Consciousness, the Brain, and Spacetime Geometry

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ABSTRACT: What is consciousness? Conventional approaches see it as an emergent property of complex interactions among individual neurons; however these approaches fail to address enigmatic features of consciousness. Accordingly, some philosophers have contended that "qualia," or an experiential medium from which consciousness is derived, exists as a fundamental component of reality. Whitehead, for example, described the universe as being composed of "occasions of experience." To examine this possibility scientifically, the very nature of physical reality must be re-examined. We must come to terms with the physics of spacetime-as described by Einstein's general theory of relativity, and its relation to the fundamental theory of matter-as described by quantum theory. Roger Penrose has proposed a new physics of objective reduction: "OR," which appeals to a form of quantum gravity to provide a useful description of fundamental processes at the quantum/classical borderline.hz Within the OR scheme, we consider that consciousness occurs if an appropriately organized system is able to develop and maintain quantum coherent superposition until a specific "objective" criterion (a threshold related to quantum gravity) is reached; the coherent system then self-reduces (objective reduction: OR). We contend that this type of objective self-collapse introduces non-computability, an essential feature of consciousness which distinguishes our minds from classical computers. Each OR is taken as an instantaneous event-the climax of a self-organizing process in fundamental spacetime-and a candidate for a conscious Whitehead "occasion of experience." How could an OR process occur in the brain, be coupled to neural activities, and account for other features of consciousness? We nominate a quantum computational OR process with the requisite characteristics to be occurring in cytoskeletal microtubules within the brain's neurons.

In this model, quantum-superposed states develop in microtubule subunit proteins ("tubulins") within certain brain neurons, remain coherent, and recruit more superposed tubulins until a mass-time-energy threshold (related to quantum gravity) is reached. At that point, self-collapse, or objective reduction (OR), abruptly occurs. We equate the pre-reduction, coherent superposition ("quantum computing") phase with pre-conscious processes, and each instantaneous (and non-computable) OR, or self-collapse, with a discrete conscious event. Sequences of OR events give rise to a "stream" of consciousness. Microtubule-associated proteins can "tune" the quantum oscillations of the coherent superposed states; the OR is thus self-organized, or "orchestrated" ("Orch OR"). Each Orch OR event selects (non-computably) microtubule subunit states which regulate synaptic/neural functions using classical signaling.

The quantum gravity threshold for self-collapse is relevant to consciousness, according to our arguments, because macroscopic superposed quantum states each have their own spacetime geometries[1-2] These geometries are also superposed, and in some way "separated," but when sufficiently separated, the superposition of spacetime geometries becomes significantly unstable and reduces to a single universe state. Quantum gravity determines the limits of the instability; we contend that the actual choice of state made by Nature is noncomputable. Thus each Orch OR event is a self-selection of spacetime geometry, coupled to the brain through microtubules and other biomolecules.

If conscious experience is intimately connected with the very physics underlying spacetime structure, then Orch OR in microtubules indeed provides us with a completely new and uniquely promising perspective on the difficult problems of consciousness.

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INTRODUCTION: CAJAL AND CONSCIOUSNESS

A century ago Santiago Ramon-y-Cajal showed the brain to be a large group of individual neuronal cells that communicate by synapses, an idea that eclipsed the previous view of the brain (put forth by Camillo Golgi) as a threaded-together reticulum, or "syncytium."[6] Cajal's discoveries led to the "neuron doctrine" and eventually to widespread analogies between the brain and computers, with neurons and synapses playing the roles of discrete information "bits." Cajal also discovered dendritic spines as key sites for adjustable synaptic plasticity; similarly, computer models of brain function use adjustably weighted connections to learn and remember. Cajal's work laid the foundation for the modern view of brain/mind as computer.

If Cajal were alive today, he would find that two types of neuronal circuits are generally believed to organize higher cognition and consciousness in cerebral cortex. One type of circuit involves sensory relays from thalamus to appropriate sensory cortex (visual input -4 visual cortex, auditory input -~ auditory cortex, etc.).[7-9] These thalamo-cortical projections release mostly small amino acid neurotransmitters such as glutamate at their cortical dendrite targets, for example, pyramidal cells. Other cortical projections arise from basal forebrain and midbrain, release acetylcholine and monoamines, and are more global in their cortical distribution. Woolf to has suggested that these global basal forebrain projections select (focus attention) and modulate sensory representations broadcast to cortical dendrites by thalamic projections, somewhat like plucking the strings of a harp.

Electrophysiological recordings reveal coherent firing of these cortical projection systems, with frequencies varying from slow EEG (2-12 Hz) to rapid "gamma oscillations" in the 30- to 70-Hz range and upward. Coherent gamma frequency oscillations (collectively known as "coherent 40 Hz") are suggested to mediate temporal

TABLE 1. Enigmatic features of consciousness and their explanation by conventional approaches and Orch OR

Enigmatic Feature of Consciousness	Conventional Approaches	Orch OR
Nature of human experience, "qualia"	"Emergence": qualia emerge at unspecified critical level of complexity of inter-neuronal interactions	Pan-protopsychism: qualia are fundamental properties of spacetime geometry accessed by Orch OR events (Whitehead's "occasions of experience)
Unitary binding, e.g., in vision, "self"	Temporal correlation, e.g., coherent 40-Hz synchrony	Unity of quantum state reduction; coherent 40-Hz-synchrony
Preconscious to conscious transition	"Emergence": consciousness emerges at unspecified critical level of complexity	Preconscious processes are quantum superpositions of possibilities (choices, perceptions) which collapse, reduce to definite classical states
Nonalgorithmic processes, non-computability (Penrose)	Not applicable	OR influenced by non-computable "Platonic" factors intrinsic to fundamental spacetime geometry
Non-deterministic "free will"	?	Experience of noncomputable influence on deterministic process
Subjective time flow; apparent time anomalies (e.g., Libet[81])	?	Time asymmetry of quantum-state collapse; atemporality of OR intervals; temporal nonlocality

binding of conscious experience and to act as the neural correlate of consciousness. [11-14] Cajal might ask: "How are these oscillations synchronized?" Possible mechanisms include pacemaker cells broadcasting coherently (i.e., via chemical synapses) to cortex, intemeurons, global network oscillations, and electrical coupling by gap junctions. Synchronization among neuronal populations dispersed widely throughout the brain occurs with zero phase lag, suggestive of electrical coupling provided by gap junctions. [15]

The role of gap junctions would be of particular interest to Cajal. In addition to chemical synapses, neurons may be electrically coupled, either by field effects or more specifically by electrotonic gap junctions, window-like portholes between adjacent neural processes (axon-dendrite, dendrite-dendrite, dendrite-glia, etc.). Gap junctions separate connected processes by only 4 nanometers and couple them electrically; neurons connected by gap junctions "behave like one giant neuron." [16]

Gap junctions are generally considered more primitive than chemical synapses, essential for embryological development, but fading into the background in mature brains. However, brain gap junctions remain active throughout adult life, and are being appreciated as more and more prevalent (though far fewer than chemical synapses). In recent years, increasing evidence points to gap junction-connected networks of cortical interneurons mediating coherent 40 Hz. [17-19]

Some interneurons connect to cortical dendrites by "dual synapses": both GABAergic (inhibitory) chemical and gap junction electrical synapses. 19 It is ironic that gap junctions connect together neurons and glia, at least transiently, into a sort of reticular syncytiumGolgi's idea overthrown by Cajal's demonstration of discrete neurons and chemical synapses. Gap junction assemblies of transiently woven-together neurons have been termed "hyper-neurons" and suggested as a neural correlate of consciousness. [20]

Cajal might also wonder how computer-like neuronal oscillations produce conscious experience. Why do we feel love, hear a flute, see the redness of a rose? Philosophers call the raw components that compose conscious experience qualia.[21]. They are one of several enigmatic features of consciousness (TABLE 1).

Proponents of computer-like neuronal oscillations account for these activities through the phenomenon of "emergence," which implies that a specific novel property occurs ("emerges") at some level in a hierarchical system, dependent on activities at both lower and higher levels of organization.[22] The brain is commonly viewed as a hierarchical system, comprising layers of organization with bottom-up, as well as top-down feedback. In the modern view Cajal's neuronal interactions are seen as the bottom level, with consciousness emerging as a novel property at an upper level of the hierarchy, for example, coherent 40-Hz oscillations. Novel properties can indeed emerge from complex interactions among simple components in a variety of systems (e.g., wetness from interactions of water molecules, music or hurricanes from vibrations of air molecules). The extrapolation is that consciousness emerges as a novel property of complex interactions among relatively simple neurons.

But Cajal might wonder why other emergent phenomena were not conscious. What critical threshold or level of complexity produced consciousness? Were neurons and synapses really that simple? Other than emergence from computer-like neuronal oscillations, what other explanations for enigmatic features of consciousness could be hidden in the brain?

SELF-SELECTION IN AN EXPERIENTIAL MEDIUM?

The problem of incorporating the phenomenon of consciousness into a scientific world-view involves finding scientific explanations of qualia, or the subjective experience of mental states.[21] On this, conventional science is still at sea. Why do we have an inner life, and what exactly is it?

As an alternative to emergence, one set of philosophical positions addressing the problem of qualia views consciousness as a fundamental component of physical reality. For example an extreme view-"panpsychism"-is that consciousness is a quality of all matter, atoms and their subatomic components having elements of consciousness[23,24] "Mentalists" such as Leibniz [25] and Whitehead [26, 27] contended that systems ordinarily considered to be physical are constructed in some sense from mental entities. Bertrand Russe11[28] described "neutral monism" in which a common underlying entity, neither physical nor mental, gave rise to both. In monistic idealism, matter and mind arise from consciousness-the fundamental constituent of reality.[29] Wheeler[30] has suggested that information is fundamental to the physics of the universe. From this, Chalmers[21] proposes a double-aspect theory in which information has both physical and experiential aspects-"pan-protopsychism."

Among these positions, the philosophy of Alfred North Whitehead[26,27] may be most directly applicable. Whitehead described the ultimate concrete entities in the cosmos as being actual "occasions of experience," each bearing a quality akin to "feeling." Whitehead construes "experience" broadly-in a manner consistent with panpsychism-so that even "temporal events in the career of an electron have a kind of `protomentality'." Whitehead's view may be considered to differ from panpsychism, however, in that his discrete "occasions of experience" can be taken to be related to "quantum events."[31] In the standard descriptions of quantum mechanics, randomness occurs in the events described as quantum state reductions-these being events that appear to take place when a quantum-level process gets magnified to a macroscopic scale.

