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To the Brink of Enlightenment

The Quantum Brain

By: Stuart HameroffM.D., Ph.D.

Quantum, as the term is used in physics, means the smallest amount of something it is possible to have. The quantum world is the microworld of quarks and leptons, which appear to be the fundamental building blocks of reality. What does this have to do with the brain? The answer is that the brain is matter—stuff—and the ultimate question for brain science is how stuff, the physical brain, gives rise to consciousness. (That it does give rise to consciousness is a root assumption of modern neuroscience.) Searching for that link, which has eluded philosophers and scientists for at least two millennia, some scientists (I am one) have begun to probe the brain at the quantum level of subatomic particles and fascinatingly strange happenings.

Jeffrey Satinover's lofty and ambitious goal in *The Quantum Brain* is not only to examine the origins of consciousness at the quantum level but to provide us with answers to an ancient, basic set of questions that will amount to "a revolution in our understanding of ourselves, of life in general, even of God." Are we (like everything else in the universe) purely mechanical, trapped in deterministic, programmed responses to a deterministic, programmed environment? Was everything set in motion for all time at the Big Bang, so that, consistent with laws identified by Isaac Newton and other great physicists, the universe is playing out an inevitable story?

If so, how can we, as conscious humans, make choices? Regardless of what we choose are we headed toward an inevitable outcome? As the biologist Thomas Huxley bleakly concluded, we may be mere “helpless spectators, conscious automata,” with no free will.

Is there an alternative? Even when physics introduces new levels of complexity, they just offer us a more intricate determinism. Nor does injecting an element of the random in our brains, at the level of nerve-cell activities, help with the problem of free will. Random is not the same as free. In fact, if there is some randomness in so-called nonlinear systems, it just accelerates deterministic processes.

Satinover, however, suggests another form of randomness: seeming uncertainty and unpredictable behavior at the quantum level of atoms and subatomic particles.

Quantum generally refers to the smallest possible discrete, fundamental amount of something. For example, photons are quanta of energy. At the atomic/subatomic scale at which quantum effects commonly occur lies a Pandora’s box of strange and seemingly irrational behavior. Mechanistic predictability breaks down. Uncertainty reigns. Definiteness disappears. Particles at the quantum level can behave of their own accord (randomly, to our eyes), as if they had a will, an ability to choose the timing and course of events. As Satinover asks: “Why does a radioactive nucleus spit out an alpha particle now but not then, and completely at random?...It just does so, whenever it wishes.” Could this “freedom” of an alpha particle, or an electron, or various quantum particles, translate into any kind of freedom of choice that we as humans covet or even recognize?

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CONSCIOUSNESS AND QUANTUM THEORY —STRANGE BEDFELLOWS

For readers who are unfamiliar with quantum theory but seek some insight into how it is being applied to the challenge of explaining consciousness—now an active international field of study—I will attempt here a brief primer on quantum physics. (Others may wish to skip ahead, where I resume the story of *The Quantum Brain*.)

The quantum realm is the foundation of our reality, yet it is a strange and mysterious place. In our everyday world (as described by classical physics), things are definite and fairly predictable. Yet at its quantum base the universe seems to be governed by different laws. This dichotomy haunts physics, for there is no obvious boundary between the quantum and classical realms.

The most bizarre quantum feature is “superposition.” Quantum particles somehow exist in multiple locations or states—in superposition of all possible states simultaneously. Objects, at least small objects, can be literally beside themselves, existing in two places at once. When such quantum superpositions end, each multiplicity of possibilities chooses one definite state or location in our familiar world of classical physics. Because quantum systems are governed mathematically by an equation called the quantum wave function, and because quantum systems seem to disappear abruptly, the transition from quantum to classical states is often termed *collapse* (or sometimes *reduction*) of the quantum wave function.

Experiments in the early 20th century seemed to show that quantum superpositions persisted until humanly observed or measured. If a machine measured a quantum system, the results appeared to remain in superposition within the machine until actually looked at by experimenters. Therefore the prevalent view in physics at that time (the “Copenhagen interpretation,” after the home city of its chief proponent, the Danish physicist Niels Bohr) was that conscious observation led to collapse of the wave function. Scientists and philosophers shook their heads at this conclusion.

