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Process, Quantum Coherence, and the Stream of Consciousness

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Process philosophy has emerged as an approach to consciousness within contemporary science although re-consideration of Whitehead and James clearly contrasts with twentieth century materialism. In spite of controversy a number of researchers have described the concept of quantum coherence within living organisms that provides the basis of new process oriented theories. Among these researchers are Penrose and Hameroff who suggest that quantum gravity yields coherent processes fundamental to the idea of consciousness. Pribram emphasizes holographic processes in the brain that give rise to quantum brain dynamics. Bohm also recognizes a central role of holographic processes in physics. The work of these researchers and the convergence with earlier work in metaphysics are described.

Many philosophers and scientists have recently shown interest in the scientific analysis of consciousness. Certainly the most prevalent contemporary approach is a scientific realism that equates consciousness with brain activity. Various imaging technologies now provide a means to observe the functioning brain and those observations can be compared with subject responses. Crick and Koch (1998) provide a review of consciousness based upon the common assumption that consciousness is an emergent phenomenon of the nervous system that can best be described by exploring its neuronal correlates. They do, however, grapple briefly with the difficulty of providing an adequate definition.

Although materialism is strongly favored by modern science, the view that consciousness is a fundamental, irreducible part of nature was prominent a century or so ago. Ideas advanced by James and Whitehead have surprisingly resurfaced in contemporary work. To study consciousness within the frame-

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work of science a researcher must make some assumptions regarding its nature. It is beyond the present scope to consider the long history of metaphysical debate regarding what those assumptions should be, but the convergence of ideas among some contemporary researchers regarding process philosophy suggests that a re-examination of the assumptions underlying modern materialism is warranted.

Dennett is a prominent advocate of the material stance who considers every brain a sophisticated computing device. Consciousness then emerges as naturally as a higher level computer language is built from a lower level language and ultimately from nothing but the on/off switches of the hardware (Dennett, 2005, pp. 6–7). Dennett strongly implies that since computers are already doing the sorts of computations only organisms were capable of a century ago, a conscious computer is to be expected as technology develops. Searle (1984, pp. 18–19) dislikes Dennett's analogy of the brain as a computer, but he too argues that consciousness is a material, biological phenomena produced by brain processes. Most contemporary philosophers and scientists similarly embrace some form of materialism although the fundamental challenge of explaining how consciousness emerges remains somewhat a mystery. There is a strong and widespread faith that scientific advancement will eventually reveal a set of purely material phenomena that somehow combine to yield consciousness but there is nothing in either physics or biology that logically requires such an assumption.

Perhaps the most compelling support for materialism is that the alternatives seem completely inconsistent with modern science. If materialism is rejected then either Cartesian dualism or some form of panpsychism are logically implied and both seem incongruent with the data of science. One of the most intriguing developments in recent years has been the view that consciousness, or something essentially mental rather than material, is absolutely fundamental in nature. If mentality is a fundamental, irreducible aspect of the world then the foundation of consciousness reduces to panpsychism or at least a proto-panpsychism such as the monads of Leibniz. This is hardly a new view, but it is new to the scientific literature and has profound implications.

If the materialists are correct then a conscious machine may eventually become plausible. Research reviewed in this paper, however, suggests that consciousness can only exist in living organisms wherein life processes are essential to organize a rudimentary mentality in the world into the consciousness experienced each time one awakens. This perspective implies that machines may well remain very limited compared to a conscious organism, exactly the view recently advanced by Penrose (1994).

Penrose in fact proposed a theory of consciousness suggesting that consciousness is indeed a fundamental aspect of nature, not simply a product of brain processes. Penrose views consciousness as an inherent aspect of physical reality that is excluded from the standard theories of physics. Surprisingly, the assumptions Penrose makes are not very different from those of orthodox theories. The proposed processes combine in novel ways to directly address the problem of consciousness. Penrose is one of several prominent researchers considered in detail below. A review of Penrose's first book on consciousness by Dennett (1989), however, summarized several common objections to his approach.

Dennett believes that there are straightforward implications of scientific orthodoxy including a mechanistic materialism that has largely settled our vision of how the physical world operates. The counterintuitive aspects of quantum physics are more like loose ends than a threat to the materialist doctrine and are relevant only at the level of atomic particles. Researchers in the life sciences need concern themselves with only classical physics since biological processes operate above the atomic levels, according to mechanical processes. Consciousness is the product of evolution that exists because it increases the probability that an organism will survive. Dennett objects that Penrose upsets this orthodoxy.

This final objection is certainly justified but Dennett's other points are by no means indisputable. For example, even the assumption that consciousness is a product of evolution was rejected by mathematician William Clifford on the basis that the environment selects among existing features, yielding gradual and continuous change. But from what processes did consciousness emerge? Clifford (1901) argued:

> . . . we cannot suppose that so enormous a jump from one creature to another should have occurred at any point in the process of evolution as the introduction of a fact entirely different and absolutely separate from the physical fact. It is impossible for anybody to point out the particular place in the line of descent where that event can be supposed to have taken place. The only thing that we can come to, if we accept the doctrine of evolution at all, is that even in the very lowest organism, even in the Amoeba which swims about in our own blood, there is something or other, inconceivably simple to us, which is of the same nature with our own consciousness, although not of the same complexity. (pp. 38–39)

He is best known for the development of Clifford algebra that predates Einstein but nevertheless was able to describe the properties of relativistic space-time. His mathematics have been particularly relevant to contemporary physicists interested in alternative formulations of quantum theory (Penrose, 2005, p. 202). Furthermore, versions of quantum theory advanced by Penrose and others, have been instrumental to contemporary consideration of panpsychism. Clearly Clifford favored panpsychism over materialism so that some form of mentality is ubiquitous in nature. In fact, the above quotation continued to state "We are obliged to assume, in order to save continuity in our belief, that along with every motion of matter, whether organic or inorganic, there is some fact which corresponds to the mental fact in ourselves" (p. 39).

Over the past decades several researchers have proposed theories of consciousness based upon quantum processes. Although many philosophers thoroughly reject any such approach, Kuttner and Rosenblum (2006) argued that even the data of the archetypal two-slit experiment indicate that Bohr's orthodox interpretation of quantum theory implies the existence of consciousness as an entity beyond its neural correlates.[1] Other researchers also argued that consciousness cannot be reduced to other variables.

David Bohm was among the best known physicists to propose an alternative version of quantum theory that incorporated consciousness within the framework of his theory. In contrast to the view that the major discoveries of physics are virtually complete, as Dennett implied, Bohm argued that particles cannot be the ultimate substance, rather they are only abstractions "from an unknown and undefinable totality of flowing movement. This means that no matter how far our knowledge of the laws of physics may go, the content of these laws will still deal with such abstractions, having only a relative independence of existence" (1980, p. 49). Bohm's work is of particular interest here both because of the theory itself and also the substantial influence he had upon the physics community and among other researchers interested in consciousness. Bohm was convinced that something fundamental was missing in the standard model and drew upon metaphysics to advance the orthodox approach taken by most physicists.