Quantum-state reduction ("collapse of the wave function"), denoted here by the letter R,[1,2] is the random procedure that is adopted by physicists in their descriptions of the quantum measurement process. It is still a highly controversial matter whether R is to be taken as a "real" physical process or whether it is some kind of illusion and not to be regarded as a fundamental ingredient of the behavior of Nature. Our position is to take R to be indeed real-or, rather to regard it as a close approximation to an objectively real process, OR (objective reduction), which is to be a non-computable process instead of merely a random one. [1,2] In almost all physical situations, OR would come about in situations in which the random effects of the environment dominate, so OR would be virtually indistinguishable from the random R procedure that is normally adopted by quantum theorists. However, when the quantum system under consideration remains coherent and well isolated from its environment, then it becomes possible for its state to collapse spontaneously, in accordance with the OR scheme we adopt, and to behave in non-computable rather than random ways. Moreover, this OR scheme intimately involves the geometry of the physical universe at its deepest levels.

Our viewpoint is to regard experiential phenomena as also inseparable from the physical universe, and in fact to be deeply connected with the very laws that govern the physical universe. The connection is so deep, however, that we perceive only glimmerings of it in our present-day physics. One of these glimmerings, we contend, is a necessary non-computability in conscious thought processes, and we argue that this non-computability must also be inherent in the phenomenon of quantum state self-reduction-the "objective reduction" (OR) referred to above. This is the main thread of argument in *Shadows of the Mind.*[2] *The* argument that conscious thought, whatever other attributes it may also have, is non-computable (as follows most powerfully from certain deductions from Godel's incompleteness theorem) grabs hold of one tiny but extremely valuable point. This means that at least some conscious states cannot be derived from previous states by an algorithmic process-a property that distinguishes human and other animal minds from computers. Non-computability *per se* does not directly address the nature of conscious experience, but it is a clue to the kind of physical activity that lies behind it. This points to OR, an underlying physical action of a completely different character from that which seems to underlie non-conscious activity. Following this clue with sensitivity and patience should ultimately lead to real progress towards understanding mental phenomena in their inward as well as outward manifestations.

In the OR description, consciousness occurs if an organized quantum system is able to isolate and sustain coherent superposition until its quantum gravity threshold for spacetime separation is met; it then self-reduces (non-computably). For consciousness to occur, self-reduction is essential, as opposed to "decoherence," reduction being triggered by the system's random environment. (In the latter case, the reduction would itself be effectively random and would lack useful non-computability, being unsuitable for direct involvement in consciousness.) We take the self-reduction to be an instantaneous event-the climax of a self-organizing process fundamental to the structure of spacetime-and apparently consistent with a Whitehead "occasion of experience."

As OR could, in principle, occur ubiquitously within many types of inanimate media, it may seem to imply a form of "panpsychism" (in which individual electrons, for example, possess an experiential quality). However, according to the principles of OR (as expounded in Penrosel,[2,32]), a single superposed electron would spontaneously reduce its state (assuming it could maintain isolation) only once in a period much longer than the present age of the universe. Only large collections of particles acting coherently in a single macroscopic quantum state could possibly sustain isolation and support coherent superposition in a time frame brief enough to be relevant to our consciousness. Thus only very special circumstances could support consciousness:

(1) High degree of coherence of a quantum state-a collective mass of particles in superposition for a time period long enough to reach threshold, and brief enough to be useful in thought processes.
(2) Ability for the OR process to be at least transiently isolated from a "noisy" environment until the spontaneous state reduction takes place. This isolation is required so that reduction is not simply random. Mass movement in the environment which entangles with the quantum state would effect a random (not non-computable) reduction.
(3) Cascades of ORs to give a "stream" of consciousness, and huge numbers of OR events taking place during the course of a lifetime.

By reaching quantum gravity threshold, each OR event has a fundamental bearing on spacetime geometry. One could say that a cascade of OR events charts an actual course of physical spacetime geometry selections. It may seem surprising that quantum gravity effects could plausibly have relevance at the physical scales relevant to brain processes, for quantum gravity is normally viewed as having only absurdly tiny influences at ordinary dimensions. However, we shall show later that this is not the case, and the scales determined by basic quantum gravity principles are indeed those that are relevant for conscious brain processes. We must ask how such an OR process could actually occur in the brain. How could it be coupled to neural activities at a high rate of information exchange; how could it account for preconscious to conscious transitions, have spatial and temporal binding, and both simultaneity and time flow? Roger Penrose and I have nominated an OR process with the requisite characteristics occurring in cytoskeletal microtubules within the brain's neurons. In our model, microtubule-associated proteins "tune" the quantum oscillations leading to OR; we thus term the process "orchestrated objective reduction" (Orch OR).

SPACETIME: QUANTUM THEORY AND EINSTEIN'S GRAVITY

Quantum theory describes the extraordinary behavior of the matter and energy which compose our universe at a fundamental level. At the root of quantum theory is the wave/particle duality of atoms, molecules and their constituent particles. A quantum system such as an atom or subatomic particle which remains isolated from its environment behaves as a "wave of possibilities" and exists in a coherent complex-number-valued "superposition" of many possible states. The behavior of such wave-like, quantum-level objects can be satisfactorily described in terms of a state vector which evolves deterministically according to the Schrodinger equation (unitary evolution), denoted by U.

Somehow, quantum microlevel superpositions lead to unsuperposed stable structures in our macro-world. In a transition known as wave-function collapse, or reduction (R), the quantum wave of alternative possibilities reduces to a single macroscopic reality, an "eigenstate" of some appropriate operator. (This would be just one of many possible alternative eigenstates relevant to the quantum operator.) This process is invoked in the description of a macroscopic measurement, when effects are magnified from the small, quantum scale to the large, classical scale.

According to conventional quantum theory (as part of the standard "Copenhagen interpretation"), each choice of eigenstate is entirely random, weighted according to a probability value that can be calculated from the previous state according to the precise procedures of quantum formalism. This probabilistic ingredient was a feature with which Einstein, among others, expressed displeasure: "You believe in a God who plays dice and I in complete law and order"(from a letter to Max Born). Penrose [1,2] has contended that, at a deeper level of description, the choices may more accurately arise as a result of some presently unknown "non-computational" mathematical/physical (i.e., "Platonic realm") theory-that is they cannot be deduced algorithmically. Penrose argues that such non-computability is essential to consciousness, because (at least some) conscious mental activity is unattainable by computers.

It can be argued that present-day physics has no clear explanation for the cause and occurrence of wave-function collapse R. Experimental and theoretical evidence through the 1930s led quantum physicists (such as Schrodinger, Heisenberg, Dirac, von Neumann, and others) to postulate that quantum-coherent superpositions persist indefinitely in time, and would, in principle be maintained from the micro to macro levels. Or perhaps they would persist until conscious observation collapses, or reduces, the wave function (subjective reduction, or "SR"). Accordingly, even macroscopic objects, if unobserved, could remain superposed. To illustrate the apparent absurdity of this notion, Erwin Schrodinger33 described his now-famous "cat in a box" being simultaneously both dead and alive until the box was opened and the cat observed.

As a counter to this unsettling prospect, various new physical schemes for collapse according to objective criteria (objective reduction, or "OR") have recently been proposed. According to such a scheme, the growth and persistence of superposed states could reach a critical threshold, at which collapse, or OR, rapidly occurs.34,35 Some such schemes are based specifically on gravitational effects mediating OR.[1,2,36--41] TABLE 2 categorizes types of reduction.

TABLE 2. Descriptions of wave-function collapse

Context	Cause of collapse (reduction)	Description	Acronym
Quantum coherent superposition	No collapse	Evolution of the wave-function function (Schrödinger equation)	U
Conventional quantum theory (Copenhagen interpretation)	Environmental decoherence, measurement, conscious observation	Reduction, subjective reduction	R, SR
New physics (Penrose, 1994)	Self-collapse induced by quantum gravity	Objective reduction	OR
Consciousness	Self-collapse by OR quantum gravity in microtubules orchestrated by MAPs, etc.	Orchestrated objective reduction	Orch OR

The physical phenomenon of gravity, described to a high degree of accuracy by Isaac Newton's mathematics in 1687, has played a key role in scientific understanding. However, in 1915, Einstein created a major revolution in our scientific worldview. According to Einstein's theory, gravity plays a unique role in physics for several reasons.[1] Most particularly, these are:

(1) Gravity is the only physical quality that influences causal relationships between spacetime events.
(2) Gravitational force has no local reality, as it can be eliminated by a change in spacetime coordinates; instead, gravitational tidal effects provide a curvature for the very spacetime in which all other particles and forces are contained.

It follows from this that gravity cannot be regarded as some kind of "emergent phenomenon," secondary to other physical effects, but is a "fundamental component" of physical reality.

There are strong arguments [42,43] to suggest that the appropriate union of general relativity (Einstein's theory of gravity) with quantum mechanics-a union often referred to as "quantum gravity"-will lead to a significant change in both quantum theory and general relativity, and, when the correct theory is found, will yield a profoundly new understanding of physical reality. And although gravitational forces between objects are exceedingly weak (feebler than, for example, electrical forces by some 40 orders of magnitude), there are significant reasons for believing that gravity has a fundamental influence on the behavior of quantum systems as they evolve from the micro to the macro levels. The appropriate union of quantum gravity with biology, or at least with advanced biological nervous systems, may yield a profoundly new understanding of consciousness.

CURVED SPACETIME SUPERPOSITIONS AND OBJECTIVE REDUCTION (OR)

According to modern, accepted physical pictures, reality is rooted in three-dimensional space and a one-dimensional time, combined together into a four-dimensional spacetime. This spacetime is slightly curved, in accordance with Einstein's general theory of relativity, in a way that encodes the gravitational fields of all distributions of mass density. Each mass density effects a spacetime curvature, albeit tiny.

This is the standard picture according to classical physics. On the other hand, when quantum systems have been considered by physicists, this mass-induced tiny curvature in the structure of spacetime has been almost invariably ignored, gravitational effects having been assumed to be totally insignificant for normal problems in which quantum theory is important. Surprising as it may seem, however, such tiny differences in spacetime structure can have large effects, for they entail subtle but fundamental influences on the very rules of quantum mechanics.