To illustrate the apparent absurdity of the notion, Erwin Schrödinger in 1935 described his now-famous thought experiment known as Schrödinger’s cat. Place a cat in a box with a vial of poison. Outside the box, a quantum event—for instance, passage/not passage of a single photon through a half-silvered mirror—is causally connected to the release of the poison inside the box. Since the photon both passes and does not pass through the mirror, the poison is both triggered and not triggered. Therefore, by Bohr’s logic, the cat must be both dead and alive until the box is opened and the cat observed. At that moment (according to the Copenhagen interpretation) the system chooses either dead cat or live cat; consciousness essentially selects reality. The precise choice or resolution in any given collapse (for example, dead cat versus live cat) was believed to be random and probabilistic, a prospect Einstein found unsettling. “God does not play dice with the universe,” he famously proclaimed.

Schrödinger intended his cat to be a “burlesque example” of the consequences of the Copenhagen interpretation, and indeed it turns out that conscious observation is not necessary for collapse of a wave function. The prevalent view today is that any interaction of a quantum superposition state with the classical environment will be disruptive, causing “decoherence.” But what happens to quantum superpositions when they neither are observed nor interact with the classical world? Do they collapse? We don’t know, so Schrödinger’s cat remains a problem.

This paradox suggests that quantum theory must be incomplete and that other approaches to the problem of collapse or reduction of the quantum wave function are needed. One suggestion is the “multiple worlds” view put forward by Hugh Everett, which holds that each apparent collapse is a branching of reality; a dead cat in this universe corresponds to a live cat in a newly formed parallel universe. If so, there must exist an infinity of worlds.

David Bohm’s schema for quantum reality avoids collapse altogether, while still other views hold out for an objective factor causing collapse or reduction. These are called objective reduction (OR) theories. For example, Ghirardi, Rimini, and Weber predicted that OR would occur at a critical number of superpositioned particles ($\sim 10^{17}$). The theory has not held up to experimental evidence, but another OR theory, put forth by the British mathematical physicist Sir Roger Penrose, and based on quantum gravity, is still in contention.

Quantum gravity is an approach to understanding the fundamental makeup of reality, a proposed geometry of space/time. Penrose begins by considering superposition.

What does it mean to be in two places at once? The answer, he decides, is that underlying reality itself—fundamental space/time geometry—actually separates during the superposition. This is very much like the multiple worlds view, but with a catch. The catch is that in the Penrose view these separations are unstable and, before leading to anything so drastic as a new universe, will reduce, or collapse, to a single, unseparated reality.

Can the phenomenon of quantum collapse explain the features of consciousness? In his books *The Emperor's New Mind* and *Shadows of the Mind*, Penrose suggests that it can, that indeed quantum gravity self-collapse is an essential feature of consciousness. He argues, in essence, that "choices" (the resolution of multiple possibilities into one definite state) made during this type of collapse are what distinguish our thought processes from the behavior of completely deterministic classical computers. Applying this line of thinking to other aspects of consciousness, Penrose suggests that preconscious processing corresponds with quantum superposition, and that instantaneous quantum gravity self-collapse corresponds with a moment of conscious experience. According to this theory, consciousness would involve a series of such quantum-state reductions.

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Penrose's stunningly strange idea begins to seem more connected to the world we know when we consider that quantum theory is being applied successfully to a new kind of computing. The collapse of multiple quantum possibilities to definite classical states is the key to a burgeoning new information technology known as quantum computation.

QUANTUM COMPUTATION— THE NEXT BIG THING

In conventional computation, elementary information exists in discrete "bit states," the basic digital 1 or 0. In what is called quantum computation, however, elementary information can exist in quantum superposition—for example, as "qubits" of both 1 and 0 simultaneously. While in this schizophrenic state, qubits interact (or compute) with each other; they each then reduce or collapse to a particular set of states—the solution or answer. Quantum computers offer enormous potential advantages for certain applications, and prototype devices have been constructed. Comparisons among brain, mind, and quantum computers are inevitable.

Other quantum features lend themselves to possible explanations of other aspects of consciousness. Two examples:

In something called "quantum coherence," particles lose their individual identity and become part of a common unit (governed by one wave function, as are lasers). This type of quantum coherence has been suggested as an explanation for the unitary nature of self, the "one-ness" of conscious experience.

In nonlocal quantum “entanglement,” particles once unified in a common quantum state remain somehow connected or “associated” at a distance. When one particle is then measured, its quantum partner reacts instantaneously, regardless of its location. This quantum coupling-over-distance has been proposed as a basis in the brain for some kinds of memory, as well as emotional and so-called paranormal connections between conscious individuals.

