



Did Consciousness Cause the Cambrian Evolutionary Explosion?

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Consciousness and Evolution

When and where did consciousness emerge in the course of evolution? Did it happen as recently as the past million years, for example concomitant with language or tool making in humans or primates? Or did consciousness arrive somewhat earlier, with the advent of mammalian neocortex 200 million years ago (Eccles, 1992)? At the other extreme, is primitive consciousness a property of even simple unicellular organisms of several billion years ago (e.g. as suggested by Margulis and Sagan, 1995)? Or did consciousness appear at some intermediate point, and if so, where and why? Whenever it first occurred, did consciousness alter the course of evolution?

According to fossil records, life on earth originated about 4 billion years ago (Figure 1).

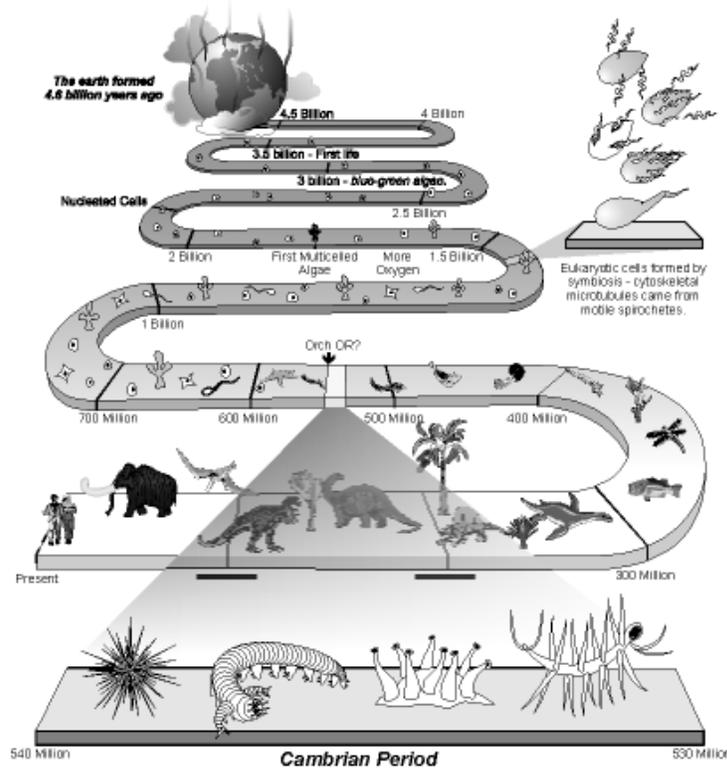


Figure 1. *The Cambrian explosion. According to fossil records life on earth originated about 4 billion years ago, but evolved only slowly for about 3.5 billion years ("pre-Cambrian period"). Then, in a rather brief 10 million years beginning about 540 million years ago (the "Cambrian period"), a vast array of diversified life abruptly emerged: the "Cambrian explosion." Exemplary Cambrian organisms depicted are an urchin similar to present day actinosphaerium, spiny worms, and a tentacled sectorian. Artwork by Dave Cantrell and Cindi Laukes based on organisms in Gould (1989) and adapted from a diagram by Joe Lertola, Time Magazine, December 4, 1995.*

For its first 3.5 billion years or so ("pre-Cambrian period") life seems to have evolved slowly, producing only single cells and a few simple multicellular organisms. The most significant life forms for the first 2 billion years of this period were algae and bacteria-like prokaryotes. Then, about 1.5 billion years ago, eukaryotic cells appeared apparently as symbiotic mergers of previously independent organelles (mitochondria, plastids) with prokaryotic cells. According to biologist Lynn Margulis (Margulis, 1975; Margulis and Sagan, 1995) microtubules and the dynamically functional cytoskeleton were also outside additions, originating as independent motile spirochetes which invaded prokaryotes and formed a mutually favorable symbiosis. Prokaryotic cells provided a stable, nourishing environment and biochemical energy to the spirochetes who reciprocated by cytoskeletal-based locomotion, sensation, mitosis and differentiation. Pre-Cambrian eukaryotic cells continued to slowly evolve for another billion or so years, resulting only in simple multicellular organisms. Then, in a rather brief 10 million years beginning about 540 million years ago (the beginning of the "Cambrian period"), there apparently occurred a world-wide dramatic acceleration in the rate of evolution: the "Cambrian explosion." A vast array of diversified life abruptly emerged: all the phyla from which today's animals are descended (e.g. Gould, 1989).

The Cambrian explosion theory has been questioned. For example, using fossil nucleotide substitution analysis, Wray et al. (1996) suggested a more linear process, with animals appearing about one billion years ago. But the more gradual, linear case assumes constant rate of nucleotide substitution. It seems more likely that nucleotide substitution also increases during increased rates of evolution, and the "abrupt" Cambrian explosion theory still holds (Vermeij, 1996). What could have precipitated the Cambrian explosion? Were climate, atmosphere, environment or some external factors important, or did a threshold of biological genetic complexity occur (e.g. Kauffman, 1995; c.f. Dawkins, 1989)? Can a particular biological functionality be identified that critically enhanced adaptation, survivability and mutation? Did purposeful, intelligent behavior accelerate evolution? The idea that behavior can directly alter genetic code formed the basis of an eighteenth century evolutionary theory by Jean-Baptiste Lamarck. No supportive evidence was found to show

that behavior directly modified genetics, and "Lamarckism" was appropriately discredited. The question of whether behavior can alter the course of evolution indirectly was discussed by Schrödinger (1958) who offered several examples (Scott, 1996). A species facing predators and harsh environment might best survive by producing a large number of offspring for cooperative support. Such a rapidly reproducing species is ripe for accelerated evolutionary development (Margulis and Sagan 1995). Another example is a species which finds a new habitat (moving onto land, climbing trees. . .) to which adaptation is facilitated by supporting mutations. Changes in behavior can also favor chance mutations which reinforce original changes, resulting in closed causal loops or positive feedback in evolutionary development (Scott, 1996). Generally, intelligent behavior can enhance a species' survivability and the opportunity for mutation by avoiding extinction.