Superposed quantum states for which the respective mass distributions differ significantly from one another will have spacetime geometries that correspondingly differ. Thus, according to standard quantum theory, the superposed state would have to involve a quantum superposition of these differing spacetimes. In the absence of a coherent theory of quantum gravity there is no accepted way of handling such a superposition. Indeed the basic principles of Einstein's general relativity begin to come into profound conflict with those of quantum mechanics.4 Nevertheless, various tentative procedures have been put forward in attempts to describe such a superposition. Of particular relevance to our present proposals are the suggestions of certain authors [2, 32, 36-41, 43-45] that it is at this point that an objective quantum state reduction (OR) ought to occur, and that the rate or timescale of this process can be calculated from basic quantum gravity considerations. These particular proposals differ in certain detailed respects, and for definiteness we shall follow the specific suggestions made in Penrose.[2,32] Accordingly, the quantum superposition of significantly differing spacetimes is unstable, with a lifetime given by that timescale. Such a superposed state will decay-or "reduce"-into a single universe state, which is one or the other of the spacetime geometries involved in that superposition.

Whereas such an OR action is not a generally recognized part of the normal quantum-mechanical procedures, there is no plausible or clear-cut alternative that standard quantum theory has to offer. This OR procedure avoids the need for "multiple universes."46,47 There is no agreement among quantum gravity experts about how else to address this problem. For the purposes of the present article, it will be assumed that a gravitationally induced OR action is indeed the correct resolution of this fundamental conundrum.

FIGURE 1 (adapted from Penrose[2] [p. 338]) schematically illustrates the way in which spacetime structure can be affected when two macroscopically different mass distributions take part in a quantum superposition. Each mass distribution gives rise to a separate spacetime, the two differing slightly in their curvatures. So long as the two distributions remain in quantum superposition, we must consider that the two spacetimes remain in superposition. Since, according to the principles of general relativity, there is no natural way to identify the points of one spacetime with corresponding points of the other, we have to consider the two as separated from one another in some sense, resulting in a kind of "blister" where the spacetime bifurcates.

A bifurcating spacetime is depicted in the lowest of the three diagrams, this being the union ("glued together version") of the two alternative spacetime histories that are depicted at the top of FIGURE 1. The initial part of each spacetime is at the lower end of each individual spacetime diagram. The bottom spacetime diagram (the bifurcating one) illustrates two

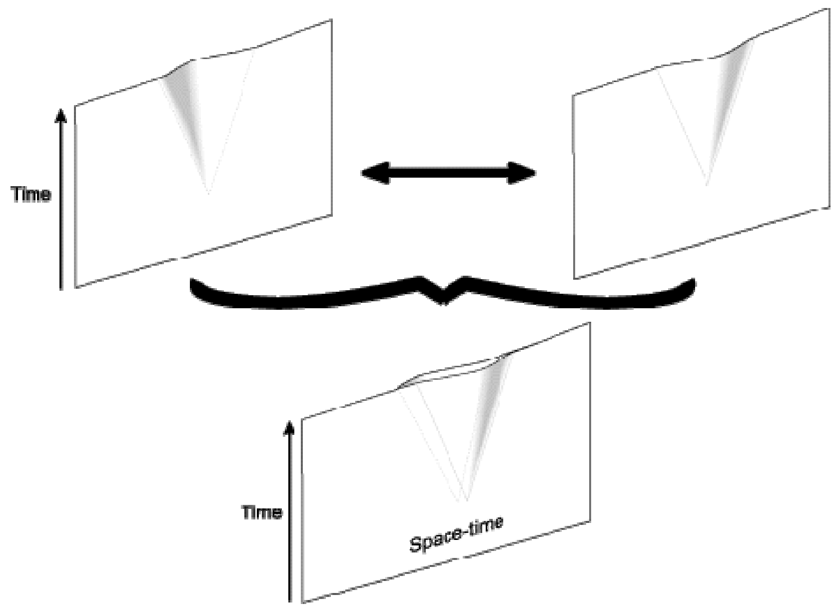

FIGURE 1. Quantum coherent superposition represented as a separation of spacetime. In the lowest of the three diagrams, a bifurcating spacetime is depicted as the union ("glued together version") of the two alternative spacetime histories that are depicted at the top of the figure. The bifurcating spacetime diagram illustrates two alternative mass distributions actually in quantum superposition, whereas the top two diagrams illustrate the two individual alternatives which take part in the superposition.

alternative mass distributions actually in quantum superposition, whereas the top two illustrate the two individual alternatives, which take part in the superposition. The combined spacetime describes a superposition in which the alternative locations of a mass move gradually away from each other as we proceed in the upward direction in the diagram. Quantum mechanically (so long as OR has not taken place), we must think of the "physical reality" of this situation as being illustrated as an actual superposition of these two slightly differing spacetime manifolds, as indicated in the bottom diagram. As soon as OR has occurred, one of the two individual spacetimes takes over, as depicted as one of the two sheets of the bifurcation. For clarity only, the bifurcating parts of these two sheets are illustrated as being one convex and the other concave. Of course there is additional artistic license involved in drawing the spacetime sheets as two-dimensional, whereas the actual spacetime constituents are four-dimensional. Moreover, there is no significance to be attached to the imagined "three-dimensional space" within which the spacetime sheets seem to be residing. There is no "actual" higher dimensional space there, the "intrinsic geometry" of the bifurcating spacetime being all that has physical significance. When the "separation" of the two spacetime sheets reaches a critical amount, one of the two sheets "dies"-in accordance with the OR criterion-the other being the one that persists in physical reality. The quantum state thus reduces (OR), by choosing between either the "concave" or "convex" spacetime of FIGURE 1.

It should be made clear that this measure of separation is only very schematically illustrated as the "distance" between the two sheets in the lower diagram in FIGURE 1. As remarked above, there is no physically existing "ambient higher dimensional space" inside which the two sheets reside. The degree of separation between the spacetime sheets is a more abstract mathematical thing; it would be more appropriately described in terms of a symplectic measure on the space of four-dimensional metrics,43 but the details (and difficulties) of this will not be important for us here. It may be noted, however, that this separation is a spacetime separation, not just a spatial one. Thus the time of separation contributes as does the spatial displacement. Roughly speaking, it is the product of the temporal separation T with the spatial separation S that measures the overall degree of separation, and OR takes place when this overall separation reaches the critical amount. [This critical amount would be of the order of unity, in absolute units, for which the Planck-Dirac constant $\hbar$ (Planck's constant over 2π), the gravitational constant G, and the velocity of light c, all take the value unity (cf. Penrose[2]).] Thus for small S, the lifetime T of the superposed state will be large; on the other hand, if S is large, then T will be small. To calculate S, we compute (in the Newtonian limit of weak gravitational fields) the gravitational self-energy E of the difference between the mass distributions of the two superposed states. (That is, one mass distribution counts positively and the other, negatively; see Penrose.[2,32]) The quantity S is then given by:

$$E = S$$

Thus, restoring standard units

$$T = \hbar E^{-1}$$

Schematically, since S represents three dimensions of displacement rather than the one dimension involved in T, we can imagine that this displacement is shared equally among each of these three dimensions of space-and this is what has been depicted in FIGURE 1. However, it should be emphasized that this is for pictorial purposes only, the appropriate rule being the one given above. These two equations relate the mass distribution, time of coherence, and spacetime separation for a given OR event. If, as some philosophers contend, experience is contained in spacetime as self-organizing processes in that experiential medium, OR events are candidates for consciousness. But where in the brain, and how, could coherent superposition and OR occur? Quantum computation uses quantum superposition-perhaps a particular type of quantum computation occurs in the brain.

Proposals for quantum computation rely on superposed states implementing multiple computations simultaneously, in parallel, according to quantum linear superposition.48-5I Rather than "bits" of 1 or 0 as in classical computers, quantum computers utilize "qubits" of superposition of both 1 and 0. The qubits interact and compute by quantum entanglement, effecting near-infinite massive parallelism and significant advantages over classical computers. A number of technological systems aimed at realizing these proposals have been suggested and are being evaluated as possible substrates for quantum computers.[52,53] A process of quantum computation/ superposition in the brain with reduction by Penrose OR would be an ideal candidate for consciousness.

MICROTUBULES

Are there quantum computation and qubits in the brain? A number of sites and various types of quantum interactions have been proposed. We strongly favor proteins as qubits, and in particular microtubules, as assemblies of entangled qubit proteins, but various organelles and biomolecular structures including clathrins, myelin (glial cells), presynaptic vesicular grids,[54] and neural membrane proteins[55] might also participate.

Proteins perform a myriad of cell functions through changes in their shape, or conformation. Conformational dynamics of proteins are regulated by quantum mechanical dipole couplings called van der Waals London forces.[56] The influential London forces seem to act in non-polar regions within proteins called hydrophobic pockets, where general anesthetic gases also exert their effects.[57] Proteins involved in anesthetic effects in erasing consciousness include receptors for acetylcholine, serotonin, GABA and glycine, as well as microtubules and other proteins. Anesthetics bind in hydrophobic pockets within these proteins by their own London forces, apparently preventing normally occurring London forces necessary for consciousness and protein conformational dynamics.[58] As London forces are quantum mechanical, the involved electrons in the absence of anesthetic (conscious state) may be expected to be in quantum superposition, indicating the protein may also be in quantum superposition of possible alternative conformational states. Quantum interactions have also been implicated in the problem of protein folding. Roitberg et al.[59] showed functional protein vibrations, which depend on quantum effects

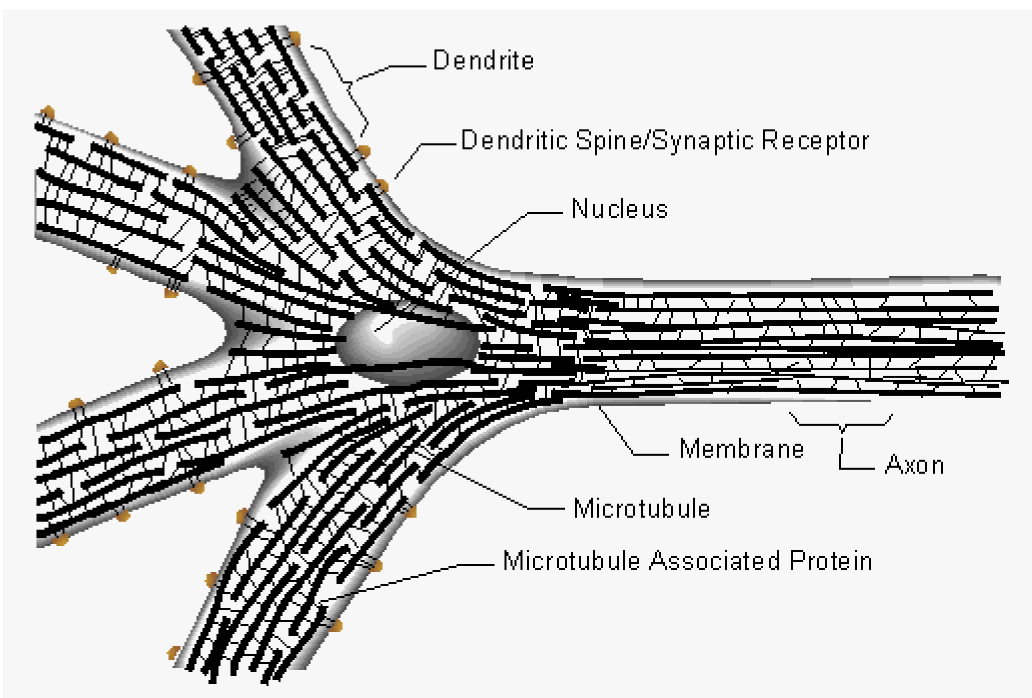

FIGURE 2. Schematic diagram of central region of neuron (distal axon and dendrites not shown), showing parallel arrayed microtubules interconnected by MAPs. Microtubules in axons are lengthy and continuous, whereas in dendrites they are interrupted and of mixed polarity. Linking proteins connect microtubules to membrane proteins including receptors on dendritic spines.

centered in two hydrophobic phenylalanine residues, and Tejada et al. [60] have evidence to suggest quantum coherent states exist in the protein ferritin. If proteins are qubits, organized geometric assemblies of qubit proteins such as microtubules could serve as quantum computers.