Bohm in particular highlighted the fundamental discrepancy between scientific orthodoxy and quantum approaches to consciousness by embracing metaphysical ideas consistent with the neutral monism of James's and Whitehead's process philosophy (Eastman and Keeton, 2004). Bohm was particularly influenced by Whitehead. It is ironic that the data of physics that were so fundamental to the development of Whitehead's ontogeny were also taken by most modern scholars as irrefutable proof of materialism and the orthodox view. Now leading physicists have argued that recent data suggest a reconsideration of process philosophy. Although the standard theories are unlikely to be overturned anytime soon there are a growing number of researchers who argue that Jamesian and Whiteheadian approaches are most compatible with recent discoveries.

The contrast with scientific materialism could not be greater. According to Whitehead "The chief error in philosophy is overstatement" resulting in the

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[1]In the typical two-slit experiment particles are fired one at a time toward two gates with an equal probability of emerging from either. If the experimenter decides to record the location of each particle sequentially, the particles spread out randomly as if each one passed through one gate or the other. Alternatively, observation of the recorded locations only after many particles are fired yields an interference pattern as if each particle passed simultaneously through both gates, consistent with quantum superposition. The key point is that the experimenter's conscious choice of how to carry out the observations determines the nature of the physical event.

"fallacy of misplaced concreteness" (1929/1979, p. 7). The scientific orthodoxy described above serves as a prime example. If materialism were correct then particles would be the ultimate actual entities of the world. Yet quantum physics revealed mysterious characteristics entirely unanticipated from the conception of particles as point events in space.

Quantum theory introduced not only a spreading wavefunction that yields a probabilistic description of particle characteristics but also non-local quantum entanglement between separated particles. It is also the case that every particle shows wavelike attributes under some conditions, such as the two-slit experiment. Advances in quantum theory over the twentieth century resulted in matter becoming less like indivisible particles and more wavelike. Whitehead in fact argued that "The atom is only explicable as a society with activities involving rhythms with their definite periods" (1929/1979, p. 78). In Whitehead's metaphysics every particle of matter is a construction from a deeper ground that ultimately reduces to actual occasions of experience, in stark contrast to the mindless particles of materialism. The actual occasions provide an "atomistic" quanta of experience that are the ultimate particulars of reality instead of the particles of matter. Whitehead called the actual occasions the "final real things of which the world is made up. There is no going behind the actual entities to find anything more real" (1929/1979, p. 18).

Similar metaphysical ideas advanced by James have also drawn the interest of Bohm and other physicists. Both Whitehead and James believed that consciousness is a fundamental constituent of the world. James similarly envisioned a monism of pure experience as the basis of the perception of the present. His concept of the stream of consciousness arose from an emphasis on the changing continuous flow of thought.

> Consciousness, then, does not appear to itself chopped up in bits. Such words as "chain" or "train" do not describe it fitly as it presents itself in the first instance. It is nothing jointed; it flows. A "river" or a "stream" are the metaphors by which it is most naturally described. (James, 1890/1950, p. 238)

The continuous flow from awakening until sleep again ensues is further characterized by smooth, holistic transition from one object to the next. In fact, James stressed that the thought-of-an-object and the object-thought-of form an inseparable whole (1904/1987, p. 1151). James further described "drops of perception" (1911/1987, p. 1061) that are taken as fundamental instead of the relation between the subjective and objective, much as Whitehead derived both consciousness and matter from the more basic occasions of experience. Contrary to Whitehead, James has argued against panpsychism. The development of his neutral monism nevertheless incorporated these drops of perception much like a Leibnizian monad, non-material yet the basis of matter as well as consciousness.

James in fact wrote:

> As "subjective" we say that the experience represents, as "objective" it is represented. What represents and what is represented is here numerically the same; but we must remember that no dualism of being represented and representing resides in the experience *per se*. In its pure state, or when isolated there is no self splitting of it into consciousness and what the consciousness is of. The instant field of the present is at all times what I call the "pure" experience. It is only virtually or potentially either object or subject as yet. For the time being, it is plain, unqualified actuality or existence, a simple *that*. (1904/1987, p. 1151)

Like James, Whitehead stressed the primordial role of experience that is the cornerstone of his monistic cosmology since experience serves as the basis of both mind and matter. Consistent with James, Whitehead stated "experience is not a relation of an experient to something external to it, but is itself the 'inclusive whole' which is the required connectedness of 'many in one'" (Whitehead, 1933/1961, p. 233). But Whitehead developed a richer metaphysical analysis than James that incorporated his insights from relativity theory and has proven particularly consonant with contemporary physics as is described below.

Of particular relevance is the view that all experience is dipolar with both a mental pole and a physical pole (Whitehead, 1929/1979, p. 36). A physical particle consists of a set of simple actual occasions that continue re-creating the particle. "So far as we can see, inorganic entities are vehicles for receiving, for storing in a napkin, and for restoring without loss or gain" (1929/1979, p. 177). The mental pole of the physical particle exists but is negligible. Living organisms enable greater complexity in the unfolding process of actual occasions so that higher order phases appear, ultimately giving rise to conscious awareness. The development of greater complexity among the occasions within living organisms is fundamental to the experience of the present moment. Whitehead's metaphysical account of the experienced present describes the stream of consciousness and parallels contemporary physical accounts of consciousness.

In particular, Bohm draws upon Whitehead's (1929/1979, p. 177) philosophical construct of a "moment" and his principle of concresence as the basis of novel physical processes central to consciousness. Although experience underlies the monism that encompasses all that exists, there are several grades of actual occasions (empty space, inorganic objects, simple organisms, conscious organisms) that exist as a moment at each level. Whitehead also considers distinct categories of existence among the actual occasions so that the deeper categories provide "Pure potentials for the specific determination of fact" that can merge together to form concrete facts (1929/1979, p. 22). These potentialities of fundamental experience exist beyond space and time but form all that come into being including the consciousness of a living organism through a process of becoming called concrescence. Whitehead described this process as "the ultimate metaphysical principle" (1929/1979, p. 21) through which many actual occasions form a novel, conjunctive unity. The potentialities begin as diverse entities that form prehensions of subsequent entities. The novel prehensions integrate through concrescence in a succession of phases ultimately terminating in one unity termed the satisfaction. The actual entity is then completed and so perishes yielding data for new prehensions (Whitehead, 1929/1979, p. 26).

The perishing of each occasion is intimately connected to the becoming of the next occasion so there is a similarity in that regard to James's stream of consciousness. Concrescence is a richer process that pertains not only to conscious thought but also to the simplest particles of matter.

> A pure physical prehension is how an occasion in its immediacy of being absorbs another occasion which has passed into the objective immortality of its not-being. It is how the past lives in the present. It is causation. It is memory. It is perception of derivation. It is emotional conformation to a given situation, an emotional continuity of past with present. It is a basic element from which springs the self-creation of each temporal occasion. Thus perishing is the initiation of becoming. How the past perishes is how the future becomes. (Whitehead, 1933/1961, pp. 237–238)

As the concrescual processes unfold the physical and mental polarities of occasions of experience, an internal structure unfolds from within the occasions. As this structure interacts with other occasions of experience the internal structure grows in complexity ultimately comprising a moment in the stream of consciousness of a perceiving organism. Each entity is related to subsequent entities like a parent with offspring. There is an internal structure that contains memory that is inherited by the becoming occasions derived from the occasions that perish. Concresence provides a richer description of the process that underlies the stream of consciousness than did James's drops of perception. A system is proposed that accounts for perception and memory completely beyond material processes, yet converges with recent work in physics.

