

## A Sonoran Afternoon

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**EDITOR'S NOTE:** *Late one summer afternoon in Arizona's Sonoran Desert, Stuart Hameroff and Alwyn Scott awoke from their siestas to take margaritas in the shade of a ramada. On a nearby table, a tape recorder had accidentally been left on and the following is an unedited transcript of their conversation.*

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**Stuart:** Tell me, Al, why are you so negative about quantum theories of the mind?

**Al:** Before trying to answer that, let's remember where we are in agreement. We both feel uncomfortable with the notion that the mind is nothing more than the switchings off and on of the brain's neurons, and we are both looking for something more. But we're looking in different places. Furthermore, I don't have anything against quantum theory. From the perspective of applied mathematics, it's really interesting to consider how Schrödinger's linear wave dynamics manages to mimic the experimentally observed properties of (say) molecular vibrations. But I don't see any need for quantum theory to explain the strongly nonlinear dynamics that are observed in the brain.

**Stuart:** What needs to be explained are the tough questions of consciousness in particular qualia, or conscious experience: Chalmers's hard problem as well as binding and other enigmatic features. I agree that nonlinear dynamics is necessary, but why not quantum theory also if it can answer these tough questions?

**Al:** Sure, we need to understand the riddle of subjective experience. I completely agree with you there. But quantum theory doesn't help much because the binding of stable and globally coherent states is a phenomenon that arises more naturally in classical nonlinear systems than in the linear theory of quantum mechanics. You simply don't need quantum theory to explain global coherence.

**Stuart:** I agree that consciousness is a globally coherent state, but globally coherent classical states are merely couplings and correlations of separate individual activities e.g. doesn't necessarily solve the binding problem. On the other hand, macroscopic quantum states such as superconductors, Bose-Einstein condensates, superfluids, and the proposed pre-conscious Orch

OR microtubule states are qualitatively different. These are globally coherent in the sense of "being one entity."

**Al:** There's lots more to classical nonlinear dynamics than neurons firing synchronously. A generic feature of classical nonlinear dynamics is the emergence of stable dynamic entities at each level of description to provide a basis for the nonlinear interactions at the next higher level of description. You don't need to assume that quantum theory is required for such behavior, examples of which abound. Benzene molecules emerge from the nonlinear forces between hydrogen and carbon atoms, just as proteins emerge from the nonlinear attractions among amino acids. Tornadoes emerge from the nonlinear dynamics of air and sunshine, just as cities and cultural configurations emerge from the very nonlinear interactions among human beings. Each of these is indeed "one entity." You can't have half of a benzene molecule.

**Stuart:** But benzene, tornadoes and individual proteins are not conscious and I would argue that quantum effects are necessary for certain activities of benzene-like rings, and proteins.

**Al:** Benzene, proteins, tornadoes, and cities emerge as globally coherent entities from classical nonlinearities. That's what I'm saying. You are right that quantum theory is needed to compute the attractions between atoms, but once calculated these can be treated as classical forces.

**Stuart:** Classical nonlinearity is needed in biology and consciousness; I just think quantum effects are also required. And while it's true that a quantum state evolves linearly according to the Schrödinger equation, highly nonlinear events occur in Penrose's "objective reduction" (OR). In OR a quantum coherent superposition state (if isolated from environmental decoherence) will continue linearly only until a specific threshold is reached. (The threshold is related to quantum gravity, and is expressed by  $E = \hbar/T$ ). At that instant, "self"-collapse of the wave function occurs, and specific classical states are chosen noncomputably. Thus the Orch OR model is nonlinear. In fact, Orch OR describes consciousness as a sequence of discrete events rather than a continuum. Penrose's noncomputable OR (Penrose, 1989; 1994; 1996) seems to me to be the ultimate manifestation of nonlinearity.

**Al:** I can't argue with Roger's theory because I don't understand it. And it would really be neat if the Orch OR model turns out to be a useful description of reality, but to repeat I don't see the need for it to explain the many nonlinearities that are observed at the various levels of biological dynamics.

