

Men Who Made a New Science

Orchestrated Reduction of Quantum Coherence in Brain Microtubules A Model for Consciousness

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Abstract

Orch OR ("Orchestrated Objective Reduction") is a theory of consciousness put forth in the mid-1990s by British physicist Sir Roger Penrose and American anesthesiologist Stuart Hameroff. Whereas most theories assume consciousness emerges from complex computation at the level of synapses among brain neurons, Orch OR involves a specific form of quantum computation which underlies these neuronal synaptic activities. The proposed quantum computations occur in structures inside the brain's neurons called microtubules.

Key Words: consciousness, microtubules, computation, neurons, orchestrated objective reduction

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In the 1970s and 1980s Hameroff attempted to show that consciousness depends on computation within neurons in microtubules, self-assembling cylindrical polymers of the protein tubulin. Microtubules organize neuronal shape and function, e.g. forming and maintaining synapses (and help single cells like

paramecium swim, find food and mates, learn and have sex without any synapses). Hameroff concluded that microtubules function as molecular-level cellular automata, and that microtubules in each neuron of the brain had the computational power of 10^{16} operations per second. Neuronal-level synaptic operations were

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regulated by these internal computations, Hameroff claimed, so attempts by artificial intelligence (AI) workers to mimic brain functions by simulating neuronal/synaptic activities would fail. But as far as explaining consciousness – why we have inner experience, feelings, subjectivity – merely adding another layer of information processing within neurons in microtubules did not help.

Meanwhile Roger Penrose, famous for his work in relativity, quantum mechanics, geometry and other disciplines, had concluded for completely different reasons that AI computational approaches were inadequate to explain consciousness. In his 1989 book *"The Emperor's New Mind"* Penrose used Kurt Gödel's theorem to argue that human consciousness and understanding required a factor outside algorithmic computation, and that the missing "non-computable" factor was related to a specific type of quantum computation involving what he termed "objective reduction" ("OR"), his solution to the measurement problem in quantum mechanics.

Penrose considered superposition as a separation in underlying reality at its most basic level, the Planck scale. Tying quantum superposition to general relativity, he identified superposition as spacetime curvatures in opposite directions, hence a separation in fundamental spacetime geometry. However, according to Penrose, such separations are unstable and will reduce at an objective threshold, hence avoiding multiple universes.

The threshold for Penrose OR is given by the indeterminacy principle $E = \hbar / t$, where E is the gravitational self-energy (i.e. the degree of spacetime separation given by the superpositioned mass), \hbar is Planck's constant over 2π , and t is the time until OR

occurs. Thus the larger the superposition, the faster it will undergo OR, and vice versa. Small superpositions, e.g. an electron separated from itself, if isolated from environment would require 10 million years to reach OR threshold. An isolated one kilogram object (e.g. Schrödinger's cat) would reach OR threshold in only 10^{-37} seconds. Penrose OR is currently being tested.

An essential feature of Penrose OR is that the choice of states when OR occurs is selected neither randomly (as are choices following measurement or decoherence) nor completely algorithmically. Rather, states are selected by a "non-computable" influence involving information embedded in the fundamental level of spacetime geometry at the Planck scale. Moreover, Penrose claimed that such information is Platonic, representing pure mathematical truth, aesthetic and ethical values. Plato had proposed such pure values and forms, but in an abstract realm. Penrose placed the Platonic realm in the Planck scale.

In *The Emperor's New Mind* Penrose suggested that consciousness required a form of quantum computation in the brain.

Quantum computation had been suggested by Paul Benioff, Richard Feynman and David Deutsch in the 1980s. The idea is that classical information, e.g. bit states of either 1 or 0, could also be quantum superpositions of both 1 and 0 (quantum bits, or qubits). Such qubits interact and compute by nonlocal quantum entanglement, eventually being measured/observed and reducing to definite states as the solution. Quantum computations were shown to have enormous capacity if they could be constructed e.g. using qubits of ion states, electron spin, photon polarization, current in Josephson junction, quantum dots etc.

During quantum computation, qubits must be isolated from environmental interaction to avoid loss of superposition, i.e. "decoherence".

Penrose argued that quantum computation which terminated not by measurement, but by his version of objective reduction, constituted consciousness (allowing Platonic non-computable influences). Penrose had no definite biological qubits for such quantum computation by OR, except to suggest the possibility of superpositions of neurons both "firing and not firing".