Surprisingly, concrescence is exactly the kind of process advanced by contemporary physicists interested in consciousness. Although Whiteheadian metaphysics was developed almost a century ago from the foundation provided by relativity and quantum theory, Shimony (1997) suggests that the advancement of physics since Whitehead's day will enable an augmentation of his approach. Recent developments in quantum biophysics are central to the hope for such advancement. The selection of contemporary research reviewed in this paper describes processes within the nervous system proposed over the last forty years using novel physical theories that, like Whitehead's and James's, predict the emergence of rudimentary experience that continuously unfolds into the stream of consciousness.

Whitehead's concrescence is also related to the more general experience of time. Physical theory must somehow account for the perception of physical reality that is divided into the past, present and future. In classical physics time is in a sense unreal, serving only as a background wherein physical processes occur with some movement chosen as an arbitrary marker of time. In both relativity and quantum theory the role of time is viewed similarly. That is, time is not incorporated as an operator that effects the physical system in any of the standard theories (Prigogine and Stengers, 1984, pp. 225, 229).

But Whitehead's unfolding processes are the very basis of time in his metaphysics. It is not correct to say that physical processes are contained within moments of time in process philosophy. Rather, Whitehead views time as a dynamic and internal part of the system that acquires some finite extension as it comes into being through concresence. But further, "It is the more radical idea that it is something different from extension — something out of which extension is *manifested.* Within this relational system, according to its properties, it may become meaningful to assign the process a finite extension" (Hansen, 2004, p. 153).

Ultimately one process is related to another in a series of successions that define an internal time very different from the conception of time in standard physical theory. Whitehead spoke of occasions extending beyond space-time, passing from phase to phase as potentialities that can enter into space-time, but may not. That is, there is a dynamic system beyond space-time that cannot be completely contained within it. "Physical time expresses some features of the growth, but not the growth of the features" (Whitehead, 1929/1979, p. 283). Contemporary researchers are interested in this line of thinking in regard to space and time within physics, but it further bears upon the stream of consciousness.

Physicist John Wheeler (1980) described a pre-space that underlies space-time but is not contained within it. A Plank scale is commonly described in physics with a smallest possible length, much smaller than any instruments can measure (10^{-33} cm) and a shortest unit of time (10^{-44} sec).[2] Beyond this scale matter, gravity, space-time and the light cone of general relativity become undefinable making it impossible even to define a before and after relationship (Bohm, 1986, p. 192). Wheeler described these smallest units of space-time as an underlying foam. He therefore suggested that relativity needs to be extended to include this order enfolded into the pre-space that exists beyond the bounds of space-time.

Furthermore, Bohm argued that quantum-mechanical field theory can be

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[2]For further discussion see Bohm (1990, pp. 279–281). In particular Bohm notes it is only possible to measure down to about 10^{-17} cm., about half way to the proposed Plank scale. There is no logical reason to exclude the possibility of undiscovered order from these smallest wavelengths, which is exactly what Wheeler and others have proposed.

expressed algebraically in a manner that allows invariant transformations into and from pre-space. From this view Wheeler's pre-space, or something conceptually similar, is a more fundamental state of physical reality that serves as the basis of the familiar physical systems described by relativity and quantum theory. Bohm (1986, p. 188) described his theory as holographic comparing the pre-space ground from which particles are manifested to the holographic image stored on film that yields an observable three dimensional image when appropriately illuminated. The information stored on the film, like pre-space, serves as the constituent from which the observable image arises. The similarity with Whitehead's concrescence from potentialities into a nexus of matter is apparent.

Like Whitehead, the view advanced here is that matter and all of the known physical reality is a subset of the broader order enfolded into pre-space. Bohm (1986, p. 192) advocates this view as well: "My attitude is that the mathematics of the quantum theory deals *primarily* with the structure of the implicate pre-space and with how an explicate order of space and time emerges from it, rather than with movements of physical entities, such as particles and fields." The great challenge is to integrate pre-geometry with a comprehensive version of quantum theory.

Bohm further suggested that Whitehead's moment and concresence can be integrated into physics through the operation of entropy at even the smallest scales. "When one puts conditions in the algebra that define these moments within a specified range of uncertainty or ambiguity, one arrives at an expression that is mathematically similar to that which corresponds to the entropy in its current quantum-mechanical representation. The suggestion is that the very possibility of defining a succession of moments in a definite order and with a certain relative separation requires a continual increase of entropy" (Bohm, 1986, p. 194). This is the basis for a conceptualization of time very different from other physical theories since time so conceived is a real part of the physical system that operates upon variables within pre-space from which it unfolds into space-time. These moments at or near the Plank scale soon acquire distinct entropic states that therefore define a certain order within the vacuum but at an infinitesimal scale. The succession of vacuum states carry the unique order forward, possibly merging with similar systems that collectively enter into space-time.

Each atom is mostly empty space but the implication here is that the structure of information from pre-space defines the order of the atom at the most basic level. What is implied is that over and above a relativistic particle there is a flow of quantum information from pre-space that can structure the particle and change the entropy. Instead of information depending upon the state of a physical system, it may be that the laws of physics yield information states that precede and inform matter. The entropy of pre-space constantly develops resulting in a distinct history of entropic states somewhat analogous to the memory of a perceiving organism since neither the particle nor the organism can ever again "perceive" the same moment.[3]

The parallel with Whitehead's philosophy is obvious. In fact, Bohm (1986, p. 196) stressed the similarity between Whitehead's concresence and his own view that moments of pre-space are fundamental not only to matter but to the emergence of successive moments of time as we experience it. Of course various biological and neurological processes are central to the perception of time, but the moments within pre-space are the fundamental ground from which some relatively autonomous part of the larger whole emerges. According to this view the source of the stream of consciousness is deeply buried in physical processes beyond the atomic level. Bohm suggested that the unfolding of information from pre-space, a kind of implicate order as he called it in his own theory, is absolutely fundamental to understanding consciousness which follows naturally in the context of his theory.

In direct opposition to materialism, the view advanced here is that process operates beneath mechanization. This does not contradict the importance of mechanistic events at the level of atoms or biomolecules, but follows Bohm and other researchers discussed below who suggest that a deeper level of analysis is needed that is consistent with process philosophy and is essential to come to terms with consciousness. Submolecular processes within living organisms converge with new physical theory. Various researchers have provided a foundation that supports this view.

In particular, Nobel Laureate Albert Szent–Gyorgi had a special talent for recognizing a micro-level of process that underlies a mechanistic macro-level in biology.[4] Consistent with William Clifford's emphasis on the gradual and continuous nature of the process of evolution, Szent–Gyorgi showed a special interest in identifying the simpler processes from which more complex structures may have been selected by the environment. Szent–Gyorgi (1972, p. 6) stated "Life has developed its processes gradually, never rejecting what it has built, but building over what has already taken place. As a result, the cell

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[3]There is a similarity between process philosophy, and the pre-space considered here, with the concept of *active matter* that emerged in the context of work on chaos theory. Chaos theory includes the study of nonlinear interactive dynamics in which an internal time is also introduced as an operator. What is suggested in the text is essentially the same idea advanced by Prigogine and Stengers (1984, p. 288): "Matter is not given. In the present-day view it has to be constructed out of a more fundamental concept in terms of quantum fields. In this construction of matter, thermodynamic concepts (irreversibility, entropy) have a role to play."

