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Consciousness and Quantum Mechanics: The Connection and Analogies

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Consciousness and the measurement problem of quantum mechanics have a logical connection and an historical involvement. Moreover, current issues in the two arenas have striking similarities. Whether or not consciousness warrants quantum mechanical consideration, analogies between quantum measurement and consciousness are tantalizing and suggestive. After a review of how the issue of consciousness arises in quantum mechanics (but not in classical physics), and after a brief discussion of the implications of the measurement problem for reductionism, we develop a series of analogies between consciousness and quantum mechanics. We conclude that any substantial advance in one arena would at the least offer hints for routes to take in the other.

Decades ago the issue of consciousness was raised to address the problem of observation, or measurement, in quantum physics (e.g., von Neumann, 1932/1955; Wigner, 1961). In recent years attention to the fundamental enigma posed by observation has increased substantially in both the physics community and in popular discussions of physics.

Also in recent years the possible relevance of quantum phenomena for the explanation of conscious experience has been discussed widely (for example, Chalmers, 1996; Squires, 1998), and specific quantum mechanisms have been

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suggested for the operation of the brain (Beck and Eccles, 1992; Penrose, 1994; Stapp, 1993, 1996). Frequently such suggestions are vigorously rejected.[1]

This paper has a two-fold purpose. The first is to explain — as simply and as straightforwardly as we can — just how the measurement problem of quantum mechanics long ago *forced* physicists to address the issue of consciousness despite deep-seated disinclinations to do so. Our second purpose is to point out some remarkable correspondences between the fundamentals of quantum measurement and those of conscious experience. Features of these two still ill-defined mysteries, one at the very top and the other at the very bottom of the reductionist pyramid, provide compelling analogies.

Though analogies can never present a firm case for a connection between two issues, exploring them have proven stimulating. Moreover, workers in each field might well benefit by being aware of efforts and advances in the other. At the very least our discussion should offer insight into the motivation of physicists, as well as others, to persistently inject quantum mechanics into discussions of consciousness.[2]

We first review why the issue of consciousness need not arise in classical physics and then how it emerges in quantum physics. We will emphasize that this emergence comes almost directly from the brute facts of experiment — rather than from some particular interpretation of the theory. After brief comments on the impact of Bell's theorem and on the implications of quantum mechanics for reductionism, we explore a number of analogies between the mystery of the quantum measurement problem and the mystery of consciousness.

Consciousness in Classical Physics

Classical physics, developed before the twentieth century, usually provides a good approximation to the fundamentally more correct quantum description when a detailed microscopic explanation is not warranted. Thus, understanding the falling of stones, the working of automobiles, or even the chemistry of digestion need not involve quantum mechanics.

Classical physics is, in principle, deterministic: given the position and velocity of all particles in the universe, everything that happens is then set. There would seem to be no room for free will in such a deterministic universe. If we nevertheless insist that we do make conscious choices, that we do have free will, we have a dilemma.[3]

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[1] One major suggestion of a role for quantum mechanics in consciousness has been derided as having the explanatory power of "pixie dust in the synapses."

[2] The quantum measurement problem was certainly the stimulus of the present authors' interest in the study of consciousness.

[3] I.B. Singer: "You have to believe in free will. You have no choice."

Classical physics had a way out of this difficulty by allowing the tacit removal of consciousness with its associated free will from the physical world. The argument is that our consciousness gains information from the physical world only through our eyes and other sense organs, whose workings are presumed to be understandable in classical terms. Moreover, our consciousness affects the physical world only through muscles and similarly understandable means. The consciousness, per se, of each person thus appears completely contained within his or her body. With this outlook, the mystery of consciousness is a benign mystery — at least a mystery outside the realm classical physics felt required to address. Classical physicists could relegate the issue of consciousness to psychology and philosophy. And that was their inclination. This tacit removal of consciousness from the physical world, we will see below, is not permitted by quantum mechanics.

In removing consciousness from the physical world one admits the existence of phenomena beyond the scope of classical physics. In fact, if classical physics is assumed to be a complete description of the world, it is argued that consciousness must be epiphenomenal — that it can have no role in determining physical phenomena (Stapp, 1997). Fundamentally, of course, classical physics is an incorrect theory, and any world view based upon its principles is flawed.

Consciousness in Quantum Mechanics

Quantum mechanics is the physics required at the microscopic level of atoms and molecules, where the predictions of classical physics are completely wrong. While the predictions of quantum physics for large objects usually do not differ from those of classical physics, for some large-scale or "macroscopic" phenomena, understanding must directly involve quantum theory. Examples of such include semiconductor electronics, lasers, superconductors, and the Big Bang.

Quantum mechanics is the most battle-tested theory in science. Not a single violation of its predictions has ever been demonstrated, no matter how preposterous the predictions might seem. Moreover many of these predictions are confirmed with impressive accuracy, some to better than one part in a hundred billion. However, anyone concerned with what the theory *means* faces a philosophical enigma: the so-called measurement problem, or the problem of observation. While classical physics could ignore consciousness, the conscious experience of observers is what quantum mechanics is about.[4]

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[4]It has been noted that books on classical mechanics talk about what is and the way things are; books on quantum mechanics talk about what is *observed*. For all *practical* purposes, however, quantum considerations end when an event is recorded by macroscopic measurement apparatus. The measurement problem is thus something few working physicists discuss — or even inform themselves about. Moreover, not all physicists who explore the problem

If quantum measurement theory impinges on consciousness, it seems natural to speculate that quantum mechanics might shed light on the problem of consciousness. Others have made the reverse connection. Chalmers (1996, p. 349), for example, claims that the central question of the quantum measurement problem is "the kind of question that a theory of consciousness ought to be able to answer."

We now illustrate the measurement problem and its relationship to consciousness with a pair of simple thought experiments. Although this is a novel presentation, it is in principle no different than the two-slit experiments described in every text on quantum mechanics and which are repeatedly demonstrated — even in the lecture room. While the results of these experiments are readily demonstrated, the interpretation can be confounding.[5]

It is simplest to describe the following two experiments in terms of the quantum *theory*, and any presentation of a theory implies an interpretation. It is the "orthodox" Copenhagen interpretation which is implicit in the following description. But it is largely from the brute facts of experiment — not from any theory-based interpretation — that the connection of physics with consciousness arises. After describing these experiments, we will restate the results in as theory-neutral a way as we can.

In the quantum theory, an object — for example, an atom — can display the properties not only of a compact, discrete particle but also those of an extended, divisible wave. The fundamental equation of quantum mechanics, the Schrödinger equation, can describe the behavior of the wave corresponding to a single atom.[6] Should such a wave encounter a semi-transparent reflecting surface (an appropriate thin film will do) the equation tells us that this wave, or "wavefunction," can be split into two equal parts, much as is a light wave both going through and reflecting from a window pane. One part then reflects from a fully reflecting surface, and the two parts of the wavefunction can finally be trapped in two boxes as shown in Figure 1. This entire apparatus is assumed isolated from any interaction with the rest of the world, which we will call the environment.

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of consciousness focus on quantum mechanics. Elitzur (1989, p. 4; see also Elitzur, 1991) points out that "Quantum mechanics . . . does not face a *real necessity* to take consciousness into account" [emphasis added]. The difference between Elitzur and others such as Penrose, Squires, and Stapp is not a different understanding of quantum physics. Rather, Elitzur boldly suggests a need for revision of the second law of thermodynamics — and thus our concept of time. He does point out that this revision would impact our understanding of both human perception *and* the quantum measurement problem.

[5]A problem frequently arising in explaining quantum mechanics is that people may think they don't understand when in fact they do. They just can't *believe*. While quantum theory accurately predicts the results we will now describe, one should not expect them to "make sense."

[6]The Schrödinger equation is the fundamental equation of non-relativistic quantum mechanics. Since the measurement problem is still with us in the relativistic case, discussion for this simpler situation is sufficient.