How did intelligent behavior come to be? Dennett (1995) describes the "birth of agency": the ability to perform purposeful actions in complex macromolecules, and thus very early in the course of evolution. He emphasizes that agency and behavior at the macromolecular level are non-conscious and clearly preceded Cambrian multicellular organisms. For example purposeful behavior surely occurred in unicellular eukaryotic ancestors of modern organisms like paramecia and euglena who perform rather complex adaptive movements. Paramecia swim in a graceful, gliding fashion via coordinated actions of hundreds of microtubule-based cilia on their outer surface. They thus seek and find food, avoid obstacles and predators, and identify and couple with mates to exchange genetic material. Some studies suggest paramecia can learn, escaping more quickly from capillary tubes with each subsequent attempt (Gelber, 1958). Having no synapses or neural networks, paramecia and similar organisms rely on their cytoskeleton for sensation, locomotion and information processing. The cytoskeleton organizes intelligent behavior in eukaryotic cells.

The Cytoskeleton, Intelligent Behavior and Differentiation

Comprising internal scaffolding and external appendages of each eukaryotic cell, the cytoskeleton includes microtubules (MTs), actin filaments, intermediate filaments and complex arrays of connected MTs such as centrioles, cilia, flagella and axonemes. MTs are hollow cylinders 25 nanometers (nm) in diameter (Figure 2).

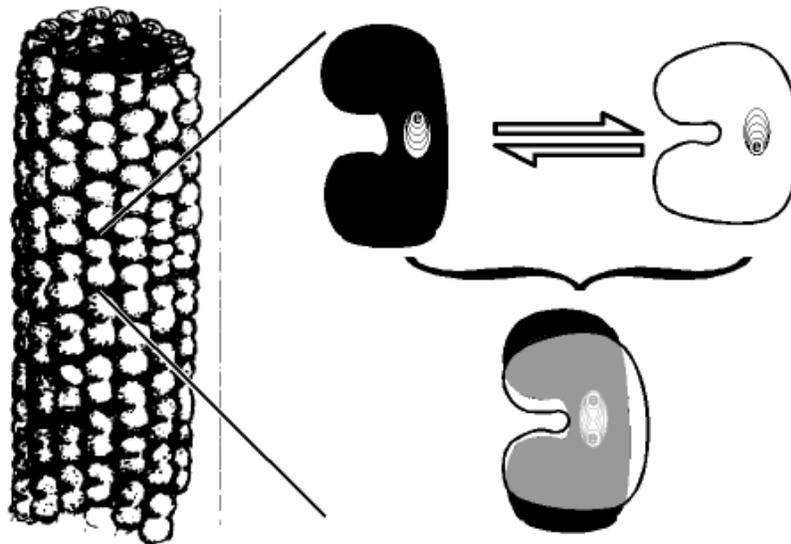


Figure 2. Left: Microtubule (MT) structure: a hollow tube of 25 nanometers diameter, consisting of 13 columns of tubulin dimers arranged in hexagonal lattice (Penrose, 1994). Right (top): Each tubulin molecule can switch between two (or more) conformations, coupled to a quantum even such as electron location in tubulin hydrophobic pocket. Right (bottom): Each tubulin can also exist in quantum superposition of both conformational states (Hameroff and Penrose, 1996).

Their lengths vary and may be quite long within some nerve processes. MT cylinder walls are hexagonal lattices of tubulin subunit proteins polar, 8 nm peanut-shaped dimers which consist of two slightly different 4 nm monomers (alpha and beta tubulin). MTs are interlinked by a variety of MT-associated-proteins to form dynamic networks which define cell shape and functions. Numerous types of studies link the cytoskeleton to cognitive processes (for review, cf. Dayhoff et al., 1994; Hameroff and Penrose, 1996a). Theoretical models and simulations suggest that conformational states of tubulins within MT lattices are influenced by quantum events, and can interact with neighboring tubulins to represent, propagate and process information in classical "cellular automata," or ferroelectric "spin-glass" type computing systems (e.g. Hameroff and Watt, 1982; Rasmussen et al., 1990; Tuszynski et al, 1995). There is some suggestion that quantum coherence could be involved in MT computation (Jibu et al., 1995).

MTs are often assembled in nine MT doublets or triplets in a mega-cylinder found in centrioles, cilia and flagella (Figure 3).

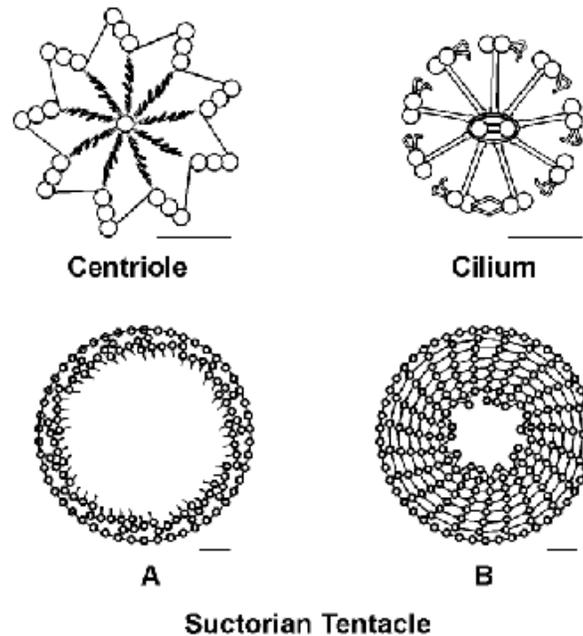


Figure 3. Primitive appendages comprised of microtubules (MTs, shown as circles; scale bars: 100 nanometers). Top left: Cross section of a centriole. Nine microtubule triplets link to a single central MT. Top right: Cilium in cross section. Nine MT doublets link to a central MT pair. Bottom left (A): cross section of a suctorian tentacle in an open, dilated phase. Bottom right (B): suctorian tentacle in a constricted phase. (Tentacle structure adapted from Hauser and Van Eys, 1976, by Dave Cantrell.) Scale bar: 100 nanometers.

