Consciousness, Microtubules and The Quantum World

Interview with Stuart Hameroff, MD, in Alternative Therapies (May 1997 3(3):70-79 by Bonnie Horgan).

Alternative Therapies: How did an anesthesiologist end up speaking at a consciousness conference?

Hameroff: I became interested in understanding consciousness as an undergraduate at the University of Pittsburgh in the late 60's. In my third year of medical school at Hahnemann in Philadelphia I did a research elective in professor Ben Kahn's hematology-oncology lab. They were studying various types of malignant blood cells, and I became interested in mitosis-looking under the microscope at normal and abnormal cell division. I became fascinated by centrioles and mitotic spindles pulling apart the chromosomes, doing this little dance, dividing the cytoplasm, establishing the daughter-cell architecture, and beginning differentiation. I remember wondering to myself how these centrioles and mitotic spindles "knew" where to go and what to do. What kind of intelligence was running the show at the cellular level?

My main interest was still consciousness, or the brain-mind problem. At that time, scientists were just beginning to appreciate that all cells, including neurons, contained the same structures that make up mitotic spindles, which are basically microtubules You see, for 30 years scientists had been using the electron microscope to look at intracellular structure. But the fixative agent osmium tetroxide was dissolving all the internal structure. It dissolved everything. So for many, many years the cell was perceived as a bag of water.

Alternative Therapies: The fixative that was used to examine the cell was dissolving the cell structure?

Hameroff: Yes. The cytoplasmic fine structure was erased. Finally in the early 70's electron microscopists switched to glutaraldehyde and saw order and structure in cytoplasm organized by networks of microtubules. Thanks to the anatomist Keith Porter and his coworkers it became obvious that the interior of a cell was like a tiny forest. Not only that, the forest was very dynamic. It was moving things around, rearranging itself, defining the shape, function, and structure of the cell. As it turned out, the same microtubules running the show in mitosis were running the show in neurons and other cells all the time. Each neuron was a network of microtubules. I came to think of the brain as a network of networks, forests within trees. When I finished medical school I thought about a research career, but opted for clinical work and matched for internship in Tucson, Arizona. I considered residency in neurology or psychiatry, but then I met Professor Burnell Brown, the chairman of the anesthesiology department at the University of Arizona medical center. He told me "If you want to know what consciousness is, study the mechanism of anesthetics." He also gave me a paper suggesting anesthetics depolymerized microtubules, and convinced me that anesthesiology was an excellent career choice. I signed on. When I finished residency Burnell offered me a faculty position, and here I am twenty years later.

Alternative Therapies: Let's talk about microtubules. Can you give me a layman's definition?

Hameroff: A cell has a skeleton, somewhat like our body has a skeleton. It's called "the cytoskeleton." Look out the window at those trees. If you put a big sheet over a bunch of closely grouped trees, that would be like a cell. The sheet would be the membrane, but the trees would be the structure inside the cell. The main trunks would be the microtubules and the connections would be microtubule-associated proteins, actin, and so on.

But unlike a forest, the cytoskeletal branches are moving cooperatively, like arms and hands, passing things along from place to place inside the cell, and rearranging themselves to change cell shape, and grow extensions like axons or dendrites.

The actual microtubule structure is quite interesting. They are hollow cylinders whose walls look something like hollow ears of corn with kernels in a hexagonal lattice. It occurred to me that the states of each of these kernels in microtubules could represent information, and that microtubules were ideal computers. That was how they were running the show.

Alternative Therapies: What functions do the microtubules perform for the cell?

Hameroff: The classical answer is that microtubules and the cytoskeleton are primarily structural, like the body's bony skeleton. However if you look carefully, microtubules are also the cell's nervous system and circulatory system. They move everything around the cell, organize shape and function, and communicate with membranes and the nuclear DNA. For example immune cells depend on cytoskeletal microtubules for recognition and response. In neurons microtubules first establish cell shape and synaptic connections, transport materials, regulate those synapses, participate in axonal neurotransmitter release, and transduce membrane receptor effects. They are everywhere, and seem to organize almost everything.

