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 connection 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 to us 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 to space-time points, and formulating laws that determine how these properties evolve over the course of time. Bohr, Heisenberg, Pauli, and the other inventors of quantum theory discovered a useful 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 a conceptual gap that blocks any rational understanding of 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 that it explicitly mentions suffice, by themselves, with no acknowledgement of the existence of consciousness, to completely specify all physical properties of the universe, including the activities of our bodies and brains. According to the conceptual structure of classical physics, everything physical would go on just the same if nothing existed but the physical properties explicitly mentioned in the theory. The second problem is that within that conceptual framework of classical physics neither planets nor electrons, nor any of the other entities, nor combinations of the entities that populate the world *make choices on the basis of ideas*. The world described by the concepts classical physics has been systematically stripped of, and is consequently bereft of, the concept of choices based on consciously experienced ideas. Thus the stubborn fact that idea-like realities do exist enforces an awkward departure of science from a purely naturalistic stance. Nonphysical features such as conscious thoughts, ideas, and feelings must be added, for no apparent naturalistic, physical, or rational reason, to the features that enter into the putative laws of nature. There is thus a conceptual mismatch between the world described by the basic laws of classical physics and the world we inhabit and do science in.

These difficulties have been much discussed by many philosophers, who have proposed many different approaches. But in view of the known failure of classical physics to be able to describe the *macroscopic properties* of systems whose behaviors can depend sensitively on the behaviors of their atomic constituents, and the further fact that orthodox contemporary physical theory brings conscious choices by human agents into physical theory in an essential way, the question must be asked whether these philosophical efforts accord with twentieth century science, or are, instead, clever ways of trying to justifying the use of approximately valid but fundamentally incorrect nineteenth century physics in a domain where that approximation is inadequate.

Both of the above-mentioned difficulties are resolved in a rationally coherent and practically useful way by quantum mechanics. On the one hand, a key basic precept of the quantum approach, as it is both practiced and taught, is that choices made by human beings play a key and irreducible role in the dynamics. On the other hand, the great disparity within classical physics between the experiential and physical aspects of nature is resolved in the quantum approach by altering the assumptions about the nature of the physical universe. The physical world, as it appears in the theory, is transformed from a structure based on *substance* or *matter* to one based on *events*, each of which has both experiential aspects and physical aspects: Each such event injects information, or “knowledge”, into an information-bearing mathematically described physical state. An important feature of this radical revamping of the conceptual foundations is that it leaves unchanged, at the practical level, most of classical physics. Apart from making room for, *and a strict need for*, efficacious conscious choices, the radical changes introduced at the foundational level by quantum mechanics preserve at the pragmatic level almost all of classical physics.

In the remainder of this introductory section I shall sketch out the transition from the classical-physics conception of reality to von Neumann’s application of the principles of quantum physics to our conscious brains. In succeeding sections I describe the most prominent of the many efforts now being made by physicists to apply von Neumann’s theory to recent developments in neuroscience.

The quantum conception of the connection 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 thereby 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 actions.

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 freely 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.

This 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 most important innovation of quantum theory, from a philosophical perspective, is the fact that it is formulated in terms of an *interaction* between the physically described world and conscious agents who are, *within the causal structure defined by the known physical laws*, *free to choose* which aspect of nature they will probe. This crack, or gap, in the mechanistic world view leads to profound changes in our conception of nature and man’s place within it.

Another key 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 quantum mathematics describes is not the locations of tiny bits of matter. What it described by the mathematics is a causal structure imbedded in space-time that carries or contains information or knowledge, but no material substance. This structure is, on certain occasions, abruptly altered by *discrete events* that inject new information into it. But this carrier structure is not purely passive. It has an active quality. It acts as a bearer of "objective tendencies" or "potentia" or "propensities" for new events to occur. (Heisenberg, 1958b, p. 53).

To appreciate this new conception of the connection between psychologically described empirical part and the mathematically described physical part of the new scientific description of physical phenomena one needs to contrast it with what came before.

The Classical-Physics Approach.

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 that make no reference to any conscious acts of experiencing. These acts are taken to be simply passive witnessings of macroscopic properties of large conglomerations (such as tables and chairs and measuring devices) 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 mathematically 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 1900 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 always stays 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.

This 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, such as location.

Thus a mathematical equation—the Schroedinger equation—that is a direct mathematical generalization of the laws of motion of classical physical theory, and that yields many predictions of incomparable accuracy, strongly conflicts with many facts of everyday experience (e.g., with the fact that the apparent location of the center of the moon is well defined to within, say 10 degrees, as observed from a location on the surface of the earth). Contradictions of this kind must be eliminated by a satisfactory formulation of quantum theory.

In order to put the accurate predictions of the quantum mathematics into the framework of a rationally coherent and practically useful physical theory the whole concept of what physical science is was transformed from its nineteenth form—as a theory of the properties of a mechanical model of Nature in which we ourselves are mechanical parts—to a theory of the connection between the physically and psychologically described aspects of actual scientific *practice*. In actual practice we are agents that probe nature in ways of our own choosing, in order to acquire knowledge that we can use. I shall now describe in more detail how this pragmatic conception of science works in quantum theory.

"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)

This 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 the two theories.

I am endeavoring here to avoid mathematical technicalities. But the essential conceptual difference between the two approaches rests squarely on a certain 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 connections 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 to-be-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 expressed in terms of a many-dimensional generalization of your desktop. This generalization is called a Hilbert space, and every observable state of a physical system is a represented by a "vector" in such a 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 observers into the physically described part of the theory, leaving, in the psychologically described part, only the stream of conscious experiences of the agents. The part of the physically described system being directly acted upon by a 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 (vector) 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 quantum link between consciousness 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 or she will act. Thus a causal dynamical connection is established between (1) a person's conscious choices of how to act, (2) that person's consciously experienced increments in knowledge, and (3) the physical actualizations of the neural correlates of the experienced increments in knowledge.

This conceptualization of the structure of basic physical theory is radically different from what it was in classical physics. Classical physics was based on a guess that very worked well for two centuries, namely the notion that the concepts that provided an "understanding" of our observations of planets and falling apples would continue to work all the way down to the elementary-particle level. That conjecture worked well until science became able to explore what was happening at the elementary-particle or atomic level. Then it was found that that simple "planetary" idea could not be right. Hence scientists turned to a more sophisticated approach that was based *less* on simplistic ontological pre-suppositions and *more* on the empirical realities of actual scientific practice.

This new conceptual structure is not some wild philosophical speculation. It rationally yields—when combined with the statistical rule associated with the theorem of Pythagoras described above—all the pragmatic results of quantum theory, which include, as special cases, all the valid predictions of classical physics!

Von Neumann shifted the boundary between the observer and the observed system, in a series of steps, until the bodies and brains of all observers, and everything else that classical physics would describe as "physical", was included as part of the observed system, and showed that this form of the theory is essentially equivalent, in practice, to the Copenhagen interpretation. But it evades an unnatural feature imposed by Bohr: it by-passes the ad hoc separation of the dynamically unified physical world into two differently described parts. Von Neumann's final placement of the boundary allows the psychological description to be—as is natural—the description of a stream of conscious experiences that are the experiential sides of a sequence of events whose physical sides actualize the neural correlates of those experiences.

It is important that von Neumann's systematic enlargement of the physical system to include eventually the bodies and brains of the observers *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 the 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 all 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. It had a long way to go before mainstream interest turned to the question of the connection between brains and conscious experiences. But 70 years of brain science has brought the empirical side up to the level where the details of the mind-brain connections 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 once one goes over to a quantum-mechanical description of the ionic components of the brain, one must follow through and treat also the conglomeration of these cloudlike entities, and the other similar components of the brain, by the quantum rules, in order to recover the connection of that mathematical structure to our conscious experiences!

According to this quantum description, the state of the brain is itself an expanding cloud-like structure in a high-dimensional space. Just as the various points in the cloud that describes a single particle represent different classically conceived possibilities for that single particle (where it is and how it is moving), so do the various points in the cloud that describe the brain represent different classically conceived possible states of that brain. This cloud-like structure can, and generally will, encompass, with appreciable weights, many conflicting classical possibilities.