[4]Albert Szent–Gyorgyi was a prominent biochemist who discovered actomyosin and the fundamental role it plays in the contraction of muscles. That work was overshadowed only by his discovery of Vitamin C for which he won the Nobel Prize for physiology in 1937. Later in his career he pioneered the study of submolecular bioelectricity, such as the movement of electrons through crystal lattices, founding an area he called bioenergetics.

resembles the site of an archeological excavation with the successive strata on top of one another, the oldest one the deepest." Szent–Gyorgi applied that view to lay the foundation for an area of study that he called "bioenergetics."

In modern biology, bioenergetics refers to the transfer and conversion of biological energy. Focus is placed upon molecular structures and molecular mechanisms involved in energy transfer within key biological processes such as photosynthesis and respiration. However, Szent–Gyorgi (1957) coined the term bioenergetics to refer to strictly submolecular transfers of energy either across a single molecule or between biomolecules. As long ago as 1941 Szent–Gyorgi proposed that electrons can propagate through crystalline structures within and between molecules, comprising semiconducting currents, entirely separate from the movement of ions. Remarkably, he suggested that water, the most common substance of the body, can serve as a liquid crystal through which semiconducting currents can flow. The propagation of energized electrons through liquid crystals within the organism is fundamental to defining the living state according to Szent–Gyorgi. His work on bioenergetics was ignored for years but gradually became very influential. At present, principles of bioenergetics are being extended to a minute scale unimaginable a few decades ago. Recent studies suggest that energy and information vital to cellular functioning exist within the nanostructures of cells.[5]

The essential role of processes within cellular nanostructures is supported by biological and physical researchers with interests that sometimes appear conceptually unrelated yet converge upon data consistent with the submolecular mechanisms Szent–Gyorgyi proposed. One of the recent developments is the work of Donald Ingber on tensegrity. Ingber states that the standard model implies that cells are only cytoplasma surrounded by an elastic membrane, something like a balloon filled with molasses. Studies of the cellular nanostructure, however, revealed an internal architecture based upon microfilaments under continuous tension. The microfilaments provide a framework for cellular architecture that is basic to the cell structure and mechanical responsiveness to forces in the environment. For instance, growth of a neural microtubule can be induced by simply pulling a nerve cell with a pipette. Determination of cellular form by microfilaments is directly related to cellular functioning. Furthermore, Ingber (1998, p. 56) states that "tensegrity structures function as coupled harmonic oscillators" that can provide a basis for nonlocal resonant interactions among cellular structures or entire cells.

In fact, the study of nonlocal resonance among cells and the propagation of energy through cellular microtubules has substantially extended the study of

[5]A nanometer is one billionth of a meter. All cells contain a cytoskeleton of protein-like molecules at this tiny scale, including cylindrical tubes known as microtubules with a diameter of only 25 nanometers.

bioenergetics within the nanostructures of cells. Not so long ago the very existence of microtubules was unknown. It now appears that they play fundamental roles in the most basic processes of biology. Hameroff (1997) believes that the cytoskeleton organizes processes occurring in mitosis, plays essential roles in cellular differentiation in the developing organism, and is important to the maintenance of cellular processes necessary to the health of the organism. Hameroff further proposes that energy and information are transmitted within the cytoskeleton of neurons. For example, Hameroff, Dayhoff, Lahoz–Beltra, Rasmussen, Insinna, and Koruga (1993) argued that the cytoskeleton provides a solid state network throughout cortical neurons. Furthermore, there is a correlation between production of proteins within microtubules and cognitive functioning. Inhibition of protein production causes cognitive deficits.

Turning to work that bears more directly upon the stream of consciousness, Pribram (1991) proposed that the perceptual image is represented as a neural hologram, created by nonlocal resonance among the spines covering the neural dendrites. Sensory stimuli induce resonance among dendritic microprocesses yielding physical changes in dendritic structures analogous to light striking the film in an optical hologram. The totality of these fluctuating resonances are called the holoscape, providing the basis of both the perceptual and memory image in Pribram's theory. Even without consideration of quantum processes, Pribram's theory provides an important convergence with conscious perception and holographic processes that Bohm appealed to in his own account of quantum consciousness.

It is interesting that the holoscape is susceptiple to influences by the dendritic cytoskeleton, implying that cytoskeletal processes also have a role in perception and memory. The relationship between memory and the cytoskeleton is supported by the discovery of a correlation between the severity of Alzheimer's disease and the amount of damage to cytoskeletal structures of the nervous system (Arriagada, Growdon, Hedley–Whyte, and Hyman, 1992). Pribram (1991, p. 279) noted that the macromolecules of protein in neural dendrites form oscillating dipoles, susceptible to amplification by cytoskeletal activity. Similarly Desmond and Levy (1988) found that long term synaptic potentiation (LTP), which is strongly implicated in episodic memory, results in changes in the shape of dendritic spines mediated by processes of the cytoskeleton. Dendritic spines become concave with a widened base after LTP is elicited, lowering electrical resistance. Further research is clearly needed to clarify the role of the cytoskeleton to memory. But at the very least it appears that the cytoskeleton plays a dynamic role in the transmission of information that contributes to mechanisms of memory.

The familiar axonal spike through which a digital signal propagates across the nervous system is not sufficient for perception and memory in Pribram's holonomic brain theory. Rather perception depends upon the nonlocal resonance among the dendritic microprocesses. Furthermore, such nonlocal resonance need not be limited to neurons since neural resonance may spread to and from the macromolecules of glial cells (Pribram, 1989, p. 63).

According to Becker (1991), the supportive, nutritive role originally ascribed to glial cells gave way to the recognition that glial cells have the potential for long range signaling, contributing to important biological processes. Following Szent–Gyorgi's admonition to approach the organism like a cellular archeologist, Becker proposes that glial cells contribute to a more primitive analog system of neural communication. He argues that neurons are in fact modified glial cells, or at least descended from common precursors. After all, both arise from the same embryonic tissue. The evolution of neurons, according to Becker, supplemented but did not replace the more primitive analog signaling system that already existed in glial cells. Consistent with Pribram's theory, Becker suggests that glial cells remain active contributors to information passed through the nervous system. Recent research has in fact verified that glial cells cooperate dynamically with neurons to contribute to information processing in the nervous system (Fields, 2004).

It takes no great leap of the imagination to extend such logic from the dynamic role of glial cells to an even more primitive dynamic role of the cytoskeleton. The cytoskeleton influences the processing of information spread through nonlocal resonance as was noted above (Desmond and Levy, 1988). One of the simplest sensory systems imaginable is the propagation of electrons, photons or similar particles through a crystalline structure (Szent–Gyorgi, 1941). Such submolecular transportation of particles through biocrystals have been discovered in modern organisms and is a rapidly growing area of research. One must wonder at what point such systems evolved. Could it be that the first living cells responded to changes in the environment through such structures that then provided the basis of more sophisticated information processing over the course of evolution? Becker and Selden (1985) discussed that hypothesis in detail.

Indirect support for such an idea can be found in the demonstration that even single cell organisms not only react to the environment but show the capacity for learning. The cytoskeleton appears to be essential to such rudimentary memory. Hameroff et al. (1993) reported that even the lowly paramecium shows reflex-like responses to environmental stimuli. For example, paramecium show an acquisition curve over trials when escaping an aversive environment, indicative of learning. Other data suggest that paramecia can learn patterns in mazes. Hameroff et al. (p. 323) suggest that these data can be explained by "signaling, information processing and working memory in paramecia microtubules." Similar processing may occur in amoeba and euglena since these too show responses to light dependent upon the microtubules. It appears that cytoskeletal structures, initially considered useful only for support and nutrient transport, play a complex information processing role even in single cell organisms.