Properties of brain structures suitable for quantum coherent superposition, OR and relevant to consciousness might include: (1) high prevalence; (2) functional importance (for example regulating neural connectivity and synaptic function); (3) periodic, crystal-like lattice dipole structure with long range order; (4) ability to be transiently isolated from external interaction/observation; (5) functionally coupled to quantum-level events; (6) hollow, cylindrical (possible waveguide); and (7) suitable for information processing. Membranes, membrane proteins, synapses, DNA and other types of structures have some, but not all, of these characteristics. Cytoskeletal microtubules appear to qualify in all respects.

Interiors of living cells, including the brain's neurons, are spatially and dynamically organized by self-assembling protein networks: the cytoskeleton. Within neurons, the cytoskeleton establishes neuronal form, and maintains and regulates synaptic connections. Its major components are microtubules, hollow cylindrical polymers of individual proteins known as tubulin. Microtubules (MTs) are interconnected by linking proteins (microtubule-associated proteins: MAPS) to other microtubules and cell structures to form cytoskeletal lattice networks (FIG. 2).

MTs are hollow cylinders 25 nanometers (nm) in diameter whose lengths vary and may be quite long within some nerve axons. MT cylinder walls comprise 13 longitudinal protofilaments which are each a series of subunit proteins known as tubulin (FIG. 3). Each tubulin subunit is a polar, 8-nm dimer which consists of two slightly different 4-nm monomers (alpha and beta tubulin). Tubulin dimers are dipoles, with surplus negative charges localized toward alpha monomers,[61] and within MTs are arranged in a hexagonal lattice which is slightly twisted, resulting in helical pathways that repeat every 3, 5, 8, 13 and other numbers of rows (Fibonacci series).

Tubulin is a peanut-shaped dimer which can undergo conformational changes, including a 30-degree hinge-like bending at monomer interfaces.[62] Three-dimensional structural analysis of tubulin by electron crystallography[63] shows large hydrophobic, non-polar pockets in which quantum interactions (van der Waals London forces: instantaneous couplings of electron pairs) can govern protein movement. Cooperative dynamics due to ferroelectric, spin glass, and Fr6hlich coherence effects have been proposed in microtubule lattices to serve information processing roles.[64-66]

While microtubules have traditionally been considered as purely structural components, recent evidence demonstrates mechanical signaling and communication functions.[67-70] Microtubules interact with membrane structures and activities by linking proteins (e.g., fodrin, ankyrin) and "second messenger" chemical signals. In neurons, microtubules self-assemble to extend axons and dendrites and form synaptic connections; microtubules then help maintain and regulate synaptic strengths responsible for learning and cognitive functions. Within dendritic spines, dynamics of actin gelation regulate spine shape, thus adjusting synaptic efficacy, a critical factor in cognition.[7l-73] (For a more complete description of the role of microtubules and other cytoskeletal structures in cognitive functions, see Refs. 4 and 74-76).

How might information processing occur in the cytoskeleton? Collective Frohlich excitations of tubulin subunits within microtubules have been suggested to support computation

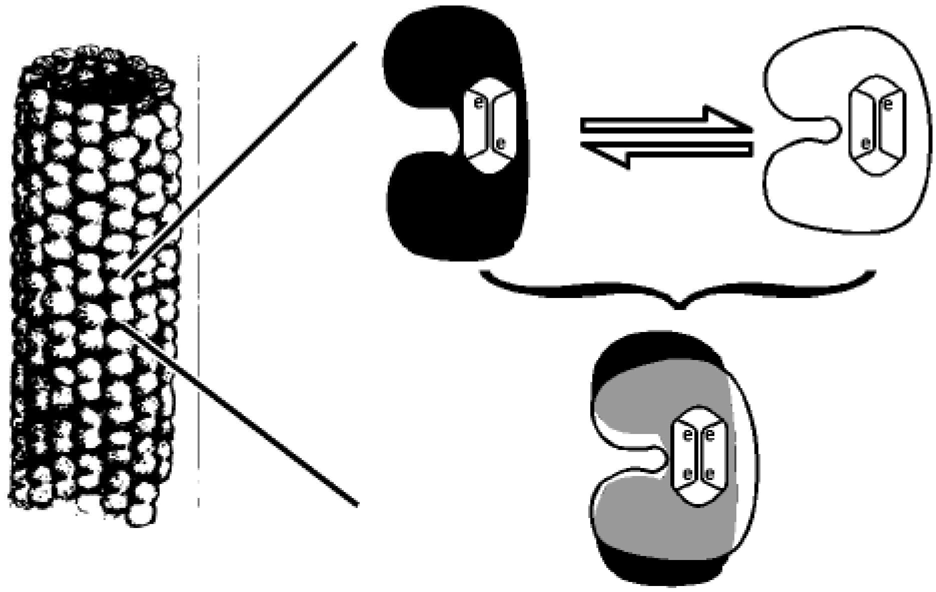

FIGURE 3. *Left*: Microtubule (MT) structure: a hollow tube 25 nanometers in diameter, consisting of 13 columns of tubulin dimers arranged in a skewed hexagonal lattice.[2] *Right top*: Each tubulin molecule may switch between two (or more) conformations, coupled to London forces in a hydrophobic pocket. *Right bottom*: Each tubulin can also exist in quantum superposition of both conformational states.[4]

and information processing via classical "cellular automata" behavior, coherently pumped by metabolic processes. [64-66] Molecular-level information processing can account for regulation of intra-neuronal activities including synaptic function, learning, and memory. However, to address the enigmatic features of consciousness, a form of quantum computation with objective reduction requires quantum superposition at the level of tubulin proteins.

QUANTUM COMPUTATION IN MICROTUBULES? THE PENROSE-HAMEROFF ORCH OR MODEL

In Refs. 4 and 5 and in summary form, 3 we present a model (Orch OR) whose key points are summarized here:

(1) Conformational states of individual tubulin proteins in brain microtubules are sensitive to internal quantum events (e.g., London forces in hydrophobic pockets) and able to cooperatively interact with other tubulins in classical "automata" computation, which regulates and interacts with chemical synapses, axon hillock, and other neural membrane activities (e.g., see FIGURE 4).

(2) Quantum superposition of London forces leads to quantum coherent superposition of tubulin conformation supporting quantum computation in microtubules. In this phase, quantum computation among tubulins evolves linearly according to the Schrodinger equation (quantum microtubule automata).

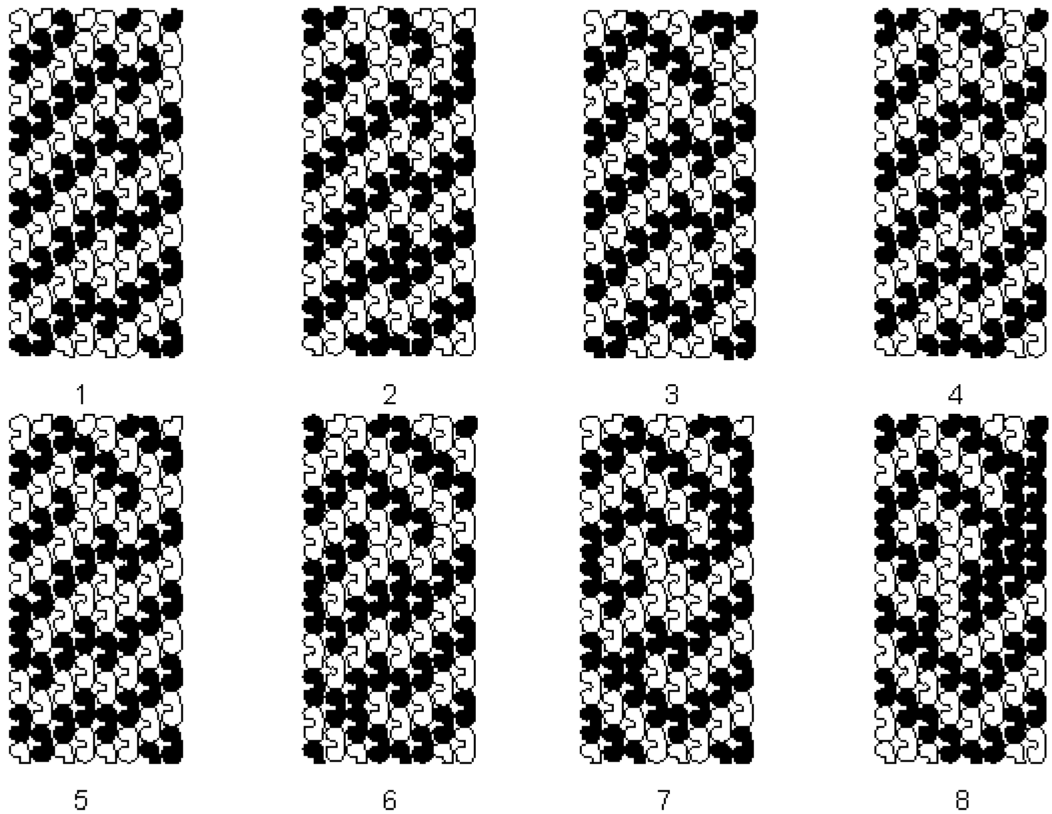

FIGURE 4. Microtubule automaton simulation.65 Black and white tubulins correspond to states shown in FIGURE 3. Eight-nanosecond time steps of a segment of one microtubule are shown in "classical computing" mode in which patterns move, evolve, interact, and lead to emergence of new patterns.

