CHAPTER 5

The conscious connection

A psycho-physical bridge between brain and pan-experiential quantum geometry

Stuart R. Hameroff and Jonathan Powell

Can conscious experience – feelings, phenomenal qualia, our 'inner life' – be accommodated within present-day science? Those who believe it can (e.g. proponents of physicalism, reductionism, materialism, functionalism, computationalism) see conscious experience as an emergent property of complex computation in networks of brain neurons. In these approaches consciousness is viewed as a higher order effect emerging from lower level, non-conscious entities.

Others believe consciousness cannot be accommodated within present day or future science. Cartesian dualists see consciousness and physical matter as separate and irreconcilable. A modern version of dualism is 'mysterianism,' or cognitive closure, which suggests that consciousness exists within science but cannot be understood by conscious beings, and we should stop worrying about it.

A third set of philosophical positions ascribes to consciousness (or its precursors) ontological status as a foundational component of reality. These positions (e.g. panpsychism, pan-experientialism, idealism) relate consciousness to irreducible ('funda-mental') components of reality, something akin to mass, spin or charge. These views take consciousness to be present in low level entities, in which – on some readings – they inherently contain a phenomenal nature or subjective experience (qualia). Consciousness or its 'proto-conscious' precursors are thus somehow built into the structure of the universe – a view that we might label *pan-protopsychism*.

Most of these views are monist in nature, in that they take reality to be, ultimately, a single entity or substance. At issue, then, are two key points: (1) the essential characteristic(s) of this monist substance, and (2) how it gives rise to apparently diverse entities like 'mind' and 'matter.' If the one reality is essentially mind-like, then we have a form of idealism – which may or may not entail panpsychism. If it is essentially physical or material, physicalism obtains.

Alternatively, the one reality can be seen as something other than mind or matter, in which case we have a form of neutral monism; Spinoza, James, and Russell are typically cited as holding this view. A contemporary form of neutral monism – one

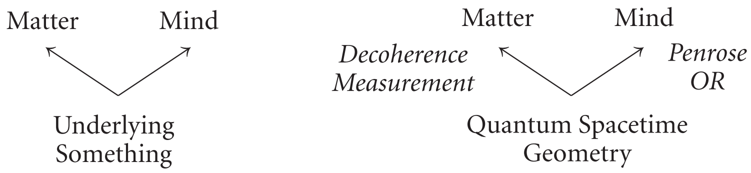

Figure 1. Left: Neutral monism, in schematic form. Right: Neutral monism in the context of modern physics. Quantum spacetime geometry is the neutral reality, and Penrose OR is the psycho-physical bridge.

defended in this paper – defines the one reality in terms of *quantum spacetime geometry*, i.e. as a consequence of the fine-grained structure of the universe. Figure 1 summarizes the situation.

The 20th century rise of computation and cognitive science cast consciousness – mind, the mental – as a computational processing of discrete (e.g. digitized) information. Regarding 'the physical,' advances in string theory, quantum field theory, quantum geometry and other approaches attempt to account for the fine structure of the physical world differently, but are all based on discrete quantized units of *information*. Wheeler (1994), Smolin (2001), Lloyd (2008) and others have suggested in various ways that information is fundamental to the nature of reality, and that in some sense the universe is composed of interactive information processing – that the universe is, in essence, a computer.

Applying an information-based reality to neutral monism, Bateson (1970), Bohm (1986), Wheeler (1994) and Chalmers (1996) proposed dual-aspect panpsychist (or near-panpsychist) theories in which information has both a) psycho/experiential/mental, and b) physical/material aspects. But the question remains: How, specifically, are these two aspects related? What is the connection between them?

This notion of a connection or bridge between mind and matter has been examined at least since the 1920s. Harvard philosopher Leonard Troland (1922) speculated about "psycho-physical bridging principles" as a way of unifying the two, and of putting mind on firm theoretical foundations. Chalmers later adopted this notion, combining it with an information-based ontology to arrive at a tentatively panpsychist theory of mind. But neither of these two men elaborated on the nature of this bridge, nor how it might function.

We propose that a pathway to understanding consciousness might be found in identifying both sides of the bridge, and the nature of the connection, i.e. the bridge itself. We attempt to describe the psycho-physical bridge using the Penrose-Hameroff Orch OR theory of consciousness. The underlying psycho/experiential/mental side that embeds proto-conscious experience is described in the physics of quantum geometry at the Planck scale, the most fundamental level of the universe. The physical/material side resides in the brain – specifically, in quantum electron dipole states mediating computations in microtubules and other biomolecular structures involved in consciousness. The connection between the two sides – the psycho-physical bridge –

is a specific process called Penrose objective reduction (OR), a proposed threshold for quantum state reduction inherent in Planck scale quantum geometry. Pan-protopsychism thus becomes the most accurate picture of our universe.

Orch OR describes how well-understood neuronal-level functions (e.g. axonal firings, synaptic transmissions, dendritic synchrony) 'orchestrate' quantum computations in microtubules within brain neuronal interiors. The quantum computations reduce to classical solutions by Penrose OR, connecting brain functions to Planck scale quantum geometry which may embed proto-conscious experiential qualities. Orch OR events are correlated with gamma synchrony EEG occurring roughly 40 times per second; conceptually, these may be seen as equivalent to Whitehead's "occasions of experience."

1. Discrete conscious moments and quantum state reductions

Pan-experiential philosopher Alfred North Whitehead (1929;1933) viewed the universe as comprised not of things, but of *events* – in other words, as a process. Two centuries earlier, Leibniz (1714) had quantized reality, describing fundamental 'monads' as the ultimate entities of reality, but Whitehead transformed monads into "actual occasions" occurring in a "basic field of proto-conscious experience." Whitehead's occasions are spatio-temporal quanta, each endowed – usually on a very low level – with mentalistic characteristics like "experience, subjective immediacy, appetition." In his view, highly organized collections ("societies") of occasions permit primitive mentality to become intense, coherent and fully conscious.

