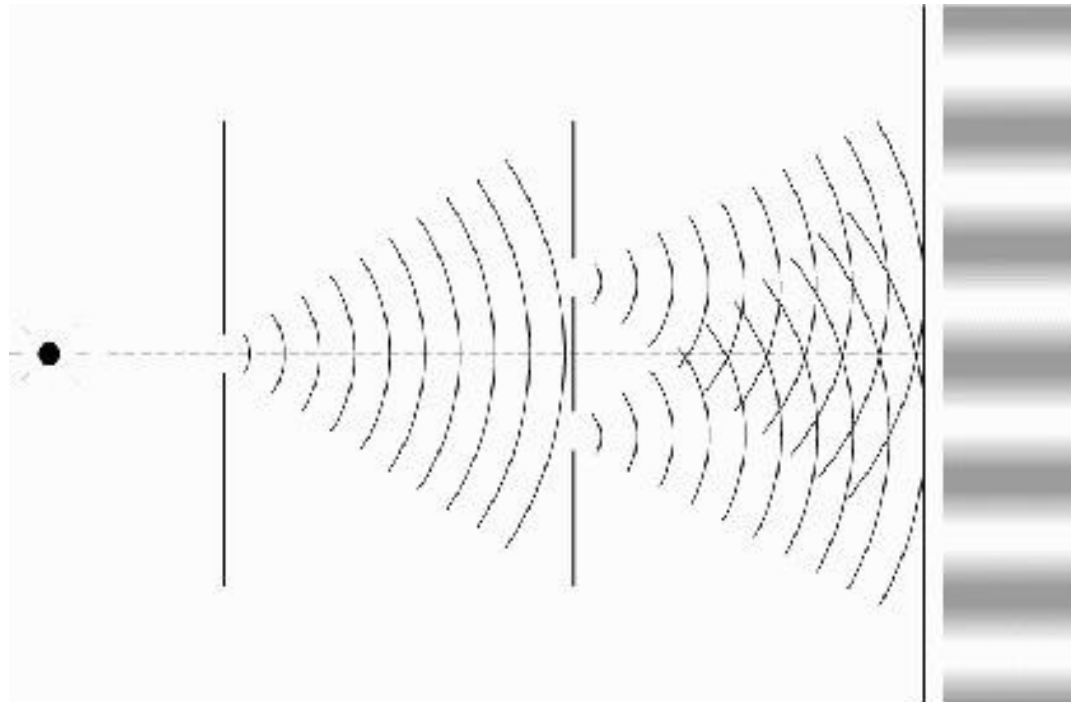


# Quantum computations in human brain – implications and criticism

- Conduction pathways in microtubules, biological quantum computation, and consciousness  
Stuart Hameroff, Alex Nip, Mitchell Porter, Jack Tuszynski  
BioSystems 64 (2002) 149-168
- Quantum physics in neuroscience and psychology: a neurophysical model of mind-brain interaction  
Jeffrey M. Schwartz, Henry P. Stapp and Mario Beauregard  
Phil. Trans. R. Soc. B (2005) 360, 1309-1327
- Falsifications of Hameroff-Penrose Orch OR Model of Consciousness and novel Avenues for Development of Quantum Mind Theory  
NeuroQuantology, Issue 1 Vol 5, March 2007, 145-174

# Some important properties of quantum mechanics

- Uncertainty  $\Delta X \Delta P \geq h/4\pi$
- Schrödinger's equation  $i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi + V \psi$
- Probabilistic nature
- Nonlocality