**Stuart:** Perhaps not. But what about consciousness?

**Al:** The special thing about consciousness it seems to me is that it emerges from all the levels of the brain's dynamics; not just one (the neurons for example) but all of them.

**Stuart:** Including quantum coherence at the level of intra-neural microtubules?

**Al:** I don't have any philosophical problems with quantum coherence playing a role in conscious phenomena, but there is no theoretical need for it. Look, the fundamental dynamics of the brain

are dissipative. We can't even construct Schrödinger's equation for a nerve impulse that is traveling along an axon. A nerve impulse is a completely classical phenomenon.

**Stuart:** Yes, and we both agree that nerve impulses *per se* can't explain consciousness. Regarding dissipation, a quantum state in the brain must be cleverly (and transiently) isolated. In the Orch OR model, quantum coherence in microtubules emerges during pre-conscious, nondissipative phases, which are isolated by actin gelation. At instantaneous collapse, gel is dissolved to "sol" (solution), information is communicated, and energy dissipates.

**Al:** To the extent that I can understand what you are saying, I'm not convinced. Are quantum effects to be anticipated in the dynamics of your microtubule solitons?

**Stuart:** Not necessarily. Classical signaling along microtubules is stipulated in Orch OR theory, and classical microtubule solitons may be involved in the "sol" open phases. The idea is that quantum (gel) isolation phases alternate with classical signaling (sol) open phases at frequencies such as 40 Hz, for example.

**Al:** Because the mass of an individual tubulin molecule runs easily into the tens of thousands of atomic mass units, the minimum length of the waves from which Schrödinger's wave packets are constructed is a very small fraction of an atomic diameter (Scott, 1996). Much too small for biochemists to worry about.

**Stuart:** A quantum superposition an actual separation of mass distribution of a very small fraction of an atomic diameter is more than enough. In Hameroff and Penrose (1996), we consider the displacement distance for superposed tubulin protein molecules "separated from themselves" in three ways: as separated protein spheres, as separations of component atomic nuclei, and as separations of component nucleons (protons or neutrons). We determined that the lowest energy collapse (and hence the predominant effect) comes with separation at the level of atomic nuclei. The entire protein is superposed, but at the level of each of its 105 atomic nuclei being separated from themselves by their 10<sup>-6</sup> nanometer diameter. This is much smaller than the wave packet. The implications of quantum coherent superposition for consciousness are irrespective of the distance of separation. The significance comes from the quantum coherent binding, from the self-collapse events which are processes in fundamental spacetime geometry (akin to Whitehead's "occasions of experience"), and from non-computable selection of post-collapse states.

**Al:** Well, I'm not talking about anything as complicated as all that. The key point is that for tubulin at biological temperatures, the size of a quantum wave packet is much less than the size of a protein molecule. For the same reason, one would not use quantum mechanics to calculate the trajectory of a howitzer round.

**Stuart:** Then this pertains to the classical soliton case, but not the quantum phase during which the mass movement is superposition.

**Al:** Let's consider how quantum theory does enter the picture. I agree that it is definitely necessary to describe the motions of the electrons that hold a molecule together because the mass

of an electron is more than four orders of magnitude less than that of a typical atom, which is small enough so its quantum wave packet can extend over several atoms. To separate the electronic motions from those of the atomic nuclei, quantum chemists use the Born-Oppenheimer approximation (Born and Oppenheimer, 1927), taking advantage of the fact that the electrons move about much more quickly than the atomic nuclei because they are so much lighter. Thus one assumes in the first approximation that the atomic nuclei are stationary. Then the forces between nuclei are calculated from the structures of electronic wave functions, which can be regarded as a nonlinear "rubber cement" that holds a molecule together. An important feature of Born's formulation is that one can estimate the errors involved so it becomes clear when quantum effects can be ignored. At the level of biochemistry, these effects are very small.