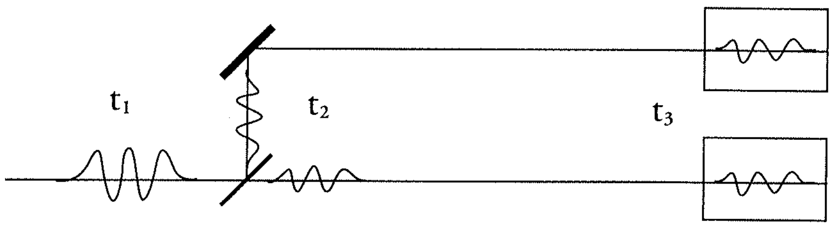

Figure 1: The total wavefunction at three successive times, t_1, t_2, and t_3.

The standard interpretation of this final situation is that the amount of the wavefunction in a particular box (mathematically, its integrated absolute square) is the *probability* of finding the atom in that box. (The generalization of this interpretation is referred to as the "measurement postulate" of quantum mechanics.) For the present case of an equally split wavefunction, this probability is 0.5 for Box A and 0.5 for Box B.

Now consider looking into a large number of box-pairs prepared in this way, each *pair* holding the wavefunction of a single atom. You would find an atom in Box A of a pair about half the time and in Box B half the time. There would always be a whole atom in one box, and the other box would be empty.[7] After finding the atom in a particular box, it is surely there. Thus the previous probability of 0.5 for each box "collapses" to unity for the box in which the atom happened to be found and to zero for the other box. The wavefunction is now totally in the box in which the atom was found. There is nothing problematic, or even unfamiliar, so far. In a carnival "shell game" you might have a pea under one of two shells with a probability of 0.5 for each shell. Lifting either shell instantaneously collapses the probability to zero for one shell and to unity for the other.

But the story according to quantum mechanics is fundamentally different. Quantum physics is completely governed by the Schrödinger equation in the same sense that classical physics is governed by Newton's laws. In classical physics if you specify the initial position and velocity, and the forces acting on an object, Newton's laws tell the future position and velocity — and there is nothing else to say. In quantum physics if you specify the initial wavefunction, and the forces acting, the Schrödinger equation gives the future wavefunction — and there is nothing else to say. Quantum mechanics presumes to tell *everything* there is about the atom's position. The atom's wavefunction tells the *whole story*. If, for example, the wavefunction is totally concentrated in some place, the atom is also there. But if the wavefunction is distributed over some region, and the wavefunction tells the whole story, the atom does not exist in a more specific position.

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[7]One can in fact see single atoms in much the way one sees dust motes in a sunbeam.

In our present case, before your observation the atom's wavefunction was symmetrically distributed in both boxes. Therefore before your look, quantum mechanics claims the atom was *not* in a particular box. But after your look it surely was in a particular box. The existence of an atom in a particular box is thus, according to quantum mechanics, an observer-created reality. We emphasize that this reality of the atom being in a particular box, which is created by an observation of its position, is the same for all subsequent observers. It is thus an observer-*created* reality, not an observer-*dependent* reality.[8]

Since an observer-created physical reality seems unreasonable, one is tempted to explain it away. Therefore reconsider the shell game for a moment. In that situation, which we describe in classical physics terms, probability was *not* the whole story. We understand there was also an actual pea under one of the shells before we looked. In the quantum mechanical case of the atom, one might similarly be inclined to say that immediately before observation, the actual atom must in fact have been in the box in which it was found. One might thus consider it reasonable to claim that the wavefunction is not the whole story, that it only gives the probability for the existence of an actual atom in one box or the other.

There is a problem with that reasonable stance: before your observation of each atom being in a particular box you could have *demonstrated* that each atom was, in fact, a wave in a "superposition state," a state in which it was simultaneously in *both* Box A *and* in Box B. The atom in this superposition state is equally in both boxes. Here's a rough description of an experiment to demonstrate that the atom was indeed in such a state before the observation.

With a not-looked-into box-pair, cut a narrow slit in each of the two boxes and allow the wavefunction to simultaneously leak out of both boxes and impinge on a photographic film at F, as shown in Figure 2a. In the central region of the film, equidistant from the two slits, wave crests from Box A and those from Box B arrive together; they thus add to give a maximum in the amplitude of the wavefunction at that point — a maximum of "waviness." At some point higher up on the film, the distance d_B from Box B is greater than the distance d_A from Box A by precisely one-half wavelength. Here crests from Box A arrive simultaneously with troughs from Box B. The two waves are thus of opposite sign at this position and cancel to give zero amplitude for the wavefunction at this point. Yet farther up on the screen, at places where

[8]While the amplitude of the wavefunction gives a "probability," it is not the probability of an actual atom *being* in a particular box. In the orthodox interpretation of quantum mechanics, which we elaborate upon below, it is explicitly the probability of *observing* the atom in a particular box when one looks. Whether an "observer" need be a conscious being, or whether a measuring instrument is sufficient to collapse a wavefunction, is argued about and will also be discussed.

d_B differs from d_A by an integral number of whole wavelengths, crests from Box A will again arrive simultaneously with crests from Box B to give a wavefunction maximum. A series of wavefunction maxima and wavefunction minima thus exist at the film.

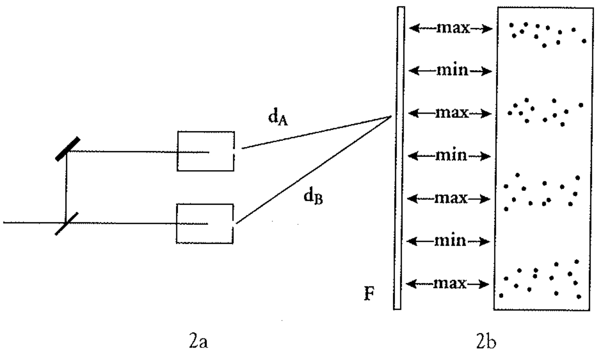

Figure 2: (a) waves emanating from slits in the two boxes travel distances d_A and d_B respectively and impinge upon a film at F; (b) the resultant pattern formed on the film by atoms from many box-pairs.

Since the amplitude of an atom's wavefunction at a particular place gives the probability for the atom to be found there, the atom emerging from the box-pair is likely to appear on the film at places where the wavefunction is large, but can never appear where it is zero. If we repeat this process with a large number of identically prepared and identically positioned box-pairs but with the same film F, many atoms land to cause darkening near positions of wave-function amplitude maxima and none appears at minima. This concentration of atoms forms the "interference pattern" on the film shown in Figure 2b.

To form an interference pattern, waves from *two sources* must overlap to cancel each other at some places. Waves emanating from a single box would "illuminate" the film almost uniformly. To form the interference pattern the wavefunction of *each* atom had to leak out of *both* boxes. Each and every atom invariably avoids appearing in the regions where the waves from the two boxes cancel. Each and every atom therefore had to obey, to "know," a geometrical rule depending on the relative position of both boxes. Therefore, the argument goes, the atom had to *be* equally in both boxes, as an extended wave. That is, it had to be in a superposition state simultaneously in both boxes.

Suppose, instead of doing this interference experiment proving each atom was a wave equally in both boxes, you look into each box-pair. As we described previously, you would find the whole atom in a particular box of each box-pair. But before your look we could have proven — with an interference experiment — that each atom was a wave equally in both boxes.

After your look it was in a single box. It was thus your observation that created the reality of each atom's existence in a particular box. Before your observation only probability existed. But it was not the probability that an actual object existed in a particular place (as was the case in the classical shell game) — it was just the probability of a future *observation* of such an object, which does *not* include the assumption that the object existed there prior to its observation. This hard-to-accept observer-created reality is the measurement problem in quantum mechanics.[9]

In the foregoing description of the box-pair experiments we presented the quantum theory narrative of what was going on. We now try for a more theory-neutral account to emphasize that it is largely the brute experimental facts which raise the issue of consciousness, not any particular theory.