(3) Quantum states in microtubules avoid random environmental decoherence by mechanisms that include actin gelation, coherent pumping, ordered water, a condensed charge phase surrounding MT, and topological quantum error correction. Enhanced surface area in actin gelation ("gel") leads to ordering of water, and isolates microtubules during the quantum phase; actin depolymerization leads to a liquid (solution: "sol") state for classical communication (see the section DECOHERENCE AND BIOLOGICAL FEASIBILITY OF QUANTUM STATES IN THE BRAIN).

(4) The proposed quantum superposition/computation phase in neural microtubules corresponds to pre-conscious (implicit) processing, which continues until the threshold for Penrose objective reduction is reached. Objective reduction (OR}-a discrete event-then occurs (FIGS. 5-7), and post-OR tubulin states (chosen non-computably) proceed by classical microtubule automata to regulate synapses and other neural membrane activities. Transitions from pre-conscious possibilities into unitary choices or experiences may be seen as quantum computations in which quantum superpositions of multiple states abruptly collapse (reduce) to definite states at each "conscious moment."

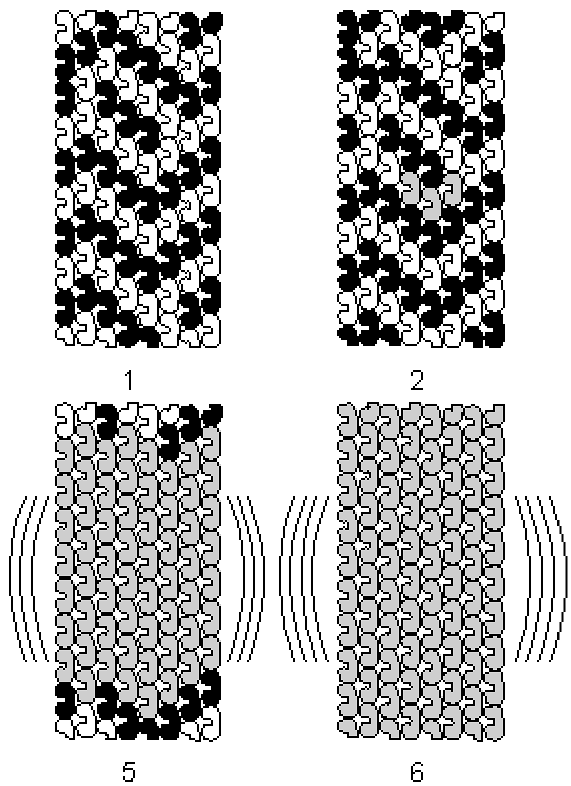

FIGURE 5. Microtubule automaton sequence simulation in which classical computing (step 1) leads to emergence of quantum coherent superposition (steps 2–6) in certain (gray) tubulins due to pattern resonance. Step 6 (in coherence with other microtubule tubulins) meets critical threshold related to quantum gravity for self-collapse (Orch OR). Consciousness (Orch OR) occurs in the step 6 to 7 transition. Step 7 represents the eigenstate of mass distribution of the collapse, which evolves by classical computing automata to regulate neural function. Quantum coherence begins to re-emerge in step 8.

(5) Orch OR events are proposed to be conscious (to have qualia, experience) because proto-conscious qualia are fundamental, embedded at the Planck scale. Each Orch OR event selects a particular configuration of fundamental geometry and a particular set of experiential qualia.

(6) Microtubule quantum states link to those in other neurons and glia by tunneling through gap junctions (or quantum coherent photons traversing membranes[77-78]). Gap junction interneurons mediate coherent 40-Hz oscillations, and enable macroscopic quantum states in networks of gap junctionconnected cells ("hyper-neurons" [20]) throughout large brain volumes (FIG. 8).

(7) Probabilities and possibilities for pre-conscious quantum superpositions are influenced by biological feedback including attachments of microtubuleassociated proteins (MAPs), which tune and "orchestrate" quantum oscillations and provide input/output during

classical ("sol") phase. We thus term the self-tuning OR process in microtubules "orchestrated" objective reduction or Orch OR.

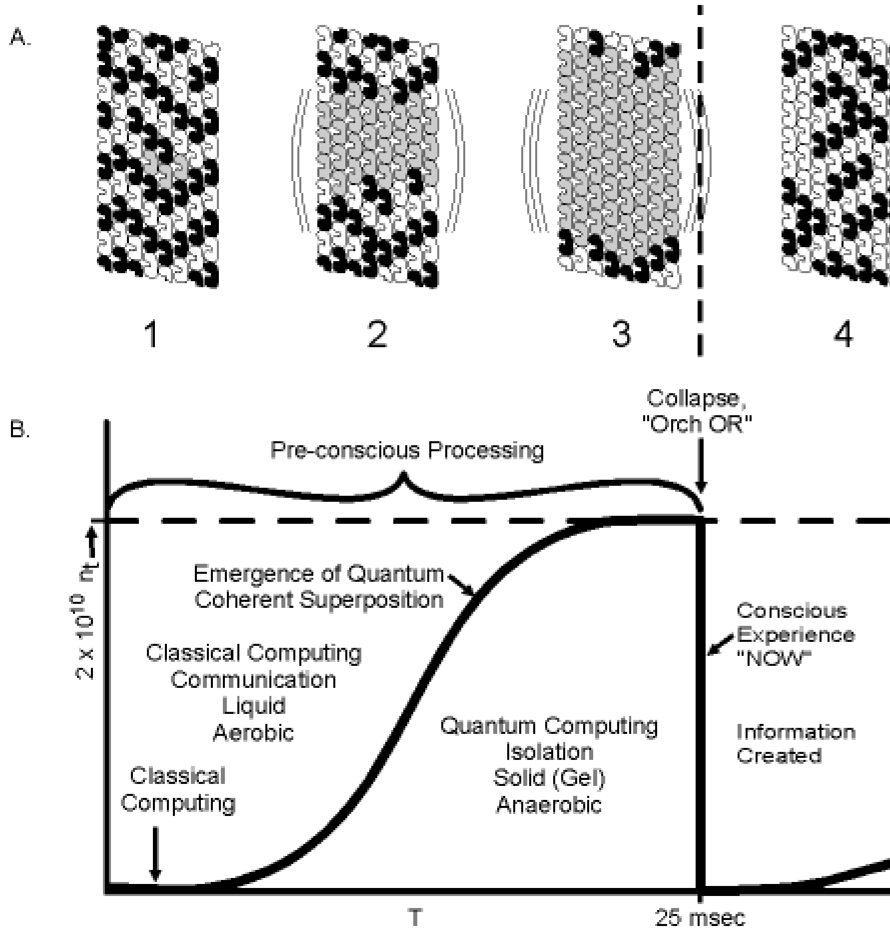

FIGURE 6. An Orch OR event. (**A**) Microtubule simulation in which classical computing (step 1) leads to emergence of quantum coherent superposition (and quantum computing [steps 2 and 3]) in certain (gray) tubulins. Step 3 (in coherence with other microtubule tublins) meets critical threshold related to quantum gravity for self-collapse (Orch OR). A conscious event (Orch OR) occurs in the step 3 to 4 transition. Tubulin states in step 4 are noncomputably chosen in the collapse and evolve by classical computing to regulate neural function. (**B**) Schematic graph of proposed quantum coherence (number of tubulins) emerging versus time in microtubules. Area under curve connects superposed mass energy E with collapse time T in accordance with $E = \hbar/T$. E may be expressed as Nt, the number of tubulins whose mass separation (and separation of underlying space time) for time T will selfcollapse. For $T = 25$ msec (e.g., 40-Hz oscillations), $Nt = 2 \times 1010$ tubulins.

(8) Orch OR events may be of variable intensity and duration of pre-conscious processing. Calculating from $E = h/T$ for a pre-conscious processing time of, e.g., T= 25 msec (40 *Hz), E* is roughly the superposition/separation of 2×10^{10} tubulins. For T= 100 msec (alpha EEG) E would involve 5×10^{9} tubulins. For T = 500 msec as a typical pre-conscious processing time for low intensity stimuli[8]), E is equivalent to 10^{9} tubulins. Thus 2×10^{10} tubulins maintained in isolated quantum coherent superposition for 25 msec (or 5×10^{9} tubulins for 100 msec, or 10^{9} tubulins for 500 msec, etc.) will self-collapse (Orch OR) and elicit a conscious event. Faster, larger superpositions may also occur, but without electrophysiological consequences. For example, sequences of

thousands of T = 10^{-6} sec (microsecond) OR events, each involving~10^{15} tubulins, may lead to climactic 25-msec OR events which do influence neurophysiology