# Quantum computer

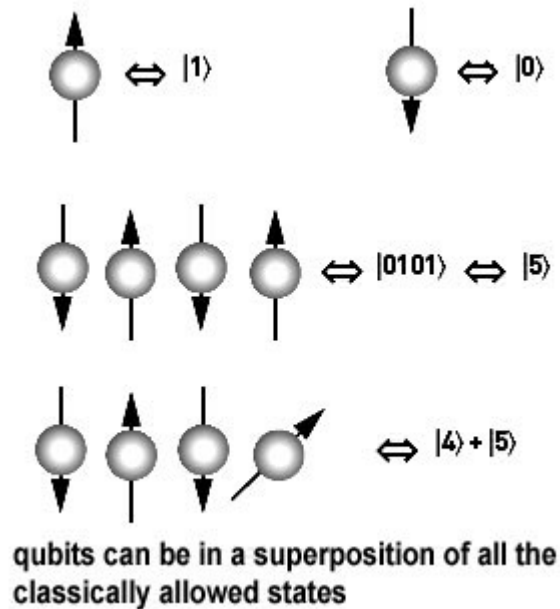
- Special computer using quantum mechanics phenomena – entanglement and superposition
- Qubit – quantum bit  $|0\rangle$   $|1\rangle$   $|0\rangle+|1\rangle$
- Qubit registers are complex-number vectors, composed of  $2^n$  complex values (basically all possible values of n-bit classical integer are covered at once)
- Computations are performed with the whole vector (thus all possible values are computed in parallel)
- Results are obtained by reading Qubit register state
- This causes wave-function collapse to one of possible states
- The idea of quantum computing is to skew the probability of given state towards correct result by interference
- The result is always probabilistic

$$|\psi\rangle = a|000\rangle + b|001\rangle + c|010\rangle + d|011\rangle + e|100\rangle + f|101\rangle + g|110\rangle + h|111\rangle$$

The state vector of 3-qubit quantum register (8 complex numbers)

# Quantum computer II

- Decoherence - „leaking“ of quantum state into environment – in practice destroys superposition (although theoretically it remains intact, but inmeasurable)
- Quantum computers usually require „hard“ conditions – liquid helium temperature.



# Copenhagen interpretation

- A system is completely described by a wave function  $\psi$ .
- $\Psi$  is deterministic and symmetric in time (no information is lost).
- Measuring devices are classical devices that register certain set of properties of system.
- Different properties (position/momentum, time/energy) cannot be measured together.
- Eigenvalues of  $\Psi$  corresponding to unobserved properties are erased from system during measurement.
- This process is called wave-function collapse.
- The collapse of wave function is inherently probabilistic and erases information.

# Copenhagen interpretation

- Orthodox Copenhagen interpretation rejects inquiry into the nature of measurement process as metaphysical.
- Schrödinger's cat  $\Psi = (|\text{dead}\rangle + |\text{alive}\rangle)/\sqrt{2}$



The cat is in superposition state until experimentator opens the box. At that moment it's wave function collapses either to dead or alive state.

# Penrose's objective reduction

- There is still no quantum theory of gravitation
- Gravitation is The Geometry of Space-Time
- Energy has mass (is mass), so the different energy distributions have different spacetime configurations
- Penrose hypothesis – objective collapse of wave function due to quantum gravitational effects
- If the effects on space-time of alternate histories of quantum state (superposition) exceed quantum gravity threshold, wave function collapses
- Gravitation is extremely weak, so relatively large quantum states can develop before collapse

# Problems with the theory of mind (or not)

- Not reducible to physics (observer problem)
- The nature of qualia
- The problem of determinism vs free will
- Binding problem – how the unitary sense of consciousness arises from the distributed action of nervous system
- The nature of awareness (unconscious becoming conscious)