With the physical apparatus described above, prepare 1,000 box-pairs, each with a single atom. Freely, or randomly, select 500 of these box-pairs for interference experiments of the kind described above. For each group of 100 of these 500 box-pairs, do an interference experiment using a different box-pair separation. By these five interference experiments you would confirm that the spacing of the darkenings on the film, which is where the atoms land, is indeed determined by the distance between the boxes of the pair. This demonstrates that each and every atom's behavior in an interference experiment depends on the separation of its box-pair. In other words, each and every atom obeys ("knows") a rule causing it to land at certain places and forbidding it from landing at other places. And since that rule depends on the box-pair separation, each atom had to "know" the box-pair separation. Thus at least *something* of each atom must have been in each box of each pair.

But now, with the 500 box-pairs not used in the above interference experiments, open each box of each pair and look in to confirm that for each box-pair there is a *whole* atom in one of the boxes and that the other box of that pair is *completely empty*. You thus seem to have demonstrated that for the first set of 500 box-pairs, the ones into which you did not look, each atom was not wholly in a particular box. And in the second set of 500 box-pairs, the ones into which you did look, each atom *was* wholly in a particular box. It was thus the experiment which you chose to do (interference or look-into) with a given box-pair which determined whether or not an atom was wholly concentrated in a particular box of that pair. Let us repeat this tricky point in

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[9]If one were in any way able to "peek" into each box-pair to discern in which box the atom was, and *then* do an interference experiment (proving that it had been in both boxes), quantum mechanics would present us with a logical contradiction. However that post-peek experiment would fail to show an interference pattern. Any observation at all which finds the atom in a particular box places it there and precludes the interference of waves emanating from both boxes.

different words. If you look into a box and find an atom, you must have caused it to be there, because, as part of an interference experiment, you could have demonstrated that it had been equally in both boxes of the pair.

We note that it is only because your choice was completely free or random that we can conclude that your observation of an atom in a particular box caused that atom to be in that box. If the choice of which box-pairs to use for the interference experiment and which to use for the look-into-the-boxes experiment were not free, if such choices were somehow predetermined, there would be no demonstration of observer-created properties. It is a crucial point that the existence of the measurement problem in quantum mechanics depends on our assumption of free will.

That the act of observation, however gentle the look, actually creates the physical properties we observe is surely a bizarre idea. It would seem that quantum mechanics is attributing an "unreasonable" behavior to the physical world. Unreasonable behavior demands an interpretation, and the one called the Copenhagen interpretation is our orthodox dogma. (Classical physics described an eminently reasonable world; it demanded no interpretation.)

The Copenhagen Interpretation

The Copenhagen interpretation of quantum mechanics was developed, with Niels Bohr as its principal architect (Bohr, 1934), soon after the strange implications of quantum mechanics were recognized. There are many versions of the interpretation, but the straightforward quantum physics textbook account tacitly accepted by most physicists asserts that the wavefunction with its probability interpretation contains everything that can be known about a physical system. And since every observable property of the system can be deduced from its wavefunction, nothing beyond the system's wavefunction exists. Observations are, of course, always made with macroscopic — therefore essentially classical — apparatus. And, it is argued, determining the behavior of that essentially classical apparatus is all we ever need care about. The Copenhagen interpretation thus maintains that quantum mechanics should be accepted pragmatically as a theory providing correct (albeit statistical) predictions for observations with classical apparatus. The seemingly deeper question, "What is really going on?" need not be asked.[10]

One might nevertheless be tempted to ask about the location of an actual atom in our box-pair just before the atom is observed. Heisenberg's answer was that atoms and other microscopic entities do not exist as "things," they exist only in "potentia," and acquire physical reality, "thingness," only by

[10]See Stapp (1972, 1996, 1997) for an impressive formulation of the Copenhagen interpretation where conscious experience is more central.

being observed. But one might object that large objects are just collections of many atoms, and we must surely regard macroscopic objects as being physically real independently of being observed.

The Copenhagen response is that "big things" indeed have a physically real existence — *for all practical purposes*. All we ever actually observe about a microscopic entity is its effect on our macroscopic, human-scale measuring instruments such as photographic film, Geiger counters, and our eyes. And these instruments behave in a completely classical manner (for all practical purposes, again). When a microscopic entity interacts with a macroscopic measuring apparatus, we can consider its wavefunction to collapse and cause one of the appropriate responses of that apparatus, a darkening of a particular spot on a film, for example, with a probability given by its wavefunction at that spot.

This argument can be seen to present a problem: we have two realms, the quantum and the classical, and the boundary between them, at which wavefunctions collapse, is not well defined. The Copenhagen response here is that a system is to be considered macroscopic when it is so large that we can no longer isolate it from complex interaction with its environment and thus the rest of the world.[11] Such a system behaves classically, for all practical purposes.

But perhaps we wish to go beyond "practical purposes." Since quantum mechanics applies in principle to the large as well as to the small (and there is good reason to believe it will be a precisely valid feature of any future theory) we might ask, "What is *really* going on?"

Extending Copenhagen

The mathematical physicist von Neumann analyzed the problem of how and when an observation is actually made, i.e., how and when the wavefunction collapses (von Neumann, 1932/1955). We apply his reasoning to our atom in a superposition state in two boxes (and we reemphasize that these boxes, until observation, are assumed to be completely isolated from the environment).

Suppose you include in Box A a piece of photographic film on which an atom would cause a dark spot. If you find the atom in Box A, there will be a dark spot on that film. But the film will be blank if the atom is found in Box B. Consider the status of the film after the atom is sent into the box-pair but before you look. The film is, of course, merely a collection of atoms obeying the Schrödinger equation. To the extent that the film and the atom interacting with it are isolated from the rest of the world, they together constitute a

[11]The rest of the world of course includes consciousness.

single quantum system with a single wavefunction. To use Schrödinger's word, the atom's state becomes "entangled" with that of the film. This means that before you look to see which box holds the atom, the atom/film system is in a superposition of the following two states: (1) the state in which the atom is in Box A and the film has a dark spot; and (2) the state in which the atom is in Box B and the film has no dark spot. The atom/film system is simultaneously in these two seemingly contradictory states.

Continue up this measurement chain. Let the film be examined by an automatic photoelectric device with a meter whose pointer indicates either "Yes, a dark spot," or "No dark spot." To the extent that this photoelectric device is also isolated from its environment, according to quantum mechanics it too is in a superposition state simultaneously reading both "Yes" and "No." It was mathematically demonstrated by von Neumann that as long as we consider systems for which the Schrödinger equation applies — which thus always evolve as superposition states — there can be no collapse.

But we *know* that should a conscious observer look at the meter, he or she becomes aware of, experiences, either a "Yes" or a "No." Thus, to the extent that quantum mechanics is the complete theory of the "external" physical world — as it certainly appears to be — only at the very end of the so-called "von Neumann chain," at our "internal" consciousness, can the wavefunction collapse. Thus, in a nutshell, the measurement problem arises because what the fundamental equation of quantum mechanics says happens, and what we can demonstrate to exist — superposition — is not what we consciously experience. Quantum mechanics accounts for our conscious experience by introducing an arbitrary assumption, the measurement postulate, which asserts that the wavefunction gives the probability of a particular future observation or conscious experience.