But Whitehead's theory of mind is counterintuitive: Is consciousness indeed quantized, composed of discrete events? Trained Buddhist meditators describe distinct 'flickerings' in their experience of reality. Buddhist texts portray consciousness as "momentary collections of mental phenomena," and as "distinct, unconnected and impermanent moments which perish as soon as they arise." Our normal conscious experience seems continuous, but so does a motion picture – even though we know it to be composed of discrete frames. There is no doubt that we perceive motion pictures as continuous despite their actual 'quantized' structure. Perhaps consciousness is the same.

Some Buddhist writings even quantify the frequency of conscious moments. For example the *Sarvaastivaadins* (von Rospatt 1995) describe 6,480,000 'moments' in 24 hours (an average of one moment per 13.3 msec), and some Chinese Buddhists as one 'thought' per 20 msec. Others describe the duration of a conscious moment as "1/64th the snap of a finger." All these are consistent with gamma synchrony.

William James (1890) initially considered consciousness a sequence of 'specious moments' but later embraced the idea of a continuous 'stream of consciousness.' The 'perceptual moment' theory of Stroud described consciousness as discrete events, rather like sequential frames of a movie.[1] Evidence in recent years suggests periodicities for perception and reaction times in the range of 20 to 50 milliseconds (gamma EEG waves; 30 to 90 Hz) and another in the range of hundreds of milliseconds (alpha and theta EEG waves; 3 to 7 Hz), the latter consistent with saccades and the visual gestalt (VanRullen & Thorpe 2001). Regarding visual consciousness, several author groups (Woolf & Hameroff 2001; van Rullen & Koch 2003) have suggested that integrated visual perceptions are a series of fast gamma waves (each corresponding to specific components of vision, e.g. shape, color, motion, meaning) riding on a slower, e.g. theta, wave. Similarly, Freeman (2006) has characterized theta wave steps with finer scale cortical dynamics as video-like frames of conscious content.

Using visual consciousness as an example, if we equate the visual gestalt with a cinematic scene, consciousness may be considered sequences of scenes (∼3 to 7 scenes per second), each composed of sequences of individual frames (∼10 to 30 frames per scene, hence 40 or more frames per second). Gamma frequency frames could relate to Whitehead's low-level mental occasions, and theta frequency scenes to his 'intense, coherent and fully conscious' occasions.

If so, what are 'occasions of experience'; what is the 'basic field of proto-conscious experience'; and, how does the brain fit in? What underlying process correlates with synchronized gamma and theta frames and scenes? Abner Shimony (1993, 1997) recognized that Whitehead's approach was potentially compatible with modern physics, specifically quantum theory, and suggested that quantum state reductions – actual physical events – could represent Whitehead's "occasions."

2. The quantum/classical divide

The material reality we perceive is the physical side of the psycho-physical bridge. But upon inspection, physical reality appears to derive from a deeper, non-material quantum level. The everyday 'classical' world is composed of matter and energy following Newton's laws of motion, Maxwell's equations for electromagnetism, and other predictable behaviors. At small scales, however, the bizarre laws of quantum mechanics reign.

Atoms and sub-atomic quantum particles may exist in two or more states or places simultaneously, more like waves than particles, and existing as multiple coexisting possibilities known as *quantum superposition,* governed by a quantum wave function. But we don't see multiple coexisting wave-like possibilities in our everyday, classical world. We see objects and particles as definite, classical material things in specific locations and states. Even when we measure atomic and sub-atomic systems they behave classically. The issue of why we don't see quantum superpositions in our everyday classical

1. For an early study, see J. Stroud, "The fine structure of psychological time," in *Information Theory in Psychology* (1956).

world is known as the 'measurement problem,' which has led to various interpretations of quantum mechanics (discussed below).

Another quantum property is 'entanglement,' or quantum coherence, in which components of a system become unified, governed by one common quantum wave function. If one member of an entangled system is measured or perturbed, other members are instantaneously affected, even over great distances.

One example of entanglement is the famous 'EPR pairs' (after Einstein, Podolsky and Rosen, who posed the problem as a thought experiment in the 1930s). Imagine two members of a quantum system (e.g. two electrons with complementary spin: if one is spin up, the other is spin down, and vice versa). If the paired electrons (both in superposition of both spin up and spin down) are separated by being sent along different wires, say to two different villages miles apart from each other, they each remain in superposition. However when one superpositioned electron is measured by a detector at its destination and reduces/collapses to a particular spin, (say spin up), its entangled twin miles away *instantaneously* reduces/collapses to the complement (spin down). The nonlocal effect has been verified with electron spin pairs, polarized photons and other quantum systems but remains unexplained.[2] Entire clouds of millions of atoms have been entangled. Non-local entanglement – referred to as 'quanglement' by Penrose – remains a fundamental mystery.

Another form of entanglement occurs in quantum coherent systems such as Bose-Einstein condensates in which a group of atoms or molecules surrenders individual identity and are governed by a single quantum wave function. If one component is perturbed, all components 'feel' it and react accordingly.

Quantum superpositions and entanglements have very practical consequences; they are used technologically in quantum information processors. Conventional classical computers represent digital information as 'bits' of either 1 or 0. In quantum computers information may be represented as quantum superpositions of both 1 *and* 0 (quantum bits, or 'qubits'). While in superposition, qubits interact with other entangled qubits, allowing computational interactions of enormous speed and near-infinite parallelism. During quantum computation, the superposed entangled system must be isolated from the environment to avoid decoherence – a loss or degradation of quantum properties. After the quantum computation has run, qubits are 'measured,' i.e. exposed to the classical environment, which causes an abrupt loss of superposition (state reduction/collapse), reducing qubit values to specific classical states (1 or 0) which constitute the solution. Measurement-induced reduction (like decoherence) introduces randomness in the choice of particular classical state outputs (the randomness is overcome by redundancy). Quantum cryptography and quantum teleportation also utilize quantum superposition and entanglement, and promise to revolutionize information processing.

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2. See A. Aspect, P. Grangier, and G. Roger (1982), "Experimental realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: a new violation of Bell's inequalities." (*Phys. Rev. Lett.* 48: 91–94).

However, the underlying mechanisms remain unknown. What does it actually mean for an object to be in two or more places or states simultaneously? How can nonlocal entanglement occur? What happens to isolated quantum superpositions?