The job of the brain is to accept clues from the environment and then to construct a “Template for Action” (an “executive” pattern of neurological activity) that, if it endures, will issue the sequence of neural signals that will cause some specific (and hopefully appropriate) action to unfold. In the cloudlike structure that represents a brain, many alternative conflicting Templates for Action can arise. The generation, within the quantum state of the brain, of important components representing conflicting classical possibilities should occur particularly when the low-level (essentially mechanical) processes cannot come to agreement on the best course of action. In this circumstance, the quantum mechanical rules allow choices to be made that produce quantum jumps that, on the psychological side, inject new experiences, associated with a newly chosen course of action, into the stream of consciousness of the human agent, and that, on the physical side, actualize brain states that contain the neural correlates of those experiences. This is the basic dynamical process that underlies the quantum approach to consciousness.

Summary.

The essential difference at the basic conceptual level between the quantum and classical approaches to consciousness is that the classical principles make no mention of consciousness. The causal 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 of 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 fix 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 4, 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. 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 provably ascertained by the methods of science. Thus Von Neumann's formulation of quantum theory provides the foundations of a *pragmatic* neuro-psycho-dynamics that is built on contemporary physical theory, rather than an inadequate classical physics. All quantum approaches to consciousness build upon this foundation laid by von Neumann, but various physicists have proposed different ways of developing that core structure. We turn now turn to the descriptions of a number of these proposals.

2. The Penrose-Hameroff Approach.

Perhaps the most ambitious attempt to create a quantum theory of consciousness is the one of Roger Penrose and Stuart Hameroff. Their proposal has three parts: The Gödel Part, The Gravity Part, and the Microtubule Part.

The Gödel Part, which is due to Penrose, is an effort to use the famous Gödel Incompleteness Theorem to prove that human beings have intellectual powers that they could not have if they functioned in accordance with the principles of classical physical theory. Proving this would reaffirm a conclusion of the von Neumann formulation of quantum theory, namely that a conscious human being can behave in ways that a classical mechanical model cannot. Penrose's argument, if valid, would yield this same conclusion, but within a framework that relies not on quantum concepts, which are generally unknown to cognitive scientists, but rather on Gödel-type arguments, which are familiar to some of them.

The general idea of Penrose's argument is to note that, due to the mathematically deterministic character of the laws of classical physics, the output at any specified finite time of any computer behaving in accordance with the classical laws should in principle be deducible, to arbitrarily good accuracy, from a finite-step procedure based on a finite set of mutually consistent rules that encompass the laws of arithmetic. But then a human being who can be adequately modeled as a classical computer should be able to know, at any finite time, the truth *only* of those statements that can be deduced from a finite-step computation based on the finite set of rules that govern that computer. Yet Gödel-theorem-type arguments allow real mathematicians to know, given *any* finite set of consistent logical rules that encompass the laws of arithmetic, the truth of mathematical statements that cannot be deduced by any finite-step proof based on those rules. This seems to imply that a real mathematician can know things that no classical physics model of himself could ever know, namely the truth of statements that his classical computer simulation could not establish in a finite time.

Filling in the details of this argument is not an easy task. Penrose spends the better part of five chapters in "The Emperor's New Mind," (Penrose, 1989) and some 200 pages in "Shadows of the Mind" (Penrose, 1994) explaining and defending this thesis. However, the Harvard philosopher Hillary Putnam challenged Penrose's conclusion in a debate appearing in the New York Times Review of Books, (Putnam, 1994) and numerous logicians have since weighed in, all, to my knowledge, challenging the validity of Penrose's argument. Thus the Gödel Part of the Penrose-Hameroff approach cannot now be regarded as having been successfully established.

The Gravity Part of the Penrose-Hameroff approach addresses a key question pertaining to the quantum dynamics: exactly *when* do the sudden "quantum jumps" occur? In von Neumann's theory these jumps should presumably occur when the neural correlates of conscious thoughts become sufficiently well formed. But von Neumann gives no precise rule for when this happens.

The lack of specificity on this issue of precisely "*when"* is a serious liability of the von Neumann theory, insofar as it is construed as a description of the ontological mind-matter reality itself. That difficulty is the basic reason why both the original Copenhagen formulation and von Neumann's extension of it eschew traditional ontological commitments. They hew rather to the pragmatic position that the job of science is to establish useful practical connections between empirical findings and theoretical concepts, rather than advancing shaky speculations about the ultimate Nature of reality. The pragmatic position is that theoretical ideas that optimally provide reliable practical connections between human experiences constitute, themselves, our best *scientific* understanding of "reality." Added ontological superstructures are viewed as not true science, because additions that go beyond optimal theoretical descriptions of connections between human experiences cannot be tested empirically.

Penrose wants to provide an ontology that has "real quantum jumps." Hence he must face the question: when do these jumps occur?. He seeks to solve this problem by linking it to a problem that arises when one attempts to combine quantum theory with Einstein's theory of gravity.

Einstein's theory of gravity, namely General Relativity, is based of the idea that space-time is not a rigid flat structure, as had previously been thought, but is rather a *deformable medium*, and that the way it is deformed is connected to the way that matter is distributed within it. This idea was developed within the framework of classical physical theory, and most applications of it are made within a classical-physics idealization. But serious problems arise when the quantum character of "matter" is considered. For, according to orthodox quantum theory, a particle, such as an electron or an ion, has no well defined location: its location is specified by a smeared out "probability cloud." But if the locations of the material particles are not well defined then, according to General Relativity, neither is the form of the space-time structure in which the particle structures are imbedded.

Penrose conjectures that Nature abhors uncertainty in the structure of space-time, and that when too much ambiguity arises in the space-time structure a quantum jump to some less ambiguous structure will occur. This "principle" allows him to tie quantum jumps to the amount of uncertainty in the structure of space-time.

There is no compelling reason why Nature should be any more perturbed by an uncertainty in the structure of space-time than by an uncertainty in the distribution of matter. However, by adopting the principle that Nature finds intolerable an *excessive ambiguity in* the *structure of space-time* Penrose is able to propose a specific rule about when the quantum jumps occur.

Penrose's rule depends on the fact that Planck's constant gives a connection between energy and time: this constant divided by any quantity of energy gives a corresponding interval of time. Thus if an energy associated with a possible quantum jump can be defined then a time interval associated with that potential jump becomes specified.

To identify the pertinent energy consider a simple case in which, say, a small object is represented quantum mechanically by a small cloud that divides into two similar parts, one moving off to the right, the other moving off to the left. Both parts of the cloud are simultaneously present, and each part produces *a different distortion* of the underlying spacetime structure, because matter is distributed differently in the two cases. One can compute the amount of energy that it would take to pull apart, against their gravitational attraction, two copies of the object, if each copy is located at the position specified by one of the two clouds. If one divides Planck's constant by this "gravitational energy" then a time interval associated with this distortion of space-time into these two disparate structures becomes defined. Penrose proposes that this time interval is the duration of time for which Nature will *endure* this bifurcation of its space-time structure into the two incompatible parts, before jumping to one or the other of these two forms.

This conjectured rule is based on two very general features of Nature: Planck's universal constant of action and the Newton-Einstein universal law of gravitation. This universality makes the rule attractive, but no reason is given why Nature must comply with this rule.

Does this rule have any empirical support?

An affirmative answer can be provided by linking Penrose's rule to Hameroff's belief that consciousness is closely linked to the *microtubular sub-structure of the neurons.* (Hameroff and Penrose, 1996)

It was once thought that the interiors of neurons were basically structureless fluids. That conclusion arose from direct microscopic examinations. But it turns out that in those early studies the internal substructure was wiped out by the fixing agent. It is now known that neurons are filled with an intricate structure of *microtubules*.

Each microtubule is a cylindrical structure that can extend over many millimeters. The surface of the cylinder is formed by a spiral chain of tubulin molecules, with each circuit formed by thirteen of these molecules. The tubulin molecule has molecular weight of about 110,000 and it exists in two slightly different configurational forms. Each tubulin molecule has a single special electron that can be in one of two relatively stable locations. The molecule will be in one or the other of the two configurational states according to which of these two locations this special electron is occupying.