An association of consciousness with quantum mechanics in this manner says little about the specific aspects of consciousness such as those discussed, for example, in the extensive volume edited by Gazzaniga (1995). It does, however, directly impinge on the so-called "hard problem" of consciousness (Chalmers, 1996), and we will largely focus on this relationship.[12]

Wigner (1961) went even further than von Neumann in connecting quantum mechanics and consciousness. After pointing out the impossibility of formulating the laws of quantum mechanics in a fully consistent manner without reference to consciousness, he speculated boldly — wildly perhaps — that consciousness directly influences the physical world by the collapsing of wavefunctions. He suggested no mechanism for such a process; he rather made the point that quantum mechanics, or physics, as presently formulated

[12]Many speculations have been put forth regarding how certain specific aspects of consciousness might involve quantum phenomena, but we will not substantially address these.

could not be a complete description of the world. Wigner's misgivings about the completeness of the quantum mechanical view were actually voiced by others decades earlier at the very inception of the theory.

Schrödinger's Cat

Some founders of quantum mechanics, including Einstein and Schrödinger, felt that though the theory worked perfectly it was too unreasonable to be the final story. Schrödinger pressed this point with his famous "hellish contraption." Instead of a photographic film in our Box A, there is a cat and a bottle of hydrogen cyanide whose cork is connected to a Geiger counter. If you find the atom in Box A, the atom will have fired the counter, pulling the cork and killing the cat. If you find the atom in Box B, the cat in Box A is alive. According to quantum mechanics, to the extent that the cat and the Geiger counter, etc., can be an isolated system, the cat is in a superposition of both the alive and dead states until its wavefunction is collapsed by a conscious observer. (Whether Schrödinger's cat — or, say, an amoeba — qualifies as a conscious observer is of course a further issue.) For Schrödinger the cat being both alive and dead was an absurdity. His story was intended as a *reductio ad absurdum* argument against taking quantum mechanics seriously.

The traditional response to Schrödinger's challenge is to calculate the vast number of orders of magnitude by which it is impossible — for all *practical* purposes — to isolate a macroscopic system. Even a single photon bouncing off the cat's tail could connect the cat's position to the environment, and thus to conscious observers. The photon can thereby constitute an observation collapsing the cat into either the living or the dead state. The need for isolation and the extreme difficulty of accomplishing it for macroscopic objects is often not fully appreciated in non-technical discussions of quantum measurement.

EPR

A more subtle challenge to quantum mechanics, and one with greater impact, was a paper by Einstein and two young colleagues, Podolsky and Rosen, now referred to as EPR. EPR claimed to prove that unobserved microscopic objects actually had physically real properties, and thus the quantum mechanical description of nature, which did not include such properties, was incomplete.

The EPR argument goes roughly like this. Consider two objects, once in contact but now widely separated, which have correlated properties (e.g., momentum or a spin component). According to quantum mechanics, although these properties do not exist until observed, definite correlations between them can be known. The states of the two objects are entangled, as were the states of the atom and the film just above.

EPR pointed out that if you observe one of the two separated objects, you could immediately know a corresponding property of its partner. For example, in a particular situation, if the spin of one was observed to be in the "up" state, the other must then necessarily be in the "down." According to quantum mechanics, the observation collapsing the wavefunction of one object into the "up" state *instantaneously* collapsed the other object, however remote, into the "down."[13]

But since a physical disturbance, or even information, cannot travel faster than the speed of light, a measurement at one location could not, EPR argued, instantaneously collapse the wavefunction at a remote location (no "spooky actions at a distance," was one way Einstein phrased this objection). Therefore, they maintained, the remote object had to have had its yet-to-be-observed property all along. Since quantum mechanics did not include such properties as realities, EPR claimed quantum mechanics to be an incomplete theory — and that, presumably, was the reason it *seemed* to involve conscious observation.

Bohr, in refuting EPR, agreed that there could be no instantaneous propagation of an actual *physical* disturbance. But he maintained that quantum mechanics' non-local aspect did in fact allow an instantaneous remote *"influence."* We will see below that this quantum non-locality, so disturbing to Einstein, is now experimentally demonstrated. Even though their existence is now completely accepted, these EPR influences remain, for many, mysterious and troubling.

Decoherence

In recent years experimental techniques have allowed quantum aspects to be observed for increasingly large objects. For this reason (and because of the growing interest in the philosophical issues related to quantum mechanics) the nature of the transition from the quantum situation to classicality has received much attention (e.g., Zurek, 1991). The cavalierly stated "collapse" of the wavefunction is replaced by a more meticulous specification of the measurement process: when a microscopic object interacts with a macroscopic system such as a measuring apparatus, or any object which interacts

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[13]This is not a straightforward classical correlation (e.g., tear a dollar bill in half, if one person has the right half the other must have the left). Our microscopic object could have been demonstrated not to be in the "up" state before being observed "up." For example, its spin would have collapsed into either "left" or "right" states by a different form of observation. A classical analogy for EPR would be the amazing situation of two twins independently flipping coins but finding that whenever one got a head the other got a tail.

with the rest of the world — the "environment" — the phases of different parts of that microscopic object's wavefunction get distorted, or "decohere." When the decoherence can be assumed to be essentially complete, a mathematical representation for such a decohered system, the density matrix, has precisely the form of a classical probability statement.

The formulation of decoherence focuses in on the measurement process to show how the phases of the wavefunction of the microscopic system average out. It makes explicit the fundamental *assumption* that we can regard a quantum mechanical formula that has the mathematical *form* of a classical probability to actually *be* a classical probability. However, since probability in quantum physics is the probability of a particular (conscious) observation, while probability in classical physics is that of a preexisting actuality, the issue of consciousness, though put aside, remains controversial and unresolved.

Alternative Interpretations of Quantum Mechanics

Two long-ignored alternatives to the Copenhagen interpretation are today receiving attention. As alternative *interpretations* of the physics they provide no new predictions for the outcome of experiments. There is thus no *experimental* criterion by which to favor or disfavor them over the Copenhagen interpretation. They do, however, offer insight into what might be going on and provide grounds for speculation about new physics.

David Bohm (1952) developed an interpretation which introduces an underlying physical reality which is, in some sense, independent of observation. It is a deterministic interpretation which thus restores a classical-like causality. Bohm achieved this picture by recasting the Schrödinger equation to show that one can logically assume the existence of objective particles whose motion is influenced by a "quantum potential." A particle's quantum potential extends throughout all space, even to regions where that particle's wavefunction vanishes — regions where the particle has no likelihood of being found. Moreover, this quantum potential influencing the motion of a particle depends instantaneously, and sometimes strongly, on the positions of all other objects, however remote they may be. There is no collapsing of the wavefunction in Bohm's picture, but although the universe is strictly deterministic, the initial conditions can never be known. There is thus still uncertainty and probability for all practical purposes.

In Bohm's interpretation, our conscious experience is the observation of his assumed classical-like particles. These classical-like particles are, in fact, introduced solely to account for our experience. The rest of the actual world, the wavefunction and the quantum potential, is forever beyond our ken. In the actual world, that part of the wavefunction in which Schrödinger's cat dies continues to work out its consequences even if we find the cat alive.

Note that a dualism is central to this interpretation, as it was in the Copenhagen interpretation. In a later work, Bohm (1980) developed his interpretation to include matter and consciousness as an unbroken whole.

A second interpretation, the many-worlds interpretation (Everett, 1957), was created to enable quantum mechanics to be applied to cosmology, including conscious observers when conscious observers exist, but not needing them to collapse wavefunctions to actuality when they do not yet exist. In this interpretation the wavefunction changes only according to the Schrödinger equation — there is no collapse. If a wavefunction branches so as to contain both a live and a dead cat, so be it, both the live and dead cat exist. This interpretation must, of course, account for our experience of seeming to see *either* a live *or* a dead cat. Everett argues that that is because the Schrödinger equation applies even to the human observer. On that branch of the wavefunction on which the cat is alive, the observer sees a live cat. And that "same observer" sees a dead one on the other branch. Both terms in the mathematical superposition, both branches, represent equally existing realities.