Centrioles are two MT mega-cylinders in perpendicular array which control cell cycles and mitosis, form the focal point of the rest of the cell cytoskeleton, and provide cell navigation and orientation. Embedded in dense electronegative material just adjacent to the cell nucleus, centrioles' structural beauty, unfathomable geometry and intricate behavior have created an air of mystery: "biologists have long been haunted by the possibility that the primary significance of centrioles has escaped them" (Wheatley, 1982; c.f. Lange and Gull, 1996).

Cilia are membrane covered mega-cylinders of nine MT doublets with an additional central MT pair which are both sensory and motor: cilia can receive information, as well as move in a coordinated fashion for locomotion, feeding or movement of material. Flagella have the same 9x2 MT arrangement as cilia, but are longer and more specialized for rapid cell movement. The basic microtubule doublet "9x2" (cilia, flagella, basal bodies...) and "9x0"(centriole) arrangements apparently originated in spirochetes prior to eukaryotes. Their cytoskeletal descendants provided agency to eukaryotes, performing a variety of purposeful behaviors.

Cytoskeletal structures also provided internal organization, variation in cell shape, separation of chromosomes and differentiation. An essential factor in evolution, differentiation involves emergence of specialized tissues and organs from groups of cells which start out alike, but began to differ and develop specific and complementary form and functions

(Rasmussen, 1996). Each eukaryotic cell contains all the genes of the organism, but only a subset are selected so that, for example, liver cells are distinct from lymphocytes. Puck (e.g. Puck and Krystosek, 1992) has shown appealing evidence to suggest that a cell's genes are activated and regulated by its cytoskeleton, and describes how differentiation requires cooperative cytoskeletal function. Tissue specialization also required factors such as actin-gelation phases in cytoplasm, MT-based extensions (cilia, axonemes. . .) and communication among cells. The most basic and primitive form of inter-cellular communication involves direct cell-cell channels such as gap junctions, or electrotonic synapses (Lo, 1985; Llinas, 1985). Cytoskeletal cooperativity among neighboring cells enabled differentiation and allowed different types of tissues to emerge. Through benefit of the resultant division of labor, higher order structures (organs e.g. axonemes, tentacles, eye cups, nervous systems. . .) with novel functions appeared (Rasmussen, 1996). These in turn led to more intelligent behavior in small multicellular animals.

The Dawn of Consciousness

According to this scenario, tissue differentiation, agency and intelligent behavior were occurring for a billion years from the symbiotic origin of eukaryotes to the Cambrian explosion (Figure 1). What then happened? Was some critical level of intelligent behavior suddenly reached? Did consciousness then appear? Could primitive consciousness have significantly improved fitness and survivability beyond previous benefit provided by non-conscious agency and intelligent behavior?

One possible advantage of consciousness for natural selection is the ability to make choices. As Margulis and Sagan (1995) observe (echoing similar, earlier thoughts by Erwin Schrödinger), "If we grant our ancestors even a tiny fraction of the free will, consciousness, and culture we humans experience, the increase in [life's] complexity on Earth over the last several thousand million years becomes easier to explain: life is the product not only of blind physical forces but also of selection in the sense that organisms choose. . ." (Scott, 1996).

By itself, the ability to make choices is insufficient evidence for consciousness (e.g. computers can choose intelligently). However non-computable, seemingly random conscious choices with an element of unpredictability may have been particularly advantageous for survival in predator-prey dynamics (e.g. Barinaga, 1996).

Another feature of consciousness favoring natural selection could be the nature of conscious experience: qualia, our "inner life" in the sense of Chalmers' "hard problem" (e.g. Chalmers, 1996a; 1996b). Organisms which are not conscious, but have intelligent behavior are (in the philosophical sense) "zombies." If a zombie organism is threatened but has no experience of fear or pain, it may not react decisively. A conscious organism having an experience of fear or pain would be motivated to avoid threatening situations, and one having experience of taste would be more motivated to find food. The experience of pleasure could well have promoted reproductive efforts.

Who were the early Cambrian organisms? Fossil records have identified a myriad of small worms, strange urchins, tiny shellfish and many other creatures (Gould, 1989) depicted in the bottom of Figure 1. Nervous systems among small Cambrian worms (by comparison with apparent present-day cousins like the nematode worm *C. elegans*) may be estimated to contain roughly hundreds of neurons. Primitive eye cups and vision were also prevalent, as were tube-like alimentary systems with a mouth at one end and anus at the other. Cambrian urchins and other creatures also featured prominent spine-like extensions seemingly comparable to axoneme spines in present day echinoderms such as *actinosphaerium*. The versatile axonemes (MT arrays more complex than those of cilia and centrioles) are utilized for sensation, locomotion and manipulation, and provide perception, agency and purposeful, intelligent behavior.

As consciousness can't be measured or observed in the best of circumstances, it seems impossible to know whether or not consciousness emerged in early Cambrian organisms (or at any other point in evolution). The simple (hundreds of neuron) neural networks, primitive vision, purposeful spine-like appendages and other adaptive structures which characterize early Cambrian creatures depend heavily on cytoskeletal function and suggest the capability for agency, intelligent behavior and the possibility of primitive consciousness. Perhaps coincidentally, a specific model (Orch OR) predicts the occurrence of consciousness at precisely this level of cytoskeletal size and complexity.

Consciousness and orchestrated objective reduction (Orch OR)

What is conscious experience? Believing contemporary understanding of brain function inadequate to explain "qualia," or experience, a line of panpsychist/panexperiential philosophers (e.g. Leibniz, Whitehead, Wheeler, Chalmers. . .) have concluded that consciousness derives from an experiential medium which exists as a fundamental feature of reality. If so, conscious experience may be in the realm of spacetime physics, and raw "protoconscious" information may be encoded in spacetime geometry at the fundamental Planck scale [e.g. Penrose's (1971) quantum spin networks-Rovelli and Smolin, 1995a; 1995b]. A self-organizing Planck-scale quantum process could select "fundamental" experience resulting in consciousness. Is there such a process?