Hameroff is an anesthesiologist, and he noted that there is close correspondence between, on the one hand, the measured effects of various anesthetics upon consciousness and, on the other hand, the capacity of these anaesthetics to diminish the ability of the special electron to move from one stable location to the other. This suggests a possible close connection between consciousness and the configurational activity of microtubules.

This putative linkage allows an empirical test of Penrose's rule to be made.

Suppose, in keeping with the case considered by Penrose, you are in a situation where one of two possible experiences will probably occur. For example, you might be staring at a Necker Cube, or walking in a dark woods when a shadowy form jumps out and you must choose "fight" or "flight," or perhaps you are checking your ability to freely choose to raise or not raise your arm. Thus one of two alternative possible experiences is likely to occur. Various experiments suggest that it takes about half a second for an experience to arise. Given this time interval, Penrose's formula specifies a certain corresponding energy. Then Hameroff can compute, on the basis of available information concerning the two configurational states of the tubulin molecule, how many tubulin-molecule configurational shifts are needed to give this energy.

The answer is about 1% of the estimated number of tubulin molecules in the human brain. This result seems reasonable. Its reasonableness is deemed significant, because the computed fraction could have come out to be perhaps billions of times smaller than, or billions of times greater than, 100%. The fact that the computed value is "in the ballpark" supports the idea that consciousness may indeed be connected *via Gravity* to tubulin configurational activity.

Given this rather radical idea—it was previously thought that gravity was not essential to consciousness (orbiting astronauts can think) and that the microtubules were merely a construction scaffolding for the building and maintenance of the physical structure of the neurons—many other exotic possibilities arise. The two configurational forms of the tubulin molecule mean that it can hold a "bit" of information, so maybe the microtubular structure forms the substrate of a complex *computer* located within each neuron, thus greatly expanding the computational power of the brain. And maybe each such computer is in fact a "quantum computer." And maybe these quantum computers are all linked together to form one giant brain-wide quantum computer. And maybe these hollow micro-tubes form wave guides for quantum waves.

These exotic possibilities are exciting and heady ideas. They go far beyond what conservative physicists are ready to accept, and far beyond what the 1% number derived from Penrose's rule actually supports. What is supported is merely a connection between consciousness and microtubular activity, *without the presence* of the further stringent *coherence conditions* required for the functioning of a quantum computer.

"Coherence" means preservation of the "phase" relationships that allow waves that have traveled via different paths to come back together so that, for example, crest meets crest and trough meets trough to build an enhanced effect. Quantum computation requires an effective isolation of the quantum informational waves from the surrounding environment, because any interaction between these waves and the environment tends to destroy coherence, and the required isolation is difficult to maintain in a warm, wet, noisy brain.

The simplest system that exhibits a behavior that depends strongly on quantum interference effects, and for which the maintenance of *coherence* is essential, is the famous "double-slit experiment." When photons of a single wave length are allowed to pass, one at a time, through a pair of closely spaced narrow slits, and each photon is later detected by some small detection device that is imbedded in a large array of such devices, one finds that *if the photonic system is not allowed to perceptibly influence any environmental degree of freedom* on its way to the detection device then the pattern of detected events depends on an *interference* between the parts of the beam passing through the two different slits. This pattern is very different from what it is if the photon is allowed to perceptibly disturb, the surrounding environment. Disturbing the environment produces a "decoherence" effect, i.e., a weakening or disappearance of the interference effects.

If a system interacts with its environment, it is difficult to prevent a "perceptible influence" of the system on the environment. If even *a single one* of the thousands of particles in the environment is displaced by a discernible amount then the coherence is lost, and the quantum interference effect will disappear.

Because the medium in which the putative quantum information waves are moving involves different conformational states of huge tubulin molecules of molecular weight ~110,000, it would seemingly be exceedingly hard to ensure that the passage of these waves will not disturb even one particle of the environment by a discernible amount.

Max Tegmark wrote an influential paper in Physical Review E. (Tegmark, 2000). It mathematically buttressed the intuition of most physicists that the macroscopic coherence required by Penrose-Hameroff---namely that the microtubular conformal states can form the substrate of a quantum computer that extends over a large part of the brain--- could not be realized in a living human brain. Tegmark concluded that the coherence required for macroscopic quantum computation would be lost in a ten trillionth of a second, and hence should play no role in consciousness. This paper was widely heralded. However, Hagan, Hameroff, and Tuszynski (2002) wrote a rejoinder in a later issue of the same journal. They argued that some of Tegmark's assumptions departed significantly from those of the Penrose-Hameroff model. The associated corrections lengthened the coherence time by 8 or 9 orders of magnitude, thus bringing the situation into a regime where the non-equilibrium conditions in a living brain might become important: energetic biological processes might conceivably intervene in a way that would make up the still-needed factor of ten thousand. However, the details of how this might happen were not supplied. Hence the issue is, I believe, still up in the air, with no detailed explanation available to show how the needed macroscopic quantum coherence could be maintained in a living human brain.

It must be stressed, however, that these exotic "quantum computer" effects are not necessary for the emergence of strong quantum effects within the general framework supplied by the combination of Penrose's rule pertaining to gravity and Hameroff's claim concerning the importance of microtubules. According to von Neumann's general formulation, the state of the brain—or of the microtubular part of the brain—is adequately represented by what physicists call the "reduced density matrix" of that subsystem. This representation depends only on the variables of that subsystem itself (i.e., the brain, or microtubular array) but nevertheless takes adequate account of the interactions of that system with the environment. It keeps track of the quantum coherence or lack thereof. Penrose's rule can be stated directly in terms of the "reduced density matrix," which displays, ever more clearly as the interaction with the environment grows, the two alternative states of the brain—or of the microtubular array—that Nature must choose between. This reduced-density-matrix representation shows that the powerful decoherence effect produced by strong interactions with the environment actually *aids* the implementation of Penrose's rule, which is designed to specify *when* the quantum jump occurs (and perhaps to which states the jump occurs). The capacity of the brain to be or not to be *a quantum computer* is a very different question, involving enormously more stringent conditions. It thus is important, for logical clarity, to separate these two issues of the requirements for *quantum computation* and for *quantum jumps*, even though they happen to be interlocked in the particular scenario described by Penrose and Hameroff.

3. The Bohm Approach.

The Copenhagen and von Neumann formulations of quantum theory are non-deterministic. Both specify that human choices enter into the dynamics, but neither specifies the causal origins of these choices. The question thus arises: what determines these choices?

One possibility is that these choices arise in some yet-to-be-specified way from what we conceive to be the *idealike aspect of reality*. That option was pursued by Penrose, with his suggestion that our thoughts are linked to Plato's world of ideal forms. Another—seemingly different—possibility is that a *physical description* exists that is more detailed than the smeared out cloudlike structures of the orthodox formulations, and that this *more detailed physical description* determines all features left undetermined in the orthodox formulations.

This second approach was developed by David Bohm (1952, 1993). His formulation of quantum theory postulates, in effect, the existence of the old-fashioned world of classical physical theory. This classical-type world is supposed to exist *in addition to the cloudlike wave function of orthodox quantum theory* and is supposed to evolve in a way completely determined by what precedes it in time. Bohm specifies new laws of motion that are able to reinstate determinism in a way compatible with the predictions of quantum theory, but at the expense of a very explicit abandonment of locality: Bohm's theory entails very strong, and very long-range, instantaneous action-at-a-distance.

One serious failing of Bohm's approach is that it was originally formulated in a non-relativistic context, and it has not yet – after half a century and great effort – been extended to cover the most important domain in physics, namely the realm of quantum electrodynamics. This is the theory that covers the atoms that make up our bodies and brains, along with the tables, chairs, automobiles, and computers that populate our daily lives. This deficiency means that Bohm's theory is, at present, primarily a philosophically interesting curiosity, not a practically useful physical theory.

Also, Bohm's theory, at least in its original form, is not really germane to the issue of consciousness. For Bohm's theory *successfully achieved its aim,* which was precisely to get rid of consciousness: i.e., to eliminate consciousness from the basic dynamical equations, just as classical physics had done.