**Stuart:** Michael Conrad points out that the Born-Oppenheimer approximation assumes that an electron and its nucleus behave like a football and the earth. The gravitational field (mass) of the football is negligible in comparison to that of the earth, so the ball follows the earth very rapidly. But the electromagnetic field of an electron and a proton are the same, independent of the mass. Delocalized electrons accelerate relative to their nuclei, and may affect nuclear motion and conformation. In superconductors, motions of the electrons clearly affect the nuclear lattice.

**AI:** Yes that's right and in ways that can be calculated.

**Stuart:** As Conrad describes it, proteins and nucleic acids are extremely complicated nonlinear systems, each with tens of thousands of electrons, protons and neutrons (Conrad, 1996). Some intra-protein electrons are very delocalized and are now known to tunnel long distances through hydrogen bond pathways. Electron delocalization also occurs in surface electrons (which cannot closely follow any specific nuclei) and in aromatic (electron resonance) ring structures in amino acids tyrosine, phenylalanine, tryptophan and histidine. These comprise water-free "hydrophobic pockets" within protein interiors, precisely where general anesthetics act (apparently by limiting electron delocalizability). Conrad observes that significantly delocalized electrons which accelerate relative to their nuclei must then absorb and emit photons whose frequencies cannot be precisely accounted for by the rotational and vibrational transitions of the nuclei. Conrad's model of quantum protein computing argues that superposition of electron states contributes to interference effects that "jiggle the nuclei," in particular the hydrogen bonds, and thereby open up new pathways of conformational self-organization. Parallelism of the electronic wave function is thereby converted to a speedup of protein conformational dynamical function.

**AI:** Sure, proteins are very complicated objects; that's why they can do so many neat things.

**Stuart:** And they may use quantum superposition to do them.

**AI:** Well that may be so, but it's not obvious. Quantum descriptions of protein dynamics are often convenient, but that doesn't mean they are necessary. [Pause.] Taking another tack, let me try to express my position this way. Brains are composed of neurons, synapses, and glial cells in the same sense that living organisms are composed of chemical atoms, and the functional organization is equally intricate. Just as one would not attempt to describe the life of an organism in terms of the motions of its constituent atoms, one cannot describe the mind in terms of the switchings of its constituent neurons. But the intricacy of this picture doesn't require quantum

effects. Life and mind emerge from the immensely complicated nonlinear and hierarchical structures of body and brain. That's where the mystery lies.

**Stuart:** How would you explain the intelligent, adaptive behavior of a single cell organism like a paramecium, which leads a rich existence without a neural network or synapses?

**Al:** That's a good point. Sherrington suggested that these little guys could be using their cytoskeletons to compute.

**Stuart:** We don't necessarily know all of the brain's hierarchical levels, nor how they interact we don't understand life. Nor do we know precisely how brains are composed of neurons. Factors like electrotonic synapses, dendritic microprocessing, the role of glia and cytoskeletal processes are generally ignored.

**Al:** I completely agree. And just as one would not try to describe a bacterium in terms of the Born-Oppenheimer force field between its constituent atoms...

**Stuart:** One might need something like quantum theory to describe a fundamental life process of the bacterium. How do we know? What is life?

**Al:** ...one cannot think of the brain merely in terms of individual neurons. Neurons organize themselves into assemblies of neurons, each of which exhibits global coherence, binding and threshold phenomena, as does an individual neuron. Thus assemblies of neurons can organize themselves into assemblies of assemblies, which in turn organize themselves into assemblies of assemblies of assemblies and so on up to the functional dynamic entities that provide the basis for the immensely complicated behaviors that underlie human consciousness (Scott, 1995).

**Stuart:** Granted. But what is it that these behaviors are underlying? What is consciousness?

**Al:** Stuart, if I knew, I would certainly share it with you, but these statements about the functional organization of the brain which are supported by many experimental studies are far removed from the considerations of quantum mechanics. There is no need to cast about for sources of mystery here; fully organized thoughts are immensely (in a precise technical sense) complicated entities, and the experiments of present day electrophysiology tell us little about how they might interact.