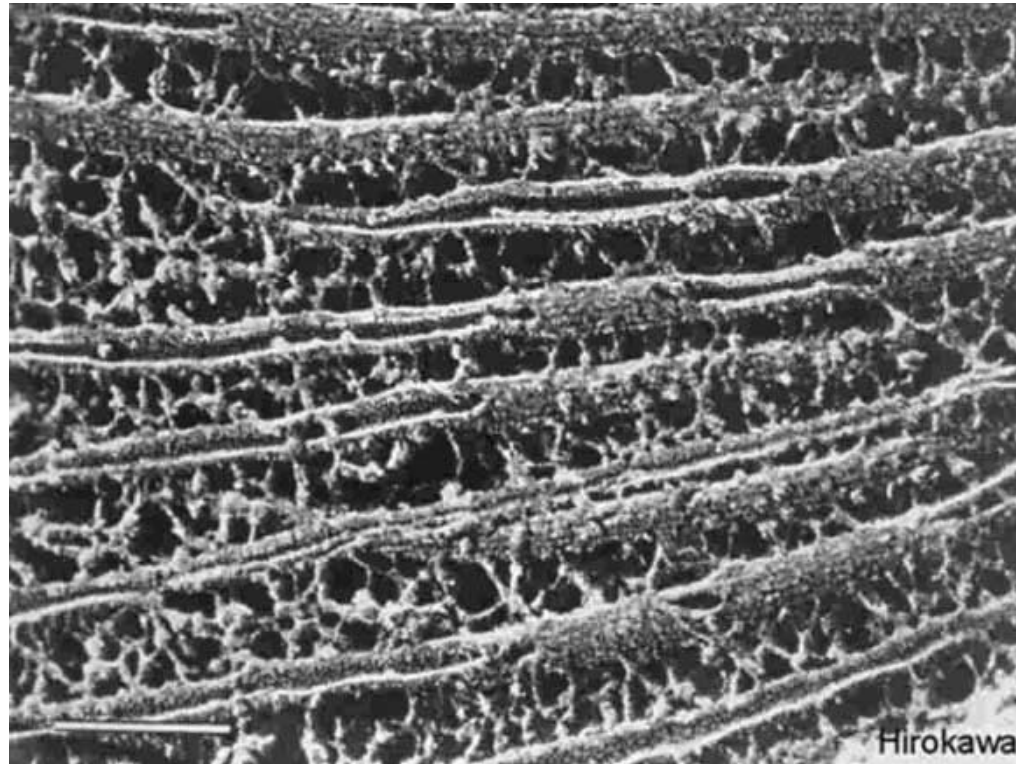


# Penrose-Hameroff theory of mind

- Brain is biological quantum computer
- Large entangled quantum states occur periodically in brain (subconscious processing phase)
- Quantum processes happen in intra-neuronal tubulin network
- Eventually quantum superposition exceeds quantum gravitational threshold and collapses - Objective Reduction
- Consciousness arouses during the wave function collapse phase – this is Objective Reduction (OR)
- During OR intraneuronal signalling takes place, preparing stage for next 25ms quantum step (orchestration of next OR)
- OR events give rise to consciousness

# Microtubules

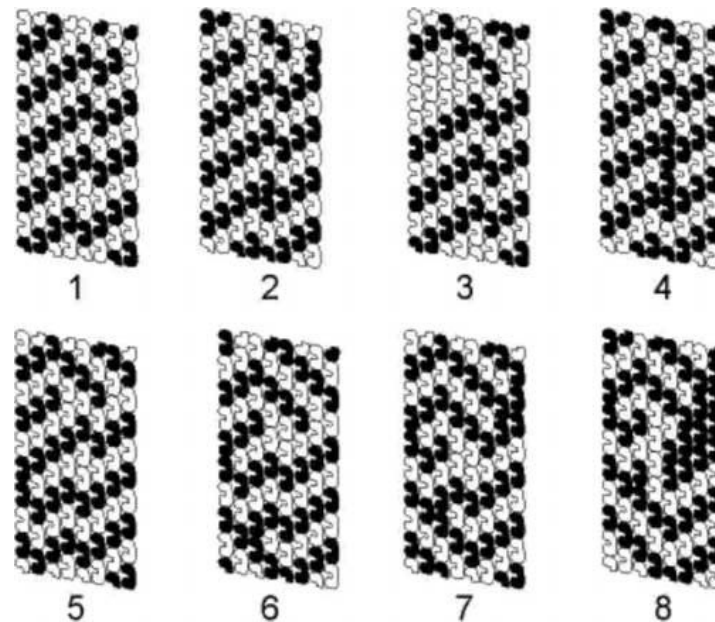
Intracellular tubular structures, composed of crystalline hexagonal lattice of tubulin dimers. In Orch OR theory they are organized to preserve quantum coherence.



The neuronal cytoskeleton. Immunoelectron micrograph of dendritic M T's interconnected by dendrite-specific M A P's. Some M T's have been sheared, revealing internal hollow core. The granular 'com-cob' surface of M T's is barely evident to close inspection. Scale bar, lower left: 100 nm s. Hirokawa, 1991.