Hameroff read *The Emperor's New Mind* and suggested to Penrose that microtubules within neurons were better suited for quantum computing with OR than were superpositions of neuronal firings. The two met in the early 1990s and began to develop the theory now known as Orch OR. "Orch" refers to orchestration, the manner in which biological conditions including synaptic-level neuronal events provide feedback to influence quantum computation with OR in microtubules.

The Orch OR model

For biological qubits, Penrose & Hameroff (P&H) chose conformational states of the tubulin subunit proteins in microtubules. Tubulin qubits would interact and compute by entanglement with other tubulin qubits in microtubules in the same and different neurons.

It was known that the peanut-shaped tubulin protein flexes 30 degrees, giving two different conformational shapes. Could such different states exist as superpositions, and if so, how? Penrose and Hameroff considered three possible types of tubulin superpositions: separation at the level of the entire protein, separation at the level of the atomic nuclei of the individual atoms

within the proteins, and separation at the level of the protons and neutrons (nucleons) within the protein. Calculating the gravitational self-energy E of the three types, separation at the level of atomic nuclei had the highest energy, and would be the dominant factor. P&H calculated E for superposition/separation of one tubulin qubit at the level of atomic nuclei in all the amino acids of the protein. They then related this to brain electrophysiology

The best electrophysiological correlate of consciousness is gamma EEG, synchronized oscillations in the range of 30 to 90 Hz (also known as "coherent 40 Hz") mediated by dendritic membrane depolarizations (not axonal action potentials). This means that roughly 40 times per second (every 25 milliseconds–msec) neuronal dendrites depolarize synchronously throughout wide regions of brain.

Using the indeterminacy principle $E = \hbar/t$ for OR, P&H used 25 msec for t , and calculated E in terms of number of tubulins (since E was known for one tubulin). Thus they were asking: how many tubulins would be required to be in isolated superposition to reach OR threshold in 25 msec, 40 times per second, corresponding with membrane-level brain-wide effects? The answer turned out to be 2×10^{11} tubulins.

There are roughly 10^7 tubulins per neuron. If all tubulins in microtubules in a given neuron were involved, this would correspond with 2×10^4 (20,000) neurons. However because dendrites are apparently more involved in consciousness than axons (which contain many microtubules), and because not all microtubules in a given dendrite are likely to be involved at any one time, an estimate of, say, 10 percent involvement gives 200,000 neurons involved in consciousness every 25 msec. These

estimates (20,000 to 200,000 neurons) fit very well with others from more conventional approaches suggesting tens to hundreds of thousands of neurons are involved in consciousness at any one time.

How would microtubule quantum superpositions avoid environmental decoherence? Cell interiors are known to alternate between liquid phases (solution: "sol") and quasi-solid (gelatinous: "gel") phases due to polymerization states of the ubiquitous protein actin. In the actin-polymerized gel phase, cell water and ions are ordered on actin surfaces, so microtubules are embedded in a highly structured (i.e. non-random) medium. Tubulins are also known to have C termini "tails", negatively charged peptide sequences extending string-like from the tubulin body into the cytoplasm, attracting positive ions and forming a plasma-like Debye layer which can also shield microtubule quantum states. Finally, tubulins in microtubules were suggested to be coherently pumped laser-like into quantum states by biochemical energy (as proposed by Herbert Frohlich).

Actin gelation cycling with 40 Hz events permits input to, and output from isolated microtubule quantum states. Thus during classical, liquid phases of actin depolymerization, inputs from membrane/synaptic inputs could "orchestrate" microtubule states. When actin gelation occurs, quantum isolation and computation ensues until OR threshold is reached, and actin depolymerizes. The result of each OR event (in terms of patterns of tubulin states) would proceed to organize intraneuronal activities including axonal firing and synaptic modulation/learning. Each OR event (e.g. 40 per second) is proposed to be a conscious event, equivalent in philosophical terms to what

philosopher Alfred North Whitehead called "*occasions of experience*".