**Stuart:** And they tell us nothing about the nature of conscious experience, the "hard problem." There is a need to cast about for something.

**Al:** Yes, and I'm suggesting that the immensely intricate nonlinear structure of the brain's dynamics is a much richer source of mystery that quantum theory will ever be. In my opinion, physicists who turn to quantum theory for explanations of such intricate phenomena are looking in the wrong direction. Quantum theory tells us how atoms interact, but little about protein dynamics and nothing about the electrophysiology of the brain.

**Stuart:** I disagree. Regulation of protein conformational dynamics is not understood, and some evidence supports quantum effects: For example, quantum coherence apparently does occur in certain proteins (e.g. BPTI, ferritin--Roitberg et al.; Tejada 1996), and quantum spin correlations are preserved in cytoplasm (Walleczek, 1995). Michael Conrad has extensively considered quantum effects in proteins.

**Al:** Well, yes, protein dynamics are very complicated. That's also my point. But to repeat it's not clear that you really need quantum theory to describe this intricacy. I spent about ten years studying quantum theories of polaronic effects in protein and at the end of the decade it was difficult to point to anything of experimental significance that could not be just as well described classically (Scott, 1992).

**Stuart:** That's not to say that quantum effects in proteins may not be experimentally shown subsequently, as the Roitberg and Tejada papers suggest. It's an extremely tricky business quantum effects are, in general, unobservable.

**Al:** If physicists are truly interested in contributing to our understanding of phenomena related to consciousness, they should acquaint themselves with the relevant neurological facts, which are far more intricate than can be expressed in a quantum formulation.

**Stuart:** I think a theory of consciousness must integrate philosophy, physics and neurobiology, so I basically agree. However the "relevant neurological facts" may turn out to include quantum effects.

**Al:** It's my view that physics and mathematics will play minor roles in this integration. [Pause.] And I have the impression that some physicists cling to the quantum approach because they are subconsciously aware that their knowledge is of limited value for understanding really interesting questions like the natures of life and mind. Physics is a science of the past.

**Stuart:** Not being a physicist, I don't take this personally, but I do think it's unfair and incorrect. Face it neither the hard problem of experience nor the nature of the universe is understood. Physics may offer solutions for both, particularly if experience is a fundamental property of the universe, as Chalmers concludes.

**Al:** On this point, I'm much more conservative than David. I don't feel comfortable with blithely assuming the existence of some new force field (or whatever) without experimental evidence for it.

**Stuart:** Experimental evidence points to the fact that reality exists. There is some fundamental makeup of the universe, we just don't know precisely what it is. The Casimir force of quantum fluctuations the quantum "foam" has just been measured (Lamoreaux, 1997). Penrose's quantum spin networks (Rovelli and Smolin, 1995) are one approach to describing reality at its most basic (Planck-scale) level. This is where ("funda-mental") experience may reside.

**Al:** And while I would have no problem with a quantum theory of neural behavior if there were some experimental evidence to support it, there is none that I know of. So I prefer to concentrate

my very limited powers of analysis on the vast and unexplored realms of hierarchical nonlinear dynamics.

**Stuart:** Your work on hierarchical emergence is extremely important. And it is true that there is currently no hard evidence for quantum coherence and OR in microtubules. Orch OR is a model. However I might add that there is currently no experimental evidence for consciousness. It is unobservable (except in ourselves). Also, the isolated quantum states predicted in Orch OR will require clever, directed experiments. It's not at all surprising assuming they do indeed exist that they haven't been verified. In a paper currently in press (Hameroff, 1997), nineteen specific testable predictions of the Orch OR model are suggested.

**Al:** Isn't the fact that we are having this conversation clear experimental evidence for consciousness?

**Stuart:** Not necessarily. I could be a zombie. In fact after another margarita or two, I may be a zombie.

**Al:** Ah...! Don't get started on zombies; the whole idea is kooky! Why worry about something that doesn't exist?

**Stuart:** Chill out, Al. Zombies are a useful philosophical concept. For example if one were able to pinpoint a threshold for consciousness in the course of evolution, non-conscious organisms below that threshold still capable of intelligent, adaptive behavior would be zombies. Wouldn't they?