Of course there's no conclusive proof that microtubules compute or process information. The dogma, or party line is that information is conveyed inside cells by cascades of chemical signals. But to me, that view of the cell as an organized soup doesn't make sense. Cytoplasm is often in a gel state - like jello. It's difficult to conceive how signals can be conveyed rapidly and accurately just by diffusion through a gel state. And in the liquid state computation and memory would be very limited. But if you look at the microtubules which spatially organize the cytoplasm • Ethey are already sitting there you see perfectly designed information processing devices, or at least I do.

In general, neuroscience has focused on the one hand on membranes Eion channels, depolarizations, and receptors, and on the other hand on genetics and the nucleus. We've ignored what's in between. I think there's something special going on with microtubules that we need to figure out.

Alternative Therapies: Do these microtubules exist in the cells of a tree?

Hameroff: They are in plant cells, but they are scarce. A plant cell might have a few, whereas human neurons have hundreds to thousands.

Alternative Therapies: So there's a difference between the cells in a dog and cells in a human? Or is the big difference between plant and animal?

Hameroff: There's a much bigger difference between plant and animal than between lower mammals and humans. There's also a difference between different types of human cells.

The model of consciousness based on microtubules which Roger Penrose and I have developed has been criticized because "we have microtubules in our earlobes and microtubules in our butts. Why aren't earlobes and butts conscious?" The answer is that the microtubules in the brain's neurons, besides being denser and more plentiful, are arrayed in parallel, whereas in other cells they radiate outward from the centrosome, or centrioles, next to the cell nucleus. Centrioles, which organize mitosis, are mysterious and elegant organelles made up of microtubules. Because neurons don't divide, the centrioles have disappeared, or are hiding, and the microtubules are all arrayed in parallel. The highly parallel arrangement can facilitate computation and quantum coherence. In our model, consciousness requires a critical degree of quantum coherence in parallel arrayed microtubules in neurons. This critical degree allows a prediction as to what evolutionary level of neural complexity will result in consciousness.

For example if you believe that animals are conscious, you have to ask "If your dog is conscious, how about a worm? How about a paramecium?. How low do you go?" A position taken by the biologist Lynn Margulis is that all cells are conscious, and that even protozoa and bacteria have a simple consciousness.

Single-cell organisms like paramecium are very interesting. They swim around gracefully to seek food, avoid predators, find mates and have a kind of rudimentary sex. Yet these single cell paramecia have no synapses or neurons. They do what they do by virtue of their microtubules. The little cilia that stick out and act like sensory organs and paddles or oars, are structures made up of microtubules and are organized by internal microtubules. So, in the case of the paramecium, the cytoskeleton and microtubules are the cell's nervous system.

However the work I've done with Roger Penrose predicts a threshold for emergence of conscious experience at a level of microtubule complexity and quantum coherence in roughly hundreds of neurons. This level is found, for example, in small worms, tiny sea urchins, and other very simple creatures. Bacteria and protozoa like paramecia are below that line, so, in this view, they would not be conscious. They would be more like proto-conscious—something like a primitive sub-conscious or dream state.

Alternative Therapies: Would you define consciousness?

Hameroff: I think of consciousness as our "inner life"—a series of multimodal integrated experiences. But then you have to define the nature of experience and that is tricky. Philosopher David Chalmers calls this the "hard problem". Why do we have this conscious experience? We needn't necessarily have it. If the world were only slightly different, we could be robot-like zombies with behavior outwardly indistinguishable from conscious beings. Chalmers points out that even if we knew the activities of each and every neuron, synapse, ion channel, receptor, molecule, etc in our brain at a given instant correlated with a given mental state, it still wouldn't

tell us anything about experience, or about why we have an inner life. The weird thing about consciousness is that it's unobservable. I think the essential ingredient of consciousness is this experience that we have. So when I talk about consciousness, I'm talking about "the hard problem" of experience.

Chalmers' view and that of other philosophers like John Searle have ruffled the feathers of many neuroscientists and other reductionists who believe that once we figure out what every neuron is doing, we will have explained consciousness. They think that consciousness emerges from the brain's neuronal firing complexity and that's all there is to it.