Recently, researchers suggested that quantum coherence can emerge within microtubules. There may be a basis for biological processes that are analogous to superconductivity and even the Josephson junction, the critical component of the most sensitive magnetometer known as the superconducting quantum interference device, or SQUID.[6] The existence of quantum coherence may provide sophisticated mechanisms for the transfer of energy and information through the smallest structures of cells. If such is the case, it clearly brings bioenergetics into the realm of quantum theory, just as Szent–Gyorgyi predicted in his seminal paper in 1941.

Every biological system is also a physical system, ultimately subject to the laws of quantum theory at the microlevel, like any physical system. Quantum theory is highly successful at describing the state of matter to a remarkable degree of accuracy. Yet even Erwin Schrödinger (1947) acknowledged that inorganic matter can be described with much more accuracy than can organic matter. There is more order and less entropy in living matter than is predicted by the laws of physics. It is unsurprising if life processes are a source of order within the organism, but Schrödinger implied that something fundamental is missing in physics, biology, or both that yields less accurate predictions with organic matter. Szent–Gyorgi's fundamental assumption that living matter is structured through a biomatrix of liquid crystals found primarily in water and by semiconducting flows of particles is clearly relevant. That is, a new set of variables are proposed that contribute to the physical order within the organism. Other researchers, however, have made substantial contributions well beyond Szent–Gyorgyi's pioneering work.

Jibu and Yasue (1993, p. 130), for instance, suggest that electrical polarizations among biomolecules interact with water molecules to provide a "quasi-crystalline structure." In their research, Jibu and Yasue describe "quantum brain dynamics" that are consistent with Szent–Gyorgi's submolecular flow of electrons but which ultimately must be subject to the principles of quantum theory. They further propose that quantum processes in the brain are fundamental to consciousness (Jibu, Pribram, and Yasue, 1996).

Quantum brian dynamics grew from earlier work by Ricciardi and Umezawa (1967) who were perhaps the first to describe the brain and consciousness within the framework of quantum physics. In contrast to our familiar sensory

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[6]In 1973 Brian Josephson, Leo Esaki, and Ivar Giaever were awarded the Nobel Prize in physics for discovering the Josephson junction. Subatomic particles can sometimes pass through a region forbidden by classical physics in a phenomenon known as quantum mechanical tunneling. In the Josephson junction, fluctuation of the magnetic field causes electrons to tunnel through a barrier so that current changes enable measurement of the magnetic field all the way to the quantum level.

experience of the world, quantum theory requires the existence of nonlocal effects in which the state of one physical system can determine the state of a second physical system, removed far enough to prevent any local interactions with the first system (Hiley and Peat, 1987, pp. 13–14).

According to Ricciardi and Umezawa, a spatially distributed system can form in living organisms which, through the principle of spontaneous symmetry-breaking, becomes the basis of top–down processing within the distributed system. Such a system is consistent with the descriptions of top–down processing found in chaos theory and phase shifts of certain physical systems such as superconductors (Bohm, 1990, p. 280). Building on that initial paper, Hiroomi Umezawa and his colleagues proposed that long range correlations within neurons develop from the interaction of two quantum fields providing a quantum coherent state within the organism (Stuart, Takahashi, and Umezawa, 1979). Others have independently developed similar ideas.

Just a year after the seminal paper by Ricciardi and Umezawa, Herbert Frohlich, a physicist with expertise in superconductivity, also proposed that quantum processes have a role in biology. According to Frohlich (1968), a thin region just inside the membrane of neurons and other cells enables energy to be transmitted in coherent waves that propagate without thermal loss much like current in a superconductor flows without electrical resistance.

Frohlich suggested that protein molecules at the cell membrane or in the microtubules might be aligned into a quantum coherent state on the macroscale if a minimum threshold of energy is attained. It has been suggested that microtubules of both neurons and glial cells will enable quantum coherence such as Frohlich proposed (Pribram, 1991, p. 270). Frohlich predicted that coherent excitations should occur between 10^9 and 10^{11} Hz, in the microwave region. The observation of non-thermal effects of microwaves upon biological tissue are consistent with Frohlich's theory (Jibu, Hagan, Hameroff, Pribram, and Yasue, 1994). Microtubules may facilitate quantum coherence by virtue of their small size and quasicrystalline structure. Frohlich further believes that coherent states within microtubules may provide structure to the water inside them. Frohlich's proposals clearly call to mind Szent–Gyorgi's biomatrix of liquid crystals conducting electrons.

Furthermore, very similar ideas have been advanced by Jibu, Hagan, Hameroff, Pribram, and Yasue (1994). Extending the quantum brain dynamics of Jibu and Yasue (1993), they proposed that long-range coherent quantum phenomena occur within cytoskeletal microtubules. The proposed quantum coherence arises from an optical system of information processing based upon the generation of photons as water molecules interact with the electromagnetic radiation associated with proteins forming walls of the microtubules.

Jibu et al. (1994, p. 199) suggest that photons can emerge within microtubules yielding a "superradiance" that is like an optical version of a superconductivity. That is, the emergence of coherent photons are predicted inside the hollow microtubules which propagate without loss of energy. This quantum coherent state is described as "self-induced transparency." The exchange of energy between the electromagnetic field (Emf) and the water molecules can create or annihilate such photons. Dicke (1954) was the first to describe superradiance, a macroscopic process that results in pulses of photons. More recently, Del Giudice, Preparata, and Vitiello (1988) stated that water can release pulses of photons in a laser-like process. Del Giudice et al. further noted that the substantial electric dipoles of water molecules can coherently interact with the surrounding Emf to generate macroscopic phenomena which could be fundamental to the organization of living matter.

According to Jibu et al. (1994), just as a superconductor spontaneously reorganizes into a new physical state so that electrons flow without resistance once the temperature drops below a critical value, so photons spontaneously reorganize to propagate along a waveguide through the water filled microtubules as if they were perfectly transparent, once the Emf reaches a critical value. This transition of a physical system into a new coherent phase as the system moves farther away from equilibrium is fundamental to the dynamics of chaos theory where it is known as spontaneous symmetry breaking (Jibu, Pribram, and Yasue, 1996). Superradiance can be understood as the result of such spontaneous symmetry breaking.

It is the Emf of the proteins that produces the phase shift to superradiance. Recall that in Pribram's brain theory the holoscape is the basis of the perceptual and memory images. As input from the sensory apparatus continually shifts the holoscape from one state to the next, the protein dipoles from which the holoscape arises are also realigned. The distribution of protein dipoles in the wall of the microtubule can excite the water molecules in the core of the microtubule. If enough protein dipoles are excited in a local region, the energy of the water molecules is phase shifted into a coherent state.

When the energy decreases, the water molecules collectively drop back to a lower energy level, resulting in the emission of a coherent photon inside the microtubule. The process can then be repeated. The proteins and water molecules thus form a cooperative system through which photons emanate through the microtubule, the entire process being driven by the sensory stimulation that activates the protein dipoles. Jibu et al. (1994) suggest that superradiance may provide an interface between the classical dynamics that can describe the movement of ions or other thermally-induced molecular activity and quantum dynamics of coherent systems free from thermal noise and loss.