Thus one implication of the Orch OR model is that consciousness is a sequence of discrete events, rather than a continuum. Yet conscious experience is subjectively uninterrupted, analogous to a movie appearing continuous to observers despite being a series of frames. The difference is that in Orch OR, each conscious event is itself an intrinsic, subjective observation. Moreover the frequency of conscious events may vary, 40 Hz being an average. If someone is excited and conscious events occur more often, (e.g. at 60 Hz), then subjectively the external world seems slower, as great athletes report during peak performance. By $E = h / t$, more frequent conscious events correspond with greater E, hence more tubulins/neurons per conscious events and greater intensity of experience. Thus a spectrum of conscious events may exist, similar to photons. There exists a spectrum of conscious quanta-like events ranging from longer wavelength, low intensity events (large t, low E) and shorter wavelength, higher intensity events (small t, large E).

QUESTIONS

Orch OR was developed in 1994, and first published in 1995 and 1996 with followup articles in 1998, 2001 and 2003. It has been greeted with a mixture of skepticism and enthusiasm, with those aligned with A.I. being particularly critical. There are some obvious questions:

Decoherence

Quantum computing technology is constructed in isolation at extremely cold temperatures to avoid decoherence – loss of quantum superposition by heat and environmental interactions. How could

microtubule quantum states persist within neurons at brain temperature of 37.6 degrees Centigrade for 25 msec or longer? Attempting to refute the possibility, physicist Max Tegmark developed a formula for decoherence time and calculated that microtubule quantum states would persist for only 10^{-13} seconds at brain temperatures, far too brief for neurophysiological effects. However Tegmark did not address the Orch OR model, but instead his own quantum microtubule formulation. He presumed superpositions of solitons separated from themselves by 24 nanometers along microtubules, rather than the Orch OR stipulations of superposition separations of femtometers at the level of atomic nuclei in proteins. This discrepancy alone lengthens the calculated decoherence time by seven orders of magnitude to microseconds (i.e. 10^{-6} sec). Physicists Scott Hagan and Jack Tuszynski, along with Hameroff, recalculated microtubule decoherence time at brain temperature using Tegmark's formula but with stipulations of Orch OR including the separation discrepancy, shielding by actin gelation, Debye layer screening, metabolic Frohlich coherent pumping and topological quantum error correction due to the particular geometry of the microtubule lattice. Decoherence times of tens to hundreds of milliseconds or longer were calculated, and the results published in the same physics journal in which Tegmark published his attempted refutation.

Indeed, some evidence supports the notion of metabolic heat-pumped quantum states in biology. Quantum spin transfer through organic benzene molecules (whose nonpolar aromatic ring is essentially identical to phenylalanine and tyrosine rings in hydrophobic pockets of tubulin) is

enhanced with increased temperature. As quantum computing would be advantageous for survival of organisms, it seems logical that mechanisms to avoid decoherence at biological temperature have evolved.

Some drugs like colchicine (used in treatment of gout) and vincristine (used in treatment of cancer) depolymerize microtubules. Why do they not cause loss of consciousness?

Colchicine affects microtubules in immune cells, responsible for locomotion, and in malignant cells vincristine affects mitotic spindle microtubules, responsible for mitosis. In both cases the drugs affect microtubules which are actively polymerizing and depolymerizing. In brain neurons, however, microtubules are stable and capped, preventing depolymerization. Moreover these drugs do not cross the blood-brain barrier and do not gain access to the brain.

If isolated quantum computation occur in microtubules within neurons, how could inputs and outputs to neuronal-level events bridge isolation without causing decoherence?

Alternating phases of 1) actin gel quantum isolation/computation and 2) liquid classical states cycle with gamma synchrony dendritic EEG membrane events. The results of each Orch OR event manifest in tubulin states act by classical signaling to regulate neuronal functions.

How could quantum states in microtubules in one neuron interact/compute with those in other neurons throughout the brain?

In 1998 Hameroff proposed that quantum states could spread among microtubules through electrotonic gap junctions, windows

between adjacent neurons and glia. At that time gap junctions were considered scarce and unimportant in mature brains. However since 1999 gap junctions have been shown to be widely prevalent, forming syncytia ("hyper-neurons") of neurons and glia throughout the brain. Moreover gap junction cortical networks mediate gamma synchrony EEG, the best electrophysiological correlate of consciousness.

Quantum states may also extend via quantum field photons (as suggested by Jibu, Yasue and Hagan in 1995) generated in microtubules and/or primary cilia in pyramidal cell dendrites.

How does the unconscious relate to Orch OR?