Bohm recognized, later on, that some understanding of consciousness was needed, but he was led instead, to the notion of an infinite tower of mechanical levels, each controlling the one below, with consciousness somehow tied to the mystery of the infinite limit. (Bohm, 1986, 1990) This infinite-tower idea tends to diminish the great achievement of the original theory, which was to reinstate physical determinism in a simple way.

Perhaps the most important use of Bohm's model is to provide an understanding of the consequences of assuming, as some philosophers do, that we live in a world in which everything is deterministically fixed by purely physical processes, and our conscious choices are epiphenomenal.

Bohm's model is an example of such a theory, which moreover agrees with the predictions of quantum theory, at least in the non-relativistic regime. It is thus instructive to examine Bohm's model, and see how, within that deterministic framework in which consciousness plays no fundamental causal role, consciousness nevertheless enters*, at the level of scientific practice*, in just the way specified by the orthodox formulations.

As explained in the introductory section, actual scientific practice involves setting up experimental conditions that promote consciously conceived objectives. In von Neumann's theory these consciously chosen actions influence the subsequent course of events in the observed system, which, according to von Neumann's version of quantum theory, is primarily the brain of the human participant. A key point is that these choices, made by the experimenter about how he or she will act, are treated in von Neumann's theory, and also by Copenhagen quantum theory, as *input data*, to be fixed by the experimenter: no matter what these choices actually are, or where they come from, or what they actually do, these conscious choices are *treated* in orthodox quantum theory as free, controllable, and knowable, input boundary conditions.

In Bohm's theory these choices are not *actually* free: freedom is an illusion. The apparently free choice is, at a deeper dynamical level, completely determined by *physical* conditions, just as it was in classical physics. However, the putative existence of this deeper dynamical underpinning does not upset scientific practice. It does not displace, within science, the orthodox quantum dynamics. The analysis by Heisenberg shows that, even within the context of a deterministic Bohmian mechanics, the human observers can never determine, or *know*, to which of the conceivable logically possible classical Bohmian worlds their experiences belong. The Heisenberg Uncertainty Principle is a limitation upon human knowledge that is not evaded by Bohm's deterministic dynamics. The most that "experiencers" can ever *know* about the Bohmian classical world of which they are a putative part is represented by a quantum mechanical cloud-like wave function.

This limitation *in human knowledge* is acknowledged by Bohm. Indeed, Bohm's theory leaves actual scientific practice the same as it is in the Copenhagen approach. This *equivalence at the practical level* of Bohm's model to the Copenhagen formulation means that the unavoidable gap *in human knowledge* mandated by the uncertainty principle forces a return, at the level of scientific practice, to Copenhagen quantum theory. The theoretically specified, *but in principle unknowable and uncontrollable information about the supposedly deterministic microscopic realities,* are replaced in actual practice by *knowable and controllable realities*, namely our human conscious choices about which actions we will take, and their consciously experienced feedbacks. But this means that the structure added by Bohm lies beyond the scope of science, in the sense that it adds nothing testable. It is pure speculation.

An important feature of quantum theory, as it is understood by physicists, is the never rebutted argument of the founders that any added superstructure of the general kind proposed by Bohm can never add anything testable, and hence lies outside science. Quantum physicists tend to be skeptical of any claim that ascribes reality to properties that are unknowable *in principle* and give nothing testable. They identify science with actual scientific practice, not untestable philosophical speculations. This attitude may be as beneficial in neuroscience as it is in atomic physics.

4. The von Neumann/Stapp Approach

John von Neumann converted Copenhagen quantum theory, in a series of steps, into a form in which the entire physical universe, including the brain of each agent, is represented in one basic quantum state, which is called the state of the universe. The state of any subsystem, such as a brain, is formed by averaging (tracing) this basic state over all variables *other* than those that describe the state of that subsystem. The dynamics consists of *three* processes.

Process **1** is the choice on the part of the experimenter about how to act. This choice is sometimes called "The Heisenberg Choice", because Heisenberg strongly emphasized its crucial role in quantum dynamics. At the pragmatic level it is a "free choice", because it is controlled *in practice* by the conscious intentions of the experimenter/participant, and neither the Copenhagen nor von Neumann formulations provide any description of the *causal origins* of this choice, apart from the thoughts, ideas, and feelings of the agent. Each intentional action involves an effort to produce a conceived experiential feedback, which, if it occurs, will be an experiential confirmation of the success of that effort.

Process **2** is the quantum analog of the equations of motion of classical physics. As in classical physics, these equations of motion are local: all interactions are between immediate neighbors. They are also deterministic. They are obtained from the classical equations by a certain *quantization* procedure, and are reduced to the classical equations by taking the *classical approximation* of setting to zero the value of Planck's constant everywhere it appears. Evolution via the quantum Process **2** normally has the effect of *expanding* the microscopic uncertainties beyond what is demanded by the Heisenberg Uncertainty Principle: the cloud of microscopic possibilities *spreads out*. This growth in the microscopic regime, if unchecked by any other process, spreads into the macroscopic domain and causes even the *centers* of large objects to tend to become diffused over large regions. The disparity between this Process-**2**-generated theoretical indefiniteness of the locations of the centers of large objects and the consciously experienced definiteness of the positions of visible objects is resolved by Process **3**.

Process **3** is sometimes call the "Dirac Choice". Dirac called it a "choice on the part of Nature." It can be regarded as Nature's answer to the question posed by Process **1**. This posed question might be: "Will the detecting device be found to be in the state that signifies “Yes, a detection has occurred”? Or, “Will the Geiger counter be observed to ‘fire’ in accordance with the experiential conditions that define a `Yes’ response?” Each Process **3** reply must be preceded by a Process **1** question. This is because the Process **2** generates a *continuous infinity* of possible questions that cannot all be answered consistently within the mathematical framework provided by quantum theory. Process **1** specifies a set of distinct allowed possible answers such that the “Pythagoras Rule” for probabilities yields the conclusion that the probabilities for the allowed possible answers sum to unity.

Process **1** brings the conscious choices made by the observer/participant directly into the dynamics. On the other hand, there is a tendency for the effect of the Process-**1** choices (of the questions) on the state of observed system to be washed out, in the long run, by the averaging over the two possible answers, `Yes’ and ‘No.’ However, it has been stressed by Stapp (1999) that if willful effort can control the *rate* at which a sequence of similar Process 1 events occur then the course of brain events could be strongly affected by mental effort. The timing of the Process-**1** events is, within the orthodox Copenhagen/von Neumann quantum theoretical framework, governed be the choice made by the experimenter/agent, and this choice is not specified by any known law of physics. But a rapid sequence of pairs of questions and answers (Process-**1**/Process-**3** events) can, by virtue of the quantum laws themselves, hold a particular pattern of neurological activity in place, against the physical forces that would, both in the absence of such pairs, and also in classical physics, tend quickly to disrupt it. If this pattern of neurological activity were to be a “Template for Action” (i.e., an “executive” pattern of neurological activity that tends to produce a specific action) then the prolongation of the activation of this “executive pattern” of brain activity can tend to cause the intended bodily action to occur, in accordance with William James’s “ideo-motor” theory of action (James, 1890, p. 522). (According to that theory, it is the holding in place of the idea of an action that tends to make that action happen.)

This fact that a sufficiently rapid sequence of consciously selected probing events can hold the associated pattern of physical activity in place longer than what would be specified either by the classical laws of motion or its quantum analog, Process **2**, is *an automatic consequence of the quantum laws of motion*. It has been extensively studied by quantum physicists, both empirically (Itano, Heinzen, Bollinger, and Wineland, 1990) and theoretically (Misra and Sudarshan, 1977), under the title “Quantum Zeno Effect.”

This quantum process can provide a physics-based account of the causal efficacy of conscious willful effort. This account corresponds closely to the ideas of William James, as is made evident by the following quotations:

> ``Thus we find that we reach the heart of our inquiry into volition when we ask by what process is it that the thought of any given action comes to prevail stably in the mind.'' (James, 1890, p. 564)

and later

> ``The essential achievement of the will, in short, when it is most `voluntary,' is to attend to a difficult object and hold it fast before the mind. ... Effort of attention is thus the essential phenomenon of will.''