Jibu et al. (1996) further proposed that the structure of the thin layer of water adjacent to the dendritic membrane also yields quantum coherence analogous to the process in microtubules. As before, the coherence arises from spontaneous symmetry breaking triggered by the charge distribution, in this case, among the perimembranous regions of dendritic spines. The sensory stimulation redistributes the charge distribution among the dendritic spines (i.e., the holoscape), triggering spontaneous symmetry breaking among water molecules of the dendritic membrane. The water molecules are phase shifted into a coherent state that again results in the emission of photons just as in the microtubules.

Jibu et al. (1996, p. 1739) state that the radiation field manifests two distinct modes, "the normal wave mode with real wave number and the evanescent wave mode with imaginary wave number." The latter describes the "evanescent photons," also called "tunneling photons," which propagate through the process of superradiance. The photons can propagate through both the inner and external region adjacent to the cell membrane and also between brain cells.

Jibu et al. (p. 1750) further propose that these evanescent photons of the inner perimembranous region and the outer perimembranous region, separated by the cell membrane constitute a Josephson junction, as when two superconducting currents are separated by a thin barrier. They suggest that quantum tunneling permits evanescent photons to pass from the inner perimembranous region to the outer region. Like the Josephson junction built into the most sensitive magnetometers, such natural Josephson junctions may also enable responsiveness to very weak magnetic fields since the magnetic flux causes tunneling through the barrier altering the flow of current. Other researchers have also stated that the Josephson effect is possible in biological cells (Del Giudice, Doglia, Milani, Smith, and Vitiello, 1989). Coupling will occur among the Josephson junctions of the dendritic microprocesses so that they make a substantial contribution to the EEG.

This superradiance is congruent with Becker's analog system of neural conduction in the sense that submolecular particles propagate through pathways formed by liquid crystals. Also in agreement with the dynamic role Becker attributes to glial cells, Jibu et al. (1994, p. 205) suggest that coherent propagation occurs among astrocytes, one type of glial cell. The biomolecules of both neurons and glial cells contribute to the structure of water molecules which interact with the dendritic membranes in a nonlocal, cooperative process according to the principles of quantum mechanics. The holoscape is a temporary stabilization that interacts with this process.

Jibu et al. (1994) develop the idea that the quantum process that stabilizes the holoscape is relevant to fundamental questions regarding consciousness: quantum coherence in the microtubules and the perimembranous region accounts for the unity of the conscious image that arises from widely distributed cortical activity. Evidence in support of this conclusion is provided by the effects of anesthesia. Anesthetics in the microtubules alter protein–water binding which may directly alter quantum coherence. Similarly, defects in the structured water are caused by chlorine ions which are suggested as the basis of the ensuing anesthetic effect (Jibu et al., 1996).

The proposition that the phase shift in microtubules to a coherent state is essential for consciousness is supported by the work of other researchers. Most notably, Hameroff and Penrose (1996) proposed that a quantum coherent state forms within microtubules and undergoes an "orchestrated reduction" that is the basis of consciousness. They examined data regarding the effects of anesthesia that indicate consciousness is dependent upon quantum coherence. According to Hameroff and Penrose, anesthetics act upon hydrophobic pockets found in cortical proteins. These hydrophobic pockets contain delocalizable electrons that are moved about by fluctuations of van der Waals energies.[7] Anesthetics lower the energy of van der Waals forces in proteins and, in turn, immobilize the electrons within hydrophobic pockets.

Hameroff and Penrose further conclude that by immobilizing these electrons they are prevented from developing quantum coherence in the hydrophobic pockets that would otherwise be present. Although Jibu and her co-workers focused upon different processes from those Hameroff and Penrose emphasized, both describe specific mechanisms of a quantum approach to consciousness within neural microtubules and both view the disruption of quantum coherence by anesthesia as the basis for the loss of consciousness.

The identification of specific physical processes such as van der Waals forces is also encouraging since an essential step toward exploring the viability of quantum theories of consciousness is to design testable hypotheses. The argument for quantum consciousness ultimately depends upon feasible experiments. The common belief that the brain is just too warm to sustain quantum coherence beyond a few microseconds, certainly not long enough to be biologically useful, is often presented as dogma that cannot be questioned. There is a certain face validity to that view, but it is premature to state that it must be so without fully considering the ideas regarding quantum coherence advanced in recent years. Although there are not many data that demonstrate quantum coherence in the nervous system it cannot be said that there is none.

For example, Hameroff (2000) described intermolecular multiple quantum coherence, a technique used to enhance MRI images. This technique depends upon quantum dipole coupling of protein spins up to a distance of a millimeter (Richter, Lee, Warren, and He, 1995). An electromagnetic pulse presented to tissue within a strong magnetic field can create such dipole couplings yielding measurable effects. These data indicate that quantum coherence is

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[7] van der Waals forces are weak attractive forces that act between electrically neutral molecules of the same substance. Polarization within a molecule can occur such that one side of a molecule is more positive and the other more negative so that attraction occurs between molecules. Similarly electron fluctuations can form polarized oscillations through interactions with nearby molecules.

not inherently impossible in the brain although it remains to be demonstrated in the absence of external magnetic fields.

It's interesting that magnetic pulses can generate quantum coherence since researchers have argued for many years that organisms are susceptible to the influence of extremely weak magnetic fields, as weak as the magnetic field of the earth. There are even data suggesting that the behavior of some organisms is influenced by weak electromagnetic pulses (Russo and Caldwell, 1971). Blackman, Benane, Rubinowitz, House, and Joines (1985) further suggested that the natural magnetic field of the earth can induce significant biological effects through the mechanism of cyclotron resonance, a complex resonance that alters the spin states or orbits of charged particles exposed to certain magnetic fields. If coherent particles or photons can propagate through microtubules or liquid crystals in the nervous system they will certainly be more susceptible to the influence of magnetic fields than are the processes involved with chemical transmitter substances that depend upon the movement of much larger ions. Demonstrations of the influence of weak magnetic fields upon organisms are consistent with the existence of quantum coherence, although certainly not direct support.

The possibility that quantum processes can play a consequential role in biology has generated both intrigue and intense criticism within the scientific community. This is not surprising. If quantum approaches to consciousness are supported it threatens the orthodox view and raises fundamental questions regarding the nature of consciousness and the integration of consciousness into modern biophysics. Many of the above researchers have discussed their work in the context of process philosophy and also Jamesian metaphysics.

For example, Pribram (1986) argues against both traditional materialist and mentalist positions and suggests that something beyond either is needed. He contends that the recent research on consciousness within the context of physics best supports the position of neutral monism consistent with James. In his view, information serves as the basis of both matter and consciousness but is itself neither material nor mental. His claim is that information in the brain is distributed widely across the cortex with a structure similar to the information distributed across the film in an optical hologram. In Pribram's theory interference patterns form among the dendritic microprocesses collectively yielding the holoscape that is the basis of the perceptual and memory images.

But the structure of information in his theory is never either exclusively material nor mental. Rather, Pribram argues for an underlying ground that gives rise to both mind and matter which is also reminiscent of the underlying quantum foam of Wheeler (1980). "I have called this pre-space-time domain a potential reality because we navigate the actually experienced reality in space-time" (Pribram, 2004, pp. 2–3). Just as the optical hologram consists of an image manifest in space and a transformed, spectral representation on the film that is illuminated to generate the visual image so the potential pre-space-time energy unfolds into cortical polarizations that comprise the holoscape.

