual observations. The nature and timings of our observational acts have no effect at all on the orbital motions described by Kepler. Galileo observed that certain falling terrestrial objects have similar properties. Newton then discovered that he could explain *simultaneously* the celestial findings of Kepler and the terrestrial findings of Galileo by postulating, in effect, that all objects in our solar system are composed of tiny planet-like particles whose motions are controlled by *laws* that refer to the relative locations of the various particles, and make no reference to any conscious acts of experiencing. These acts are taken to be simply passive witnessings of macroscopic properties of large conglomerations of the tiny individually-invisible particles.

Newton's laws involve instantaneous action at a distance: each particle has an instantaneous effect on the motion of every other particle, no matter how distant. Newton considered this non-local feature of his theory to be unsatisfactory, but proposed no alternative. Eventually, Albert Einstein, building on ideas of James Clerk Maxwell, constructed a *local* classical theory in which all dynamical effects are generated by contact interactions between mathematical described properties localized at space-time points, and in which no effect is transmitted faster than the speed of light.

All classical-physics models of Nature are *deterministic*: the state of any isolated system at any time is completely fixed by the state of that system at any earlier time. The Einstein-Maxwell theory is deterministic in this sense, and also "local", in the just-mentioned sense that all interactions are via contact interactions between neighboring localized mathematically describable properties, and no influence propagates faster than the speed of light.

By the end of the nineteenth century certain difficulties with the general principles of classical physical theory had been uncovered. One such difficulty was with "black-body radiation." If one analyzes the electromagnetic radiation emitted from a tiny hole in a big hollow heated sphere then it is found that the manner in which the emitted energy is distributed over the various frequencies depends on the temperature of the sphere, but not upon the chemical or physical character of the interior surface of the sphere: the spectral distribution depends neither on whether the interior surface is smooth or rough nor on whether it is metallic or ceramic. This universality is predicted by classical theory, but the specific form of the predicted distribution differs greatly from what is empirically observed.

In 1990 Max Planck discovered a universal law of black-body radiation that matches the empirical facts. This new law is incompatible with the basic principles of classical physical theory, and involves a new constant of Nature, which was identified and measured by Planck, and is called "Planck's Constant." By now a huge number of empirical effects have been found that depend upon this constant, and that conflict with the predictions of classical physical theory.

During the twentieth century a theory was devised that accounts for all of the successful predictions of classical physical theory, and also for all of the departures of the predictions of classical theory from the empirical facts. This theory is called quantum theory. No confirmed violation of its principles has ever been found.

The Quantum Approach.

The core idea of the quantum approach is the seminal discovery by Werner Heisenberg that the classical model of a physical system can be considered to be an *approximation* to a quantum version of that model. This quantum version is constructed by replacing each numerical quantity of the classical model by an *action*: by an entity that acts on other such entities, and for which the order in which the actions are performed matters. The effect of this replacement is to convert each point-like particle of the classical conceptualization—such as an electron—to a smeared-out cloudlike structure that evolves, almost always, in accordance with a quantum mechanical law of motion called the Schroedinger equation. This law, like its classical analog, is local and deterministic: the evolution in time is controlled by contact interactions between localized parts, and the physical state of any isolated system at any time is completely determined from its physical state at any earlier time by these contact interactions. The cloud-like structure that represents an individual "particle", such as an electron, or proton, tends, under the control of the Schroedinger equation, to spread out over an ever-growing region of space, whereas according to the ideas of classical physics an electron is always localized in a very tiny region.

The local deterministic quantum law of motion is, in certain ways, incredibly accurate: it correctly fixes *to one part in a hundred million* the values of some measurable properties that classical physics cannot predict.

However, this local deterministic quantum law of motion does not correlate directly to human experience. For example, if the state of the universe were to have developed from the big bang solely under the control of the local deterministic Schroedinger equation then the location of the *center* of the moon would be represented in the theory by a structure spread out over a large part of the sky, in direct contradiction to normal human experience.

The smeared-out character of the position of (the center-point of) a macroscopic object, is a consequence of the famous Heisenberg Uncertainty Principle, combined with the fact that tiny uncertainties at the microscopic level usually get magnified over the course of time, *by the Schroedinger equation acting alone*, to large uncertainties in macroscopic properties.