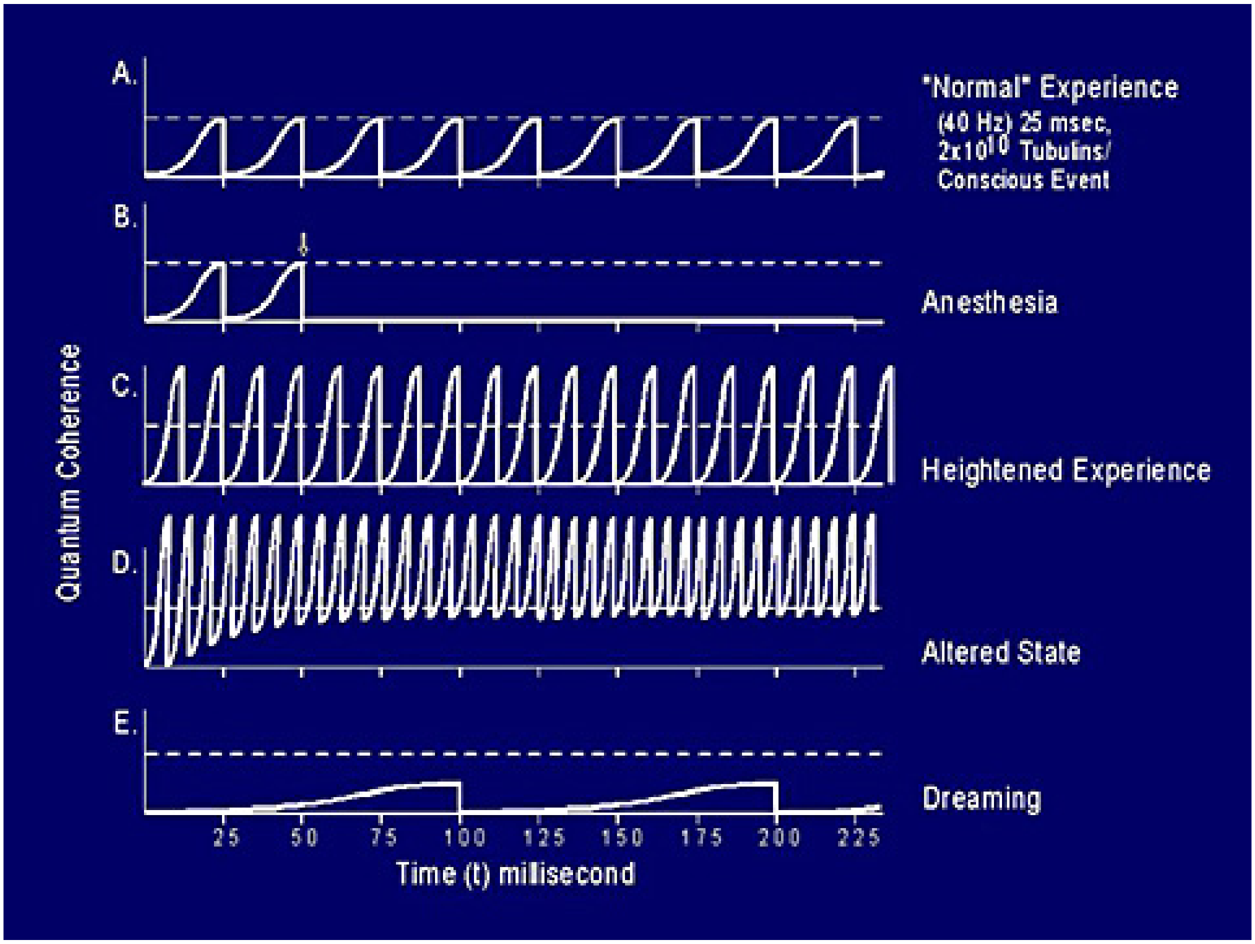

FIGURE 7. Quantum superposition/entanglement in microtubules for five states related to consciousness. Area under each curve is equivalent in all cases. (**A**) Normal 40-Hz experience: as in FIGURE 6. (**B**) Anesthesia: anesthetics bind in hydrophobic pockets and prevent electron delocalizability and coherent superposition. (**C**) Heightened experience: increased sensory experience input (for example) increases rate of emergence of quantum superposition. Orch OR threshold is reached faster, at higher intensity of experience, and more frequently. (**D**) Altered state: even greater rate of emergence of quantum superposition due to sensory input and other factors promoting quantum state (e.g., meditation, psychedelic drug, etc.). Predisposition to quantum state results in baseline shift and collapse so that conscious experience merges with normally subconscious quantum computing mode. (**E**) Dreaming: prolonged subthreshold quantum superposition time.

(9) Each brain neuron is estimated to contain about 10^7 tubulins.[82] If, say, 10 percent of each neuron's tubulins became coherent, then Orch OR of tubulins within roughly 20,000 (gap junction-connected) neurons would be required for a 25-msec conscious event, 5,000 neurons for a 100-msec event, or 1,000 neurons for a 500-msec event, etc. Microsecond events would involve roughly one billion neurons, 1% of brain capacity.

(10) Each instantaneous Orch OR event binds superposed information encoded in microtubules whose net displacement reaches threshold at a particular moment: a variety of different modes of information is thus bound into a "now" event. As quantum state

reductions are irreversible in time, cascades of Orch OR events present a forward flow of time and "stream of consciousness."

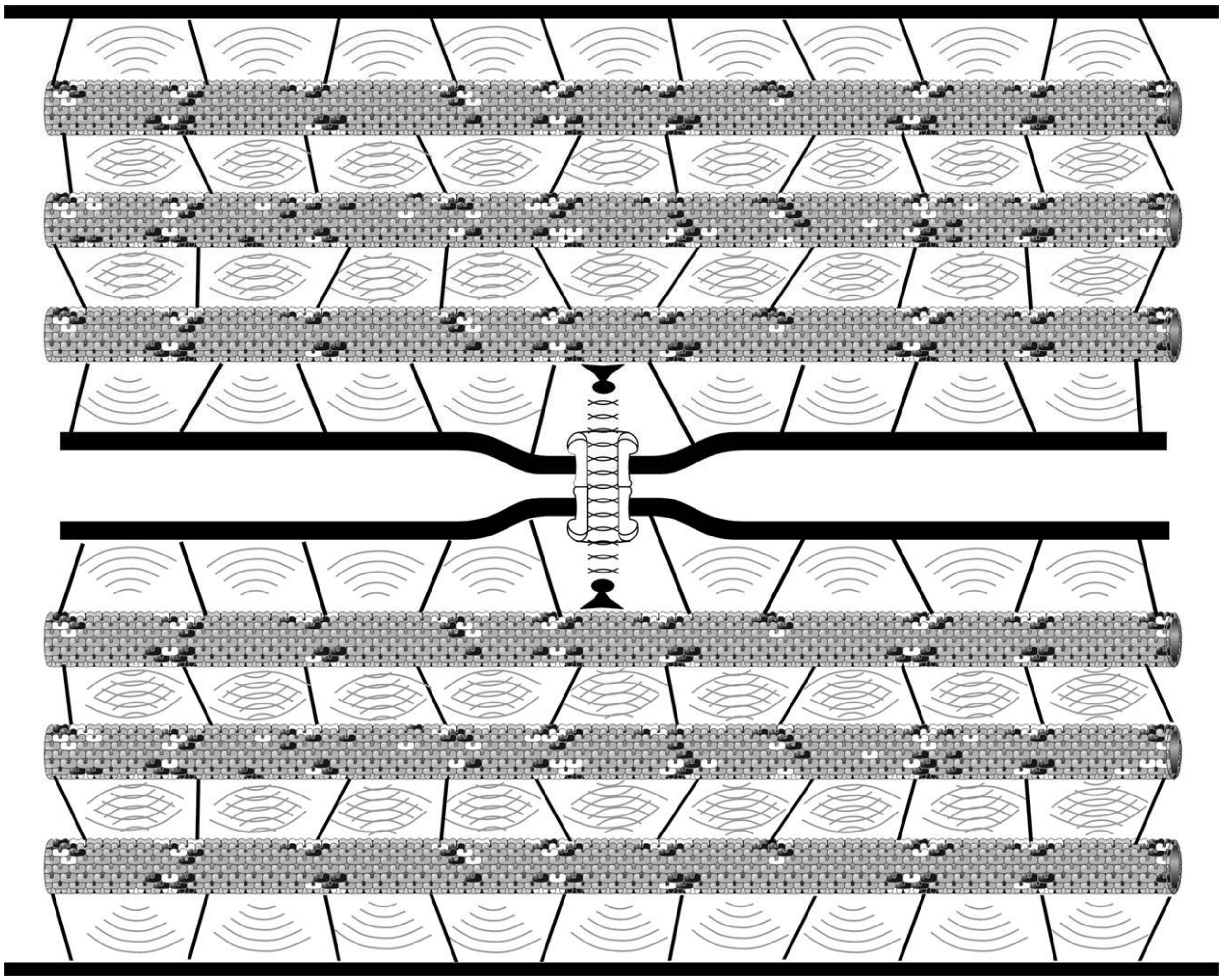

FIGURE 8. Schematic representation of a gap junction connecting two dendrites in which microtubules are in quantum superposition/quantum computation “tuned” by interconnecting MAP proteins, as suggested in the Penrose–Hameroff Orch OR model. On either side of the gap junction, dendritic lamellar bodies79,80 containing mitochondria may act as tunneling diodes to convey the quantum state between the dendrites.

DECOHERENCE AND BIOLOGICAL FEASIBILITY OF QUANTUM STATES IN THE BRAIN

The Orch OR model and other quantum approaches have significant explanatory potential for enigmatic features of consciousness (TABLE 1). However, technological quantum devices often require extreme cold to avoid thermal decoherence by environmental interactions which would otherwise disrupt quantum coherent superposition. As brain environment is considered "warm, wet, and noisy," survival of superposition over times relevant to neurophysiology (e.g., 25 msec for 40 Hz) may seem unlikely. Is the brain truly "warm, wet, and noisy"?

Yes, the brain is warm, but lasers maintain quantum coherence at warm temperatures by incoherent pumping. In the Orch OR model biochemical energy and heat may collectively pump tubulin dipoles and surrounding water [83,84] to produce coherence and avoid decoherence. In any case technological quantum devices are operating at ever-increasing temperatures, including room-temperature magnetic quantum cellular automata. [85]

Is the brain wet? The brain is 60 percent water, but interiors of neurons and all of our cells exist in alternating phases of (1) liquid (solution, "sol") and (2) solid (gelatinous, "gel"). The solid, gel phase is caused by polymerization of the cytoskeletal protein actin. The particular character of actin gel depends on the specific type of actin cross-linking. Of the various types of gels, some are viscoelastic, but others (e.g., those induced by the actin cross-linker avidin) are solid and can be deformed by an applied force without any response.[86] Cycles of actin gelation/solution can be quite rapid, occurring for example at 40 Hz. In neurons cycles of actin gelation/solution correlate with release of neurotransmitter vesicles from presynaptic axon terminals.[87,88] In dendritic spines, whose synaptic efficacy mediates learning, rapid actin gelation and motility mediate synaptic function, and are sensitive to anesthetics.[71-73]

Even in the "sol," or liquid phase of cytoplasm, water within cells is not truly liquid and random. Water molecules form various transient forms, and water within cells is to a large extent "ordered," and plays the role of an active component rather than inert background solvent. Cytoskeleton including actin gel binds water, and neutron diffraction studies indicate several layers of ordered water on such surfaces, with several additional layers of partially ordered water.[89-91] Within a dense actin gel water may be completely ordered.