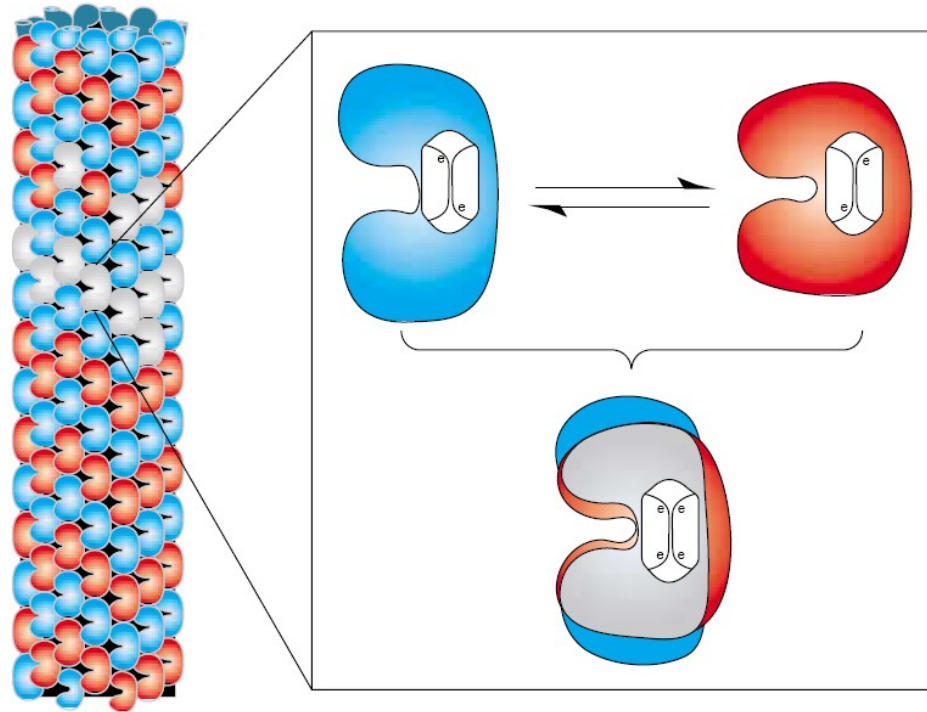
# Microtubules as cellular automata

- It is proposed that tubulins in MT can act as cellular automata, creating self-organizing patterns capable of processing and storing information.