This contradiction between a mathematical theory that is a direct mathematical generalization of classical physical theory—and that yields many predictions of incomparable accuracy—with the facts of everyday experience is the basic problem that an adequate interpretation of quantum theory must resolve.

In order to place the accurate predictions of the quantum mathematics into the context of a rationally coherent and practically useful theory the whole concept of what physical science is, or should be, was transformed from its nineteenth form, as a theory of the properties of a mechanical model of Nature in which we ourselves are mere mechanical parts, to a theory of the relationship between the physically and psychologically described aspects of actual scientific practice, in which we act as agents that probe nature in ways of our own choosing. It is worthwhile to see in slightly more detail what this revised conception of science means and how it works.

"The Observer" and "The Observed System" in Copenhagen Quantum Theory.

The original formulation of quantum theory is called the Copenhagen Interpretation because it was created by the physicists that Niels Bohr had gathered around him in Copenhagen. A central precept of this approach is that, in any particular application of quantum theory, Nature is to be considered divided into two parts, "The Observer" and "The Observed System." The Observer consists of the stream of consciousness of a human agent, together with the brain and body of that person, and also the measuring devices that he or she uses to probe The Observed System.

Each Observer describes himself and his knowledge in a language that allows him to communicate to colleagues two kinds of information: *How he has acted* in order to prepare himself - his mind, his body, and his devices - to receive recognizable and reportable data; and *What he learns* from the data he thereby acquires. This description is in terms of the conscious experiences of the agent himself. It is a description of his intentional probing actions, and of the experiential feedbacks that he subsequently receives.

In actual scientific practice the experimenters are free to choose which experiments they perform: the empirical procedures are determined by the protocols and aims of the experimenters. This element of freedom is emphasized by Bohr in statements such as:

> "To my mind there is no other alternative than to admit in this field of experience, we are dealing with individual phenomena and that our possibilities of handling the measuring instruments

> allow us to make a choice between the different complementary types of phenomena that we want to study. (Bohr, 1958, p. 51)

The freedom to choose is achieved in the Copenhagen formulation of quantum theory by placing the empirically/psychologically described Observer outside The Observed System that is being probed, and then subjecting only The Observed System to the rigorously enforced mathematical laws.

The Observed System is, according to both classical theory and quantum theory, describable in terms of mathematical properties assigned to points in space-time. However, the detailed forms of the laws that govern the evolution in time of this mathematical structure, and of the rules that specify the connection of this mathematical structure to the empirical facts, are very different in these two theories.

I am endeavoring here to avoid mathematical technicalities. But the essential conceptual difference between the two approaches rests squarely on a basic technical difference. This difference can be illustrated by a simple two-dimensional picture.

The Paradigmatic Example.

Consider an experiment in which an experimenter puts a Geiger counter at some location with the intention of finding out whether or not this device will “fire” during some specified time interval. The experiment is designed to give one of two possible answers: ‘Yes’, the counter will fire during the specified interval, or ‘No’, the counter will not fire during this specified interval. This is the paradigmatic quantum measurement process.

This experiment has *two* alternative mutually exclusive possible responses, ‘Yes’ or ‘No.’ Consequently, the key mathematical relationships can be pictured in a *two*-dimensional space, such as the top of your desk.

Consider two distinct points on the top of your desk called *zero* and *p*. The displacement that would move a point placed on *zero* to the point *p* is called a *vector*. Let it be called *V*. Suppose *V* has unit length in some units, say meters. Consider any two other displacements *V1* and *V2* on the desk top that start from zero, have unit length, and are perpendicular to each other. The displacement *V* can be formed in a unique way by making a (positive or negative) displacement along *V1* followed by a (positive or negative) displacement along *V2*. Let the lengths of these two displacements be called *X1* and *X2*, respectively. The theorem of Pythagoras says that *X1* squared plus *X2* squared is one (unity).

Quantum theory is based on the idea that the various experiencable outcomes have "images" in a vector space. The vector V1 mentioned above is the image, or representation, in the vector space of the possible outcome 'Yes,' whereas V2 represents 'No.' I will not try to describe here how this mapping of possible experiencable outcomes into corresponding vectors is achieved But the basic presumption in quantum theory is that such a mapping exists.