Experiments near the turn of the 20th century seemed to show that the multiple possibilities in quantum superpositions persisted until observed by a conscious human. This led prominent quantum theorists like Bohr, Heisenberg and Wigner to conclude that *consciousness* caused quantum state reduction, that consciousness 'collapsed the wave function' (this is the so-called Copenhagen interpretation, reflecting the Danish origin of Nils Bohr, its leading proponent). This pragmatic approach allowed quantum systems to be studied successfully, putting aside both consciousness and underlying reality.

Modern interpretations consider any interaction of superposed systems with the classical environment to cause loss of superposition and to 'decohere' the quantum state to randomly chosen classical states. But again, the fate of *isolated* superpositions is unknown.

Another approach is the 'multiple worlds' hypothesis which asserts that every superposition is a *separation in the universe itself*, and that each possibility evolves into its own universe.[3] Hence there exists an infinite number of worlds co-existing in perpetual superposition.

David Bohm (e.g. Bohm & Hiley 1993) proposed that the wavefunction contains active information which guides the movement of particles, and that consciousness was associated with active information. Both Bohm and the multiple worlds view avoid quantum state reduction, or collapse of the wave function. Henry Stapp's view (Stapp 2004) identifies consciousness with collapse/reduction.

Some theories propose an objective threshold for quantum state reduction, hence 'objective reduction' (OR). One such OR threshold was proposed by Ghirardi, Rimini and Webber, who suggested that spontaneous self-collapse occurs when a critical number of particles are in superposition. Subsequent experiments, however, have failed to confirm their threshold.

The objective reduction (OR) of Roger Penrose is, at its base, similar to the multiple worlds view in which each superposition is a separation in the underlying fabric of the universe, expressed as quantum spacetime geometry. But according to Penrose the spacetime separations are unstable and will spontaneously self-collapse/reduce to single spacetime geometries at a specified objective threshold degree of separation. These OR events are quantum level processes – ripples – in the fundamental geometry of the universe. Penrose proposed that such objective reductions were essential to consciousness.

So: What *is* the fundamental geometry of the universe?

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3. The classic study was done by Everett in 1957; see his article "Relative state formulation of quantum mechanics." (*Rev. Mod. Physics*, 29: 454–462).

3. The psycho/experiential side of the psycho-physical bridge: Quantum spacetime geometry

Atoms, atomic nuclei and electrons occupy only a small fraction of an atom's volume – most of an atom is empty space. What is empty space?

Democritus (circa 400 BCE) described empty space as a true void, whereas Aristotle saw a background "plenum" filled with substance. Maxwell's 19th-century "luminiferous ether" sided with Aristotle, but attempts to detect the ether failed. Furthermore, Einstein's special relativity suggested that there was no background pattern or structure at all. However, Einstein's general relativity related mass to curvature in a geometric spacetime 'metric,' and swung the pendulum back to the view of an underlying pattern in 4-dimensional spacetime. Where, then, is the pattern? At what level of the universe could quantized information occur and interact?

As we go down in scale from the size of atoms (10^{-8} centimeters), spacetime is smooth and featureless until eventually we find granularity at the incredibly small 'Planck scale' of space and time (10^{-33} centimeters, 10^{-43} seconds). The Planck scale is the basement level of reality – the ground floor, if you will.

The best description of Planck scale geometry is through *loop quantum gravity* related to Penrose spin networks. (In comparison, string theory attempts to describe particles and energy through vibrating strings, but doesn't include the background medium in which the strings vibrate.) Penrose portrayed the Planck scale as a dynamical web of spin networks.[4] Taking spin as an irreducible, fundamental entity, spin networks define spectra of discrete Planck scale volumes and configurations which dynamically evolve and define spacetime geometry. Smolin (2001) has described quantum spin networks as continually evolving, as being in some way alive. They may also qualify for Whitehead's 'basic field of protoconscious experience.'

The amount of potential information in Planck scale spin networks is vast; each Planck scale volume, or 'pixel of reality,' may be shaped by a huge variety of combinations of 'edge' lengths, number of spins per edge, and nonlocal interactions. In addition to the enormous potential variety in each Planck scale pixel, their sheer number compared to our macroscopic scale is enormous – there are roughly 10^{107} Planck volumes or pixels in the volume of a human brain, far greater than the number of particles in the universe.

Whether or not spin networks, twistor theory, loop quantum gravity or other approaches are correct, the fine structure of the universe is constructed of Planck scale quantum geometry whose configurations and dynamics lead to all matter and energy. Other avenues have suggested a holographic arrangement, so that Planck scale patterns and information may recur, fractal-like, at various larger scales.

If consciousness derives from fundamental, irreducible entities (e.g. 'protoconscious qualia'), they should be embedded in Planck scale geometry. Where else

4. See *Quantum Theory and Beyond* (1971; E. Bastin, ed.).

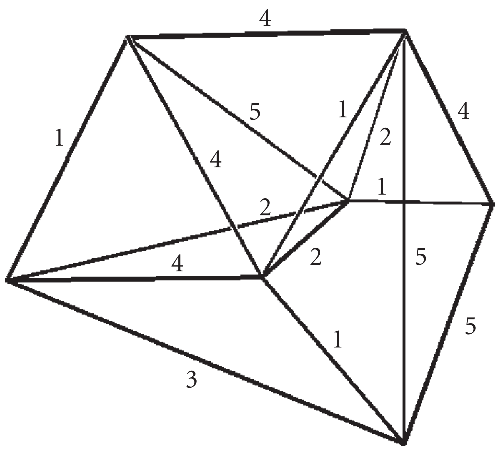

Figure 2. A spin network quantum mechanical description of the geometry of spacetime. Spin networks describe a spectrum of discrete, evolving Planck scale volumes and configurations (with permission from Smolin (Life of the Cosmos, Oxford University Press; 1997). Average length of each edge is the Planck length (10^{-33} cm); numbers indicate quantum spin values along each edge.

could they be embedded? Fundamental spacetime geometry is all there is! Quantum geometry is the prime candidate to contain proto-conscious experience. But a huge question remains: How could it connect to the brain to produce the richness of conscious experience?