**Al:** H'm, that's an interesting idea.

**Stuart:** Actually, now that I think of it, having another glass or two would put me in a state quite opposite that of a zombie. I would be having a rather pleasant experience, but be relatively incapable of intelligent adaptive behavior. Quite the opposite of the "zombie" state in which I'm driving my car but thinking of something entirely different.

**Al:** In his Varieties of Religious Experience, William James lists bibulosity as the first level of transcendental experience. But get back to evolution. When and how do you think that consciousness emerged?

**Stuart:** I'd bet on small worms and spiny urchins in the early Cambrian sea floor 540 million years ago. The reasoning is explained in my chapter for the Tucson II book.

**Al:** Look, we agree that consciousness exists as an aspect of reality; the question is: How do we characterize it? Ten to a hundred billion nerve cells, each of which is locally described by the Hodgkin-Huxley equations, provide the basis for a very intricate nonlinear field theory. Immensely intricate. Such a system is not a product of theoretical imagination; it is supported by many thousands of carefully reviewed experimental research papers in electrophysiology. And a really intricate nonlinear field theory with functional significance at many levels of dynamic reality is our best bet for ultimately comprehending consciousness.

**Stuart:** How do we know that neural membrane firing activities describable by Hodgkin-Huxley equate to consciousness?

**Al:**I'm not claiming that, and I don't think that they do. As I've said, the real nonlinear picture is much more intricate. One has many levels of activity from active patches of nerve membrane to action potentials on nerve fibers to behaviors of whole neurons to assemblies of neurons to assemblies to assemblies to. . .the mind boggles. . .to the complex behaviors that characterize a fully developed brain. But it doesn't stop even there. Each brain is a component an atom, if you will in a particular human culture. As a classical nonlinear field theory, this picture can easily explain global coherence, binding, threshold phenomena, free will, and so on. As I've said, it's much richer and more intricate than linear quantum theory will ever be.

**Stuart:** But why not also look down the hierarchical organization to the quantum level? Why arbitrarily pick membrane patches as the fine grain?

**Al:**At the end of the day, I suppose, it comes down to intuition. My whole professional life thirty-five years has been devoted to the study of classical nonlinear dynamics. [Pause.] My little finger tells me that quantum effects aren't important. [Pause.] Of course, that's not an argument, is it?

**Stuart:** Perhaps not, but I have great respect for intuition. It's a non-computable process. It's just that my intuition and Roger's is that quantum effects in microtubules are necessary to explain enigmatic features of consciousness.

Let's look at five enigmatic features of consciousness: [Counting on his fingers.] (1) the nature of experience, (2) binding, (3) free will, (4) non-computability, (5) transition from pre-conscious processes to consciousness. You are claiming that classical nonlinear effects, or "emergence," can explain 2 through 5, but without 1 the hard problem of experience 2 through 5 are empty. For example in the transition from pre-conscious processes to consciousness, you are saying that nonlinear threshold phenomena can explain the transition. But transition into what? If the hard problem of experience isn't explained, then nonlinear threshold transitions are not necessarily explanatory. The same is true of binding and global coherence. Synchronization of neural firing activities doesn't solve anything unless a mechanism for conscious experience is attached. It's just a correlate of consciousness. A macroscopic quantum coherent state, however, does truly "bind" its components into a unified entity.

**Al:**Classical nonlinear dynamics also truly binds components into unified entities. Think of a tornado or Jupiter's Great Red Spot.

**Stuart:** As I said before, tornadoes and the Great Red Spot are not conscious. But why not? Tornadoes and the Great Red Spot are self-organizing processes in a medium (atmospheric gases) which happens not to bear an intrinsic property or component of experience. The emergent property is wind, not mind.