The vector *V* represents the state of The Observed System, which has been prepared at some earlier time, and has been evolving in accordance with the Schroedinger equation. The vector *V1* represents the state that this observed system would be known to be in if the observed outcome of the measurement were 'Yes.' The vector *V2* represents the state that the observed system would be known to be in if the observed result of the measurement were 'No.' Of course, the directions of the two perpendicular vectors *V1* and *V2* depend upon the exact details of the experiment: on exactly where the experimenters have placed the Geiger counter, and on other details controlled by the experimenters.

The outcome of the probing measurement will be either *V1* (Yes) or *V2* (No). The predicted probability for the outcome to be 'Yes' is *X1* squared and the predicted probability for the outcome to be 'No' is *X2* squared. These two probabilities sum to unity, by virtue of the theorem of Pythagoras. The sudden jump of the state from *V* to either *V1* or *V2* is called a "quantum jump." The general theory is express in terms of a many-dimensional generalization of your desktop. This generalization is called a Hilbert Space.

The crucial, though trivial, logical point can now be stated: The two alternative possible outcomes, 'Yes' or 'No' of the chosen-by-the-experimenter experiment are associated with a pair of perpendicular unit-length vectors called “basis vectors”. The *orientation* (i.e., directions) of the set of “basis” vectors, *V1* and *V2,* enters into the dynamics as a *free variable* controlled by the experimental conditions, which are specified in practice by choices made by experimenters. The orientation of the set of basis vectors is thus, from a mathematical standpoint, a variable that can be, and is, specified *independently* of the state *V* of the system being probed.

This entry into the dynamics of choices made by the experimenters is not at all surprising. If the experimenters are considered to stand outside, and apart from, the system being observed, as specified by the Copenhagen approach, then it is completely reasonable and natural that the choices made by the experimenters (about how to probe The Observed System) should be treated as variables that are independent of the variables that specify the physical state of the system they are probing.

Bohr (1958: 92, p. 100) argued that quantum theory should not be applied to living systems. He also argued that the classical concepts were inadequate for that purpose. So the strict Copenhagen approach is simply to renounce the applicability of *contemporary* physical theories, both classical and quantum, to neurobiology.

Von Neumann’s Formulation.

The great mathematician and logician John von Neumann (1955/1932) rigorized and extended quantum theory to the point of being able to corporate the devices, the body, and the brain of the observer into the physically described part of the theory, leaving, in the psychologically described part, only the stream of conscious experiences of the agent. The part of the physically described system being directly acted upon by the psychologically described “observer” is, according to von Neumann’s formulation, *the brain of that observer*. (von Neumann, 1955, p. 421). The quantum jump of the state of the brain of an observer to the ‘Yes’ basis state then becomes the representation, *in the state of that brain*, of the conscious acquisition of the knowledge associated with that answer ‘Yes.’ Thus the physical features of the brain state actualized by the quantum jump to the state V1 associated with the answer ‘Yes’ constitute the *neural correlate* of that person’s conscious experience of the feedback ‘Yes.’ This fixes the essential link between quantum physics and neuroscience.

This is the key point! Quantum physics is built around “events” that have both physical and phenomenal aspects. The events are physical because they are represented in the physical/mathematical description by a “quantum jump” to one or another of the basis state vectors defined by the agent/observer’s choice of what question to ask. If the resulting event is such that the ‘Yes’ feedback experience occurs then this event “collapses” the prior physical state to a new physical state compatible with that phenomenal experience. Mind and matter thereby become dynamically linked in a way that is causally tied to the agent’s free choice of how he will act. Thus a connection is dynamically established between a person’s conscious experience and the actualization of set of physical properties. The form of this connection is determined in part by a choice that, according to the theory, is made by the person, but is not fixed by the laws of contemporary physics.

This logical structure is not some wild philosophical speculation. It rationally yields, when combined with the statistical rule indicated already above, all the pragmatic results of quantum theory, which include, as special cases, all the valid predictions of classical physics!

Von Neumann showed that his formulation of the theory is essentially equivalent, in practice, to the Copenhagen interpretation. But it evades the unnatural limitations imposed by Bohr: it by-passes the ad hoc separation of the dynamically unified physical world into two differently described parts. This allows the psychological description to be—as is natural—the description of a stream of conscious experiences that is closely tied to an associated sequence of physically described events in the brain.