Central to Pribram's theory of consciousness is the assumption that something like a Leibnizian monad emerges from the pre-space-time energy. Leibniz described fundamental particles called monads that were part mind and part matter and served as the foundation of both. In Pribram's (1997, p. 314) theory Gabor's quantum of information is used to describe even the pre-space-time energy and is analogous to the monad. Pribram (1993, p. 535) further states that Gabor's quantum of information "describes not only an elementary neural but also an elementary psychological communicative process." Both mental information and matter arise out of the same pre-space-time energy. The structure of information is simultaneously unfolded into the conscious image and the brain activity of the holoscape. One mirrors the other so that consciousness and brain unpack the same structure of information. Mind and matter are both taken to be manifestations of the deeper ground. Rather than mind/matter dualism, Pribram advocates a neutral monism that nevertheless retains a duality between the enfolded potentialities and the unfolded image. There is no "ineffable mind" as in dualism, only transformations of energy into quanta of mind or quanta of matter.

The convergence of Wheeler's pre-space with the physics developed by David Bohm was briefly described above. Pribram (1986) also suggested that the work of physicist David Bohm is particularly relevant here. Like Pribram, Bohm (1980) suggests that consciousness and matter arise from common variables not recognized in the orthodox interpretation of quantum theory.

To examine the relevance of Bohm's work in further detail, it must be recognized that his work was closely related at the outset to ideas that had been developed by Louis deBroglie, one of the founders of quantum theory. Bohm presented an alternative version of quantum theory that incorporated a quantum potential, similar in many respects to deBroglie's earlier pilot wave. According to Bohm (1990, p. 279) "One may think of the electron as moving under its own energy. The quantum potential then acts to put form into its motion, and this form is related to the form of the wave from which the quantum potential is derived." The quantum potential contains active information that guides the particle like a radar signal can guide an ocean liner on autopilot. The information inherent in the quantum field provides an order to matter. It is this active information of the quantum field that is the basis of the "mind-like behavior of matter" (Bohm, 1990, p. 281). Consciousness and matter both arise from the same deeper reality, the quantum field. Fundamental to Bohm's theory is the description of an implicate order of potential states in physics that unfolds to yield an explicate order that is manifest to the senses. Bohm considers Wheeler's pre-space one type of implicate order although Bohm developed his own theory that presents ideas beyond

Wheeler (1980). Bohm (1986) provides a non-technical overview of his implicate order. In any event, the convergence between Bohm's implicate order and Pribram's pre-space-time is obvious. Bohm too described his view of nature as a holographic order.

Although Bohm developed his concept of implicate order over many years, one essential idea remained constant. The world manifest to the senses arises out of an unobservable order of potentialities enfolded into the vacuum, in accordance with the alternative version of quantum theory Bohm proposed. Although theorists have described an inherent energy of the vacuum at least since the 1930s, it was easy to ignore in most descriptions of physical states and has played a fairly minor role in physics. That situation is changing. According to Krauss and Turner (2004), for instance, the vacuum has acquired a central role in quantum physics. They suggest that the cosmological constant introduced by Einstein in 1917 but later abandoned has re-emerged through the back door of the vacuum in modern quantum theory. This is a remarkable development that is entirely consistent with Bohm's (1980, p. 192) view of the vacuum as a structured, multidimensional implicate order. Consciousness can only be incorporated into science when science becomes deep enough to incorporate implicate order.

The place of consciousness in Bohm's version of quantum theory is essentially consistent with Pribram's theory. Bohm also suggested that consciousness arises from something like a Lebnizian monad that emerges out of the implicate order. But Bohm went a step further than Pribram and argued that Whitehead's "occasions of experience" are even closer to the basic element of consciousness, which Bohm (1980, p. 207) called a "moment." In contrast to the point events taken as the basic element in the theory of relativity, in Bohm's theory both consciousness and matter exist as potential states within the implicate order that become explicated as a moment with some extension in space and duration in time.

Since both mind and matter are the aspects of reality manifest as such moments, there is a convergence with Whithead's argument presented at the outset that occasions of experience compose all aspects of the world and are therefore the "really real things." Like Whitehead, Bohm suggested that all matter contains a moment of consciousness within it, which he described as "rudimentary consciousness," represented mathematically in his theory by the quantum potential. Bohm (1990) concluded his paper on the relationship of mind to matter by emphasizing the "deeper reality" that gives rise to both mind and matter. Since both emerge from the deeper ground of implicate order both are fundamental aspects of the world. Consciousness cannot be derived from matter anymore than matter can be derived from consciousness.

Describing Bohm's perspective, Pribram stated that observation of nature through the lenses of our instruments and our eyes objectify and focus our view so that the phase relations of the implicate order are destroyed. But if we could somehow perceive the world with the phase relations intact, the holographic order would manifest itself, beyond space-time. Observation of a physical system yields an explicated manifestation of it but the system nevertheless arose from the deeper reality and remains connected to the holographic ground. Within that deeper ground Bohm argued that each physical system must further interconnect to larger systems within the implicate order.[8] In the words of Pribram (1997) "Each organism, like a Leibnizian monad, re-presents the universe, and the universe reflects, in some manner, the organism that observes it. The perceptions of an organism cannot be understood without an understanding of the nature of the physical universe and the nature of the physical universe cannot be understood without an understanding of the perceptual process" (p. 316).

Both Pribram and Bohm argued that the properties of matter and radiation reflect the deeper reality from which they arise. Pribram (1997) suggested that the Plank–Einstein equations $mc^2 = h\upsilon$ and $p = h/\lambda$ reflect a wave/particle duality that is fundamental in nature. The description of the world that emerges by combining the constants of quantum theory and relativity theory together reveal a relationship between the dynamic, wave-like aspect typically associated with radiation (i.e., υ and p) and the localized particle-like aspect typically associated with matter and photons (i.e., m and h/λ). Of course, matter also shows a wave-like state under certain circumstances, such as the two-slit experiment, and radiation reveals a particle-like nature when observed with a photon counter. The wave/particle duality also reflects the implicate/explicate duality of Bohm's theory in which the dynamic potentialities of the implicate order become explicated in space and time. Both Bohm and Pribram appeal to the quantum potential, or the de Broglie wave, with the same phase as the wavefunction given in the Schrödinger equation as the bridge between the implicate potentialities and manifest explicate order. This is expressed in their theories of consciousness as the explication of information potentialities from the implicate order through the quantum potential (Pribram, 1997, pp. 316–320).

Although consciousness cannot be directly measured, Bohm's theory provides some mathematical expression of its place in physics. Consciousness is part of the unfolding implicate order. Any full understanding of consciousness must go beyond brain processes and look to the basic processes of nature at the quantum level according to Bohm. According to both Bohm and Pribram mind arises from fundamental principles of physics so that mind and matter reflect the duality of the implicate and explicate orders.

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[8]Separation is therefore never absolute in nature since whatever relatively autonomous systems emerge remain part of the interconnected whole (Bohm, 1980, p. 156). Every organism reflects this deeper ground.