Still later, James says:

> ."Everywhere, then, the function of effort is the same: to keep affirming and adopting the thought which, if left to itself, would slip away.''

The conclusion here is that the apparent capacity of our conscious efforts/choices to influence our physical actions, which seems so puzzling and necessarily illusory within classical physics, has a straightforward explanation within quantum theory. This causal connection follows directly from the orthodox quantum laws of motion. Moreover, the details of how the process works is in close accord with William James's account of how willful effort brings about intended actions. Unlike the situation in classical physics, these willful choices themselves are not controlled by the known laws of physics. There is, therefore, no warrant in contemporary physical theory for the assumption that our human choices are strict consequences of local mechanical processes akin to, or analogous to, those appearing in the classical physics approximation. The classical approximation completely wipes out the uncertainties within which the free choices are allowed to act. This approximation contracts the spreading cloud-like structures of quantum theory into narrow pencil-like beams, thus eliminating the freedom provided by quantum theory that Bohr strongly emphasized. In contrast to the Process **3** choices on the part of nature, which are subject to statistical laws, and hence are forced to be "random", the Process **1** choices on the part of agents are not subject to any known law, statistical or otherwise, and hence need not be ruled by pure chance. This is important, because it is often claimed by the ill-informed that all of the indeterminateness introduced by quantum theory is controlled by statistical laws, and is hence "random". But the crucial Process 1 choices on the part of the agents are not subject to any known *statistical or deterministic* conditions.

In quantum theory the connection between mental effort and physical action can be explained as a *causal consequence of the laws of quantum physics*, combined with an assumption that an agent's conscious effort to produce some experientially characterized effect increases the rapidity of a set of Process-**1** probing actions that focus attention on the intended experience. The experiential side of each such Process-**1** action/event is specified by an intended (projected) experiential state. The physical side collapses the prior physical state of the brain to a sum of two parts. The first part is the part of the prior state in which the neural correlate (Template for Action) of the conscious intention is definitely present. The second part is the part of the prior state in which the neural correlate of the conscious intention is definitely not present. In quantum theory there are generally parts of the prior state that are not compatible with either of those possibilities. Those parts are eliminated by Process **1**, which is thus associated with *asking* a question. Process **3** gives nature's immediate answer: it collapses the state to the 'Yes' part or to the 'No' part. These pairs of abrupt events can be regarded as the "posing by agents" and the "answering by nature" of specific experientially formulated questions with 'Yes' or 'No' answers. *These events with their associated experiential and physical sides are the basic building blocks of quantum mechanics.* Between such event-pairs the state evolves via the local mechanical process **2** that is analogous to the local deterministic law of motion in classical physics.

This tripartite quantum dynamics involving Choice, Causation, and Chance (Processes **1**, **2**, & **3**, respectively) and the implementation of Will (Volition) via the conscious control of the rapidity of Process **1** events, provides the mathematical and logical foundation of a *pragmatic* quantum approach to neuro-psychology. How well does this pragmatic quantum approach work in actual practice?

Pashler's Analysis.

A great deal of experimental work in the field of The Psychology of Attention is summarized in Harold Pashler's recent book of that title [Pashler, 1998].

Pashler organizes his discussion by separating perceptual processing from post-perceptual processing. The former covers processing that, first of all, identifies such basic properties of stimuli as location, color, loudness, and pitch, and, secondly, identifies stimuli in terms of categories of meaning. The post-perceptual process covers the tasks of producing motor and cognitive actions beyond mere categorical identification. Pashler emphasizes [p. 33] that ``the empirical findings of attention studies specifically argue for a distinction between perceptual limitations and more central limitations involved in thought and the planning of action.'' The existence of these two different processes, with different characteristics, is a principal theme of Pashler's book. [pp. 33, 263, 293, 317, 404.] He argues that the former processes are carried out in parallel, but that the latter processes, which seem to require effortful choosing, operate in series, and have a capacity that, although limited, can often be enlarged by willful effort.

Pashler's conclusion is based on the analysis of a huge array of recent experiments. But the central finding is succinctly illustrated in a finding dating from the nineteenth century, namely that mental exertion reduces the amount of physical force that a person can apply. He notes that ``This puzzling phenomena remains unexplained.'' [p. 387]. However, if we take the sequence of Process I events associated with an agent to have a limited "capacity" in terms of events per second, then this effect is a natural consequence of quantum theory. Creating a physical force by muscle contraction requires a *conscious effort* that prolongs the existence of the neural template for action, in opposition to the Process-**2**-generated tendency of the brain to evolve toward a more relaxed state. This prolongation is produced by the Quantum Zeno Effect, and its effect is roughly proportional to the number of bits per second of central processing capacity that is devoted to the task. So if part of this processing capacity is directed to another task, then the applied force will diminish.

This example is just one simple case, but it illustrates the general principle. The identification of Pashler's limited central serial "capacity" with the rate of occurrence of Process **1** events, assumed to be increasable by willful effort, up to a limit, appears to explain the general features of all of the many diverse empirical results cited by Pashler in support of his thesis. (Schwartz, Stapp, & Beauregard, 2003; Stapp, 2001)

The apparent success of this quantum psychophysical theory in accounting for Pashler's data does not mean that classical physics could not be supplemented in some ad hoc way that would enable it to match that performance. However, the von Neumann theory allows the data to be explained directly in terms of *the already existing explicitly described tripartite process that constitutes the core of contemporary basic physical theory*, whereas an explanation based on classical physics is predicated on the untenable idea that the classical concepts of causation can be extrapolated from the motions of planets and falling apples to the motions of ions inside nerve terminals. It rests on a theory that is not only demonstrably false, but that claims to be dynamically and logically complete without entailing the existence of a part of reality that we know does exist, namely human consciousness. In contrast, von Neumann's equations specify definite dynamical connections between consciousness and brain activity, and they do so in a theoretical framework that automatically entails all of the valid predictions of classical physics. So what is the rationale, in neuro-psychology, for rejecting the fundamental equations and ideas of contemporary physics, which can mathematically account for the "directly observed" causal efficacy of consciousness, and also explain all of the valid classical features of phenomena, in favor of an extrapolation of "planetary" concepts into a microscopic regime where they are known to fail.

The Libet Experiment.

Perhaps the best way to understand the essence of the quantum approach to consciousness is to see how it applies to the famous Libet experiments pertaining to willful action. (Libet, 2003)

The empirical fact established by the Libet data is that when an action is 'willed'– such as 'willing' a finger to rise– a readiness potential (RP) appears *before* the conscious experience of 'willing' appears. The most straightforward conclusion is that the causal efficacy of "free will" is an illusion. The motion of the finger seems clearly to be caused by neural activity that began well before the conscious act of "willing" occurs. Thus consciousness is seemingly a *consequence* of neural activity, not a *cause* of it.

The quantum mechanical analysis of this experiment leads to a more subtle conclusion.

In the Libet experiment the original commitment by the subject to, say, "raise my finger within the next minute" will condition his brain to tend to produce *a sequence* of potential RP's distributed over the next minute. That is, the cloud of quantum possibilities will begin to generate a sequence of possible RP's, each one beginning at a different time. Each such RP will be associated with the 'Yes' answer to the question "Shall I choose (make an effort) to raise my finger now?" If the answer is 'No' then the 'template for the action of making an effort to raise the finger at that moment' will not be actualized, and the brain state associated with the answer 'No' will then evolve until the possibility of actualizing the template and RP corresponding to a later moment of choice arrives. When the brain activity associated with any *one* of these RP's reaches a certain triggering condition the Process **1** action associated with that particular RP will occur. Because the original commitment is spread over a minute the probability, for any individual RP in this sequence, for Nature's answer to be `Yes' will be small. Hence most of the possible RP's up to the one corresponding to some particular moment will *not be actualized*: they will be eliminated by the `No' answer on the part of Nature. But for one of these Process **1** events the associated Process **3** will deliver the answer "Yes," and the associated experience e will occur. Up to this point the conscious will has entered only via the original commitment to raise the finger sometime within the next minute. But in order to be efficacious the later experience e must contain an element of effort, which will cause the Process **1** associated with this experience (or a very similar one) to occur quickly again, and then again and again, thereby activating the Quantum Zeno Effect. This will cause the finger-raising template for action to be held in place, and the effect of this will be the issuing of the neural messages to the muscles that will cause the finger to rise. Without this willful effort, which occurs in conjunction with the answer 'Yes', the sustained activation of the template for action will not occur and the finger will not rise. The willful effort causes the rapid repetition of the Process 1 action to occur. This holds the template in place, which causes the finger to rise. Thus the rising of the finger is caused, in the quantum formulation, by the willful effort, in concordance with the idea expressed by James (1892, 227)

> "I have spoken as if our attention were wholly determined by neural conditions. I believe that the array of things we can attend to is so determined. No object can catch our attention except by the neural machinery. But the amount of the attention which an object receives after it has caught our attention is another question. It often takes effort to keep mind upon it. We feel that we can make more or less of the effort as we choose. If this feeling be not deceptive, if our effort be a spiritual force, and an indeterminate one, then of course it contributes coequally with the cerebral conditions to the result. Though it introduces no new idea, it will deepen and prolong the stay in consciousness of innumerable ideas which else would fade more quickly away."