The necessary implication of these speculations would be that evolution has created biological mechanisms for organized quantum processes, and one of these is quantum computation in the brain. There is a fairly long list of proposed quantum structures in the brain at the level of the neuron or smaller: receptor proteins, membrane lipids, presynaptic vesicle release structures, gap junctions, neurotransmitter molecules, calcium ions, DNA, RNA, and microtubules. Roger Penrose and I have put forth a model of consciousness based on quantum computation in microtubules within the brain’s neurons. But although these quantum models can potentially solve enigmatic features of consciousness, they are viewed skeptically for apparently good reason. Quantum computers of the technological realm require isolation and near-absolute-zero temperatures to work. The brain operates at our body temperature, is 60 percent water, and is electromagnetically noisy. Large-scale quantum states are deemed to be impossible in the brain because a single ion, photon, or thermal vibration can cause decoherence and random reduction to classical states. No way, says the conventional wisdom, can large-scale quantum states take place within the physiology of the brain.

But wait. Proponents of a quantum approach to consciousness (and I am unabashedly one) point to brain mechanisms that may provide necessary quantum isolation. For example, the microtubules that are part of the skeleton of neurons have quantum-protective ion layers and are encased in a protective gel. There are other ways as well that our brain biology may have solved the problem of sustaining quantum isolation. After all, since quantum computation is likely to be beneficial to an organism’s survival, perhaps four billion years of evolution managed to solve the decoherence problem.

So the question is: At what level of organization do quantum effects cease to exist in, or become “washed out” of, a system like the brain? Where in the brain does the wave function collapse? Where is the quantum/classical boundary? Conventional wisdom says that quantum effects are washed out at a fairly low level, say, at the level of individual molecules and ions. On the other hand, advocates of a quantum consciousness view see more highly organized and spatially extended quantum states—for example, in and among different microtubules in the same neuron and other neurons.

This question returns us to Jeffrey Satinover’s book, for in it he searches for the quantum world within the brain.

DESCENDING INTO THE QUANTUM BRAIN

Conventional wisdom sees the brain as a “nested hierarchy” of information-processing systems. In this schema, the firings of nerve cells and the transmissions between them are at the bottom level of the hierarchy— the fundamental units of information, analogous to bits in a digital computer. Unfortunately, these classical, deterministic activities are unable to account for free will (or other enigmatic features of consciousness). We are driven to delve more deeply inside the neuron, searching for a way to connect up with the quantum level, where our deterministic shackles may fall aside.

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Alas, however, the same conventional wisdom—for physicists, at any rate—holds that delicate quantum effects cease to exist in warm biological systems. Presumably that would make them unavailable to influence activities on the level of the neuron. The challenge is to show how brain-cell firings and communication between cells may be influenced by weak, delicate, and very small-scale quantum processes. To put it another way: At what level of organization are quantum effects available to us to explain biological phenomena? Can that level, in turn, influence activities at the neural level?

Seeking an answer, Satinover takes us downward to a finer scale of biological processes, inside neurons at the level of the neuron’s internal scaffolding, or cytoskeleton. The interiors of neurons and other cells are organized networks of interconnected protein polymers. Among them are the microtubules that make up the cytoskeleton. As the name implies, the cytoskeleton is thought to provide the cell’s structural support. In addition, however, cytoskeletal microtubules appear to Satinover (and to me) to process information, acting in effect as the individual brain cell’s nervous system.

Here is the link we have been seeking between neural-level and quantum-level processes. Situated in scale between neural-level and quantum-level activities, microtubules seem well positioned for such a role. The questions are: How can microtubules process information? How is that information processing couples to higher-scale neural activities, on one side, and lower-scale quantum effects, on the other?

First, how can microtubules process information? Whatever the process, it must be self-organizing, since no one built a computing system in our cells. Satinover tells us about two well-known ways that computation systems organize themselves. Information scientists call these lattice systems, in which the state of each lattice component depends on the states of its neighboring components, according to some rules. This mutual rule following is a kind of natural organization, or self-organization. Simple rules in simple lattices can lead to complex self-organization information patterns. One example is the growth of crystals, but self-organizing activities may occur at any level, from the growth of crystals to the formation of galaxies, from protein dynamics to the universe as a whole. The structure of microtubules provides particular advantages for two kinds of self-organizing systems called *cellular automata* and *spin glass behavior*. An appendix in *The Quantum Brain* provides an excellent spin glass view of microtubules by the biophysicist Jack Tuszynski.