Unconscious, pre-conscious, sub-conscious content evident in dreams as well as Jungian, Freudian and mystical approaches may manifest as quantum information which reduces to classical information with each conscious moment.

Can Orch OR account for features of consciousness unexplainable by conventional approaches?

Brain electrophysiological activities corresponding with sensory perceptions occur after seemingly conscious responses to those perceptions have occurred. Consequently conventional approaches conclude that such responses are unconscious, that conscious control is an illusion. Various aspects of sensory inputs (e.g. visual shape, color, motion, and meaning) are processed in different brain regions, and at different times, yet we are conscious of unified objects. Conventional approaches conclude that real time unified conscious experience does not occur, but is constructed after the fact, and inserted into memory. Thus according to conventional

approaches, real time conscious experience and control are illusion; consciousness is epiphenomenal.

Experiments in the 1970s by Benjamin Libet suggested that conscious experience of sensory inputs requires up to 500 msec of brain activity, but is referred backward in time to the initial input. Quantum mechanics allows backward time effects as long as causal paradox is not possible (killing your grandmother, preventing your birth is one commonly cited example). Backward referral of unconscious quantum information avoids possible causal paradox, and could explain Libet's results; real time unified sensory experience and conscious control, rescuing consciousness from the unfortunate role of illusory epiphenomenon.

Microtubules are found in all eukaryotic cells. Are all cells conscious?

According to Orch OR, consciousness occurs with each OR event by $E = \hbar/t$, the larger the superposition the faster it will reach threshold. This presents a fairly stringent condition because large superpositions which would reach OR quickly enough to be useful are difficult to isolate from decoherence. For example, if superpositioned microtubules in a typical cell ($\sim 10^5$ tubulins) were isolated, OR threshold would be reached only after 33 minutes. However gap junction-linked dendrites of tens to hundreds of thousands of brain cortical neurons include enough microtubules entangled in one quantum state to reach threshold for OR in reasonably short durations (e.g. 25 msec, 40 Hz). Further, brain neurons may have evolved anti-decoherence mechanisms not present in other cells.

Will technological quantum computers be conscious?

As presently envisioned, quantum computers will utilize superpositions of electron spin or current, photon polarization or atomic location. None of these have significant superpositioned/separated mass and thus E would be very, very small, and t very, very long. Conceivably, quantum computers constructed of fullerene technology could reach OR threshold and be conscious.

What about OR occurring in other contexts?

Large superpositions may occur cosmologically, e.g. in the core of neutron stars. Such large superpositions would reach OR threshold very quickly, but presumably have no orchestration and hence no cognition.

Italian astrophysicist Paola Zizzi (2003) has suggested that during the inflationary period of the Big Bang, the entire universe was in superposition (there being no external environment to cause decoherence) which reached threshold for OR after 10^{-33} seconds, reducing to our present, single universe. The implication is that inflation ended with a cosmic OR event – a moment of consciousness – of which each of our present individual consciousnesses are literal microcosms. This idea has been referred to as the Big Wow theory.

Why do Orch OR events cause subjective experience? This is known as the 'hard problem'. Precursors of conscious experience (proto-conscious qualia) are postulated to exist as fundamental, irreducible components of the universe like

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mass, spin or charge embedded at the Planck scale since the Big Bang. OR events select particular patterns of proto-conscious qualia.

When did consciousness evolve?

Proto-conscious qualia must be postulated to have existed since the Big Bang. The question then is, when did biological systems get sufficiently complex to have OR events in reasonably brief times? Organisms at the beginning of the Cambrian evolutionary explosion (small worms and urchins) may have achieved OR events in hundreds of msec. Perhaps their new found awareness and noncomputable choices enhanced their survival, precipitating the Cambrian explosion.

Is Orch OR testable?

20 testable predictions of Orch OR were published in 1998. A number of these have been validated, others are being tested. Orch OR is falsifiable.

CONCLUSION

Orch OR can account for all enigmatic features of consciousness including timing, binding, pre-conscious to conscious transition and the hard problem of conscious experience. Orch OR is consistent with all known neurophysiology, but depends on proposed physics and biology. Orch OR has withstood numerous attempts at refutation, and is testable and falsifiable. Although controversial, it is the most complete theory of consciousness, spanning in detail physics, molecular biology, neuroscience, cognitive science and philosophy.

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