Applications in Neuropsychology

This theory has been applied to Neuropsychology. (Oschner, Bunge, Gross, & Gabriel, 2002; Schwartz, Stapp, & Beauregard, 2003). In these studies human subjects are first instructed how to alter their mental reactions to emotionally-charged visual stimuli by adopting certain mental strategies. For example, the subjects are trained how to reduce their emotional reaction to a violent or sexual visual scene by cognitively re-evaluating the content; for example, by interpreting or contextualizing it in a different way. Their reactions to such stimuli are then studied using fMRI under differing choices of mental set. The brain scans reveal profoundly different patterns of response to the stimuli according to whether the subject does or does not apply the cognitive re-evaluation. Without cognitive re-evaluation the brain reaction is focused in the limbic system, whereas when cognitive re-evaluation is employed the focus shifts to pre-frontal regions. This demonstrates the powerful effect of cognitive choices upon brain functioning.

This effect is not surprising. Within the pragmatic framework this effect appears as a causal connection between a psychologically described input variable, namely a knowable and controllable free conscious choice, and an ensuing brain behavior. Quantum theory contains a mechanism that can explain this empirically observed apparent causal effect of the conscious choice upon the ensuing brain activity, but no explanation of any causal effect of brain process upon our conscious choices. The contending classical approach asserts that the causal connections are wholly in the opposite direction. It claims that both the conscious choice and the subsequent brain behavior are both consequences of prior physical processes.

Superficially, it might seem that there is no way to decide between these contending theories, and hence that a scientist is free here to choose between classical physics and quantum physics. It might be argued that the dispute is all words, with no empirical or theoretical content. However, the claim that the sufficient *cause* of the subject's subsequent brain state does not include the controllable variable that *empirically* controls it is prima facie unreasonable. It would become reasonable only if supported by strong theoretical arguments or empirical evidence. But there is no strong theoretical support. The only theoretical support for this prima facie implausible claim comes from a physical theory, classical physics, whose domain of applicability fails in principle to cover the phenomena in question. The more accurate physical theory that *should* cover these phenomena provides no support at all for an epiphenomenal explanation of this data

This argument does not *prove* that a classical-type causal explanation that leaves consciousness out is rationally untenable. However, if one were to search for evidence to support the classical idea then most scientists would probably agree that one must, at this point in time, expect the data to be at least *compatible* with the predictions of quantum theory. But then the example provided by Bohm's model becomes instructive. That model is deterministic at the purely physical level, without reference to consciousness. To be sure, it involves, in a direct way, instantaneous long-range action at a distance, and it has not been made compatible with the special theory of relativity. But the model does give an idea of how consciousness *might* in principle be rendered impotent in a model compatible with the *predictions* of quantum theory. However, as discussed in the section on Bohm's model, the Heisenberg uncertainty principle excludes the possibility of knowing anything about, or testing for the presence of, the proposed causal substructure. This circumstance argues for the adoption in neuroscience of the attitude adopted in atomic physics: avoid the introduction of speculative concepts that are unknowable and untestable in principle, and, instead, treat conscious choices in the way that they actually enter scientific practice, namely as empirically knowable and controllable input parameters.

The basic elements of von Neumann's theory are the experiences of conscious agents, and the neural correlates of those experiences, the NCC's. The fundamental building blocks of quantum theory are "information/action events". On the psychological level, each Process **1** event focuses attention and effort on an intended experiential/informational feedback. On the physical level this event reduces (collapses) the state of the brain to a sum of two terms, one of which is the neural correlate of the intended experience, and the other of which is the neural correlate of the negation of that possibility. Contemporary physical theory gives no statistical or deterministic conditions on the choice of the intended action. But Nature's feedback is required to conform to the "Pythagoras" statistical rule described above.

How is the necessary connection between the experiential and physical regimes established? The answer is by trial and error empirical testing of the correspondence between "the feeling of the conscious effort" and "the feeling of the experiential feedback". Every healthy alert infant is incessantly engaged in mapping out the correspondences between efforts and feedbacks, and he/she builds up over the course of time a repertoire of correspondences between the feel of the effort and the feel of the feedback. This is possible because different effortful choices have, according to the quantum equations, different physical consequences, which produce different experiential consequences. This whole process of learning depends crucially upon the causal efficacy of chosen willful efforts: if efforts have no actual consequences then how can learning occur, and the fruits of learning be obtained by appropriate effort.

The focus here has been on the theoretical foundations of pragmatic neuroscience. However, von Neumann's formulation makes the theory more amenable to ontological interpretation.

The essential difference between quantum theory and classical physics, both ontologically construed, is that the classical state of the universe represents a purported *material* realty, whereas the von Neumann quantum state of the universe represents a purported *informational* reality. This latter reality has certain matter-like features. It can be expressed in terms of micro-local entities (local quantum fields) that evolves by direct interactions with their neighbors, *except* when certain abrupt "reductions" or "collapses" occur. These sudden changes are sometimes called "quantum jumps." In orthodox pragmatic quantum theory what the state represents is the collective knowledge of all agents. Hence it abruptly changes whenever the knowledge of any agent changes. This behavior is concordant with the term "our knowledge" used by the founders of quantum theory. Thus the quantum state has a *form* that manifests *certain* of the mechanical properties of matter, but a *content* that is basically idealike: it represents an objective kind of knowledge that changes when someone acquires knowledge.

This radical revamping of physics was not something lightly entered into by the founders of quantum theory, or docilely accepted by their colleagues. A blithe disregard, in the study of the mind-brain connection, of this profound and profoundly relevant revision by scientists of the idea of the interplay between the experiential and physical aspects of nature is not easy to justify. .

If one shifts over to an explicitly ontological interpretation, the question arises "What systems besides human beings are *agents?* There is currently a lack of replicable empirical data that bears on this question, and I shall therefore not enter into philosophical speculation.

It needs to be emphasized that everything said about the von Neumann theory is completely compatible with there being very strong interactions between the brain and its environment. The state S(t) of the brain is what is known as the statistical operator (reduced density matrix) corresponding to the brain. It is formed by averaging (tracing) over all non-brain degrees of freedom, and it automatically incorporates all of the decoherence effects arising from interactions with the environment. The key point is that strong environmental decoherence does not block the Quantum Zeno Effect.

There is an approach to quantum theory that tries to ignore von Neumann's Process **1** (and Process **3** as well). This approach is called the "many-minds" or "many-worlds" approach. No demonstration has been given that such a radical break with orthodox quantum theory is mathematically possible. Hence I do not include it among the possible quantum approaches to consciousness described here.

Von Neumann's theory provides a general physics-based psycho-physical framework for studying the neuroscience of consciousness. We now turn to some efforts to tie this structure to the detailed structure of the brain

5. The Eccles-Beck Approach.

Sir John Eccles suggested in 1990, in the Proceedings of the Royal Society (Eccles, 1990), that quantum theory plays a key role in the workings of the conscious brain. Based in part on his discussions with Henry Margenau (See Margenau, 1984), Eccles noted that the statistical element in quantum theory allows an escape from the rigid determinism of classical physics that has plagued philosophy since the time of Isaac Newton. In his later book "How the self controls its Brain" Eccles (1994) notes that, "There is of course an entrenched materialist orthodoxy, both philosophic and scientific, that rises to defend its dogmas with a self-righteousness scarcely equaled in the ancient days of religious dogmatism." He says at the outset that, "Following Popper (1968) I can say:

I wish to confess, however, at the very beginning, that I am a realist: I suggest somewhat like a naïve realist that there is a physical world and a world of states of consciousness, and that these two interact."