This bizarre interpretation needs interpretation itself, and two have arisen. One championed by DeWitt (1970) has the separate branches corresponding to separate but non-communicating "worlds," with the conscious observer existing in each of them. Others, in particular, Squires (1990a), feel that Everett's work implies a single external quantum world with all possibilities existing but different consciousnesses coexisting within the observer. This latter view is sometimes referred to as the many-minds interpretation and is favored by Chalmers in his discussion of the hard problem of consciousness (Chalmers, 1966).

Bell's Theorem

Quantum mechanics describes a world that can be seen to lack objective physical properties and involve instantaneous "influences" at large distances. It describes what is thus, in some sense, an unreasonable world. A "reasonable" world should have objects with objectively real properties, properties which do not depend on observation to exist. And in a reasonable world objects should be "separable," i.e., what happened to one object should not be able to instantaneously influence another arbitrarily remote object. In the 1960s John Bell (1964; see also Bell, 1980, which contains the 1964 reference), pondering EPR, wondered whether it was possible for *any* theory describing such a reasonable world to agree with all experimentally observable facts.

Bell proved a remarkable theorem regarding any theory describing such a reasonable world. Bell started with two premises (which he likely did not believe to be true): (1) objects can have properties independently of their being observed ("reality") and (2) objects can be separated so that what happens to one cannot instantaneously influence another remote object ("separability" or "locality").[14] Note that both of these seemingly reasonable postulates are violated by quantum mechanics. Bell showed that in any world in which these two postulates were true, a mathematical relation, now called "Bell's inequality," must exist between certain experimentally measurable quantities. Since neither Bell's postulates nor his proof involve quantum mechanics, the theorem is completely general; it holds for *any* theory. More recently, Stapp (1988) has produced a proof of Bell's theorem using only the locality postulate.

Actual EPR-type experiments showed a clear-cut violation of Bell's inequality (in precisely the manner predicted by quantum mechanics). Thus the final conclusion now is that our world is surely non-local. We are permanently stuck with what Einstein called "spooky actions at a distance." "Reality" in the above sense is still an open question.

Consciousness and Reductionism

Physicists developing quantum mechanics did not seek involvement with the philosophy of consciousness; it was forced upon them. Unlike the well-specified issues physicists comfortably deal with, the issues here remain ill-defined and largely untestable. (It could not be otherwise. Consciousness is yet to be clearly defined or tested in fields that confront it intentionally.) However, testable or not, the mere involvement of consciousness with physics challenges the reductionist view of science which has been dominant for three centuries.

With a reductionist view, explanations of psychological phenomena are often sought in biological terms. In a strong version of reductionism, all psychological phenomena are, in principle, biologically explicable. Consciousness itself is considered by some to be nothing but a manifestation of its bioelectrical neural correlates. As the next step, all biological phenomena can be considered ultimately chemical and electrical. And hardly any chemist doubts that chemical phenomena are fundamentally the interactions of atoms based on quantum physics. And physics, with its explicitly stated fundamental postulates, supposedly rests firmly on basic empirical ground. We can represent this unidirectional reductionist view of explanation schematically by the pyramid in Figure 3a.

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[14]Bell's theorem and the relevant experiments are treated in most quantum physics texts published in the last decade. It was too philosophical an issue for physics texts in earlier days.

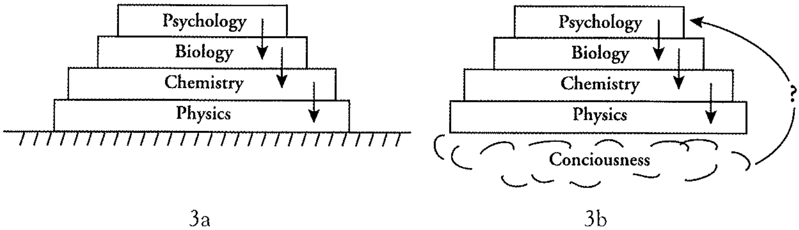

Figure 3: (a) the reductionist pyramid; (b) the reductionist pyramid with consciousness added.

Quantum mechanics, physics' most fundamental theory, challenges such a reductionist view. A crucial premise of the quantum theory, the measurement postulate, explicitly assumes that the wavefunction gives the probability of a particular observational result or conscious experience, not the probability of a pre-existing reality. While there is no agreement on the implications of this entry of consciousness as a fundamental issue in physics, any simplistic view of an objective empirical base upon which physics rests is surely challenged. Therefore add (a somewhat cloudy) consciousness at the base of our pyramid as in Figure 3b. Since consciousness is part of psychology, the nature of explanation no longer seems unidirectional.

We emphasize that the "consciousness" usually encountered in psychology and that encountered in physics may be separated by too many hierarchical levels to ever be related by common explanation. But at this stage, where many crucial questions in both arenas are still not well formulated, attention to certain remarkable correspondences may well be fruitful.[15]

Analogies

In the previous sections of this paper we show how the issue of consciousness arises in quantum physics and thereby impels some physicists to address the mystery of consciousness, even though quantum physics tells very little about *specific* aspects of consciousness. In that treatment we aimed for the most rigor consistent with the level of the discussion. However, in reflecting on the implications of the quantum aspects of nature for issues of consciousness, one is motivated to speculate. And the speculated relationships of quantum phenomena with consciousness go beyond what the findings of physics demand to what they might suggest. Many such suggestions can be identified with compelling analogies between quantum phenomena and consciousness.

[15]Omnès (1994), for example, emphasizes that quantum mechanics offers so many hints about logic, language, and the nature of scientific information that it seems worthwhile to try making use of it.

Analogies involving physics with seemingly unrelated spheres have in the past proved fruitful. Historians identify even loose analogies with classical physics as having had vast impact at very different hierarchical levels (for example, see Gillispie, 1960). Newton demonstrated that a natural law (his "universal equation of motion," Force = mass x acceleration, or F = Ma) governed matter both on earth and in the heavens. It presented the natural world as comprehensible. Analogies with that revelation kindled the intellectual movement called the "Enlightenment."[16]

Newton's physics, per se, was almost irrelevant for the rapid advance of engineering and agriculture which followed the publication of his work. But analogies with Newtonian mechanics were crucial in spurring the industrial revolution. And even in areas remote from science, Adam Smith and Karl Marx were each stimulated by Newtonian analogies to see a (quite different) natural law governing political economy.[17] The first book treating sociology as a science (by Comte in 1856) was called *Social Physics;* people were particles, "social atoms." In psychology the ideas of both Freud and Skinner have been traced to their Newtonian roots (Gillispie, 1960).

Though quantum mechanics has been with us for over seven decades, and its implications rival those of Newton's physics, analogies with its basic ideas have been less fruitful. But they are tempting. Several of the founders of quantum mechanics (including Bohr, Born, Heisenberg, and Pauli) suggested societal analogies which are far broader and considerably looser than the analogies with consciousness we will discuss.[18] Such more specific analogies between the quantum aspects of nature and corresponding aspects of consciousness are so compelling that a fundamental advance in either the measurement problem or consciousness would almost surely impact thinking in the other.

Most of what we discuss here relates to the hard problem of consciousness, which, arguably at least, ". . . has dominated recent discussions of consciousness" (Stapp, 1997). It is this aspect of the problem of consciousness that most speaks to the issue of the measurement problem in quantum mechanics.

Experience. Events in the physical world bring about the neural correlates of consciousness. But these electrochemical phenomena are just further

[16] Nature and Nature's laws lay hid in night:
God said, Let Newton be! And all was light.

Epitaph Intended for Sir Isaac Newton — Alexander Pope

[17] Smith called his the "invisible hand"; Marx claimed to have found the equation of motion of political economy.

[18] The impact of these attempts to relate quantum mechanics to politics and other aspects of society has recently been discussed in relation to contemporary controversies related to the study of the methods of science (Beller, 1998).

aspects of the physical world. What seems somehow different is our *experience* of things: pain, redness, or the experience of seeing the pointing of a meter to "7" on its scale. How the physical world brings about such actual conscious experiences is the "hard problem" of consciousness (Chalmers, 1996).