Alternative Therapies: Are you saying that single cells, these paramecia, do not have a sense of self? That they do not have experience? And that at a certain level, when you get enough neural cells containing enough microtubules, a sense of self emerges?

Hameroff: That's right, but the number which is "enough" depends on the time. For example if all the microtubules in about 100 neurons were in a quantum state for 500 milliseconds—a half second —a conscious event would then occur. For a more intense experience involving 1000 neurons, it would be 50 milliseconds. We claim each event is conscious because it selects a pattern in fundamental reality, and we conclude that experience is "funda-mental"—embedded at the nitty-gritty level of the universe. A series of conscious events gives a stream of consciousness.

But let me back up since you brought up the important concept of "self". Another facet of consciousness is that we have a unitary sense of self. Despite the fact that in any given instant we may have a hundred billion neurons firing all over the brain, we somehow have a sense of oneness. You are one person, I am one person. The sense of self also occurs in visual physiology. If you look at this microphone sitting here, it has numerous features—the fact that it's vertical is processed in one part of your brain, the fact that it's black is processed in another part, and the fact that it has a little red line on it is processed in yet another. But somehow, it all comes together as one entity. This unity, or binding is a feature of consciousness, which, along with the others, can be explained by quantum theory.

Alternative Therapies: You can explain these?

Hameroff: I believe that proper application of quantum theory to neurobiology can explain them, or at least a new version of quantum theory, as Roger Penrose has been suggesting.

I see five difficult features of consciousness. The first two we have already discussed: the hard problem of experience, and the unitary sense of self. Two others are free will and the transition from preconscious processing to consciousness itself. This transition problem is interesting because it turns out that neurons active in a preconscious mode subsequently become conscious. It's not like the information goes from one part of the brain to another and becomes conscious by virtue of just being there. Consciousness happens all over the place, and in the same neurons that were preconscious. So some event happens. Some process, or transition is occurring.

The fifth feature would be what Roger Penrose calls "noncomputability" which is what woke me up to why the reductionist approach to consciousness is faulty.

As I said, I couldn't accept the reductionist approach that consciousness involved a hundred billion neuronal switches analogous to a computer, and I was interested in the idea that microtubules were processing information inside neurons. But people would say, "You've taken it one level down. You're being even more reductionist than the reductionists. Maybe even *reductio ad absurdum*." I realized that even if microtubule information processing was essential for normal neural cognitive function, it didn't really explain consciousness any more than information processing at the neural level.

Then I read Roger's book *The Emperor's New Mind*, which argued from a mathematical standpoint that there are things about human thought and consciousness that are noncomputable. That is, our thought processes are non-algorithmic, they cannot be simulated on a computer. His book angered the artificial intelligence people because he was saying that you can work until you're blue in the face on a computer, but it will never be conscious. There was something else. And according to Roger, that involved quantum theory.

Alternative Therapies: Would you explain what you mean by quantum theory?

Hameroff: It has to do with reality. What is reality? We have this view of reality as concreteness-the desk is here, the pencil is there, and so forth. But if you look at what our universe is made of, if you look at atoms or subatomic particles various experiments tell us that they exist • Eat least some of the time—not as particles, but as waves. So all the components of your body and everything in this room, if taken by themselves under the right conditions, aren't in any one definite place at any one time. They are actually spread out over space, and are best described by a probability distribution. What this means is that mass is not the concrete stuff that we are used to, and can switch back and forth to a wave-like state.

Yet in our world, things are definite. Things are concrete and real and specific. Everyone agrees that small things can be wave-like, and described by a quantum wave function, but large things are concrete. So where's the transition? What causes things to become particle-like and definite? This transition is called reduction, or collapse of the wave function. There has as yet been no completely satisfactory answer to this problem.

Another important aspect of quantum theory is that once two particles have interacted, even if they appear to go their separate ways, they remain connected. There is this nonlocal connectedness. Distance doesn't matter and time doesn't matter. This is called "quantum nonlocality" or "quantum coherence." This feature has been proposed to explain the binding problem in vision and in "self".