For readers who have hung on through these technicalities, your reward has come. Information processing at the level of microtubules within each neuron would provide an enormous increase in the brain's computing power. Conventional approaches consider the brain's 10^{11} neurons, each with thousands of synapses switching thousands of time per second, to yield roughly 10^{16}—or 10,000 trillion— operations per second. But this gigantic number may only scratch the surface of the brain's power. At the cytoskeletal level that we have been discussing, roughly 10^{7} microtubule protein subunits in each neuron, switching on the order of nanoseconds, would give roughly 10^{16} operations per second per neuron (and roughly 10^{27} operations per second in an entire brain). Indeed, evidence clearly shows that microtubules do propagate signals. Several types of couplings between microtubules and membrane activities are recognized.

The bad news is that this vast increase in computational power still does not solve the enigmatic features of consciousness. Satinover plunges more deeply into the brain. To follow, we must scale one final level of complexity.

PROTEIN DYNAMICS—THE DANCE OF LIFE

Satinover's descent downward to computation carried out by microtubule subunits implies that the brain's fundamental units of information (akin to "bits" in binary computers) are neither neural firings nor synaptic transmissions but "protein conformational states." Dynamic structural changes in proteins control the submicroscopic world; they are the machinery inside cells. Protein conformational changes play in real time on what our genes have given. Here Satinover makes his stand in defense of the quantum brain. At this level, he tells us, the quantum world meets biology.

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Perhaps not surprisingly, how proteins do take form at this level is another mystery. What are called "conformational transitions" occur at many scales, but those on which protein functioning depends generally occur roughly in the nanosecond range. These processes include some that are well known to brain scientists: ion channels opening and closing, enzymes catalyzing, proteins moving things around inside cells, and the proposed tubulin switching in microtubule information processing. What remains mysterious about these processes— and involves us in yet further technicalities— is how proteins arrive at their optimal conformation.

Proteins have a large amount of energy; they are only marginally stable. Consequently, any protein's form is a delicate balance among countervailing forces. Strong, relatively static forces, like various chemical bonds, cancel each other out. That leaves control of the final form to the weakest, although most numerous, forces. These are called (after 20th-century physicist Fritz Wolfgang London, whose work gave rise to quantum chemistry) "quantum mechanical London forces"—instantaneous electron couplings that may be the key to consciousness. Consider this fascinating piece of evidence. When we are anesthetized, our consciousness is erased by anesthetic gas molecules, which bind within a variety of neural proteins in regions where London forces act. The anesthetics bind weakly, but impair the normally occurring quantum London forces. When anesthetic gas molecules float away and normal quantum London forces resume, patients awake fully from their anesthesia. Consciousness is completely restored. Are protein conformation dynamics, as governed by quantum forces, the key to consciousness?

THE PUNCHLINE

Satinover proposes two ways that the quantum behavior of electrons may work in protein conformation dynamics. The first is that quantum randomness “shakes and stirs” electrons (and other particles) to help proteins find their target shape or conformation. The second is that critical electron movements involve quantum “tunneling” among different regions of a protein, which allows electrons to penetrate barriers, exist in superposition of different locations, and “sample” multiple conformations simultaneously. Electron tunneling over significant distances within proteins has now been demonstrated experimentally. In these ways, proteins take advantage of two aspects of quantum behavior: quantum randomness and quantum tunneling.

What about quantum states or processes at higher levels of brain organization (for example, in microtubule quantum computation, as Roger Penrose and I have proposed)? Forget it. According to conventional wisdom, and to Satinover, such effects are washed out by decoherence.

Where does this take us? Unfortunately, not very far. *The Quantum Brain* seems to tell us merely that the quantum world lends a few parlor tricks to biology, but only in isolated and random ways. There is no unified quantum state, no quantum computation, no free will, no connectedness, and no place for consciousness. Satinover’s conclusions about free will, life, and God ring hollow. He hints at a deep connection between our brains and the quantum world, but cannot deliver.

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It is a pity. His book is informative, clear, and groundbreaking but, in my opinion, misses its target as a result of two erroneous, though understandable, assumptions. The first is that quantum effects are washed out—decohere—at a low level in biological systems. The second is that quantum processes are truly random. Both are scientific dogma, but both could be wrong.

The decoherence issue is being fought, and investigated. Time will tell. But what about quantum randomness? Is the universe truly random at its core? A closer look suggests otherwise.