Eccles gives "two most weighty reasons" for rejecting the classical-physics-based concept of materialism. (Eccles 1994, p, 9) First, classical physics does not entail the existence or emergence of the defining characteristic of consciousness, namely "feelings," and hence entails no theory of consciousness. Second, because the Nature of the mapping between brain states and states of consciousness never enters into the behavior of an organism, there is no evolutionary reason for consciousness to be closely connected to behavior, which it clearly is.

Eccles' approach to the mind-brain problem has three main points. The first is that consciousness is composed of elemental mental units called psychons, and that each psychon is associated with the activation of a corresponding macroscopic physical structure in the cerebral cortex that Eccles calls a *dendron*. It is anatomically defined, and is connected to the rest of the brain via a large number of synapses.

The second point is the claim that quantum theory enters brain dynamics in connection with exocytosis, which is the release of the contents of a "vesicle" – filled with neurotransmitter – from a nerve terminal into a synaptic cleft.

The third point is a model developed by the physicist Friedrich Beck that describes the quantum mechanical details of the process of exocytosis.

The first claim, that psychological processes have elemental units associated with dendrons, places Eccles' theory somewhat apart from those who have suggested that *the electromagnetic field* in the brain might serve as the carrier of the physical correlate of consciousness. (McFadden, 2002; Pockett, 2000, 2002: Stapp, 1985, 1987; Taylor, 2002) Evidence for the electromagnetic hypothesis has been presented particularly by McFadden. However, the very close causal connection between the activation of a dendron and the activation of an electromagnetic field in the neighborhood of that dendron makes it difficult to distinguish between these two proposals empirically.

More germane to our topic is the second component of Eccles' proposal, namely that quantum effects are important in brain dynamics in connection with cerebral exocytosis. This conclusion is plausible, and indeed inescapable. Exocytosis is instigated by an action potential pulse that triggers an influx of calcium ions through ion channels into a nerve terminal. These calcium ions migrate from the ion-channel exits to sites on or near the vesicles, where they trigger the release of the contents of the vesicle into the synaptic cleft. The diameter of the ion channel through which the calcium ion enters the nerve terminal is very small, less than a nanometer, and this creates, in accordance with the Heisenberg uncertainty principle, a correspondingly large uncertainly in the direction of the motion of the ion. That means that the quantum wave packet that describes the location of the ion spreads out, during its travel from ion channel to trigger site, to a size much larger than the trigger site (Stapp 1993; Stapp,2003). That means that the issue of whether or not the calcium ion (in combination with other calcium ions) produces an exocytosis is a quantum question basically similar to the question of whether or not a quantum particle passes through one or the other slit of a double-slit experiment. According to quantum theory the answer is 'both.' Until the brain process reaches the level of organization corresponding to the occurrence of a Process I action one must in principle retain *all* of the possibilities generated by the Schroedinger equation, Process **2**. In particular, one must retain both the possibility that the ion activates the trigger, and exocytosis occurs, and also the possibility that the ion misses the trigger site, and exocytosis does not occur.

For cortical nerve terminals the observed fraction of action potential pulses that result in exocytosis is considerably less than 100%. This can be modeled classically. (Fogelson & Zucker, 1985) But the large Heisenberg uncertainty in the locations of the triggering calcium ions, entails that the classical uncertainties will carry over to similar quantum uncertainties, and the two possibilities at each synapse, 'exocytosis' and 'no exocytosis', will, prior to the occurrence of the Process **3** action, *both be present* in the quantum state S(t). If N such synaptic events occur in the brain during some interval of time in which no Process **3** events occur, then the state S(t) of the brain will evolve during that interval into a form that contains (at least) 2^N contributions, one for each of the alternative possible combinations of the 'exocytosis' and 'no exocytosis' options at each of the N synapse events.

There is a lot of parallel processing and redundancy in brain dynamics and many of these possible contributions may correspond to exactly the same possible experience 'e'. But in real life situations where there could be several different reasonable actions, one cannot expect that every one of the 2^N alternative possible brain states will be a neural correlate of *exactly* the same possible 'e'. If the agent is conscious then the von Neumann Processes **1** and **3** must enter to determine which of the various alternative possible experiences 'e' actually occurs.

The analysis just given assumes, in accordance with the model of Fogelson and Zucker, that the condition that triggers exocytosis is the presence of a specified number of calcium ions on a trigger site. Beck (2003) considers another possibility. He says that the "low exocytosis probability per excitatory impulse …means that there is an activation barrier against opening an ion channel in the PVG (presynaptic vesicular grid). He proposes that "An incoming nerve pulse excites some electronic configuration to a metastable level, separated energetically by a potential barrier V(q) from the state that leads to the unidirectional process of exocytosis." In this scenario the state in which the exocytosis does occur can be considered to be connected by a *quantum tunneling process* to the state where it does not occur.

Beck's tunneling mechanism would achieve the same result as the mechanism, described above, which is based simply on the spreading of the wave packets of the calcium ions due to Heisenberg's uncertainty principle. Both mechanisms lead to the result that the brain state S(t) will contain 2^N states, defined by the independent 'exocytosis or no exocytosis' option at each of the N synapses. Hence the Eccles-Beck model does not lead to any essential difference, as regards this key point, from the model that emphasizes the spreading of the calcium ions inside the nerve terminal. (Of course, it should not be thought that these explicitly considered effects are the *only* places where quantum effects enter into brain dynamics. These explicitly treated processes are just special case where enough empirical evidence is available to make a calculation, and where the alternative possibilities should feed into the generation of non-identical brain states.)

The Eccles-Beck proposal does, however, differ significantly from the von Neumann/Stapp proposal in regard to their third point. The von Neumann/Stapp theory attributes the efficacy of will to the assumed power of mental effort to increase the rate of Process **1** actions, whereas the Eccles-Beck proposal attributes the efficacy of will to the assumed power of mental effort to modify *the probabilities associated with the Process **3** action*, the collapse of the quantum state.

The von Neumann/Stapp proposal stays rigorously within the framework of relativistic quantum field theory, and hence produces no causal anomalies, such as the possibility of sending messages backward in time. The Eccles-Beck proposal, by violating the basic quantum probability rules, would in principle allow such anomalies to occur.

It is often emphasized, *correctly*, in connection with quantum approaches to brain dynamics, that "the environment" will be affected differently by interactions with the brain states in which an exocytosis has or has not occurred, and that this difference will destroy, almost immediately, all (practically achievable) interference effects between these macroscopically distinct states.

This *environmental decoherence effect* is automatically included in the formulas used here, which refer explicitly to the brain state S(t), which is the brain-state statistical operator obtained by averaging (tracing) over all non-brain variables.

It is then sometimes concluded, *incorrectly*, that one can immediately replace the brain state S(t) by just *one* of these 2^N components. That conclusion might follow if one were to ignore Process **1**, which is part of the brain process that defines which of our alternative possible thoughts occurs next. Because Process **1** is part of the process that determines which thought occurs next, it should depend upon the state S(t) of the brain *before* the thought occurs, not on the part of that state that will eventually be actualized. Hence all of the 2^N components of S(t) should be retained prior to the Process **3** collapse,' whether they interfere or not:

The model of the brain used above, with its 2^N well defined distinct components is, of course, highly idealized. A more realistic model would exhibit the general smearing out of all properties that follows from the quantum smearing out of the positions and velocities of all the particles. Thus the state S(t) prior to the collapse cannot be expected ever to be rigorously divided, solely by Process **2** action, including interaction with the environment, into strictly orthogonal non-interfering components corresponding to distinct experiences. It is Process **1** that makes this crucial separation, not Process **2**. The recognition of the need to bring in a *separate process to define the question* is the critical element of the Copenhagen approach, and it was formalized by von Neumann as Process **1**. Any attempt to leave out Process **1** faces daunting challenges.