The collapse problem has been around for a while. Famous quantum theorists Bohr and Wigner and Heisenberg concluded that things are in a wave-like state until they are observed by a conscious human being, that consciousness causes collapse of the wave function. As weird as this seems, experiments seemed to show wave-like behavior up to the point that the results are observed by a conscious observer. A machine could measure a quantum system and record the

results, and the system would still remain wave-like until somebody actually looked at the results. To illustrate the absurdity of this, Schrödinger came up with his thought experiment about the cat—Schrödinger's cat.

You put a cat in a box. Then you have poison that can be triggered by a quantum event-perhaps a half-silvered mirror that you send an electron through. The electron has a fifty-fifty chance of actually going through the mirror. If it goes through, it triggers the poison. So there's a 50% chance that the cat is dead, and a 50% chance that the cat is alive. But according to quantum theory, until the observation is made, the electron both did and didn't go through the mirror, and the cat is therefore both dead and alive. Schrödinger said that according to quantum theory, until a conscious observer opens the box and looks, the cat is both dead and alive.

Alternative Therapies: I got tripped up when I read that. What about the cat? The cat knows whether he's dead or alive. Maybe I don't know, but the cat knows.

Hameroff: That's a good point, but I think Schrödinger would have said it doesn't matter what the cat knows—that if the cat were truly both alive and dead, he or she would be both conscious and non-conscious. Schrödinger's point was that the conscious observer interpretation was absurd. The problem is that other explanations are even weirder. For example in the Everett many-worlds view, each time a quantum collapse occurs in our world, an alternative collapse outcome occurs in a newly formed parallel universe. In this view, all possible universes exist! Other interpretations like that of David Bohm's deny that collapse occurs, that the universe is actually wave-like and we just think it's concrete and definite.

This paradoxical confusion may be resolved by Roger Penrose's "objective reduction." Roger takes quantum superposition seriously, as an actual separation of mass from itself. To understand that, he claims, we must consider the underlying spacetime geometry which comprises the universe—the most basic level of reality. This forces one to think about what the universe is actually made of.

In physics, time can go backwards or forwards and physicists normally think of "spacetime" as a four-dimensional continuum. But what is spacetime at its most basic level? What is reality way below the level of atoms, way below the level of quarks. What is the empty space of the universe? Where are we?

Various experiments have shown that as one gets down to a size scale of 10^{-33} centimeters, spacetime geometry is no longer smooth, but "granular", or quantized. Branches of quantum theory have predicted that at this level—which is called the Planck scale—quantum particle/waves known as virtual photons continuously pop into and out of existence. This is often envisioned as churning quantum fluctuations—the "quantum foam"—which impart dynamic structure and measurable energy. This baseline energy of the universe is called zero point energy and was recently measured and verified. The universe is, in some sense, alive. The question now is whether this zero point energy is random, or has some organized form or patterns. Is there information at that level? If so, is consciousness somehow connected to it? Are we "plugged in" to the universe? We'll get back to these questions.

So we have this picture of empty space at its most basic level being highly dynamic and perhaps organized. As we go up in scale, what about mass, or objects? According to Einstein's general relativity, mass, or gravity, *is* curvature in spacetime—the larger an object, the greater the curvature of spacetime. We usually think of this in terms of large objects like the sun or the earth. This is how Einstein's theory was proven—the mass of the sun bends light coming from stars behind it toward us. At that level, the curvature is easily measurable. Roger's point was that it also holds true for small objects. Very small objects would have very small curvatures.

So let's return to the question of quantum superposition. Roger's view is that a system in superposition where mass is separated from itself involves simultaneous curvatures of underlying spacetime in opposite directions—a separation, or bubble in spacetime.

If we have a quantum system that's small, we can imagine how an atom, for example, can be separated from itself, and how there can be a small separation, or tiny bubble in spacetime. But as a quantum superposed system gets bigger and bigger, it's going to meet some threshold in nature, some objective factor, that will cause it to collapse. Roger considered that the separation in underlying spacetime was the limiting factor. When a separation, or bubble in spacetime became too great, it collapsed to one state, or another. We can imagine that if this didn't occur, if the separation continued, a separate universe would shear off as the Everett many-worlds view suggests.