PLATO AT THE PLANCK SCALE

What is underlying reality? Since Einstein’s theory of general relativity we have had a notion of a space/time that curves in accord with mass, giving us the common notion that “space is curved.” We also know that as we go down in scale—far smaller than atoms and subatomic particles—we reach the bottom floor of Einstein’s space/time continuum. The Planck scale, named after German physicist Max Planck, is related to the smallest measures of length and time that have any meaning. At the infinitesimally small Planck scale of 10^{-33} cm and 10^{-43} sec, space/time is no longer smooth, but quantized and fluctuating. In the esoterica of descriptions of the actual makeup of space/time at this level, physicists speak of such things as Planck-scale spin networks, twistors, and vibrating superstrings.

Einstein's theory of general relativity tells us that mass causes curvature in space/time geometry. This holds for large-scale objects, but what about small scales? Penrose tried to effect a tentative union of quantum theory and relativity by equating the location of a mass with curvature in space/time geometry at the Planck scale. What this means, in simpler terms, is that a particle in one location is equivalent to a particular space/time curvature, and the same particle in another location is equivalent to curvature of space/time geometry in a different, or opposite, direction. So quantum superposition is a separation in space/time, a bubble or blister in the basic level of reality. If the superposition avoids decoherence, the separation will continue until the threshold for Penrose OR is met, at which instant reduction to one specific space/time curvature occurs. A new, particular reality is chosen.

Moreover, according to the Penrose view, the choices are neither deterministic nor random, but they are "noncomputable" and for that reason unpredictable—influenced by the fine structure of space/time geometry, information embedded at the Planck scale. Penrose sees Platonic values like mathematical truth, aesthetics, and ethics as included in Planck-scale information and playing an influential role in noncomputable conscious choices. Noncomputability, Penrose argues, is a key feature of conscious processes. It may also help us avoid the trap of mechanistic determinism.

Consider a deterministic robot trained and programmed to sail a boat. The robot has a target port to which to sail, senses the wind, and adjusts the direction of the boat accordingly by a series of maneuvers ("jibes" and "tacks"). Assume that the capricious wind is actually the noncomputable factors embedded in fundamental reality. Each time the robot prepares to jibe or tack, the wind may subtly shift and the resultant direction be slightly altered. Accordingly the robot and boat occasionally find themselves in a different port than that to which they intended to sail. Similarly, our consciousness may involve a series of quantum collapses, each influenced by Platonic information, leading to sometimes surprising choices and perceptions. Is this free will? Allowing our choices to be influenced by hidden Platonic values is not exactly free, but it can provide the experience of nondeterministic, nonrandom selection.

What about God? In my view, God is space/time geometry, the universe itself. At the fine grain of the Planck scale is a wealth of Platonic values and raw experience instilled at the Big Bang, ready to be accessed by, and to influence, conscious processes. And space/time geometry has nonlocality, which means that at the fundamental level everything is connected. We are connected to one another and to the universe.

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Although I chide Jeffrey Satinover for succumbing to conventional wisdom (how many historical examples does one need to realize conventional wisdom is often wrong?), I do enthusiastically recommend his book. It takes us to the brink of enlightenment.

EXCERPT

Set in motion once for all time at the Big Bang, particles that later happen to comprise a human brain have no freedom of action whatsoever, neither individually nor as an ensemble. That we think of ourselves as "free;" as having "minds" capable of "choosing"; indeed, that we even think we think: illusion all. What we like to call "will" is at most the inevitable by-product of mechanical interactions of the brain's parts. Illusory "mind" can influence neither what the brain does, nor the bodily actions the brain sets into motion.

Poets, mystics, philosophers and theologians have always insisted that this game of universal billiards has both players and purpose—and their followers have ever fought over who and what these are. But ever since the Enlightenment, science has argued that it is both impossible and unnecessary to know whether the opening break was that of a cosmic Minnesota Fats of incomparable foresight, or of a merely comic amateur. In either case, the cue stick lies long abandoned; the player long gone from the shot, the table, the game. The pool hall itself is empty, though the neon lights burn on. In the words of Harvard astronomer Margaret Geller: "Why should [the universe] have a point? What point? It's just a physical system, what point is there?"

For all the millennia that human beings looked at the universe as guided, purposeful and pregnant with meaning, its operations remained mysterious. But once science arose, the universe swiftly began to yield its secrets. By shifting so wholeheartedly to this point of view that not even life, not even human life, is exempted, science has found itself able to break open even seemingly impenetrable mysteries of mind: learning, intelligence, intuition—all of these can now be extensively understood in wholly mechanical terms. What's more, they are being mimicked by man-made machines. More powerfully than has any prior scientific discovery, the unlocking of the brain seems to confirm the scientists' hypothesis that everything—the mind of man included—is machine.

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