4. Penrose OR – the conscious connection

Penrose OR is a theoretical construct which addresses several issues. It is a proposed solution to the measurement problem in quantum mechanics, explaining the fate of isolated quantum superpositions. It ties together quantum mechanics and general relativity, two branches of science which have been irreconcilable. And it offers an accounting of consciousness as a sequence of discrete events, each event being an objective reduction occurring in the brain.

Penrose OR is in one way similar to Everett's multiple worlds view, in which each superposition is a separation in underlying reality, i.e. with each and every superposition the universe bifurcates, or separates, with each possibility branching off to form a new universe, a new reality. Thus, according to this view, there exist an infinite number of parallel universes. For the Schrödinger's cat story (i.e. assuming superposition of such a macroscopic object is possible), each time the box is opened the universe bifurcates into one universe with a live cat, and another universe with a dead cat. But how are we to envision the universe – the fabric of reality – separating from itself?

For illustration we can ignore the details at the Planck scale and condense 4-dimensional spacetime into a 2-dimensional spacetime sheet: one spatial dimen-

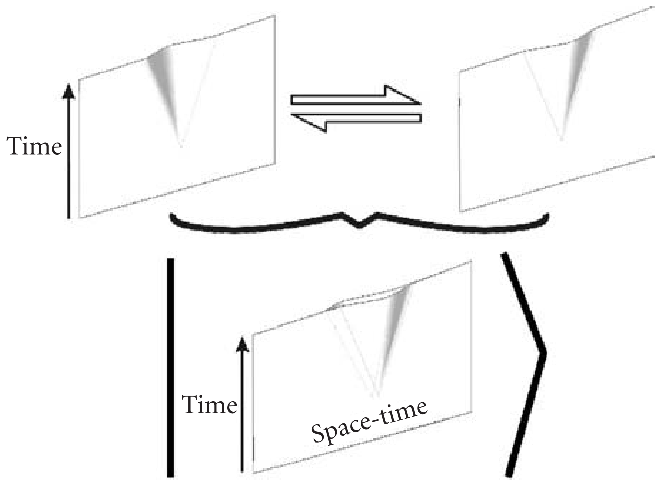

Figure 3. Four dimensional spacetime may be schematically represented by a two dimensional ”spacetime sheet” with one dimension of space and one dimension of time. Mass is equivalent to curvature in spacetime, and the two spacetime curvatures (top) represent mass in two different locations or conformations respectively. At bottom, mass in quantum superposition (separated from itself) is simultaneous spacetime curvature in opposite directions, a separation, bubble or blister in spacetime geometry. At a critical degree of separation, the system becomes unstable and must select either one state or the other (from Penrose 1994: 338).

sion and one time dimension (Figure 3, top). This spacetime is slightly curved, in accordance with Einstein’s general theory of relativity, in a way which encodes the gravitational fields of all distributions of mass density. Each mass density – each object or particle – effects a spacetime curvature, albeit tiny for small objects.

The idea of large objects causing large spacetime curvature is familiar. Einstein had predicted that the spacetime curvature of our sun would bend light from stars, distorting their position from our vantage point. Some 50 years after this prediction, Sir Arthur Eddington made the critical observations during a solar eclipse to prove Einstein’s hypothesis. However, the idea of small, quantum objects causing small spacetime curvatures was first put forth by Penrose.

Consequently we can view any mass in one location as spacetime curvature in a particular direction, and location of the mass in a different location as spacetime curvature in another direction. Therefore quantum superposition of a particle in two locations may be considered simultaneous curvatures in opposite directions (Penrose 1989, 1994). As in the multiple worlds view, the spacetime sheet separates into two opposing curvatures, resulting in a ‘bubble’ or ‘blister’ in underlying reality (Figure 3, bottom).

Strictly speaking the separations cannot be considered to have any true ‘width,’ or ‘length,’ as spacetime defines its dimensions, rather than exists in dimensions. However, metaphorically we can consider that the distance between the separated space-

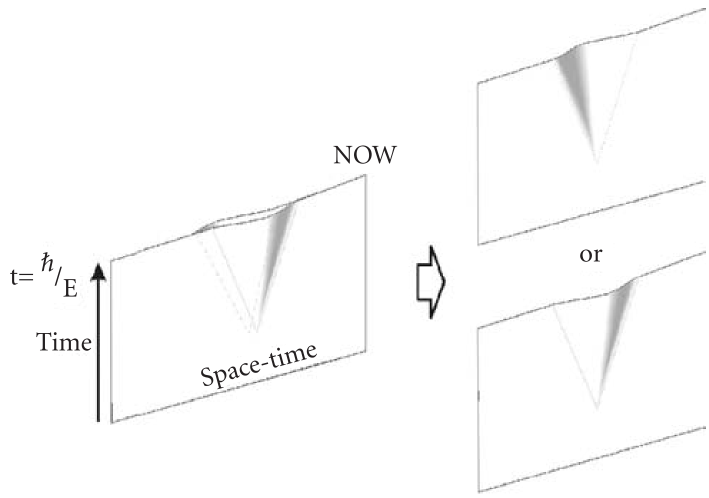

Figure 4. Penrose OR. Left: 2-dimensional space-time sheet in superposition. When time t becomes equal to ħ/E (NOW), OR occurs and (Right) one of the possible spacetime curvatures is selected as classical reality. Penrose proposed such OR moments incorporate conscious experience.

times (width) is on the order of a Planck length (10^{-33} centimeters) whereas the length may be macroscopic, on the order of the mass separation distance, e.g. nanometers (10^{-8} centimeters) or larger, or the distance over which mass separation distance occurs (e.g. ~10 centimeters, as may occur in the brain). That such 'narrow' separations have significant consequences may seem surprising. However, an analogy may be drawn to earthquakes in which the earth separates only slightly, but over a great length or faultline, with significant consequences.