A self-organizing quantum process operating at the interface between quantum and macroscopic states, objective reduction (OR) is Penrose's (1989; 1994; 1996) quantum gravity solution to the problem of wave function collapse in quantum mechanics. According to quantum theory (and repeatedly verified experimentally), small scale quantum systems described by a wave function may be "superposed" in different states and/or places simultaneously. Large scale "macroscopic systems," however, always appear in definite "classical" states and/or places. The problem is that there is no apparent reason for this "collapse of the wave function," no obvious border between microscopic quantum and macroscopic classical conditions. The conventional explanation (the "Copenhagen interpretation") is that measurement or observation by a conscious observer collapses the wave function. To illustrate the apparent absurdity of this notion, Schrodinger (1935) described a now-famous thought experiment in which a cat is placed in a box into which poison is released when triggered by a particular quantum event. Schrodinger pointed out that according to the Copenhagen interpretation, the cat would be both dead and alive until the box was opened and the cat observed by a conscious human.

To explain this conundrum, many physicists now believe that intermediate between tiny quantum-scale systems and "large" cat-size systems some objective factor disturbs the superposition causing collapse, or reduction to classical, definite states and locations. This putative process is called objective reduction (OR). One increasingly popular OR viewpoint (initiated by Karolyhazy in 1966 Karolyhazy, et al., 1986) suggests this "largeness" is to be gauged in terms of gravitational effects and in Einstein's general relativity, gravity is spacetime curvature. According to Penrose (1989; 1994; 1996), quantum superposition actual separation (displacement) of mass from itself causes underlying spacetime to also separate at the Planck scale due to simultaneous curvatures in opposite directions. Such separations are unstable and a critical degree of separation (related to quantum gravity) results in spontaneous self-collapse (OR) to particular states chosen non-computably.

In Penrose's OR the size of an isolated superposed system (gravitational self-energy E of a separated mass) is inversely related to the coherence time T according to the uncertainty principle $E = h / T$, where h (actually " \hbar ") is Planck's constant over 2π . T is the duration of time for which the mass must be superposed to reach quantum gravity threshold for self-collapse. Large systems (e.g. Schrodinger's 1 kg cat) would self-collapse (OR) very quickly, in only 10^{-37} seconds. An isolated superposed single atom would not OR for 10^6 years. Somewhere between those extremes are brain events in the range of tens to hundreds of milliseconds. A 25 millisecond brain event (i.e. occurring in coherent 40 Hz oscillations) would require nanogram (10^{-9} gram) amounts of superposed neural mass.

In the Penrose-Hameroff "Orch OR" model (e.g. Penrose and Hameroff, 1995; Hameroff and Penrose, 1996a; 1996b), quantum coherent superposition develops in microtubule subunit proteins ("tubulins") within brain neurons and glia. The quantum state is isolated from environmental decoherence by cycles of actin gelation, and connected among neural and glial cells by quantum tunneling across gap junctions (Hameroff, 1996). When the quantum gravity threshold is reached according to $E = h/T$, self-collapse (objective reduction) abruptly occurs. The pre-reduction, coherent superposition ("quantum computing") phase is equated with pre-conscious processes, and each instantaneous OR, or self-collapse, corresponds with a discrete conscious event. Sequences of events give rise to a "stream" of consciousness. Microtubule-associated-proteins "tune" the quantum oscillations and the OR is thus self-organized, or "orchestrated" ("Orch OR"). Each Orch OR event selects microtubule subunit states non-computably which classically regulate synaptic/neural functions. Because the superposed protein mass separation is also a separation in underlying spacetime geometry, each Orch OR event selects a particular "fundamental" experience.

Consider a low intensity conscious sensory perception, for example as activity in sensory cortex after lightly touching a finger. Such an event was shown by Libet et al (1979) to have a pre-conscious time of 500 msec until conscious awareness. For $T = 500$ msec of quantum coherent superposition, $E =$ self-collapse of approximately 10^9 tubulins. As typical neurons contain about 10^7 neurons, Orch OR predicts involvement of roughly 10^2 to 10^3 neurons (interconnected by gap junctions) for rudimentary conscious events. For more intense conscious events, for example consistent with 25 msec "cognitive quanta" defined by coherent 40 Hz activity (e.g. Crick and Koch, 1990; c.f. Llinas, e.g. Joliot et al, 1994), superposition and self-collapse of 2×10^{10} tubulins (and 10^3 to 10^4 neurons) would be required.

How might Orch OR have happened? One possibility is that quantum coherence emerged in eukaryotic MT assemblies via the Fröhlich mechanism as a by-product of coordinated dynamics and biochemical energy (e.g. Fröhlich, 1968; 1970; 1975). Quantum coherence could also be an intrinsic property of the structure and geometry of microtubules and centrioles introduced to eukaryotes by spirochetes. Development of actin gels provided isolation for MT quantum states, and inter-cellular gap junction connections (suitable for quantum tunneling) enabled larger and larger quantum states among MTs in many connected cells. At some point in the course of evolution, sufficient quantum coherence to elicit Orch OR by $E = h/T$ was reached. Rudimentary "conscious" events then occurred. Organisms began to have experience and make conscious, non-computable choices.

Three candidates for Cambrian consciousness

Here three biological scenarios consistent with the Orch OR model for early Cambrian emergence of consciousness are considered. Each case involves MTs containing a minimum of 10^9 tubulins, suitable for a 500 msec conscious event.

1. sufficiently complex gap junction-connected neural networks (hundreds of neurons e.g. small worms).
2. primitive vision (ciliated ectoderm eye cup-e.g. small worms).
3. geometrical microtubule arrays (e.g. axoneme spines in small urchins such as actinosphaerium, tentacles in suctorians).

Many early Cambrian fossils are small worms with simple nervous systems. In Hameroff and Penrose (1996b) we speculated that among current organisms, the threshold for rudimentary Orch OR conscious events (500 msec pre-conscious time) may be very roughly at the level of 300 neuron (3×10^9 neural tubulin) nematode worms such as the well studied *C elegans*. This should be roughly the same neural network complexity as early Cambrian worms which could apparently burrow, swim, or walk the ocean floor with tentacles and spines (Figure 1; Gould, 1989).