An analogous problem arises in quantum theory. In the physical world described by the Schrödinger equation, *all* possibilities evolve, no particular thing ever actually *happens*. Before our observation, the atom we discussed above was in both boxes simultaneously. If an isolated measuring instrument interacts with a system in a superposition state, quantum mechanics tells us that the instrument's meter simultaneously indicates readings corresponding to all the states of the superposition. (Similarly, Schrödinger's cat is both dead and alive.) To account for our actual experience of particular events — the atom in the upper box, or the meter reading "7," or the cat alive — "the measurement postulate" is patched into the quantum theory to account for the fact that observation somehow brings about a "collapse" of the superposition state wavefunction into a single experienced reality. How observation can bring about such actuality is the measurement problem in quantum mechanics. How quantum mechanics' physical world of "only possibilities" brings about our experience of actual events could be called the "hard problem" of quantum physics and is analogous to the hard problem of consciousness. This issue does not arise in classical physics.

For both consciousness and quantum mechanics some theorists assert that no "hard problem" in fact exists. Identifying the conscious experience of redness or the experience of seeing "7" on the meter with the neural correlates of that consciousness experience, a materialist or identity theorist can claim there is nothing more to say. Similarly, identifying the observation of "7" on the meter with a collapse of the wavefunction leading to that pointer position, a majority of physicists would likewise claim there is nothing more to say. Whether or not a legitimate "hard problem" actually exists is today an argued issue in both consciousness studies and physics.[19]

Duality. Arguably at least, the existence of consciousness can never be deduced from the fundamental biology and electrochemistry of the material brain. The consciousness we experience is postulated to be an independent phenomenon. Thus a duality is suggested in consciousness theory (for example, Chalmers, 1995). The traditional reference is to the mind–body duality. Analogously, the existence of our experienced particular outcomes cannot be deduced from the fundamental Schrödinger equation, according to which all

[19]In psychology and philosophy the problem of conscious experience has gained considerable attention in the last decade or so. The same is true for the analogous measurement problem of quantum mechanics. This may be a coincidence, but perhaps something in society today motivates attention to both issues.

possibilities continue forever to evolve. For example, an object's spreading wavefunction is the only physical reality given by the Schrödinger equation, but observation finds the object at a particular location, i.e., as a "particle." The particle nature we experience is, in a strict sense, independent of the fundamental physics given by the Schrödinger equation, and is introduced separately through the measurement postulate. Thus a duality is also suggested in quantum theory (for example, Squires, 1991). The traditional reference is to the wave–particle duality.

The unexplained process by which the physical realm described by quantum mechanics is connected to the classical-seeming realm of our experience can be considered to take place essentially anywhere along the von Neumann measurement chain. The placement of the boundary between the quantum and the classical realms can be seen as arbitrary. Klein (1991) emphasizes the movability of this "cut" as an example of the beauty of the quantum theory. The pragmatic attitude is to use quantum mechanics where one must and simpler classical mechanics where one can. For practical purposes, the cut is then considered to be at the (ill-defined) boundary between the microscopic and the macroscopic. Others (von Neumann, Wigner, and Stapp, for example) explicitly place it at the point of conscious perception. But no matter where you slice it, quantum mechanics is fundamentally dualistic, and the dualism looks much like that involved in consciousness.

Classical physics does not rule out the possibility of an extension to include conscious experience within its framework. But some theorists deny the possibility of duality by arguing that a signal from a non-material mind could not carry energy and thus could not influence material brain cells (e.g., Dennett, 1991). Because of this inability of a mind to supply energy to influence the neurons of the brain, it is claimed that physics demonstrates an inescapable and fatal flaw of dualism. However, no energy need be involved in determining to *which particular* situation a wavefunction collapses. Thus the determination of which of the physically possible conscious experiences becomes the actual experience is a process that need not involve energy transfer. Quantum mechanics therefore allows an escape from the supposed fatal flaw of dualism. It is a mistake to think that dualism can be ruled out on the basis of physics.

"Non-physical" influences. If we accept a duality, mind and brain are separate entities, but the mind somehow influences the brain. There is, of course, no accepted physical model for such interaction. It is sometimes speculated that the connection of the mind with the material brain takes place by some presently unknown, perhaps in some sense "non-physical," influence. Seemingly non-physical quantum mechanical influences are actually demonstrated in the EPR-type interactions discussed above, where the observation of one object of a correlated pair collapses the wavefunction not only of that

object but the wavefunction of its remote partner as well. Such EPR influences connecting one object with another are instantaneous and undiminished over (arbitrarily) large distances. They do not involve any known physical force. Though Einstein derided such influences as "spooky actions at a distance," we now know they exist.

In studies of both consciousness and the quantum measurement problem, seemingly non-physical influences are sometimes seen to hint of a need to look outside the presently conceived boundaries of science. Should no purely bioelectrochemical model of the brain be able to account for consciousness, we apparently must go beyond usual reductive explanations to seek fundamentally new principles, the "psychophysical principles" suggested by Chalmers, for example. The quantum measurement problem raises analogous suggestions of the need for new principles.

In the quantum mechanical case two new fundamental principles have actually been proposed. They have opposite motivations regarding the connection of quantum mechanics with consciousness. In one proposal the need for physics to address issues of observation and consciousness appears almost avoided, while in the other, addressing consciousness is the main intent. In the first (Ghirardi, Rimini, and Weber, 1986), a new unexplained process is postulated, something beyond standard quantum mechanics and the Schrödinger equation, for which a modification is proposed. This speculated new process would rapidly collapse the wavefunctions of large objects while allowing small objects to display their strange superpositions. It would thus remove the problem illustrated by Schrödinger's cat. There is, however, no experimental evidence for any phenomena of this kind, and the issue of observation for objects of atomic scale would remain in any event, leaving the fundamental measurement problem unresolved. In the second proposal, Penrose (1994) postulates similar automatic collapses due to quantum gravitational effects for objects that approach macroscopic size. He even points to sites in the brain (microtubules in neurons) where he speculates superposition states exist and collapses take place. In contrast to the Ghirardi et al. proposal, Penrose's explicitly connects each such collapse to a conscious experience.[20]

Observer-created reality. Pop psychology's, "I create my own reality," argues for the creation of one's perceived social reality. But sometimes a stronger role for consciousness is implied, such as metaphysical effects of the conscious mind on the body or even on external phenomena. Discussions involving consciousness can range to the extreme such as the solipsism of Berkeley's: "To be is to be perceived." Though it would be preposterous to

[20]It may not be proper in the case of quantum mechanics to regard a proposed new principle as non-physical, no matter how strange it might seem. If shown to be valid, it would no doubt be encompassed within an expanded version of physics.

take a solipsistic view literally, the quantum measurement situation can be framed similarly. A frequently seen succinct summary of the Copenhagen view is: "No (microscopic) phenomenon is a real phenomenon until it is an observed phenomenon." We illustrated the basis for this statement in the observer-created reality of an atom's existence in one of the two boxes. The Schrödinger's cat story forced this observer-created reality into the macroscopic realm — in principle, at least.

Quantum mechanics actually poses a further dilemma. Only those states of our atom in which it is wholly in one box or the other are ever actually observed. We firmly infer but never directly see the strange state which is a superposition of these two states, i.e., the state in which the atom is simultaneously in both boxes. We never actually see the strange state in which Schrödinger's cat is simultaneously dead and alive. But in the quantum theory the status of the states we actually observe is completely equivalent to those we never observe. Why we see only certain special states is not explained by the quantum theory.