In the multiple worlds view, each possible spacetime sheet – each side of the blister – evolves into a separate universe. In Penrose's view these separations, bubbles, or blisters are, however, unstable; somewhat like soap bubbles, they will eventually reduce, or collapse, to one particular curvature or the other, with the reductions occurring virtually instantaneously – actual events producing definite classical reality from quantum possibilities. The instability is inherent in the properties of spacetime geometry (quantum gravity) and constitutes an *objective* threshold for an isolated quantum state reduction, hence 'objective reduction.'[5]

This whole process has a direct bearing on the mind. Penrose proposed that objective reductions *are conscious*, and convey experiential qualities and conscious

5. Penrose has quantified the formulation in the following way. Objective reduction due to the quantum gravity properties of fundamental spacetime geometry occurs at a time t given by the Heisenberg indeterminacy principle $E=\hbar/t$, in which E is the magnitude of superposition/separation (one graviton), ħ is Planck's constant over 2π, and t is the time until reduction. The magnitude E is related to the gravitational self-energy of the superposition and may be calculated from the amount and distance of mass "separated from itself."

choice. Hameroff and Penrose (1996b) proposed this occurred due to pan-experiential qualities embedded in Planck scale geometry – that which we are calling pan-protopsychism. As actual events occurring in a medium which may be construed as a 'basic field of proto-consicous experience,' Penrose OR qualifies as Whiteheadian occasions (as suggested by Abner Shimony), and provide a psycho-physical bridge between pan-experiential quantum geometry and the brain. But where in the brain are OR events able to interface? What is the physical (brain) side of the psycho-physical bridge?

5. The biological side of the psycho-physical bridge – the Orch OR model

A connection from the Planck scale to the brain – a psycho-physical bridge – implies influence scaling up from infinitesimally tiny lengths and energies to result in conscious perceptions and choices, and hence causal efficacy in the classical world. To bridge this daunting chasm of scale, a quantum lever or amplifier must exist in the brain which is sensitive to Planck scale influence, and able to control or regulate neuronal processes relevant to consciousness. If we assume consciousness emerged during evolution, such functional quantum effects in biomolecules must have preceded consciousness, and have played (and continue to play) some general role in biological systems. Yet technological quantum devices must be isolated to near absolute zero to prevent decoherence. How can quantum systems control high energy biomolecules? It appears that isolated quantum zones exist within biomolecules, forming extended quantum phases in living systems (Hameroff 2008).

Proteins, lipids and nucleic acids based on carbon chemistry are the primary components of organelles and cells. They are described by various characteristics, one being solubility – a molecule's ability to dissolve in a particular solvent. Water is the major solvent in biomolecular systems.

Water is a *polar* molecule, with exposed electrical charges (positive on one end, negative on the other) allowing charge interactions with neighboring waters and charged molecules. Organic biomolecules generally have charged groups on their exterior surface which interact with and dissolve in water, and are referred to as 'hydrophilic' (water-loving).

Another type of solvent, e.g. benzene, is *non-polar*, hence oil-like, or fatty. This type excludes water (oil and water do not mix), and is referred to as hydrophobic (water-fearing).[6]

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6. The degree of polar/hydrophilic versus non-polar/hydrophobic is quantified by the Hildebrand solubility co-efficient lambda λ. Water, the most polar solvent, has a very high λ coefficient of 48 SI units; the non-polar benzene has a low λ equal to 18.7 SI units (Hildebrand Solubility Parameters: /MPa1/2 = 2.0455 × /cal 1/2cm$^{-3/2}$ Standard Hildebrand values from Hansen, *Journal of Paint Technology* Vol. 39, No. 505, Feb 1967; SI Hildebrand values from Barton, *Handbook of Solubility Parameters*, CRC Press, 1983 and Crowley, et al., *Journal of Paint Technology* Vol. 38, No. 496, May 1966. http://sul-server-2.stanford.edu/byauth/burke/solpar/solpar2.html).

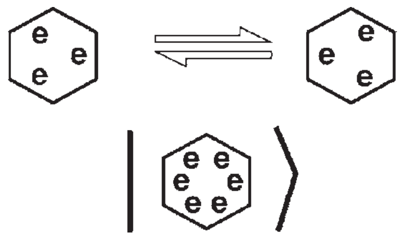

Figure 5. Six-carbon benzene (phenyl) ring with 3 mobile electrons. Top: electrons shift between two possible locations. Bottom: Quantum superposition of both location possibilities. Electron locations indicate electron cloud dipole fluctuations, i.e. van der Waals London forces

Organic biomolecules are generally 'amphiphilic', e.g. having both polar and non-polar regions. *Exterior* surfaces of biomolecules are polar, hydrophilic and water soluble. Within *interiors* of sufficiently large biomolecules are regions which are non-polar, hydrophobic and oil-soluble. Extended non-polar hydrophobic phases develop when biomolecules assemble and organize into structures and organelles. Lipid membranes contain an internal hydrophobic planar layer composed of non-polar groups in cholesterol and other lipids.[7]

Proteins have internal non-polar 'hydrophobic pockets' composed of amino acid residues (including the electronic ring structures of amino acids tryptophan, tyrosine and phenylalanine). These arrangements enable electron resonance effects in non-polar regions throughout biomolecules, organelles, cells and organisms. Most importantly, within this phase, quantum effects are shielded from decohering interactions with the polar environment.

As real-time engines of living systems, proteins provide movement, force and information processing. Protein ion channels, enzymes, receptors, cytoskeletal proteins all function by a process of *conformation*, or shape-changing. For many proteins, conformation is a delicate balance between countervailing chemical energies, such that quantum (London) forces in hydrophobic pockets are pivotal.

The benzene (or phenyl) ring is six carbons with 3 delocalizable carbon double bonds, i.e. three mobile electrons within a confined region which overall is electrically neutral (Figure 5). Electron location movements are described as electron cloud dipole fluctuations. Coupling between electron cloud dipoles, e.g. between neighboring benzenes, occurs via a type of van der Waals force called the London force.

When benzene and water are mixed, non-polar benzenes self-associate, pushed together by water – the hydrophobic effect – and attracting each other by London forces between electron cloud dipoles. Non-polar molecules aggregate into stable, low-lambda regions, e.g. oil droplets, shielded from polar interactions with environmental water. In biology, these effects drive protein folding and other forms of self-organization.