Another candidate for the Cambrian emergence of Orch OR consciousness involves the evolution of visual photoreceptors. Amoeba respond to light by diffuse sol-gel alteration of their actin cytoskeleton (Cronly-Dillon and Gregory, 1991). Euglena and other single cell organisms have localized "eye spots" e.g. regions at the root of the microtubule-based flagellum. Cytoplasm may focus incident light toward the eye spots and pigment material shields certain angles to provide directional light detection (e.g. Insinna, this volume). Euglena swim either toward or away from light by flagellar motion. Having no neurons or synapses, the single cell euglena's photic response (sensory, perceptive and motor components) depend on MT-cytoskeletal structures.

Mammalian cells including our own can respond to light. Albrecht-Buehler (e.g. 1994) showed that single fibroblast cells move toward red/infra-red light by utilizing their MT-based centrioles for directional detection and guidance ("cellular vision"); he also points out that centrioles are ideally designed photodetectors (Figure 4).

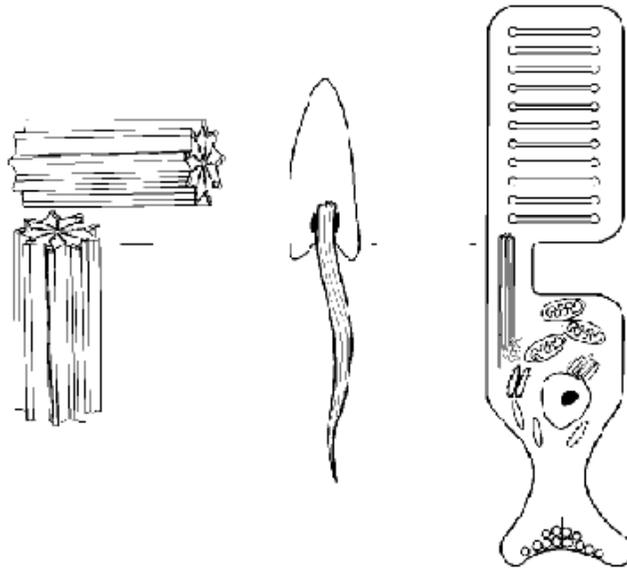


Figure 4. Photoreception/phototransduction mechanisms at all stages of evolution involve the nine MT doublet or triplet structures found in centrioles, cilia, flagella and axonemes. Left: The centriole is a pair of MT-based mega-cylinders arrayed in perpendicular (Lange and Gull, 1996). Albrecht-Buehler (1994) has identified centrioles as the photoreceptor/phototransducer in photosensitive eukaryotic cells. Middle: Flagellar axonemes are the photosensitive structures in protozoa such as *Euglena gracilis*. Right: Cilia in rod and cone retinal cells in vertebrate eyes (including humans) bridge two parts of the cells. Photosensitive pigments (rhodopsin) is contained in the outer segment (top) while cell nucleus, mitochondria and synaptic connection are contained in the cell body (bottom). Light enters the eye (from the bottom in this illustration) and traverses the cell body and cilium to reach the rhodopsin-containing outer segment. Adapted from Lange and Gull (1996) and Insinna (1997) by Dave Cantrell. Scale bars: 100 nanometers.

Jibu et al (1994; 1996) have predicted that cellular vision depends on a quantum state of ordered water in MT inner cores (Figure 5).