Quantum field theorists have historically proposed that ordering of cytoplasmic water leads to biological quantum states through spontaneous symmetry breaking and generation of bosons. Specifically it has been suggested that water in the hollow microtubule core and on MT surfaces is ordered by microtubule dynamics leading to spontaneous symmetry breaking and generation of evanescent photons, "super-radiance" and "self-induced transparency" of photons in microbule cores .[78]

Charged surfaces (cytoskeleton, membranes) also attract soluble ions of the opposite charge, leading to plasma-like layers (Debye layer) which can have quantum properties, and/or quantum isolation properties. At precisely physiological pH there exists a plasma sleeve around microtubules that could serve to isolate MT quantum processes from thermal decoherence.[92]

Is the brain noisy? Intracellular noise, presumably from thermal energy of water, would be obviated by coherent pumping and ordered water. Apparent electrical noise as manifest in electrophysiological recordings may be something other than noise. Electrophysiological recordings of single cell events detect fluctuations in baseline voltage over various time scales, but eliminate them by signal averaging. The assumption is that background fluctuations are meaningless noise. However, this background "noise" has been found to correlate over wide regions of brain, suggesting it isn't noise at all, but some ongoing activity of unknown etiology that could indicate underlying order or coherence.[93,94] The brain may not be as inhospitable to quantum states as generally believed.

Recently physicist Max Tegmark [95] attempted to "refute" the possibility of quantum computation in brain microtubules (MT) on the basis of calculated decoherence times of 10^{-13} sec by ions in the brain's milieu. Tegmark determines the time to decoherence τ due to the long range electromagnetic effects of an environmental ion to be:

$$\tau \cong \frac{4\pi\varepsilon_0 a^3 \sqrt{mkT}}{Nq_e^2 s}$$

where τ is the decoherence time, ε_0 is the tissue dielectric permittivity (estimated at 10 to 100), *a* is the distance from the microtubule quantum state to the nearest decohering ion, *m* is the mass of the decohering ion, *k* is Boltzmann's constant, *T* is brain temperature (37 degrees centigrade), *N* is the number of elementary charges in the superpositioned tubulin mass (18), *q* is the charge of an electron, and ε_0 is the maximal "separation" between the positions of the tubulin mass in the alternative geometries of the quantum superposition. Several problems appear to invalidate Tegmark's approach.

A full reply to Tegmark is available,[96] of which key points are summarized here: Tegmark's formula for decoherence has the (root of) temperature in the numerator. Consider the limiting cases for Tegmark's formula: as temperature goes to absolute zero, decoherence times go to zero, and as the temperature becomes impossibly high, decoherence times become long. As this is the opposite of what actually occurs, the formula itself is highly suspect.

The quantum microtubule model which Tegmark attacks is not the Orch OR model, nor any other previously published model, but one of his own invention. Tegmark imagines a soliton traveling along a microtubule, with the soliton separated from itself (s in Tegmark's formula) by 24 nanometers ($\sim 10^{-8}$ m). This is apparently a quantum version of a purely classical soliton model put forth by Sataric et al., in 1993.[97] In the Orch OR model the separations *s* is at the level of atomic nuclei within each tubulin, hence *s* is in femtometers, 10^{-15} m. This discrepancy accounts for an erroneous 10^{-7} reduction in Tegmark's calculated decoherence time.

Tegmark also mistakenly considers microtubules as lines of charge, rather than lines of dipoles, thus neglecting permittivity, another false 10^{-2} to 10^{-1} reduction in his calculated decoherence time. Thus correctly applying Tegmark's (albeit disputed) formula to Orch OR (appropriately altering separation s and permittivity ε_0) changes the calculated decoherence time ϑ from Tegmark's 10-13 sec to a range of 10^{-5} to 10^{-4} sec.

The target for decoherence time in the Orch OR model is the time scale for recognized neural events in the range of 10^{-2} to 10^{-1} sec (e.g., coherent 40 Hz, alpha EEG, evoked potentials, etc). There are two possible ways in the framework of the Orch OR model to sufficiently avoid decoherence. In the more direct approach, decoherence must be avoided (coherence must be sustained) for tens to hundreds of milliseconds so that threshold is reached for Penrose objective reduction as described by $E = \hbar/T$ in neurophysiologically relevant time.

In a second approach the critical time for avoidance of decoherence is given by a "collective" coherent pumping mechanism, the manner in which lasers manifest quantum coherence at warm temperatures. If the microtubule system including water molecules ordered at cytoskeletal surfaces is indeed coherently pumped by biochemical energy, along the lines of the mechanism proposed by Frohlich, then this cohering mechanism will repeatedly refresh the environment and avoid decoherence. Coherent oscillations in the nanosecond time scale would be expected, so the target for avoiding decoherence would be 10^{-9} sec.

This type of collective effect has been suggested to protect quantum states from thermal decoherence in high-temperature superconductors.[98]

The target for sustained coherence in Orch OR is thus either 10^{-9} sec, or 10^{-2} to 10^{-1} sec, depending on whether or not Frohlich-like coherent pumping[83,84] is required. Tegmark's equation correctly applied to the Orch OR model would predict decoherence time τ of 10^{-5} to 10^{-4} sec. This is long enough for the Orch OR model with Fröhlich oscillations, and long enough for microsecond Orch OR events, a sequence of which would lead to neurophysiological events.

The other critical parameter in Tegmark's equation is a^3, in which a is the distance from the quantum state to the nearest decohering ion (in quantum computing terminology: the "decoherence-free zone"). Tegmark uses a of 24 nanometers, though he calculates it from the center of the microtubule, meaning roughly 12 manometers from the microtubule surface.

As previously described, several strategies may have evolved to isolate and sustain quantum states in microtubules, which would modify a. In addition to coherent pumping these include ordered water at cytoskeletal surfaces, ionic "double layers," gelation/encasement, and quantum error correction codes.

When encased in actin gelation, the water-ordering surfaces of microtubules are within a few nanometers of actin surfaces, which also order water. Thus a bundle of microtubules transiently encased in actin gelation may be isolated through the entire bundle, with a thus equal to about half the width of the bundle, hundreds of manometers. As a^3 appears in the numerator of Tegmark's equation, an increase in a of one order of magnitude (i.e., from Tegmark's 24 nm to several hundred nm of a microtubule-actin bundle) increases decoherence time three orders of magnitude. Applied to the previously corrected values of 10^{-5} to 10^{-4} sec, this results in a microtubule bundle decoherence time of 10^{-2} to 10^{-1} sec, precisely that required for Orch OR.

Based on quantum technology, the particular structural geometry of microtubules may serve to avoid decoherence in several ways. In high-temperature superconductors, stable quantum states are promoted by two-dimensional (as opposed to either one-dimensional or three-dimensional) lattice structures, which provide a "delicate balance between order and fluctuations. "[99] Microtubules are two-dimensional lattice structures wrapped into cylinders.

Technological quantum computing is, in general, feasible because of the use of quantum error correction codes which may be facilitated by topologios-for instance, toroidal surfaces[l00,101] lot in which global, topological degrees of freedom are protected from local errors and decoherence. Topological quantum computation and error correction have been suggested in microtubules. [102] The microtubule lattice features a series of helical winding patterns which repeat on longitudinal protofiliaments at 3, 5, 8, 13, 21 and higher numbers of subunit dimers (tubulins). The repeat intervals of these particular winding patterns match the Fibonacci series and define attachment sites of microtubule-associated proteins (MAPS). These same global patterns are found in simulations of self-localized phonon excitations in microtubules,103 suggesting that topological global states in microtubules may be resistant to local decoherence.[102] Penrose [104] suggested that the Fibonacci patterns on microtubules may be optimal for error correction.

Another possible feature promoting quantum coherence would be involvement of nuclear spin in protein conformational regulation. Nuclear spin coherence is quite stable, lasting for seconds. Superposition separation in Orch OR occurs at the level of atomic nuclei, where nuclear spins may couple London forces to protein conformation. [105] A new method for magnetic resonance imaging (MRI) of the brain is based on detection of nuclear spin quantum coherence.

It turns out that quantum dipole couplings of water and protein nuclear spins separated by distances ranging from 10 microns to 1 millimeter yield detectable MRI signals correlating with conscious activity. [106,107] The quantum coherence is induced by the MRI magnet and excitation, and so is basically an induced artifact. However, the fact that the brain can support detectable quantum coherence of any kind over such distances is surprising to most observers, and supports the possibility of endogenous, intrinsic quantum coherence.

Conditions for Orch OR require spread, or entanglement of the quantum state, among microtubules in, say, 2×10^{10} tubulins, or roughly 20,000 neurons distributed throughout the brain for a 40-Hz, 25-msec event.

Assuming that isolation is achieved in microtubule bundles within neurons, how could the quantum state traverse cell membranes and/or synapses? It has been proposed that quantum optical phonons generated by microtubule dynamics result in 50-micron coherent zones.[78] We suggest another possibility-that gap junctions may enable the spread via quantum tunneling. Gap junctions separate cytoplasm within connected neuronal and/or glial processes by only 4 nm, within range for quantum tunneling. Specific mitochondria-containing organelles (dendritic lamellar bodies) are found on opposite sides of gap junctions between dendrites, attached to microtubules by connecting proteins[79,80] (FIG. 8). (Dendritic-dendritic processing has been cited as a possible primary site of consciousness. [108,109]) Perhaps tunneling between pairs of dendritic lamellar bodies permits spread of microtubule quantum states throughout "hyper-neurons,"[20] (e.g., 20,000 Cajal neurons momentarily unified by gap junctions)

How would quantum hyper-neurons interact in terms of chemical synapses? Woolf [110,111] argues that acetylcholine binding to dendritic receptors results in MAP2 decoupling from microtubules, and suggests that the isolation facilitates microtubule quantum states. A possible scenario is then: synaptic event → MAP2-MT decoupling → actin gelation → quantum isolation → quantum coherent superposition → Orch OR.

CONCLUSION: PERCEPTION/VOLITION, EVOLUTION, AND SUBJECTIVE EXPERIENCE

The Orch OR model has significant explanatory potential for the enigmatic features of consciousness (TABLE 1). A main tenet in Orch OR is that pre-conscious processing is equivalent to the quantum superposition phase of quantum computation. Potential possibilities interact in the pre-conscious, quantum superposition phase and then abruptly self-collapse: a moment of conscious awareness, a slight quake/rearrangement in spacetime geometry. As quantum state reductions are irreversible, cascades of such Orch OR events present a forward flow of subjective time and "stream of consciousness" which charts a course through fundamental spacetime geometry.

Perception/Volition

The Orch OR scheme is applicable to cognitive activities. Functions like face recognition and volitional choice may require a series of conscious events arriving at intermediate solutions, but for the purposes of illustration we shall consider single events.