6. The Jibu-Yasue Approach.

The preceding sections are conservative and incomplete. They are conservative because they: (1), build on the orthodox philosophy of quantum theory, which recognizes that science, like every human endeavor, arises from the fact that human beings choose their actions, and experience the feedbacks; and (2), exploit the quantum laws that relate these choices to those feedback.

The preceeding sections are incomplete because they say very little about the actual brain mechanisms.

In regard to this second point there is a related question of how memories are stored. Karl Pribram has suggested (Pribram, 1966, 1991) that consciousness operates on principles similar to that of a hologram, in which tiny variations of a myriad of physical variables, dispersed over a large region, combine to modulate a carrier wave. These physical variables might be the strengths of the synaptic junctions. Pribram identifies the dendritic network (a dense set of neural fibers) as the likely substrate of such a brain process.

This holographic model would appear to be implementable within quantum electrodynamics, which is the physical theory that would normally be expected to control brain dynamics. However, Umezawa and co-workers (Riccardi & Umezawa, 1967; Stuart, Takahashi, & Umezawa, 1978; 1979) have suggested that an exotic physical process is involved, namely a process similar to what appears in the theory of superconductively. That theory is characterized by the existence of a continuum of states of the same (lowest) energy, and Umezawa has suggested that long-term memory is associated with the breaking the symmetry of these ground states, instead of, for example, enduring changes in the physical structures of nerve cells.

Jibu and Yasue (Jibu 1995) have attempted to weave these ideas of Pribram and Umezawa into a unified quantum theory of brain dynamics (QBD). Their theory takes the substrate associated with Umezawa's ideas to be the water that pervades the brain. Excitations of certain states of the water system are called corticons, and they interact with photons in the electromagnetic fields of, for example, the dendritic network. They say:

"With the help of quantum field theory, we have found that the creation and annihilation dynamics of corticons and photons in the QBD system in the sub-microscopic world of the brain to be the entity we call consciousness or mind."

However, they have not made clear why "the creation and annihilation dynamics of corticon and photons" should possess the defining characteristics of conscious processes, namely the fact that they are "feelings": Conscious experiences have a quality of "feelingness" about them that is not contained in, or entailed by, the physical concepts of corticons and photons, or of the dynamics of these entities that they claim "*to be the entity we call consciousness or mind."* Thus their work does not address the basic question of how rationally to get the concepts that characterize the experiential aspects of reality out of the concepts of the physical theory. That question is the one that was answered by the work of von Neumann, and that has been the primary focus of this entry.

GLOSSARY

Quantum Jumps. The "mystery of quantum theory" is concentrated wholly in the peculiarities of the quantum jumps, which seem to have both subjective experiential aspects associated with "increases in knowledge" and also objective physical aspects associated with changes in the expectations or potentialities for future quantum jumps. In the chapter "The Copenhagen Interpretation" in his book "Physics and Philosophy", Heisenberg (1958b, p.54) says "When the old adage `*natura non facit saltus'* (nature makes no jumps), is used as a basis for criticism of quantum theory, we can reply that certainly our knowledge can change suddenly and that this fact justifies the use of the term `quantum jump'". This explanation stresses the subjective/experiential knowledge-increasing aspect of the quantum jumps, and is very much in line with the words of Bohr. But Heisenberg then begins a further discourse with the words "If we want to know what happens in an atomic event". He then speaks of "the transition from 'possible' to 'actual' that takes place as soon as the interaction of the object with the measuring device, and hence with the rest of the world, comes into play." He says that this transition from `possible' to `actual' is "is not connected to the registration of the result in the mind of the observer", but that "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 in the probability function." In this account there are two different kinds of jumps, one purely physical, and occurring at the device, and one purely psychological/experiential, and occurring in the mind of the observer. The idea is that the probability function is a mathematical construct that lives in the minds of human scientists, and represents "our knowledge", and that it consequently "jumps" when our knowledge increases. There are also physical jumps that occur at the devices. But what happens in a person's *brain* when an abrupt increase in his knowledge occurs? A brain is similar in many ways to a measuring device: there is energy available to magnify quickly the effects some small triggering event. And how does one explain the fantastic accuracy of quantum calculations if the quantum mathematics that exists in our minds is not closely related to what is really happening? The von Neumann formulation answers these questions by shifting the boundary between the observed system and the observer so that the physically described state includes the brain of the observer, and the two kinds of "jumps" described by Heisenberg become two aspects of a single kind of quantum jump that occurs at the mind-brain interface. Von Neumann's Process **1** is the physical aspect of the choice on the part of the human agent. Its psychologically described aspect is experienced and described as a focusing of attention and effort on some intention, and the physically described aspect consists of the associated choice of the basis vectors and of the timings of the action. Then there is a feedback quantum jump whose psychologically described aspect is experienced and described as an increment in knowledge, and whose physical aspect is a "quantum jump" to a new physical state that is compatible with that increment in knowledge. Thus the two aspects of the conceptual foundation of science, the objective/mathematical and the subjective/experiential, are linked together, *within the theory*, in the conceptual structure of the quantum jump.

Planck's Constant. This number, discovered by Max Planck in 1900, is a number that characterizes quantum phenomena. It specifies a definite connection between energy and frequency. The energy carried by a quantum entity, such as an electron or photon (a quantum of "light"), divided by Planck's constant, defines a "frequency" (the number of oscillations per second) that is associated with this entity. Thus Planck's constant links together a discrete "lump" or "quantum" of energy with an oscillatory motion of specified frequency. This constant thus forms the basis for linking a property normally associated with a "particle", namely a discrete amount of energy, with a property that is associated in quantum theory with a wave motion. In classically describable phenomena the products of energy and frequency of the individual quantum entities that combine to produce the macroscopic phenomena is so small on the scale of observable parameters as to be individually undetectable, even though the macroscopically measurable properties of materials depend strongly upon the quantum properties of their constituent elements.

Quantum Zeno Effect. The equations of motion of a quantum system differ in many ways from the classical equations. One such way is this: The motion of a planet, as described by Kepler's empirical laws, and by Newton's theoretical ones, are such that the motion does not depend on how often we look at it. But the evolution in time of an observed quantum system depends on Process **1**, which is specified in the theory by observational choices made by the experimenter/observer/agent. In the case of a planet the effect of our observations are negligible. But experiments on atoms (Itano, Heinzen, Bollinger, and Wineland, 1990) show that the behavior of atoms can be strongly affected by the rapidity at which Process **1** events are occurring. If these events occur sufficiently rapidly then the normal behavior of the atom, such as a transition from an excited state to a state of lower energy, is slowed down. This was predicted by quantum theory, and the empirical results are in good agreement with theoretical predictions. This slowing effect is called the Quantum Zeno Effect. (Misra and Sudarshan, 1977). If the observed system is the brain of an agent then, as a consequence of evolutionary and educational processing, this brain could be expected to become very sensitive to variations in the character of the Process **1** events. This is because "Templates for Action" could be held in place longer than normal by "free" choices made agents, and this could strongly influence behavior. Such an effect would elevate the choices made by human agents from their status in classical physics as mechanically determined epiphenomenal side effects to causes that, *in principle*, are not fully traceable within contemporary physical theory to purely physical processes, and hence are properly treatable as empirical inputs.

Template for Action. This is an "executive" patterns of neurological activity that if held in place for an extended period will issue the sequence of neural signals that will initiate and monitor a particular physical (or perhaps mental) action.

Gödel's Incompleteness Theorem. "Any finite set of rules that encompass the rules of arithmetic is either inconsistent or incomplete: it contains either statements that can be proved to be both true and false, or statements that cannot be proved to be either true or false."

Heisenberg's Uncertainty Principle. This principle asserts the mathematical fact that within the logical framework provided by quantum theory the position and momentum (velocity times mass) of a quantum entity cannot be simultaneously defined to arbitrary accuracy. The product of the uncertainties in these two quantities is given by Planck's constant. This principle limits, *in principle*. the applicability of the classical concept of the deterministic motions of the planets in the solar system to case of the motions of the ions in a human brain.

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