7. DNA and RNA have internal non-polar 'pi electron stacks' composed of hydrophobic regions of nucleic acids.

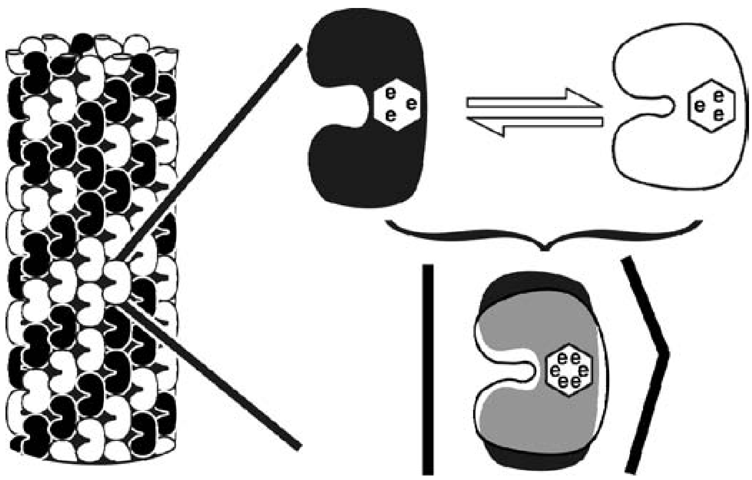

Figure 6. Left: Microtubule: a hollow cylinder of 25 nanometers diameter, consisting of tubulin proteins arranged in a skewed hexagonal lattice. Right top): Each tubulin molecule may switch between two (or more) conformations, coupled to quantum electron dipoles in a hydrophobic pocket. Right (bottom): Each tubulin can also exist in quantum superposition of both conformational states.

These quantum forces are essential to consciousness, as evidenced by the action of anesthetic gas molecules. Anesthetic gas molecules selectively erase consciousness, sparing other brain activities. They bind by London forces in non-polar, hydrophobic pockets in a group of brain proteins (receptors, channels, components of cytoskeletal microtubules, etc.). Presumably, such subtle quantum actions prevent or inhibit the normally-occurring quantum forces required for consciousness.

Hydrophobic pockets must be large enough for anesthetic gases to fit, thus during anesthesia quantum processes due to electron resonance in smaller non-polar regions continue, perhaps essential to non-conscious life functions. Cooperative resonance and entanglement among quantum forces in biomolecular assemblies have been proposed as an underlying mechanism of living systems (Hameroff 2008).[8]

Among anesthetic-sensitive proteins, *tubulin* – the constituent protein of *microtubules* – is arrayed in geometric lattices particularly suited to computation.[9] The Penrose-Hameroff model of 'orchestrated objective reduction' (Orch OR) proposes that neuronal processes potentially related to consciousness may be regulated by quantum computations occurring in cytoskeletal microtubules within the brain's neurons.

8. For an earlier study, see H. Fröhlich, (1975): "The extraordinary dielectric properties of biological materials and the action of enzymes." (*Proceedings of the National Academy of Sciences, 72)*.

9. See S. Hameroff and R. Watt, (1982): "Information processing in microtubules." (*Journal of Theoretical Biology*, 98).

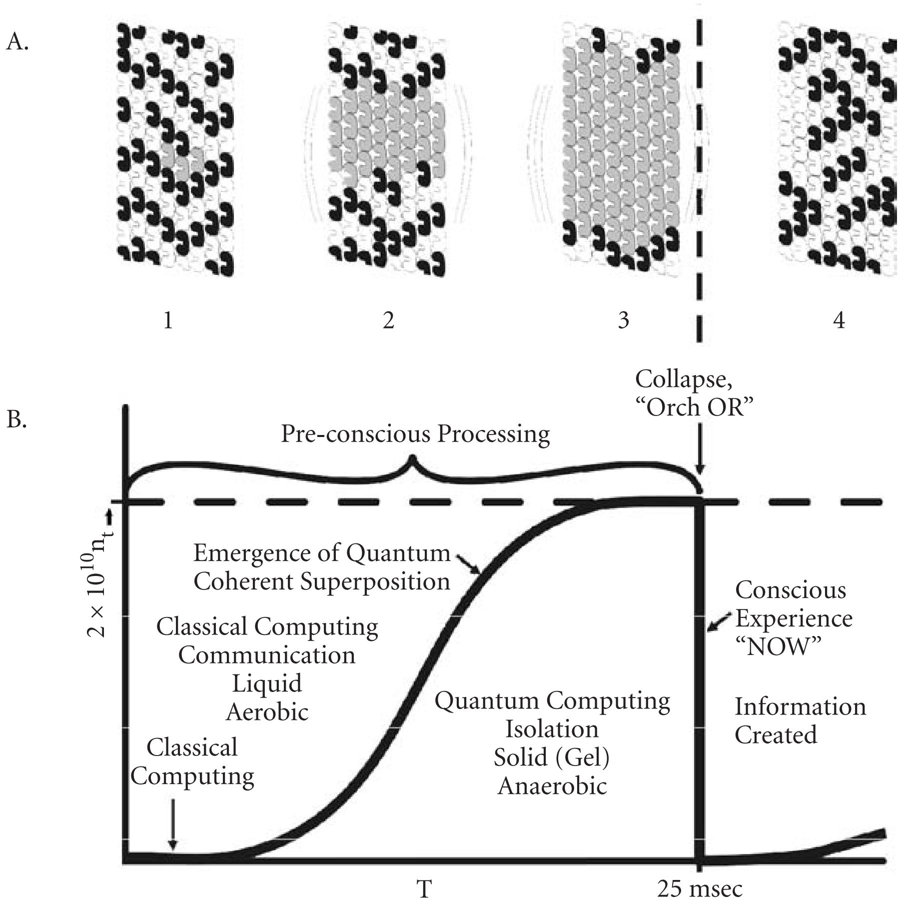

Figure 7. An Orch OR event. A. Microtubule classical computing (step 1) leads to emergence of quantum coherent superposition and quantum computing (steps 2&3) in certain (gray) tubulins. In Step 3 superposition meets critical threshold related to quantum gravity for self-collapse (Orch OR). A conscious 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 neuronal 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 N_t, the number of tubulins whose mass separation (and separation of underlying spacetime) for time t will self collapse. For T = 25 msec (e.g. 40 Hz oscillations), $N_t = 2 \times 10^{10}$ tubulins.