An answer to this question which directly involves human consciousness and observer-created reality is suggested by Squires (1990b). In quantum theory a measuring apparatus collapses a wavefunction into one of the states characteristic of the measuring apparatus, one of the apparatus' so-called eigenstates. For example, if the measuring apparatus is a piece of film, its eigenstates are the states in which different sets of its grains are "exposed." Thinking of the film as the observer (with a Copenhagen interpretation view) the film collapses the spread out wavefunction of an impinging atom or photon to the position of one of its grains. Going beyond Copenhagen, Squires argues that the eigenstates of the ultimate observer, a conscious human, are always those of position; the only thing we ever actually observe is position. The shape of something is the position of its parts, motion is determined by position at two different times, we feel something by the position of pressure on our skin, even color is determined by light intensity at the position of certain cones in the retina. The difference between a live cat and a dead cat can be considered to be the position of the cat's parts. If humans are position-measuring instruments, we would never see superpositions which correspond to something simultaneously being in different positions. Squires speculates that observers with a different kind of consciousness might collapse wavefunctions differently — and, to us, "strangely."

The binding problem. Binding creates the unity of conscious experience in which disparate psychological units or pieces of information are hooked together to form the complete perceptual event. How this happens is termed the binding problem (Hardcastle, 1994, 1996). With the relative absence of multi-modal association areas in the cortex, it is not clear how, for example, a cat's color, size, and orientation come together to form a perception of the total cat. Or, to be more specific, it is not clear how observing the tip of a cat's tail protruding from behind the door suddenly creates the concept of a whole cat behind the door. Somehow the mind can almost immediately connect a single aspect or part with the total entity.[21]

An analogous immediate connection of a single aspect or part with the complete entity is a fundamental characteristic of the collapse of the wavefunction in the observation process. An object's total wavefunction can be widely distributed in space and in a superposition state representing all of the possible outcomes of an observation. But the entire wavefunction instantaneously collapses to just one actual outcome when a particular location or a particular aspect is observed. Thus when Schrödinger's cat is in the simultaneously dead and alive superposition state, the tip of its tail is simultaneously low on the floor of the box (in the dead state) and high in the air (in the living state). Observing the tip of the cat's tail to be in the high state immediately, by EPR-type influences, collapses the entire wavefunction and creates the complete cat in the living state.

Non-locality/non-spatiality. In consciousness, the phenomenon of non-locality, or the more striking speculation of non-spatiality, seems likely related to binding. As an example, the experience of a flash of yellow light is apparently not located in a particular part of the brain. The conscious experience of a physical entity is suggested to have a non-local, even a non-spatial, character (Clarke, 1995; McGinn, 1995). Similarly, when the wavefunction of our single atom was spread over two boxes, the atom itself was not located in either single box. (Recall that, according to quantum mechanics, the wavefunction is the whole story; there is no "actual atom" in addition to the wavefunction.) Objects in quantum mechanics are quite generally non-local. In fact, after Bell's theorem and the experiments it stimulated, we know that non-locality is necessarily inherent in any theory that correctly describes the world.

The analogy of quantum aspects of nature with a non-spatial consciousness is stronger yet. Strictly speaking, the wavefunction for our atom was not *inside* the two boxes. The wavefunction of an object does not exist in physical space the way water waves or electromagnetic waves exist in classical physics. The wavefunction — all that physically exists according to the standard interpretation of quantum mechanics — resides in a multidimensional "Hilbert space." As an example, consider the wavefunction of a diatomic molecule, where the probability of one atom's being in a particular place depends on the position of its partner. This two-atom wavefunction is a function of the three coordinates of each atom. It is a function in a six-dimensional space. The wavefunction of a system of N objects exists in a

[21] We do not suggest that binding seems a problem beyond normal resolution within neuroscience.

3N-dimensional mathematical space. (Classical probability functions can be similarly multidimensional.) As is sometimes suggested for consciousness, wavefunctions are non-spatial.

Observing one's thoughts. According to the Heisenberg uncertainty principle (which can be deduced from the Schrödinger equation) an observation of the position or shape of an object makes its motion less certain. On the other hand, an observation of the object's motion introduces an uncertainty in its position. David Bohm suggested something like the following analogy. If I concentrate on (observe) the content of a thought (in a sense, its position or shape), I inevitably change its development, or where it is going (in a sense, its motion). On the other hand, if I concentrate on where a thought is going, I lose the sharpness of its content.

This analogy can be extended. A collection of particles which have once interacted with each other acquire a permanent EPR entanglement. Their behaviors are therefore correlated. Should a new particle interact with any single member of the collection, it immediately entangles with every other. It joins the many-particle entangled state. An observation of any one particle instantaneously collapses aspects of the total wavefunction and thus remotely influences the behavior of each of the others. The degree of influence depends upon the extent of the mutual entanglement. Analogously, a new input to conscious memory seems to immediately associate (entangle) with all previously associated items. Concentrating on (observing) any particular memory item brings to conscious awareness (collapses) aspects of all the others and influences them. The degree of influence on various memory items depends upon the extent of the mutual association.

Parallel processing. The brain appears to have a natural rate of processing information which is vastly slower than that of a computer. Nevertheless, in many situations, for example, moral judgements, face recognition, and even, according to Penrose (1997), certain very simple chess moves, the brain can come to appropriate conclusions faster than any computer. To simultaneously assess complex situations and determine appropriate behavior, the brain gets its power not by speed but, probably, by parallelism — by considering many aspects at the same time.

The computer industry, constantly pressing for more power, now looks to parallelism. Classically, large-scale parallelism requires a large number of processors each running one program. But in a quantum computer (Lloyd, 1995; Williams and Clearwater, 1998) each logical element, instead of being in one state or another (1 or 0), can be in a superposition state (simultaneously 1 and 0). If we start a quantum computer with all its input bits in superpositions of 1 and 0, the computer can then be in a superposition of all possible inputs. A quantum mechanical logic circuit can then carry out all computations at once. Stapp (1997) argues that quantum processes are in principle so vastly superior in solving search-for-appropriate-behavior problems that it is likely that organisms use quantum search procedures.

A serious problem intrinsic to quantum mechanical computation is decoherence: if the relative phases of parts of the system are disturbed by interaction with the environment external to it, the system cannot function. The required isolation is difficult to achieve or even to envision and prompts objections to suggestions for the practical realization of quantum computers. It also stimulates objections to suggestions of quantum phenomena being significant in the brain. In principle at least the isolation problem is not insurmountable. Superconductors and superfluids are macroscopic quantum mechanical systems where some contact with the environment does not cause decoherence. There is no fundamental reason prohibiting more complex phenomena to be sufficiently isolated. Stapp (1997) and Lloyd (1996) point out that even a small quantum effect could give a large enhancement.

The psychological interpretation. Analogous to those who hold to identity theory and deny the existence of the hard problem in consciousness, some deny the existence of an unsolved hard problem in quantum mechanics. The collapse of the wavefunction is held to be merely the manifestation of the decoherence of a quantum system in its interaction with the macroscopic environment. If the quantum aspects of nature are counterintuitive, those claiming that no real measurement problem exists would tell us to just admit that nature need not correspond to human intuition. Accepting that position, instead of seeing the measurement problem as a phenomenon of nature needing exploration, can we see it as an issue in psychology worth investigation? Namely, what is it about the human mind that causes the observed quantum aspects of nature to be so counterintuitive?

Merely to say that we evolved in a world where classical physics was a good approximation is not enough. We evolved in a world where the sun apparently moved across the sky as the earth stood still. Nevertheless, the once counterintuitive Copernican picture was soon accepted. We evolved in a world where things moved slowly compared to the speed of light. Though it is difficult for physics students to become comfortable with relativity's demonstration of time passing at different rates in different frames, they soon accept it with equanimity. We find no need for "interpretations" of relativity. The situation in physics with quantum mechanics is unique.