So, somehow, built into the universe is a kind of glue—quantum gravity—that prevents the universe from shredding all the time. Separations continue only to a certain degree—an objective criterion • Ethen must reduce, or collapse to avoid forming another world. These objective reductions are actually a self-organizing process at the fundamental level of the universe.

So why is this important for consciousness?

Remember Chalmers "hard problem" of the nature of experience. What is our inner life, our experience, or "qualia"? Chalmers concluded that experience is fundamental—an irreducible feature of reality, like for example charge, mass or quantum spin. This is in line with a long history of panpsychist/panexperiential philosophy. People like Leibniz in the 18th century, and Russell, Whitehead and Wheeler in this century saw the universe as being composed of fundamental units or events, each having a primitive psychological being. Whitehead's panexperiential view seems most consistent with modern physics. He said that consciousness is a process of events occurring in a wider, basic field of raw proto-conscious experience. Whitehead's events, which he called "occasions of experience" are quite comparable to quantum state reductions, as was pointed out by the philosopher Abner Shimony. This suggests that consciousness may involve a self-organizing process of objective reductions occurring at the Planck scale.

The idea is that experience is encoded or exists at this fundamental level. If you then have superposition and self-collapse, a particular type of experience is selected. So the experience is a property at that level, and when you have this self-organizing process you access and select particular patterns or particular geometries of experience. So that the smell of a rose or sound of an oboe is actually a particular geometry at the "funda-mental" level of spacetime.

From the standpoint of physics, Penrose clarified two types of collapse: one, if a quantum system interacts with it's environment—if it is observed—it will collapse; and two, if a quantum system self-collapses by "objective reduction" due to the spacetime separation threshold.

When quantum systems collapse, to which state of various possible states do they collapse? Think of a quantum system which collapses from, say, a superposed state of both A and B to a classical state of either A or B. If the collapse occurs by environmental interaction, the choice of A or B is computable, or probabilistic. It's going to be fifty-fifty. But if the collapse occurs by self-collapse, by objective reduction criterion, there's a non-computable element. That is, there is some other factor influencing which state it's going to fall into. Roger wrote a great deal in his books about why non-computability is an essential feature of consciousness. So what is this non-computable element? Roger suggests it could be something we don't yet know about, something perhaps engrained at the Planck scale from the Big Bang. Something intrinsic to the universe.

It turns out that systems in quantum superposition can perform massively parallel and efficient computing and collapse to the solution. This is the basis for so-called quantum computing which is currently a very hot topic. No one has yet built one, but in principle they are possible, and their theoretical capabilities far surpass classical computers. However as envisioned, technological quantum computers will collapse by environmental interaction, and will therefore be computable and in our view non-conscious.

For collapse to be non-computable, and thus in our view to be a conscious event, a quantum superposed system must be isolated from it's environment long enough to reach the quantum gravity threshold. How long is that?

Roger linked the amount of superposed mass to the time until self-collapse through a very fundamental formula in physics: the indeterminacy principle. If the size of the superposition—the mass separated from itself—is termed E, for its gravitational self energy, then E is equal to a constant over the time T till self-collapse occurs. It basically says that the size is inversely related to the time. Therefore, a small system like an atom or electron, if isolated, would stay in superposition for a very long time, almost indefinitely. On the other hand a large system, if isolated and in quantum superposition, would only stay in superposition for a very short time.

We did some calculations on this. If you think about Schrödinger's cat being about 1 kilogram, if it were isolated in its box it would self-collapse in only about 10^{-37}. So that solves that problem. The cat is so large that it wouldn't last in superposition long enough to be noticable. From our standpoint, it would either be dead or alive. But an atom, if isolated, would stay in superposition for 10^{7} years.

If an objective reduction process were occurring in the brain, it should occur at time scales relevant to known neurophysiological processes—namely T should be in the range from tens of milliseconds to hundreds of milliseconds. This turns out to require superposed mass energy E in the range of nanograms of a biomaterial such as microtubules.

Roger had concluded that this objective reduction must be happening in our brains, that making a decision, taking a course of action, recognizing or identifying something, forming an opinion, or

whatever all involved superposed possibilities collapsing into one. In his first book, Roger didn't have a good structure for biological

Alternative Therapies: How did you end up working with Roger Penrose?