These processes are isolated and shielded from environmental decoherence by a variety of evolutionary adaptations (Hameroff & Penrose 1996a, 1996b; Hagan et al. 2002).

An essential feature of the Penrose-Hameroff Orch OR model is that tubulins become quantum superpositions of alternative conformations, and function as qubits by interacting nonlocally (entangling) with other tubulin qubits so that microtubules act as quantum computers (Figure 6). Microtubules whose tubulins are in quantum super-

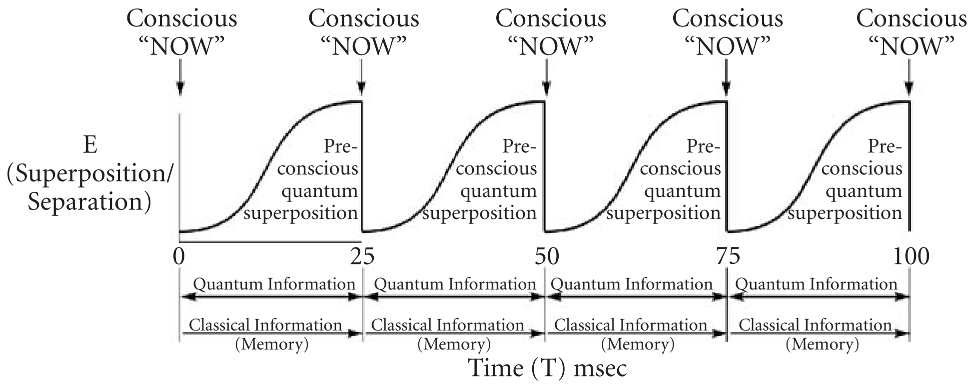

Figure 8. A sequence of OR conscious events occurring every 25 msec (consistent with brain activity at a frequency of 40 Hz). Pre-conscious quantum information reaches OR threshold (by E=ħ/T) resulting in an instantaneous conscious quantum state reduction "NOW" which may be equated to Whitehead "occasions of experience."

position in a particular neuron may entangle with those in other neurons via quantum tunneling across window-like 'gap junctions' between neurons. Gap junction-defined groups of neurons mediate gamma synchrony EEG, the best measurable correlate of consciousness.

Microtubules exist in all our cells, but only in the brain (presumably) are sufficiently large numbers of tubulins isolated from decoherence and entangled to reach threshold (by $E=\hbar/t$) in reasonably short times, and thus to manifest consciousness.

When enough entangled tubulins are superpositioned long enough to reach OR threshold (by $E=\hbar/t$), a conscious event (Whiteheadian 'occasion of experience') occurs. The classical tubulin states chosen in the OR event proceed to regulate classical neural activities, e.g. trigger axonal action potentials, adjust synaptic strengths and rearrange the cytoskeleton, thus exerting causal efficacy, learning and memory.

Gamma synchrony EEG correlating with consciousness is on the order of 25 milliseconds (1/40th second). For OR/Whitehead events in the brain to correspond with gamma-synchronized events we can use $E=\hbar/t$ and set t = 25 milliseconds (coherent 40 Hz). E is then equivalent to superposition/separation of approximately 2×10^{10} tubulins. Estimating for the percentage of tubulins per neuron involved in consciousness gives roughly *10,000 to 100,000 neurons* involved in each gamma-synchronized OR/Whitehead/conscious event.[10]

10. One apparent problem with this approach is that Planck scale gravitational energies proposed to influence protein conformational dynamics are exceedingly tiny compared even to ambient energies, often expressed as kT (Boltzmann's constant k times temperature T). The gravitational self-energy of one superpositioned tubulin is roughly 10^{-21} electron volts (eV) per tubulin, or 2×10^{-10} eV (10^{-28} joules) per 25 millisecond OR event. Ambient energy kT is approximately 10^{-4} eV (or 10^{-22} joules), 6 orders of magnitude greater than the gravitational self energy E. However the OR-induced 10^{-28} joules occur instantaneously. If we approximate the

Thus Orch OR provides a possible connection between quantum spacetime geometry – a possible repository of proto-conscious experience – and brain processes regulating consciousness.

6. Consciousness in the universe

Consistent with a general framework of neutral monism, a pan-protopsychist Orch OR places precursors of consciousness in Planck scale quantum geometry, the most basic level comprising the universe. Such precursors are presumably embedded in some way as *discrete information states*, along with other entities that give rise to the particles, energy, charge and/or spin of the classical world.

For Orch OR to be logically consistent, any quantum state reduction occurring via Penrose OR as determined by $E=\hbar/t$ would comprise a moment of conscious experience – a quantum of consciousness, a Whiteheadian 'occasion of experience' – regardless of whether it occurred in a brain, a biological system in general, or an inanimate object. Aside from biological brains, where else in nature might this occur? Is consciousness happening 'here and there' throughout the universe? It turns out that the conditions for $E=\hbar/t$ are rather stringent.

$E=\hbar/t$ means that superpositions which persist long enough (avoiding decoherence) to reach a time threshold t will collapse to classical states with a moment of conscious experience. Because E and t are inversely related, larger superpositions (larger E) will reach threshold sooner, i.e. with shorter time t. Smaller superpositions (smaller E) will require longer times t. In all cases, environmental decoherence resulting in loss of quantum superposition must be avoided long enough to reach threshold t for consciousness. Decoherence may be avoided through shielding and screening isolation, active pumping (e.g. lasers), quantum error correction topologies and/or decoherence-free subspaces (Hagan et al. 2002).

A single electron in superposition has a very small E, and would require a very long t – about 10 million years – to reach threshold. If a superpositioned electron avoided decoherence for 10 million years, according to Orch OR it would have a moment of consciousness. E is also purported to relate to the intensity of the experience, so the electron's moment of awareness would be extremely dull (analogous to a low energy, long wavelength photon). A large system in superposition (large E) would have a very brief t, and a high intensity experience (like a high energy, short wavelength photon). For example, superposition of a one kilogram rock avoiding decoherence would reach threshold for OR after only 10^{-12} seconds, and have a high intensity conscious mo-

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time interval to be within one Planck time of 10^{-43} seconds, each OR event delivers gravitational *power* (energy/time) equivalent to an instantaneous jab of 10^{13} watts (joules/sec), roughly 1 kilowatt per tubulin protein.

ment. Does this imply a rock could be conscious, perhaps even more conscious (higher intensity) than we humans?