**Al:**The emergent property of much of our neurophilosophy is also wind.



**Stuart:** Yes [chuckle], but philosophy can be useful in attempting to understand consciousness. For example a line of panpsychist and panexperiential philosophers have suggested that experience is a fundamental feature of reality Spinoza, Leibniz, Whitehead, Wheeler and now Chalmers. Leibniz's "monads" are fundamental geometric regions of reality which bear experiential qualities. Whitehead's "occasions of experience" are events which occur in a wider field of raw experience.

The Orch OR model links these purely philosophical positions with the physics of reality at its most basic level. The Planck scale (10<sup>-33</sup> cm) is where spacetime geometry is no longer smooth. The best description of spacetime at this level may be Penrose's quantum spin networks (Rovelli and Smolin, 1995) and this could be where "proto-conscious" raw experience resides. We term this "funda-mental" geometry. Orch OR events are self-organizing quantum events at the Planck scale which select and reconfigure funda-mental geometry.

This is an inescapable if seemingly bizarre conclusion.

**Al:**I still don't see how your quantum state gets to be conscious.

**Stuart:** It's not the state, it's a sequence of self-collapse events in a postulated proto-conscious medium. Funda-mental experience is accessed and selected with each Orch OR event. Consciousness is stepwise rather than continuous. Don't you agree?

**Al:**I only know what goes on in my head, and that seems continuous.

**Stuart:** Movies seem continuous, but they are actually sequences of frames.

**Al:**And you can't claim that your conclusion is inescapable because so many see it differently. [Pause.] Shall we mix another pitcher?

**Stuart:** Well, it's inescapable to me. Yes, mas margaritas! Let's find that bibulous "anti-zombie" state of pure experience.

## References

Born, M. and Oppenheimer, J.R. 1927. Zur Quantentheorie der Molekeln. *Annal. Physik* 84: 457-484.

Conrad, M. 1996. Percolation and collapse of quantum parallelism: A model of qualia and choice. 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 469-492.

Hameroff, S.R. 1997. Funda-mental geometry: The Penrose-Hameroff Orch OR model of consciousness. In: *Geometric issues in the foundations of science-Proceedings of a conference honoring Roger Penrose*. Eds N Woodhouse. Oxford Press. In 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. pp 508-540 Also published in *Mathematics and Computers in Simulation* 40:453-480. <http://www.u.arizona.edu/~hameroff/penrose1>

Hameroff, S.R. and Penrose, R. 1996b. Conscious events as orchestrated spacetime selections. *Journal of Consciousness Studies* 3(1):36-53. <http://www.u.arizona.edu/~hameroff/penrose2>

Lamoreaux, S.K. 1997. Demonstration of the Casimir force in the 0.6 to 6 micron range. *Phys. Rev. Letts.* 78:5-8.

Roitberg A., Gerber R.B., Elber R. and Ratner M.A. 1995. Anharmonic wave functions of proteins: quantum self-consistent field calculations of BPTI. *Science* 268:1319-1322.

Rovelli C. and Smolin L. 1995. Spin networks in quantum gravity. *Physical Review D* 52:5743-5759.

Rovelli C. and Smolin L. 1995. Discreteness of area and volume in quantum gravity. *Nuclear Physics B* 442:593-619.

Scott, A. 1995. *Stairway to the mind*. New York: Springer-Verlag (Copernicus).

Scott, A. 1992. Davydov's soliton. *Physics Reports* 217:1-67.

Scott, A. 1996. On quantum theories of the mind. *Journal of Consciousness Studies* 3: 484-491.

Tejada J., Garg A., Gider S., Awschalom D.D., DiVincenzo D.P. and Loss D. 1996. Does macroscopic quantum coherence occur in ferritin? *Science* 272:424-426.

Walleczek, J. 1995. Magnetokinetic effects on radical pairs: a possible paradigm for understanding sub-kT magnetic field interactions with biological systems. in *Electromagnetic Fields: Biological Interactions and Mechanisms*. M Blank (ed) *Advances in Chemistry* No 250 American Chemical Society Books Washington DC.