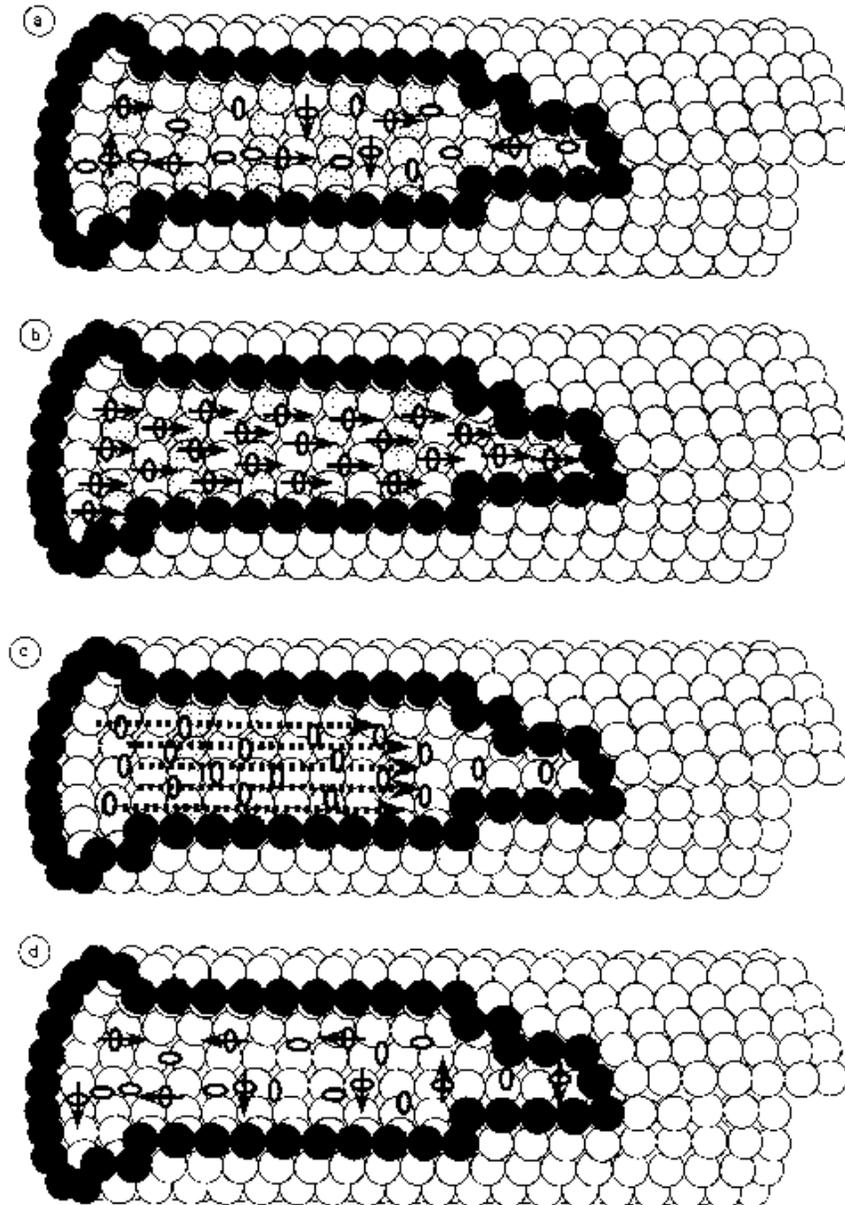


Figure 5. A schematic representation of the process of superradiance in a microtubule proposed by Mari Jibu, Kunio Yasue and colleagues (Jibu et al., 1994). Each oval without an arrow stands for a water molecule in the lowest rotational energy state. Each oval with an arrow stands for a water molecule in the first excited rotational state. The process is cyclic (a to b to c to d to a b) and so on. A) Initial state of the system of water molecules in a microtubule. Energy gain due to the thermal fluctuations of tubulins increases the number of water molecules in the first excited rotational energy state. B) A collective mode of the system of water molecules in rotationally excited states. A long-range coherence is achieved inside a microtubule by means of spontaneous symmetry breaking. C) A collective mode of the system of water molecules in rotationally excited states loses its energy collectively, and creates coherent photons in the quantized electromagnetic field inside a microtubule. D) Water molecules, having lost their first excited rotational energies by superradiance, start again to gain energy from the thermal fluctuation of tubulins, and the system of water molecules recover the initial state (a). With permission from Jibu et al. (1994).

They postulate a nonlinear quantum optical effect termed "superradiance" conveying evanescent photons by a process of "self-induced transparency" (the optical analogue of superconductivity). Hagan (1995) has observed that cellular vision provided an evolutionary advantage for single cell organisms with cilia, centrioles or flagella capable of quantum coherence.

In simple multicellular organisms, eyes and visual systems began with groups of differentiated light-sensitive ciliated cells which formed primitive "eye cups" (up to 100 photoreceptor cells) in many phyla including flatworms, annelid worms, molluscs, crustacea, echinoderms and chordates (our original evolutionary branch Cronly-Dillon and Gregory, 1991). The retinas in our eyes today include over 10^8 rod and cone photoreceptors each comprised of an inner and outer segment connected by a ciliated stalk. As each cilium is comprised of about 300,000 tubulins, our retinas contain about 3×10^{13} tubulins per eye. (Retinal rods, cones and glia are interconnected by gap junctions- Leibovic, 1990.) Conventional vision science assumes the cilium is purely structural, but the centriole/cilium/flagella MT structure which Albrecht-Buehler has analyzed as an ideal directional photoreceptor may detect or guide photons in eye spots of single cells, primitive eye cups in early multicellular organisms, and rods and cones in our retinas. Quantum coherence leading to consciousness could have emerged in sheets of gap junction-connected ciliated cells in eye cups of early Cambrian worms.

Perhaps consciousness occurred in even simpler organisms? Many Cambrian fossils are similar or related to present day species having particularly interesting MT geometrical arrangements. For example actinosphaerium (echinosphaerium) nucleofilum is a present-day echinoderm, a tiny sea-urchin heliozoan with about one hundred rigid protruding axonemes about 300 microns in length (Figure 4). Appearing similar to spines of Cambrian echinoderms, actinosphaerium axonemes sense and interact with environment, provide locomotion, and are each comprised of several hundred MTs interlinked in a double spiral (Figure 6).

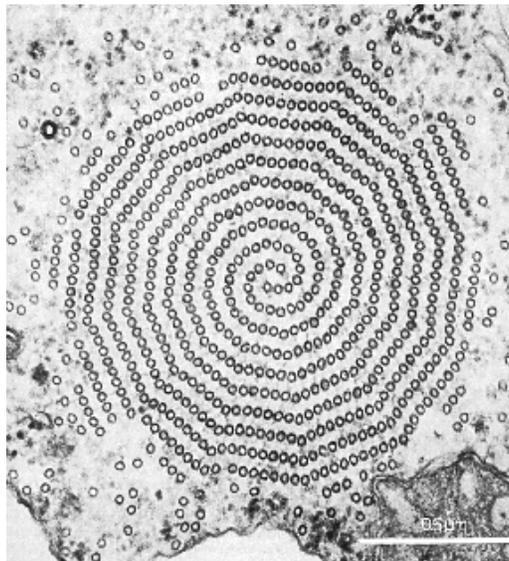


Figure 6. Cross-section of double spiral array of interconnected MTs in single axoneme of actinosphaerium, a tiny heliozoan related to sea urchin echinoderms present at the Cambrian evolutionary explosion (Figure 1). Each cell has about one hundred long and rigid axonemes which are about 300 microns long, made up of a total of 3×10^9 molecules of tubulin (Roth et al., 1970; Dustin, 1985). Scale bar: 500 nm (with permission from L.E. Roth).

Each axoneme contains about 3×10^7 tubulins, and the entire heliozoan contains 3×10^9 tubulins (Roth et al., 1970) perhaps coincidentally the precise quantity predicted by Orch OR for a 500 msec conscious event.

Allison and Nunn (1968; c.f. Allison et al., 1970) studied living actinosphaerium in the presence of the anesthetic gas halothane. They observed that the axoneme MTs disassembled in the presence of halothane (although at anesthetic concentrations two to four times higher than that required for anesthetic effect).