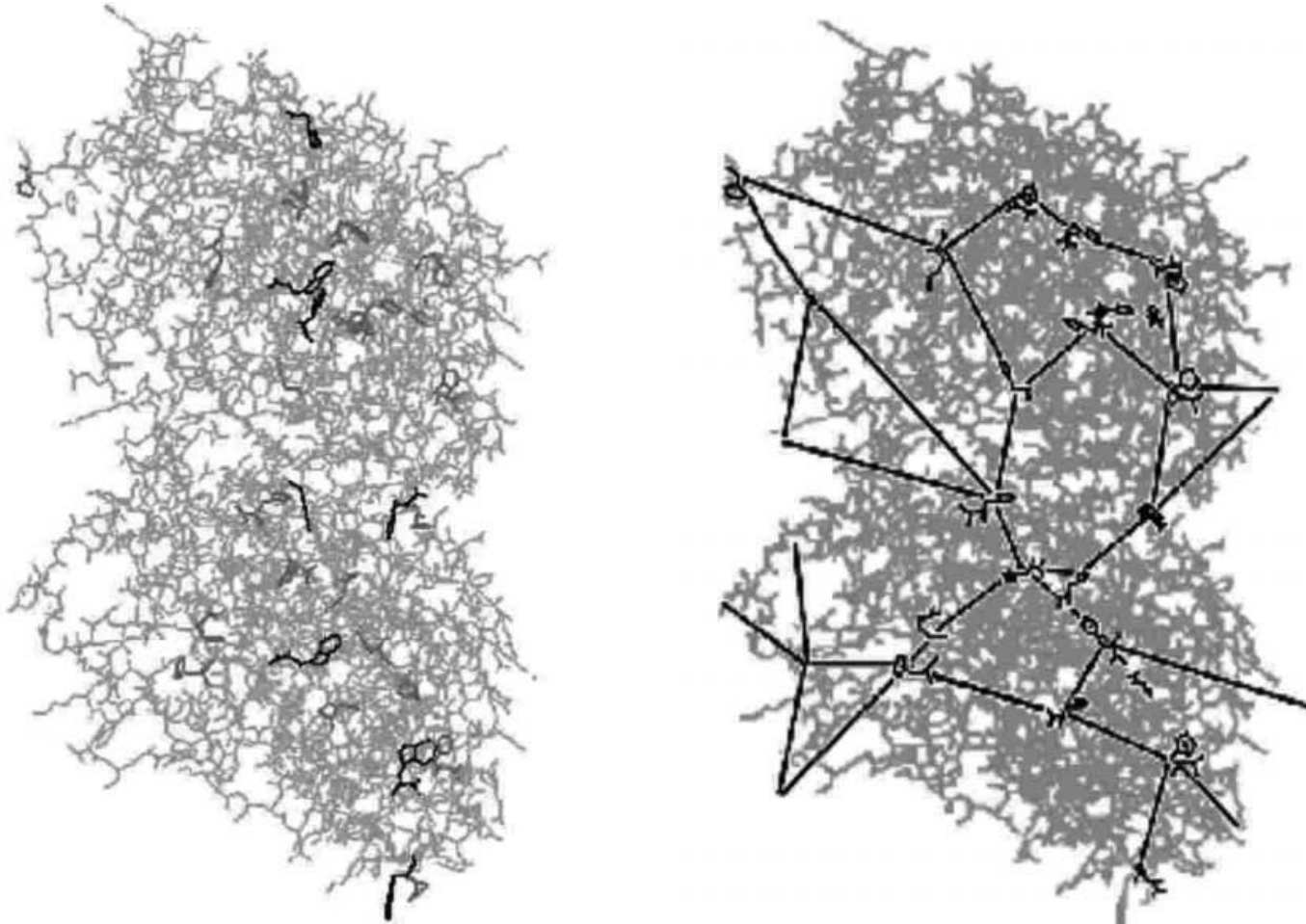
Microtubule automaton simulation (from Rasmussen et al., 1990). Black and white tubulins correspond to states shown in Fig. 4. Eight ns time steps of a segment (eight of 13 protofilaments) of one microtubule are shown in ‘classical computing’ mode in which patterns (‘gliders’) move, evolve, interact and lead to emergence of new patterns.

# Tubulin as Qubit register



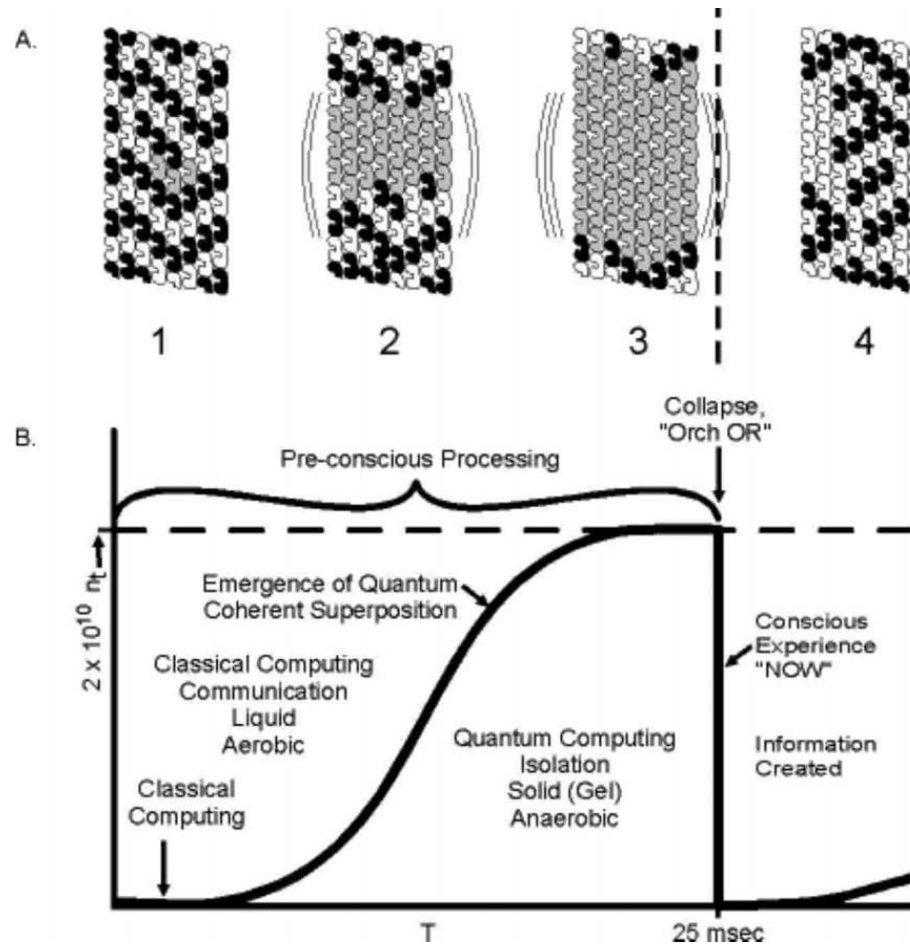
Left: microtubule, a cylindrical lattice of tubulin proteins. Right (Fig. 1): coupled to position of a pair of quantum coupled electrons in an internal hydrophobic pocket, each tubulin may occupy two classical conformations (top) or exist in quantum superposition of both conformational states (bottom). A tubulin may thus act as a classical bit (top) or as a quantum bit, or ‘qubit’.