Probably not. Rocks are composites of various types of atoms bound together by strong covalent bonds allowing little flexibility for influence by quantum processes. Electrons and other quantum-level particles comprising the structure of a rock are generally tied up in these chemical bonds, and mobile electrons within the rock have little or no influence on other components (unlike the situation in anesthetic-sensitive proteins whose conformation is leveraged or amplified by activities of electrons).

Another consideration is what 'superposition' of a rock would actually mean. Would a rock be separated from itself as one object, or separated at the level of its constituent atoms or sub-atomic particles? Large scale superpositions are more readily obtained in crystal-like structures composed of geometric arrays of one type of atom or particle.

Consider a particular type of rock made entirely of carbon atoms in a crystal-like structure of benzene-type rings with delocalizable electrons ('graphene') – otherwise known as diamonds. Indeed, quantum spin effects occur in diamonds at room temperature. However, only the mobile electrons within the diamond are in quantum superposition, as the carbon nuclei are held rigidly in the classical structure. Because of their low mass (small E), by $E=\hbar/t$, electrons in superposition within a diamond (assuming they avoided decoherence caused by, e.g., light passing through it) would require a very long time to reach threshold for OR and a conscious moment – something like 1 year for 10 million superpositioned electrons.[11]

On the other hand, Penrose observed that interiors of neutron stars may have huge quantum superpositions which would reach OR with very large E, brief t and high intensity.[12] By Orch OR criteria such events would indeed be conscious. But because the conditions are presumably random, such conscious moments would lack cognitive information processing: OR without Orch. Similarly, OR conscious moments without cognition may be occurring in various crystal-like, large scale quantum materials throughout the universe.

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11. Similarly, technological quantum computers will utilize superpositions of electrons or other small particles as qubits, and they too will have very small E, requiring extremely long decoherence-avoiding t for conscious moments. On the other hand, anesthetic-sensitive brain proteins have non-negligible mass whose conformational states are coupled to quantum electron states. For technological quantum computers to be conscious, according to Orch OR, they would require quantum electrons coupled to significant mass, e.g. perhaps in Fullerene-type structures.

12. The idea that stars might have 'minds' of some sort was speculated on by J. B. S. Haldane in the 1930s: "It is not inconceivable that in such [stellar] systems resonance phenomena of the complexity of life and mind might occur. ... [I]t is conceivable that the interior of stars may shelter minds vastly superior to our own, though presumably incapable of communication with us." (1934: 97). But he was far from the first; Plato, Aristotle, and several of the ancient Greeks argued that stars were ensouled.

Astrophysicist Paola Zizzi has applied Penrose OR to the problem of inflation in the early universe. During the Big Bang, the universe expanded (inflated) rapidly – for about 10^{-33} seconds. But rapid inflation then stopped abruptly, and expansion has been slow ever since. Zizzi (2002) considered that during inflation the universe was in quantum superposition of multiple possible universes. Using $E=\hbar/t$ and setting E to the mass of the universe, Zizzi calculated that OR threshold would be met, surprisingly, at 10^{-33} seconds into the Big Bang, and conjectured that the end of inflation coincided with the universe undergoing a *cosmic conscious moment* (the 'Big Wow'). She further suggested our individual consciousnesses are literal microcosms related to the initial cosmic conscious moment.

It is argued, then, that pan-protopsychic qualities leading to conscious experience are woven into the quantum entanglements of the universe. This should be no less mysterious than electromagnetic fields emerging from Planck scale precursors of charge and spin. But is the Planck scale information random? Or is there a plan, rhyme or reason? Penrose proposed that non-computable information, including 'Platonic' values, might be encoded in Planck scale geometry. Could there be not only proto-conscious experience, but also *wisdom* and *intelligence* in the fine grain of reality?[13]

7. Conclusion

Cognitive brain functions, including sensory processing and motor control of behavior, are often non-conscious – terms like 'easy problems,' 'zombie modes,' or 'auto-pilot' apply here. These non-conscious functions are explained by synaptic neurocomputation in axonal-dendritic networks, i.e. the brain's neuronal firings and synaptic transmissions acting like 'bit states' and switches in computers. They are not really easy, but at least approachable through neurocomputation. Consciousness, however, does not naturally derive from neurocomputation – hence the 'hard problem.'

But consciousness and non-conscious cognition are not separable. At times, habitual auto-pilot modes become driven or accompanied by conscious experience. We often walk or drive while daydreaming, seemingly on auto-pilot with consciousness somewhere else. When novelty occurs we consciously perceive the scene and assume conscious control. So rather than a distinction between non-conscious auto-pilot modes on the one hand, and conscious experience on the other, the essential distinction is between non-conscious modes which at any given moment are, or are not, accompanied by some added fleeting feature which conveys conscious experience and

13. The two authors differ on this. SH agrees with Penrose on non-random Platonic Planck scale information, whereas JP does not. David Bohm, incidentally, would clearly agree: "in a way, nature is alive, as Whitehead would say, all the way to the depths. And intelligent. Thus it is both mental and material, as we are…" (1982: 39).

choice. That feature, the neural correlate of consciousness (NCC), appears to involve spatio-temporal envelopes of gamma synchronized dendritic activity moving through input layers in the brain's neurocomputational networks. Dendritic synchrony conveys a 'conscious agent' able to experience and control – tune into and take over – otherwise non-conscious neurocomputation.

The conscious agent is Orch OR. It operates in microtubules within gamma-synchronized dendrites, generating e.g. 40 conscious moments per second. Each conscious moment, each occasion of experience, is, according to Penrose OR, an event or transition in spacetime geometry. Consciousness is a sequence of transitions, of ripples in fundamental spacetime geometry, connected to the brain through Orch OR. Pan-protopsychism thus provides the best general framework for understanding the mind-matter bridge, and hence the nature of reality.