Somewhat similar to axonemes are larger prehensile tentacles in suctorians such as akinetopsis and heliophyra. Small multicellular animals, suctorians (Figure 37.1) have dozens of tiny hollow tentacles which probe their environment and capture and ingest prey such as paramecium. The prehensile tentacles range from about 300 microns up to one millimeter in length. Their internal structure is comprised of longitudinal arrays of about 150 microtubules in a ring

around an inner gullet through which prey/food passes (Figure 37.3). MTs apparently slide over one another in a coordinated fashion to provide tentacle movement and contractile waves involved in food capture, ingestion and other adaptive behaviors. The activity is interrupted by the anesthetic halothane (Hauser and Van Eys, 1976). A single suctorian tentacle (150 MTs, length 500 microns) contains about 10^9 tubulins the predicted requirement for a 500 msec Orch OR event. Perhaps consciousness arose in the probings of a Cambrian suctorian tentacle?

Would such primitive Orch OR experiences in a Cambrian worm, urchin or suctorian be anything like ours? What would it be like to be a tentacle? A single, 10^9 tubulin, 500 msec Orch OR in a primitive system would have gravitational self-energy (and thus experiential intensity) perhaps equivalent to a "touch lightly on the finger" experience. However our everyday coherent 40 Hz brain activity would correspond to 25 msec events involving 2×10^{10} tubulins, and so our typical experience would be some 20 times more intense. We also would have many more Orch OR events per second (e.g. 40 vs maximum of 2) with extensive sensory processing and associative memory presumably lacking in Cambrian creatures. Nonetheless, by Orch OR criteria, a 10^9 tubulin, 500 msec Orch OR event in a Cambrian worm, urchin or tentacle would be a conscious experience: a smudge of awareness, a shuffle in fundamental spacetime.

Conclusion

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"). It is suggested here that:

1. Occurrence of consciousness was likely to have accelerated the course of evolution.
2. Small worms, urchins and comparable creatures reached critical biological complexity for emergence of primitive consciousness at the early Cambrian period 540 million years ago.
3. Cooperative dynamics of microtubules, cilia, centrioles and axonemes were the critical biological factors for consciousness.
4. Cytoskeletal complexity available in early Cambrian animals closely matches criteria for the Penrose-Hameroff Orch OR model of consciousness.
5. Orch OR caused the Cambrian explosion.

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References

Albrecht-Buehler G. 1994. Cellular infra-red detector appears to be contained in the centrosome *Cell Motility and the Cytoskeleton* 27(3):262-271.

Allison, A.C., Hulands, G.H., Nunn, J.F., Kitching, J.A., and MacDonald A.C. 1970. The effects of inhalational anaesthetics on the microtubular system in *Actinosphaerium nucleofilum*. *J. Cell Science* 7:483-499.

Allison, A.C., and Nunn, J.F. 1968. Effects of general anesthetics on microtubules. A possible mechanism of anesthesia. *Lancet* 2:1326-1329.

Barinaga, M. 1996. Neurons put the uncertainty into reaction times. *Science* 274:344.

Chalmers, D.J., 1996a. *The conscious mind In search of a fundamental theory*. Oxford University Press, New York.

Chalmers, D.J., 1996b. Facing up to the problem of consciousness In: *Toward a Science of Consciousness The First Tucson Discussions and Debates*, S.R. Hameroff, A. Kaszniak and A.C. Scott (eds.), MIT Press, Cambridge, MA. pp 5-28.

Crick F.H.C. and Koch C. 1990. Towards a neurobiological theory of consciousness. *Seminars in the Neurosciences* 2:263-275.

Cronly-Dillon J.R. and Gregory R.L. 1991. *Evolution of the eye and visual system (Vision and visual dysfunction Vol 2)* CRC Press, Boca Raton.

Dayhoff, J.E., Hameroff, S., Lahoz-Beltra, R. and Swenberg, C.E. 1994. Cytoskeletal involvement in neuronal learning: a review. *Eur. Biophys. J.* 23:79-93.

Dawkins, R. 1989. *The selfish gene (revised edition)* Oxford Press, Oxford U.K.

- Dennett D.C. 1995. Darwin's dangerous idea: Evolution and the meanings of life. Touchstone, New York.
- Eccles J.C. 1992. Evolution of consciousness. Proc. Natl. Acad. Sci. USA 89(16):7320-7324.
- Fröhlich, H. 1975. The extraordinary dielectric properties of biological materials and the action of enzymes. Proc. Natl. Acad. Sci. 72:4211-4215.
- Fröhlich, H. 1970. Long range coherence and the actions of enzymes. Nature 228:1093.
- Fröhlich, H. 1968. Long-range coherence and energy storage in biological systems. Int. J. Quantum Chem. 2:641-649.
- Gould, S.J. 1989. Wonderful life The Burgess shale and the nature of history. W.W. Norton, New York.
- Gelber, B 1958. Retention in Paramecium aurelia. J. Comp. Physiol. Psych. 51:110-115
- Hagan, S. 1995. personal communication.
- Hameroff S. 1996. Cytoplasmic gel states and ordered water: Possible roles in biological quantum coherence. Proceedings of the Second Advanced Water Symposium, Dallas, Texas, October 4-6, 1996. <http://www.u.arizona.edu/~hameroff>
- Hameroff S. 1997. Fundamental geometry: The Penrose-Hameroff Orch OR model of consciousness. In: Geometry and the foundations of science: Contributions from an Oxford conference honoring Roger Penrose. Oxford Press.
- Hameroff, S.R. and Penrose, R. 1996a. Orchestrated reduction of quantum coherence in brain microtubules: A model for consciousness. In: Toward a Science of Consciousness The First Tucson Discussions and Debates, S.R. Hameroff, A. Kaszniak and A.C. Scott (eds.), MIT Press, Cambridge, MA. Also published in Mathematics and Computers in Simulation 40:453-480. <http://www.consciousness.arizona.edu/hameroff/penrose1.html>
- Hameroff, S.R. and Penrose, R. 1996b. Conscious events as orchestrated spacetime selections. Journal of Consciousness Studies 3(1):36-53. <http://www.consciousness.arizona.edu/hameroff/penrose1.html>.
- Hameroff S.R. and Watt R.C. 1982. Information processing in microtubules. Journal of Theoretical Biology 98:549-561 174:371-380.
- Hauser M, Van Eys H 1976. Microtubules and associated microfilaments in the tentacles of the suctorian heliophyra erhardi matthes. J Cell Sci ?XXX 589-617.
- Insinna, E.1997. Co-evolution of vision and consciousness. In: Toward a Science of Consciousness 1996 The second Tucson discussions and debates. Eds S Hameroff, A Kaszniak, A Scott. MIT Press, Cambridge (in press).
- Jibu, M. 1990. On a heuristic model of the coherent mechanism of the global reaction process of a group of cells. Bussei Kenkyuu (Material Physics Research) 53 (4):431-436 (in Japanese).
- Jibu M, Pribram KH, Yasue K 1996. From conscious experience to memory storage and retrieval: The role of quantum brain dynamics and Bose condensation of evanescent photons. Int J Mod Physics B (13&14):1735-1754.
- Jibu, M., Hagan, S., Hameroff, S.R., Pribram, K.H. and Yasue, K. 1994. Quantum optical coherence in cytoskeletal microtubules: implications for brain function. BioSystems 32:195-209.
- Joliot M., Ribary U. and Llinas R. 1994. Human oscillatory brain activity near 40 Hz coexists with cognitive temporal binding. Proc. Natl. Acad. Sci. USA 91(24):11748-11751.
- Karolyhazy, F. 1966. Gravitation and quantum mechanics of macroscopic bodies. Nuo. Cim. A, 42:390-402.
- Karolyhazy, F., Frenkel, A. and Lukacs, B. 1986. On the possible role of gravity on the reduction of the wave function. In Quantum Concepts in Space and Time, R. Penrose and C.J. Isham (eds.), Oxford University Press.
- Kauffman, S. 1995. At home in the universe. Oxford Press, N.Y.
- Lange B.M.H. and Gull K. 1996. Structure and function of the centriole in animal cells: Progress and questions. Trends in Cell Biology 6:348-352.
- Leibniz, G.W. 1768. Opera Omnia. 6 volumes, Louis Dutens, ed. Geneva.
- Leibovic, K.N. 1990. Science of Vision. Springer-Verlag NY.