# Electron paths in tubulin lattices



Histidines in the tubulin dimer. Left: histidine locations in front view. Right: Histidines interconnected by estimated shortest paths. Typical separations are 1 nm.

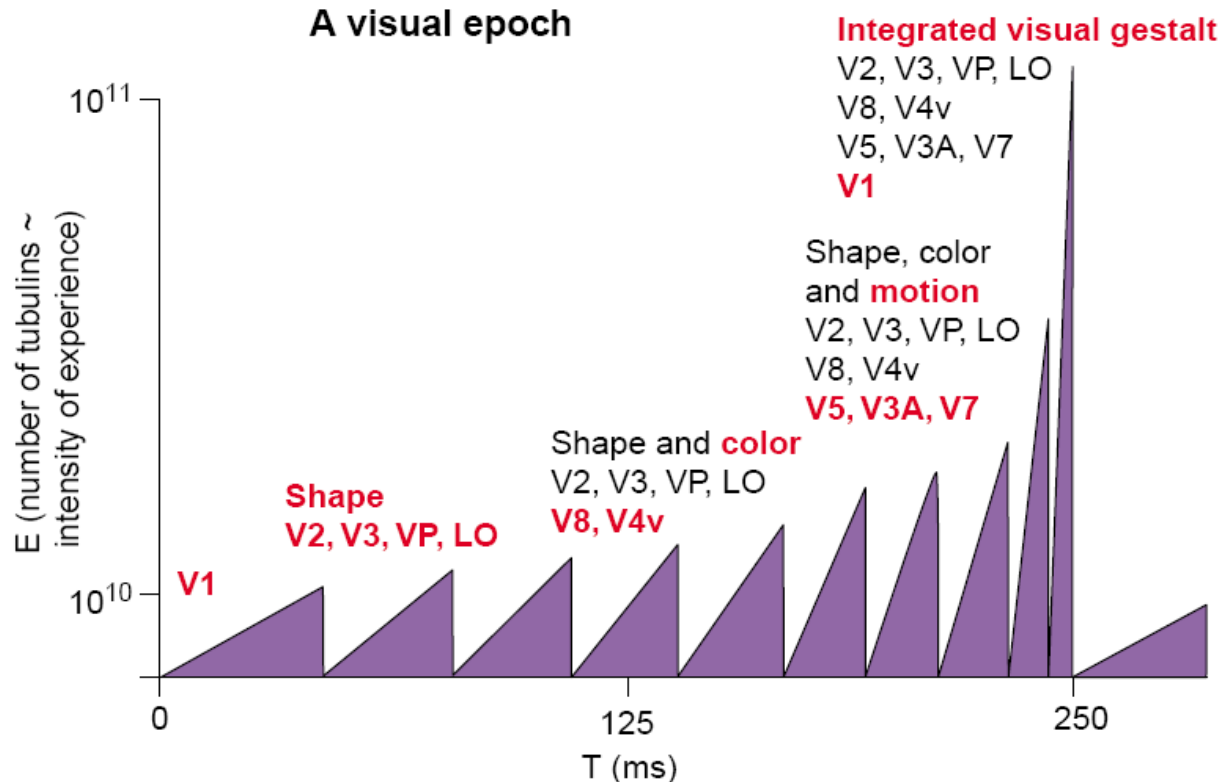
# Microtubules as cellular automata II



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, 3) in certain (gray) tubulins. Step 3 (in coherence with other microtubule tublins) meets critical threshold related to quantum gravity for selfcollapse (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 Mts. 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  $T = 25 \text{ ms}$  (e.g. 40 Hz oscillations),  $Nt = 2 \times 10^{10}$  tubulins.

# Visual information processing

(Woolf and Hameroff, 2001)



A crescendo sequence of several  $\sim 25$  ms quantum computations (i.e. oscillating near to 40 Hz) constitutes a visual epoch lasting 250–700 ms. The time until Orch OR (threshold for conscious event) is given by the indeterminacy principle:  $E = h/T$  (where  $E$  is related to magnitude of the superposition,  $h$  is Planck's constant over  $2\pi$ , and  $T$  is the time until self-collapse). Thus the larger the isolated superpositions (higher intensity, more vivid experience) the more quickly they will reduce.

# Penrose and Hameroff 1995

- Tubulin configuration is determined by the position of electrons in aromatic channels inside molecules
- Electrons are entangled across tubulin molecules, potentially across neurons through gap junctions
- Quantum states of tubulin is isolated/protected from environmental decoherence by various mechanisms (actin gelation, ordered water, coherent pumping)
- Microtubule quantum processing is „orchestrated“ by MAP (microtubule associated proteins) during liquid phase which alternates with solid phase approximately at 40Hz.
- Following preconscious quantum processing tubulin superpositions collapse by Penrose OR mechanism. Classical output states are chosen non-algorithmically and govern neurophysiological events .
- The reduction of wave function (OR) is „conscious moment“ .



# Implication to psychology

Enigmatic features of consciousness and possible solutions via the Orch OR model

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Enigmatic feature of consciousness	Classical explanations	Possible Orch OR solutions
Essential nature of human experience ('qualia', the 'hard problem')	'Emergence': conscious experience emerges from computational complexity	Pan-protopsychoist philosophy; qualia are fundamental features of spacetime geometry, accessed by quantum gravity OR
Unitary sense: 'binding problem'	Temporal synchrony e.g. coherent 40 Hz	(1) Non-local quantum coherence; indivisible macroscopic quantum state (e.g. Bose-Einstein condensate); (2) Instantaneous self-collapse of superpositioned states (Orch OR)
Transition from pre-conscious processes to consciousness	No apparent threshold	Collapse, or reduction of the quantum wave function, a la quantum computation
(Apparent) 'free will'	None	Non-computability in quantum gravity OR

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# Georgiev's comments

- Split brain patients have two minds, so axons are needed for unity of consciousness
- There is extensive ion flow through gap junctions, so it is highly improbable that quantum entanglement could extend through these
- Subjective time flow is not needed for consciousness (argument against the cruciality of OR in mind)
- All processes involving proteins in cells collapse in around 10-15 picoseconds (to make them irreversible). How can microtubules participate in other cellular functions, if they have coherent states spanning several milliseconds.
- There is no GTP hydrolyzing associated with structural tubulin (no coherence pumping)
- The distinction of subconscious and conscious domains is not scientific at all and not needed
- There is no experimental evidence of „special“ properties of mind, like spanning time intervals, free will etc.
- Cell interior is not in chemical equilibrium and energy dissipation destroys decoherence in picoseconds timeframe

# Criticism

- Quantum mechanics does not need Orch OR for completeness (contrary to popular opinion Copenhagen interpretation is complete)
- Psychology does not need quantum processes to describe the working of mind (although neurologists may need it)
- It is still highly questionable that quantum coherence can last long enough for quantum computing to take place in brain
- Quantum theory of mind can be viewed as modern rise of dualism
- It is already extended to cover interpersonal entangled quantum state (telepathy).