Hameroff: When I read his book *The Emperor's New Mind* it seemed to me that he had an essential mechanism but lacked the proper biological structure. He talked about the possibility of superposition of nerves either firing or not firing, but he seemed rather open about it. I wrote him a letter and included some of my papers about microtubules and mentioned that I was going to be in England. He wrote back and said he'd like to meet with me. So I went to Oxford and sat in his office, which was disheveled in a very organized way, and we talked for several hours. At that time, I didn't know if we would collaborate or not but was happy to find out a few weeks later that Roger had described my ideas in a lecture he had given at Cambridge.

We met again at a conference in northern Sweden in 1993, and began to try to match the physics to the biology. Then after our first Tucson consciousness conference in • E4, I took Roger and his wife Vanessa, David Chalmers and several other people to hike the Grand Canyon. It was a great experience. We had tremendous intellectual exchanges in a fantastic environment. Roger's ideas began to fall together for me.

Two months later I took a mini-sabbatical with my son in Copenhagen. Roger was there and we began to formulate our objective reduction model. We concluded that the microtubule-associated proteins tuned the quantum coherence, and so we called the model "orchestrated objective reduction", or "Orch OR".

Self collapse in the time range of neurophysiological events like tens to hundreds of milliseconds, which is where most cognitive events occur, turns out to require superposed mass in the nanogram range. We figured out how many microtubules it would take to self collapse after a few hundred milliseconds, and that turned out to be about a billion tubulins • Etubulin" being the subunits of microtubules. Making some rough guesses, we could say that it would take somewhere between a hundred and ten-thousand neurons for a single conscious event.

We were concluding that consciousness was a series of discrete events, that you have one discrete event, and another discrete event, and another, another, another. You have a series of them that gives rise to a stream of consciousness. The number, 10,000 neurons, was interesting because many other approaches to cognition show that an assembly of neurons in the range of 10,000 is important.

We started working on our first paper. Roger wrote the part about quantum theory and I wrote the part about microtubules, and we slowly worked out the details of the model. This was in the summer of '94, and the paper wouldn't be published till • E6. But in early '95, reductionist philosopher Pat Churchland and her graduate student Rick Grush published a paper in the *Journal of Consciousness Studies* attacking our model, even before it had been published! It was an ambush. But in retrospect, it was a big favor, The *Journal of Consciousness Studies* said, "You can respond in the next issue, but you have only two weeks." It was a good motivation, because in two weeks we had a paper, going back and forth by fax.

Their main criticisms of the microtubule involvement in consciousness was that colchicine, a drug taken to treat gout, depolymerizes microtubules. So Grush and Churchland said, "These people take colchicine for gout. It dissolves the microtubules, and yet they don't go unconscious." The reason that this objection is irrelevant is twofold: first, colchicine crosses the blood-brain barrier in very, very low concentrations. Second, it only works on microtubules that are in the assembly-disassembly process, that are dynamic, whereas the microtubules in the brain are stable. They don't disassemble. The way colchicine works is that if something disassembles, it prevents reassembling. Microtubules that aren't in this process are unaffected. There were some other issues about anesthesia that they had misinterpreted, and stuff about Roger's non-computability, quantum effects and so on. But basically we answered their objections point by point, and were able to explain our ideas.

Then in 96, our full model paper came out and we also published a follow-up paper addressing the hard problem of experience, getting down to the spacetime business.

Alternative Therapies: Let's say your model is true. How can we use that model? How will it affect the world we live in?

Hameroff: Whether it's this model, or some other, understanding consciousness would have tremendous implications in medicine, computer science, entertainment technology, communications, philosophy, spirituality, and culture.

In his books, Roger talked about Platonism—the idea that mathematical truth, aesthetics, ethics, the perception of beauty are somehow built into the universe. The implication was that however these were built into the universe, this is what influenced the collapse in the objective reduction. So when our thoughts collapse, we're influenced-or we can be influenced-by these Platonistic factors engrained at the Planck scale.

Our sense of right and wrong, of beauty and of mathematical truth being built into the universe has tremendous implications for philosophy and spirituality. We just have to tune into it, or allow it to guide us.