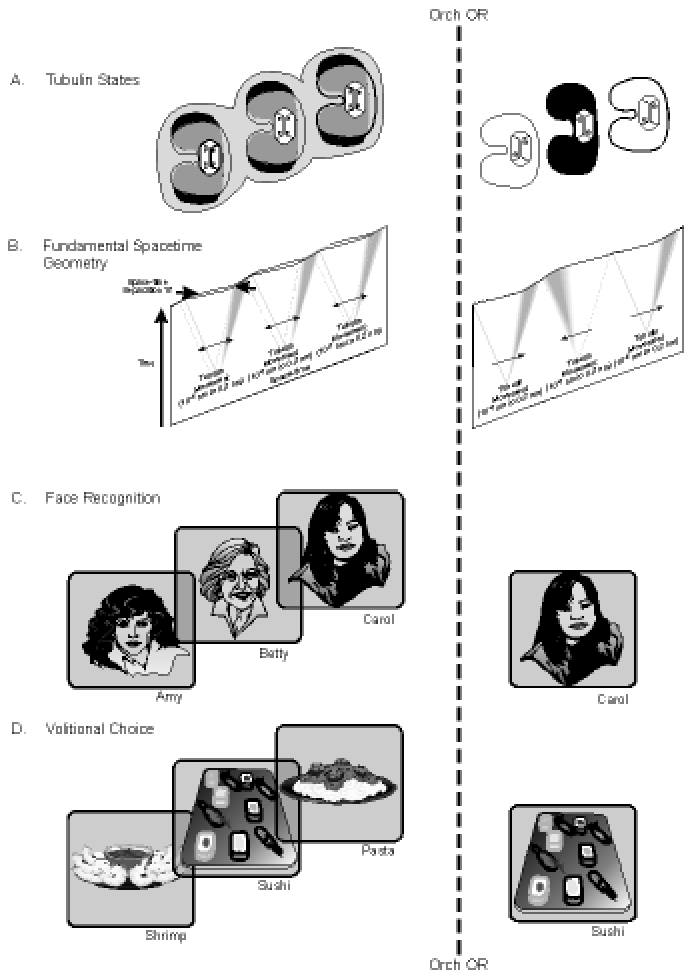

FIGURE 9. An Orch OR event. (**A**) *(left)* Three tubulins in quantum superposition prior to 25-msec Orch OR. After reduction *(right),* particular classical states are selected. (**B**) Fundamental spacetime geometry view. Prior to Orch OR *(left),* spacetime corresponding with three superposed tubulins is separated as Planck scale bubbles: curvatures in opposite directions. The Planck-scale spacetime separations, S, are very tiny in ordinary terms, but relatively large mass movements (e.g., hundreds of tubulin conformations, each moving from 10-6 to 0.2 nm) indeed have precisely such very tiny effects on the spacetime curvature. A critical degree of separation causes Orch OR and an abrupt selection of single curvatures (and a particular geometry of experience). (**C**) Cognitive facial recognition: A familiar face induces superposition *(left)* of three possible solutions (Amy, Betty, Carol) which "collapse" to the correct answer Carol *(right).* (**D**) Cognitive volition: Three possible dinner selections (shrimp, sushi, pasta) are considered in superposition *(left),* and collapse via Orch OR to choice of sushi *(right).*

Imagine you briefly see a familiar woman's face. Is she Amy, Betty, or Carol? Possibilities may superpose in a quantum computation. For example during preconscious processing, quantum computation occurs with information (Amy, Betty, Carol) in the form of "qubits" of superposed states of microtubule tubulin subunits within groups of neurons. As threshold for objective reduction is reached, an instantaneous conscious event occurs. The superposed tubulin qubits reduce to definite states, becoming bits. Now, you recognize that she is Carol! (an immense number of possibilities could be superposed in a human brain's 10^{19} tubulins).

In a volitional act possible choices may be superposed. Suppose for example you are selecting dinner from a menu. During pre-conscious processing, shrimp, sushi, and pasta are superposed in a quantum computation. As threshold for objective reduction is reached, the quantum state reduces to a single classical state. A choice is made. You'll have sushi! In both perception and volition, non-computable influences may be exerted which reflect Platonic influences encoded in fundamental spacetime geometry. [1,2]

Evolution

Where in the course of evolution may consciousness have evolved? The Orch OR model implies that an organism able to sustain quantum coherence among, for example, 10^9 tubulins for 500 msec would be capable of having a conscious experience. More tubulins coherent for a briefer period, or fewer for a longer period ($E = \hbar / T$) will also have conscious events.

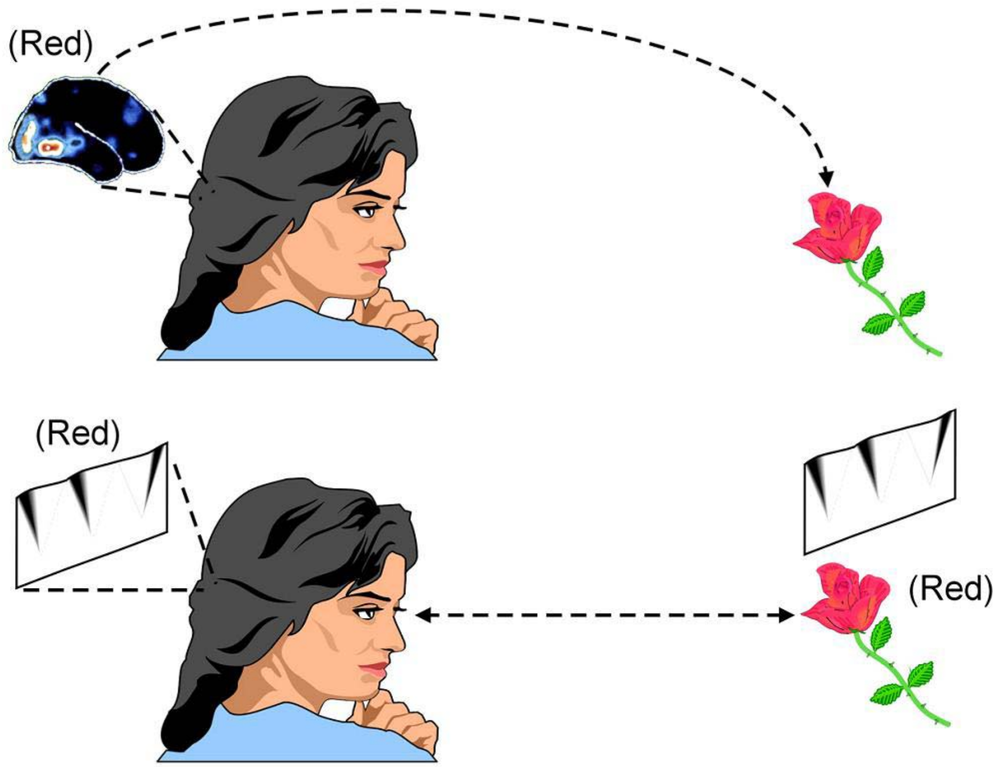

FIGURE 10. An Orch OR event. (**A**) (*left*) Three tubulins in quantum superposition prior to 25-msec Orch OR. After reduction (*right*), particular classical states are selected. (**B**) Fundamental spacetime geometry view. Prior to Orch OR (*left*), spacetime corresponding with three superposed tubulins is separated as Planck scale bubbles: curvatures in opposite directions. The Planck-scale spacetime separations, S, are very tiny in ordinary terms, but relatively large mass movements (e.g., hundreds of tubulin conformations, each moving from 10−6 to 0.2 nm) indeed have precisely such very tiny effects on the spacetime curvature. A critical degree of separation causes Orch OR and an abrupt selection of single curvatures (and a particular geometry of experience). (**C**) Cognitive facial recognition: A familiar face induces superposition (*left*) of three possible solutions (Amy, Betty, Carol) which "collapse" to the correct answer Carol (*right*). (**D**) Cognitive volition: Three possible dinner selections (shrimp, sushi, pasta) are considered in superposition (*left*), and collapse via Orch OR to choice of sushi (*right*).

Human brains may be capable of, for example, 2×10^{10} tubulin, 25-msec experiences, but what about simpler organisms? The place of consciousness in evolution is unknown, but the actual course of evolution itself may offer a clue. Fossil records indicate that animal species as we know them today including conscious humans all arose from a burst of evolutionary activity some 540 million years ago (the "Cambrian explosion"). MT-based cilia and organelles were apparently common in primitive vision and sensory systems, and organisms present at the beginning of the Cambrian explosion included small worms and urchins whose modern descendants of similar form and size include the well-studied nematode C. *elegans,* and the spiny urchin *Echinosphaerum. C. elegans* has 307 neurons (about 3×10^9 tubulins) and *Echinosphaerum* has 3×10^9 tubulins in each of its spiny axonemes.[112] Quantum coherent assemblies of this number of tubulins would reach threshold for objective reduction in about 133 msec, a not unreasonable duration for isolation and avoidance of decoherence by actin gelation and ordered water. Perhaps the onset of rudimentary consciousness by Orch OR in these simple organisms precipitated the Cambrian explosion?[113]

Subjective Experience

In our approach experiential "qualia" derive from pan-protopsychism-qualia are patterns in fundamental spacetime geometry accessed and selected by the Orch OR process. Our view also suggests that consciousness is a sequence of discrete events. It may be interesting to compare our considerations with subjective viewpoints that have been expressed with regard to the nature of the progression of conscious experience. For example, support for consciousness consisting of sequences of individual, discrete events is found in Buddhism: trained meditators describe distinct "flickerings" in their experience of reality. [114] Buddhist texts portray consciousness as "momentary collections of mental phenomena," and as "distinct, unconnected and impermanent moments which perish as soon as they arise." Each conscious moment successively becomes, exists, and disappears-its existence is instantaneous, with no duration in time, as a point has no length. Our normal perceptions, of course, are seemingly continuous, presumably as we perceive "movies" as continuous despite their actual makeup's being a series of frames. Some Buddhist writings even quantify the frequency of conscious moments. For example the Sarvaastivaadins[115] described 6,480,000 "moments" in 24 hours (an average of one "moment" per 13.3 msec), and some forms of Chinese Buddhism describe one "thought" per 20 msec. These accounts, including variations in frequency, are consistent with our proposed Orch OR events. For example a 13.3-msec pre-conscious interval would correspond with an Orch OR involving 4×10^{10} coherent tubulins, and a 20-msec interval with 2.5×10^{10} coherent tubulins. Thus Buddhist "moments of experience," Whitehead "occasions of experience," and our proposed Orch OR events seem to correspond tolerably well with one another.

Consciousness has an important place in the universe. Orch OR in microtubules is a model depicting consciousness as sequences of non-computable self-selections in fundamental spacetime geometry. If experiential qualia are qualities of spacetime, then Orch OR indeed begins to address the nature of conscious experience in a serious way.

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