If no measurement problem, no hard problem, actually exists in quantum mechanics, what is it then about the organization of our brains that makes quantum mechanics, nature's most fundamental law, so hard to accept without lingering qualm? An answer to this question could be called the "psychological interpretation of quantum mechanics." The intellectual outlook analogous to denying the hard problem in quantum mechanics is denying the hard problem in consciousness and claiming that conscious experience is merely a manifestation of the neurobiology. If so, what is it in the organization of our brains that makes consciousness, the most fundamental aspect of our being, so hard to accept without lingering qualm?

Explicit Models

In presenting analogies between consciousness and quantum mechanics which may motivate the development of explicit theories, we have not done justice to the existing models of consciousness involving quantum mechanics — notably those of Beck and Eccles (1992), Stapp (1993, 1996), and Penrose (1994). We consider such attempts important, even profound. For speculations to mature to solid theories, they must of course display practically testable predictions exposing themselves to the risk of falsification. Some of the physics behind present models may in fact be testable, but without agreed-upon tests for the existence of consciousness, the establishment of a quantum mechanical aspect of consciousness must remain elusive. It is not inconceivable, however, that experimental evidence of macroscopic quantum phenomena in the brain could be obtained, and any such demonstration would surely be suggestive of the connection of quantum phenomena with consciousness.

Conclusion

The so-called "easy problems" of consciousness, those focussing upon the neural correlates of consciousness, no doubt fit into the picture presented by classical physics, a world view without exotic mystery. Postulating the hard problem of consciousness introduces a mystery. The introduction of an unnecessary mystery is surely objectionable. However, the experiments stimulated by Bell's theorem show that our world cannot ever be explained in terms of a local reality. The EPR influences that many regard as mysterious must thus exist in *any* correct fundamental theory of nature. Our world seems to display an intrinsic mystery. The objection that postulating the hard problem of consciousness introduces an unnecessary and new mystery is thus somewhat less strong.

With the quantum theory, physicists encountered a philosophical enigma: the measurement problem. In addressing it they and others have been forced to raise issues involving consciousness. And in studies of the hard problem of consciousness, philosophers and others continue to speculate about a role for quantum phenomena. Whether or not quantum mechanics will be relevant in explanations of consciousness is an open question. But the two fields do seem to have something to say to each other, and certain analogies can be tantalizing. It would be surprising if a substantial advance in one arena provided no insight into the other. It is not inconceivable that the hard problem of consciousness and the hard problem of quantum mechanics might just possibly be aspects of the same mystery. Quantum phenomena being relevant to consciousness is a long shot, but there seem to be no easy shots at the hard problem.

References

Beck, F., and Eccles, J.C. (1992). Quantum aspects of brain activity and the role of consciousness. *Proceedings of the National Academy of Science*, *89*, 11357–11361.

Bell, J. S. (1964). On the Einstein–Podolsky–Rosen paradox. *Physics*, *1*, 195–200.

Bell, J. S. (1980). Speakable and uspeakable in quantum mechanics. Cambridge, England: Cambridge University Press.

Beller, M. (1998). The Sokal hoax: At whom are we laughing? *Physics Today*, *51*, 29–34.

Bohm, D. (1952). A suggested interpretation of quantum mechanics in terms of "hidden" variables. *Physical Review*, *85*, 166–193.

Bohm, D. (1980). *Wholeness and the implicate order*. London, England: Routledge & Kegan Paul.

Bohr, N. (1934). *Atomic theory and the description of nature*. Cambridge, England: Cambridge University Press.

Chalmers, D. (1995). Facing up to the problem of consciousness. *Journal of Consciousness Studies*, *2*, 194–219.

Chalmers, D. (1996). *The conscious mind*. New York: Oxford University Press.

Clarke, C. J. S. (1995). The nonlocality of mind. *Journal of Consciousness Studies*, *2*, 231–240.

Dennett, D. C. (1991). *Consciousness explained*. New York: Little Brown.

DeWitt, B. (1970). Quantum mechanics and reality. *Physics Today*, *23*, 30.

Elitzur, A. C. (1989). Consciousness and the incompleteness of the physical explanation of behavior. *The Journal of Mind and Behavior*, *10*, 1–20.

Elitzur, A. C. (1991). Neither idealism nor materialism: A reply to Snyder. *The Journal of Mind and Behavior*, 12, 303–308.

Everett, H. (1957). "Relative state" formulation of quantum mechanics. *Reviews of Modern Physics*, 29, 454–462.

Gazzaniga, M. S. (Ed.). (1995). *The cognitive neurosciences*. Cambridge, Massachusetts: MIT Press.

Ghirardi, G.C., Rimini, A., and Weber, T. (1986). Unified dynamics for microscopic and macroscopic systems. *Physical Review*, *D34*, 470–491.

Gillispie, C.C. (1960). *The edge of objectivity*. Princeton: Princeton University Press.

Hardcastle, V. (1994). Psychology's binding problem and possible neurobiological solutions. *Journal of Consciousness Studies*, *1*, 66–90.

Hardcastle, V. (1996). How we get there from here: Dissolution of the binding problem. *The Journal of Mind and Behavior*, *17*, 251–266.

Klein, S.A. (1991). The duality of psycho-physics. In A. Gorea (Ed.), *Representations of vision* (pp. 231–249). New York: Cambridge University Press.

Omnès, R., (1994). *The interpretation of quantum mechanics*. Princeton: Princeton University Press.

Lloyd, S. (1995). Quantum-mechanical computers. *Scientific American*, *273*, 140–145.

Lloyd, S. (1996). Universal quantum simulators. *Science*, *273*, 1073–1078.

McGinn, C. (1995). Consciousness and space. *Journal of Consciousness Studies*, *2*, 220–230.

Penrose, R. (1994). *Shadows of the mind: A search for the missing science of consciousness*. New York: Oxford University Press.

Penrose, R. (1997). *The large, the small, and the human mind*. New York: Cambridge University Press.

Squires, E. (1990a). *Conscious mind in the physical world*. Bristol, England: Adam Hilger.

Squires, E. (1990b). Why is position special? *Foundations of Physics Letters*, 3, 87–93.

Squires, E., (1991). When does a wave become a particle? In P. Cvitanovic, I. Percival, A. Wirzba (Eds.). *Quantum chaos – Quantum measurement* (pp. 273–281). Dordrecht, Netherlands: Kluwer Academic Publishers.

Squires, E. (1998). Why are quantum theorists interested in consciousness? In S. Hameroff, A. Kaszniak, and A. Scott (Eds.), *Toward a science of consciousness* (pp. 609–618). Cambridge, Massachusetts: MIT Press.

Stapp, H. P. (1972). The Copenhagen interpretation. *American Journal of Physics*, *40*, 1098–1116

Stapp, H. P. (1988). Quantum nonlocality. *Foundations of Physics*, *18*, 427.

Stapp, H. P. (1993). *Mind, matter and quantum mechanics*. New York: Springer–Verlag.

Stapp, H. P. (1996), The hard problem: A quantum approach. *Journal of Consciousness Studies*, *3*, 194–210.

Stapp, H. P. (1997). Science of consciousness and the hard problem. In L. Vandervert (Ed.), *Understanding tomorrow's mind: Advances in chaos theory, quantum theory, and consciousness in psychology* (pp. 69–92). New York: Institute of Mind and Behavior. (Special issue of *The Journal of Mind and Behavior*)

von Neumann, J. (1955). *Mathematical foundations of quantum mechanics*. Princeton, New Jersey: Princeton University Press. (Originally published 1932)

Wigner, E. (1961). Remarks on the mind–body problem. In I. J. Good (Ed.), *The scientist speculates* (pp. 284–302). London, England: Heinemann.

Williams, C. P., and Clearwater, S. H. (1998). *Explorations in quantum computing*. New York: Springer–Verlag.

Zurek, W. H. (1991). Decoherence and the transition from quantum to classical. *Physics Today*, *44*, 36–44.