Alternative Therapies: Would this be synonymous to the collective unconscious, the archetypes, the primal patterns in our psyche?

Hameroff: Quite possibly—engrained at the most fundamental level of the universe.

Alternative Therapies: In one of your papers, you showed a diagram of the microtubules affecting each other.

Hameroff: That diagram shows that signaling can occur along microtubules. It shows that there are two excitable membranes. If you have tubulins in solution and you depolarize one membrane, nothing happens to the other one. But if you make bridges of chains of tubulins between the two and then depolarize one membrane, the other one also fires. It just shows that there is signaling capability across the tubulin bridges.

Alternative Therapies: So are your microtubules communicating with my microtubules, so to speak? Are we all affecting each other?

Hameroff: If you are implying some kind of psi, or ESP phenomena, or interconnectedness, not by that mechanism. That's a very direct mechanical mechanism. What you are suggesting would require a quantum mechanism.

We had a session on parapsychology at the Tucson II consciousness conference. Dick Bierman, a physicist at the University of Amsterdam gave the last talk. He has done many retro-psychokinesis experiments where you actually seem to influence things that have already happened, as long as they hadn't been viewed. He concluded that psi, or parapsychological effects, occur and can only be explained by quantum nonlocality. It's tricky because-supposedly-information can't be transferred. But there can be correlations. If psi effects exist, then the other things you were talking about, like the collective unconscious, can exist too.

But we're talking about two things: one is some type of correlation among people, and the other is some kind of interaction between individual people and what's fundamental in the universe.

Alternative Therapies: You made a comment earlier that the paramecium was alive but not conscious. What's the difference in your mind?

Hameroff: I'm presuming it doesn't have experience. The paramecium has a preconscious, what we would call "dreaming" mode, but seems very unlikely to sustain quantum coherence long enough to reach self-collapse. They would have to maintain isolation for about 50 seconds for a single conscious event.

We have used 500 milliseconds of isolated quantum coherence as a criterion for when consciousness can occur, and that turns out to be the level of hundreds of neurons, which is the level of complexity of the nervous systems of small worms. Interestingly enough, this relates to evolution.

It turns out that evolution is nonlinear. Life started about 4 billion years ago-simple life, algae, and so forth. Then came the nucleated cell, then eukaryotic cells, but still, life evolved very minimally, reaching only very simple multicellular organisms until about 540 million years ago. Then, abruptly, there was this huge acceleration in evolution, which is called the "Cambrian Explosion."

Within 10 million years, all the phyla that exist today formed, and life took off. Why? Well, there are a lot of possible reasons. But it turns out that the size of the organisms at the beginning of the Cambrian explosion very closely matched what we would predict for conscious experience. They were small worms and tiny sea urchins. Fossils of these urchins, for example, look very much like present day tiny urchins whose spines are giant complexes of microtubules. So the hypothesis is that these were the first conscious entities, that one day there was sufficient quantum coherence in the nervous system of one of these the worms or the spines of an urchin to self collapse and experience happened-some little urchin or worm suddenly had an experience.

Having experience and being able to choose non-computably was beneficial for survival and evolution accelerated.

Alternative Therapies: Considering everything you've learned about reality, what are your personal opinions about life, about spirituality?

Hameroff: The more I learn about reality, the more unreal it becomes. I believe in the universe. I think we are connected to it at a fundamental level.

Alternative Therapies: Is there anything else you'd like to say?

Hameroff: Because your readers are medically oriented, there are a couple of obvious biological criticisms of our model that I should probably discuss. First, how can a quantum state exist in an apparently noisy, thermal, chaotic system like the brain? The only known techn ological examples of quantum states are things such as superconductors, superfluids, Bose-Einstein condensates and lasers. Except for the laser, these require cooling to near absolute zero to stop thermal oscillations so they atoms can all be aligned coherently. But the brain is very warm, so you have thermal oscillation. With a laser, you pump the energy to get a macroscopic quantum state. We think there is a biochemical pumping mechanism driving quantum coherence in the brain's microtubules.