It is important that von Neumann’s enlargement of the physical system to include the body and brain of the observer *does not disrupt the basic mathematical structure of the theory.* In particular, it does not alter *the critical need to specify the orientation of the set of basis vectors* (e.g., V1 and V2) in order to make the theory work. *The* *specification of basis states continues to be undetermined by anything in contemporary physical theory*, *even when the physical description is extended to include the entire physical world, including the bodies and brains of the human observers.*

This leap by von Neumann from the realm of atomic physics to the realm of neuroscience was way ahead of its time: neuroscience was then in a relatively primitive state compared to what it is today, and had a long way to go before mainstream interest turned to the question of the connection between brains and conscious experiences. But seventy years of brain science has brought the empirical side up to the level where the details of the mind-brain relationships are being actively probed, and intricate results are being obtained that can be compared to the predictions of the psycho-physical theory prepared long ago by John von Neumann.

It is evident that a scientific approach to brain dynamics must *in principle* use quantum theory, in order to deal properly with brain processes that depend heavily on chemical and ionic processes. For example, the release of neurotransmitter from a nerve terminal is controlled by the motions of calcium ions, and these ions are small enough so that the deterministic laws of classical physics necessarily fail: quantum theory must *in principle* be used to describe the ion dynamics. But then the state of the brain is in principle a cloud-like structure that can encompass many conflicting classical possibilities. The generation, within the quantum state of the brain, of conflicting classical possibilities should occur particularly when the low-level essentially mechanical processes cannot come to agreement on the best course of action. A higher order "executive decision" is needed. It is probably important in this connection that, unlike the mechanical evolution generated by the local deterministic Schoedinger equation, the quantum jumps associated with conscious experiences are intrinsically nonlocal: they access *together* physical features that are located over extended portions of the brain. This will be discussed later.

Summary.

The chief differences at the basic conceptual level between the quantum and classical approaches to consciousness is that the classical principles make no mention of consciousness. The structure is in principle completely “bottom up.” Everything is, in principle, fully determined by what goes on at the microscopic atomic level, and any dependence of microscopic properties upon macroscopic properties, or on consciousness, is, in the end, a round-about consequence of laws expressible exclusively in terms of properties of atomic particles and the physical fields that they produce. But in quantum theory the local-deterministic (i.e., bottom-up) physical process is *in principle causally incomplete*: it fixes, by itself, neither our actions nor our experiences, nor even any statistical prediction about how we will act or what we will experience. The bottom-up process *alone* is unable to make statistical predictions, because the statistical predictions depend upon the choice of a set of basis vectors, and the bottom-up local-deterministic quantum process does not fix this choice.

This reorganization of the dynamical structure leads to an altered perspective on the entire scientific enterprise. The psychologically described empirical side of scientific practice is elevated from its formerly subservient status - as something that should be *deduced* from, or constructed from, the already-dynamically-complete physical side - to the new status of co-equal dynamical partner. Science becomes the endeavor to describe the *two-way interplay* between the psychologically and physically described aspects of nature, rather than an attempt to deduce the existence and properties of our streams of conscious experiences from a presumed-to-be-dynamically-complete local mechanical model.

Within the von Neumann framework our conscious choices control the orientations of the basis vectors. These choices can strongly influence our actions. Thus these influences need not be illusions. The theory provides, as we shall see in the section 3, a specific mechanism that allows our conscious “free” choices to significantly influence our physical actions.

Pragmatic Neuroscience.

Von Neumann, in his 1932 book followed the Copenhagen tack of focusing on scientific practice rather than ontological issues: those issues need not be dealt with in order to have a pragmatically useful scientific theory of atomic phenomena. Indeed, it can be argued that science is intrinsically pragmatic rather than ontological: the true nature of things, other than our experiences themselves, can never be found by the methods of science.

Von Neumann's formulation of quantum theory provides the foundations of a pragmatic neurodynamics of the conscious human brain that is built on pertinent contemporary physical theory, rather than inadequate classical physics. All quantum approaches to consciousness build upon the foundation laid by von Neumann, but various physicists have advanced different ways of developing that core structure. We turn now turn to the descriptions of a number of these proposals.

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