- Libet, B., Wright, E.W. Jr., Feinstein, B. and Pearl, D.K. 1979. Subjective referral of the timing for a conscious sensory experience. *Brain* 102:193-224.
- Llinas, R.R. 1985. Electrotonic transmission in the mammalian central nervous system. In: *Gap junctions*, Eds MVL Bennett, D.C Spray. Cold Spring Harbor Laboratory. pp337-353.
- Lo, C.W. 1985. Communication compartmentation and pattern formation in development. In: *Gap junctions*, Eds MVL Bennett, D.C Spray. Cold Spring Harbor Laboratory pp 251-263
- Margulis, L. 1975. *Origin of Eukaryotic Cells*. Yale University Press, New Haven.
- Margulis, L. and Sagan, D. 1995. *What is life?* Simon and Schuster, N.Y.
- Penrose, R. 1994. *Shadows of the Mind*, Oxford Press, Oxford, U.K.
- Penrose, R. 1989. *The Emperor's New Mind*, Oxford Press, Oxford, U.K.
- Penrose, R. 1971. in *Quantum Theory and Beyond*. ed E.A. Bastin, Cambridge University Press, Cambridge, U.K.
- Penrose, R. 1996. On gravity's role in quantum state reduction. *General relativity and gravitation*. 28(5):581-600.
- Penrose, R. and Hameroff, S.R. 1995. What gaps? Reply to Grush and Churchland. *Journal of Consciousness Studies* 2(2):99-112.
- Puck, T.T. and Krystosek A. 1992. Role of the cytoskeleton in genome regulation and cancer *Int. Rev Cytology* 132:74-108.
- Rasmussen S. 1996. personal communication.
- Rasmussen, S., Karampurwala, H., Vaidyanath, R., Jensen, K.S. and Hameroff, S. 1990. Computational connectionism within neurons: A model of cytoskeletal automata subserving neural networks. *Physica D* 42:428-449.
- Roth, L.E., Pihlaja, D.J. and Shigenaka, Y. 1970. Microtubules in the heliozoan axopodium. I. The gradion hypothesis of allosterism in structural proteins. *J. Ultrastr. Res.* 30:7-37.
- Rovelli C. and Smolin L. 1995. Discreteness of area and volume in quantum gravity. *Nuclear Physics B* 442:593-619.
- Rovelli C. and Smolin L. 1995. Spin networks in quantum gravity. *Physical Review D* 52(10):5743-5759.
- Saubermann, A.J. and Gallagher, M.L 1973. Mechanisms of general anesthesia: Failure of pentobarbital and halothane to depolymerize microtubules in mouse optic nerve. *Anesthesiology* 38:25-29.
- Schrödinger, E. 1935. Die gegenwärtigen situation in der quantenmechanik. *Naturwissenschaften*, 23:807-812, 823-828, 844-849. (Translation by J.T. Trimmer (1980) in *Proc. Amer. Phil. Soc.*, 124:323-338.) In *Quantum Theory and Measurement* (ed. J.A. Wheeler and W.H. Zurek). Princeton University Press, 1983.
- Schrödinger, E. 1958. *Mind and Matter*. Cambridge University Press, Cambridge U.K.
- Scott A. 1995. *Stairway to the mind*. Springer-Verlag.
- Scott, A.C. 1996. Book review: Lynn Margulis and Dorion Sagan "What is life?" *Journal of Consciousness Studies* 3(3):286-287.
- Vermeij, G.J. 1996. Animal origins. *Science* 274:525-526.
- Tuszynski, J., Hameroff, S., Sataric, M.V., Trpisova, B. and Nip, M.L.A. 1995. Ferroelectric behavior in microtubule dipole lattices; implications for information processing, signaling and assembly/disassembly. *J. Theor. Biol.* 1995. 174:371-380.
- Wheatley J.N. 1982. *The centriole: A central enigma of cell biology*. Elsevier, Amsterdam.
- Wray, G.A., Levinton, J.S. and Shapiro, L.H. 1996. Molecular evidence for deep precambrian divergences among metazoan phyla. *Science* 274:568-573.

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