The next problem is how do you isolate the quantum state from environmental interaction? One of the first things you learn in cell biology is that cytoplasm exists in two phases—in a solution state and in a gel state, and goes back and forth between the two. It turns out the transitions can occur very rapidly, for example in the range of 40 transitions per second.

So we've proposed that the microtubule quantum coherence is isolated and protected by gelation. The quantum coherence occurs in the gel phase, and then the collapse occurs and you have a liquid phase in which the microtubule information communicates. If it were a totally isolated system, you could have consciousness, but you could never communicate. But if you have 40 cycles per second of -quantum coherence, collapse; quantum coherence, collapse; quantum coherence, collapse-you have cycles of isolation, communication; isolation, communication; isolation, communication. This suggests consciousness is a series of discrete events, rather than a continuum.

There's evidence for this in Buddhism, in which meditators in a deep meditative state report a flickering of their consciousness. They've even counted these flickerings and quantified them, and they report them occurring something like every 20 milliseconds, which is basically consistent with the brain's coherent 40-Hz oscillations. The coherent 40 Hz has been suggested to solve the binding problem we talked about earlier-the unity of a sense of self, binding it all together. I don't think a temporal correlation *per se* can explain it, but the 40-Hz coherence might be the clocking mechanism for this sol-gel transformation. The point is, you have these discrete conscious events roughly 40 times a second.

The other issue is how you can have macroscopic quantum state across synapses, across membranes, to involve, say, thousands of neurons. This may be explainable by gap junction

electrotonic synapses, which are very primitive physical channels between neurons and other cells.

Another issue is our subjective sense of time. According to physics, time doesn't flow—time can go backwards or forwards, and yet we seem to have a subjective sense of forward-flowing time. The self-collapse of the wave function is irreversible, so if you have a series of irreversible steps, you would have the sense of time moving forward.

This relates to the sense of time dilation, in that the frequency of conscious events may vary. Michael Jordan, the basketball player seems to react faster and better than anybody else. He was asked once, "How do you do that?" and responded: "When I'm playing well, time slows down. The other players are in slow motion" Just like when people are in a car accident, sometimes time slows down.

Alternative Therapies: That's very true. I was bucked off a horse once and time slowed down. For whatever reason, I fell very gently and slowly to the ground and didn't get hurt.

Hameroff: Yes. Something enabled you to have more conscious events during that moment. Maybe it was a second, but it seemed to you like 10 seconds. You had ten times as many conscious events as you normally would, which allowed you to react more quickly. And Jordan does it all the time. So if you have more conscious events per second, time subjectively seems to slow down.

Patients who undergo general anesthesia, when they wake up, have no clue as to how long they were asleep. Under anesthesia they don't have conscious events, so time doesn't flow. It just doesn't exist for them while they are asleep.

There's a paper in the Tucson I book about psychedelic drugs which basically do the opposite from anesthetics. Within receptor proteins psychedelics enhance electron mobility, therefore enhancing the macroscopic quantum state. So it's possible to have expanded consciousness due both to increased intensity and more conscious events per time. Plus there’s a merger of the conscious with the sub-conscious.

Alternative Therapies: I have one further question, which is: Where is it all going? If life hit a new acceleration point, a point of critical mass at which evolution speeded up, where is it going? Are we headed to more conscious experiences per second? Is that what's in our future?

Hameroff: I think something interesting is going to happen, but I don't know what. It could be that, for some, consciousness will expand. But this will be countered by increased crowding and technological interference having opposite effects. So unfortunately it could be like wealth—the rich get richer and the poor get poorer. Some will become more conscious, others less.

The last thing I want to say is about health. I think just about every aspect of health and disease is related at some level to consciousness, and in every system, the microtubules are essential. Think of the macrophages and lymphocytes of the immune system—recognition, amplification, mobility and engulfment of foreign invaders all occur by the cytoskeleton.

There are many papers about the role of the cytoskeleton in genome regulation in cancer. There is ample evidence for the fact that the cytoskeleton regulates the genes, decides which genes to turn on, and so forth, not only in terms of differentiation in development, but also in health and in steady state. I think consciousness, cytoskeleton and quantum coherence play essential roles in health and disease.

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See also:

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