The alternative theory of consciousness developed by Penrose and Hameroff (1996) also depends upon fundamental aspects of both general relativity and quantum theory. According to the Penrose–Hameroff "Orch OR" model, consciousness has a non-computational aspect that emerges from the very nature of space-time at the smallest level. Penrose proposed that quantum coherence emerges when the wave function describing a particle is in a superposition supporting at least two different states that are ultimately collapsed by "quantum gravity" operating at the Plank scale of space-time (Penrose, 1994, pp. 337–346). Penrose argues that a particle in a superposition with two possible outcomes implies two different space-time geometries associated with each of the two potential states of the particle.

Penrose believes it is the evolving differences between the space-time geometries that yield state reduction of the coherent state to one outcome or the other. The collapse of the coherent state by quantum gravity results in an orchestrated reduction (Orch OR) in the theory Penrose and Hameroff described. Penrose and Hameroff (1996) proposed that orchestrated reduction readily occurs in microtubules of the brain. Most remarkable is the hypothesis that consciousness is embedded into the nonlocal space-time configuration. The collapse of the wavefunction collapses the consciousness embedded within the potential space-time configurations yielding a qualia of consciousness within the selected space-time configuration. Penrose and Hameroff theorize that the subjective stream of consciousness we each experience occurs only because of the continuous process of orchestrated reduction in neural microtubules yielding one moment of consciousness after the next.

In contrast to the central importance Penrose and Hameroff placed on the collapse of the wave function, Bohm appealed to the deeper quantum field that continually unfolds to give rise to the stream of consciousness. It must be noted that quantum gravity is unnecessary for Bohm (1987) since he actually does away with the collapse of the wave function. Bohm's theory underwent several revisions but he always focused on some version of a determinate, deeper quantum field instead of the collapse of an indeterminate wave function, ultimately appealing to the unfolding of implicate order of potentialities into an observable explicate order. In spite of fundamentally different mechanisms in their theories Bohm nevertheless agrees with Penrose and Hameroff that consciousness is inherent in the world and is manifested through the principles of quantum physics.

Hameroff, like Bohm, saw a convergence between quantum theory and Whitehead's ontogeny. The qualia that ostensibly results from Penrose and Hameroff's orchestrated reduction is a fundamental part of reality that can be conceptualized as equivalent to Whitehead's "actual occasions of experience" (Hameroff, 2003, p. 73). The theoretical positions taken by Hameroff and Bohm in that sense both embrace panpsychism, recognizing consciousness as a fundamental force of nature. Although the specific processes proposed by Penrose and Hameroff are somewhat different from those described by Bohm there is an extraordinary convergence regarding quantum coherence in the brain and the integration of consciousness into the fabric of space-time.

In fact, there is a further convergence among these researchers regarding consciousness and information at the quantum level. Information and consciousness intuitively belong together so it is unsurprising that scientific theories of consciousness converge upon the place of information in science. Yet classical physics is entirely deterministic and it is only the physical properties that are causally effective. Information about the planets does not influence their location. Neither does information acquire any causal role in the theory of relativity but the state of a physical system is directly dependent upon it in quantum theory.

The two-slit experiment described above is one striking example in which the experimenter's observations actively determine the outcome of the data. The role of observation and information are fundamental even to Bohr's orthodox interpretation of quantum theory. Stapp (2007) states that quantum mechanics actually replaces the concept of material substance with informational structure since a particle is no longer conceptualized as a point event in space but as a set of potentialities spread over some possible locations as is mathematically described by the Schrödinger equation. Rather than values of physical parameters it is "the process of acquiring information or knowledge pertaining to the location of that object" (Stapp, 2007, p. 302) that determines the final physical event.

Information is fundamental to the orthodox interpretation of quantum theory but the alternate versions of quantum theory developed by Bohm, Penrose, and Hameroff, and by Jibu, Yasue, and Pribram assign a still deeper significance to information so that it emerges as a primordial concept in these theories. Understanding the active role of information and understanding consciousness are closely integrated in the work of these theorists, in spite of some consequential differences among them. This active, causally effective information is something beyond orthodox quantum theory. That is, a bit of information typically describes the Boolean outcome of a system that can be readily described even by classical physics, such as a switch that is toggled on or off. But how are Shannon's bits to be integrated with the causally effective information associated with conscious observation?

Chalmers (1996) discusses the relationship of information to consciousness in detail. Chalmers's approach to consciousness was influenced in part by his awareness that even matter becomes much less mechanical and much more ephemeral when studied at smaller and smaller scales so that descriptions in terms of probability and information become as appropriate as descriptions in terms of mass or energy. Chalmers (1996, chapter 8) introduced the concept of an "information space" (p. 278) and appealed to the "double aspect of information" (p. 284) so that, in his view, the same information state underlies a physical realization on one hand and a phenomenal realization on the other. It is only when information is grounded in the phenomenal or protophenomenal properties that it acquires a deeper meaning beyond the Boolean choice of the standard theory.

Chalmers (1996, p. 305) wrote:

> The ontology that this leads us to might truly be called a double-aspect ontology. Physics requires information states but cares only about their relations, not their intrinsic nature; phenomenology requires information states, but cares only about their intrinsic nature. This view postulates a single basic set of information states unifying the two. We might say that internal aspects of these states are phenomenal, and the external aspects are physical.

Quantum consciousness as conceived by the above researchers converges upon ideas similar to this double aspect of information and phenomenology as part of nature. Chalmers notes that this ontology is closely related to a neutral monism, which is particularly consistent with Pribram. As was detailed above, Pribram (1997, p. 314) applies Gabor's quanta of information to pre-space-time energy and compares it to a Leibnizian monad. Pribram essentially views these information-based monads as protophenomenal but they unfold into both the material and phenomenal. He asserts that the monads are entropic and causally effective (Pribram, 1986, p. 515) but he favors a Jamesian neutral monism over Whitehead's view that emphasized the phenomenal nature intrinsic to the deeper ground (Pribram, 1986, p. 512).[9] Although Pribram is reluctant to embrace panpsychism, Hameroff, Bohm, and others have advanced a Whiteheadian panpsychism in one form or another. Even though contemporary terminology has emerged such as pan-experientialism or pan-protopsychist that may reduce the negative connotations that some associate with any form of panpsychism, contemporary researchers nevertheless acknowledge that it is worth serious consideration in spite of the fact that it fell out of favor a century ago (Chalmers, 1996, p. 305).

There are obvious similarities among Pribram's monad, Bohm's moment of consciousness, and the Penrose and Hameroff qualia. In contrast to the neutral monism favored by Pribram, Penrose is sometimes described as Platonic. There is an element of idealism implied by orchestrated reduction, and in fact by Bohm's theory too. The collapse of the quantum mechanical vector is completely random in orthodox quantum theory but the fine grain of space-time geometry that Penrose and Hameroff describe is curved by the quantum gravity revealing an inherent "Platonic information" that yields a non-random

[9]See Chalmers, 1996, pp. 154–155.

although non-computable collapse (Hameroff, 2003, p. 73). In contrast to the orthodox view, there is information embedded in space-time that becomes the qualia upon wave function collapse. Continual collapse throughout the microtubules of the brain collectively constitute the stream of consciousness.

Furthermore, Hameroff likened his view to the idealism of Whitehead, as did Bohm. Bohm, however, saw the need to reconceptualize Whitehead's occasion in light of the understanding of quantum uncertainty that developed subsequent to Whitehead's time (Bohm, 1986, p. 183). When Bohm spoke of a moment of consciousness that was like Whitehead's occasion he further introduced an ambiguity associated with the potential states described by the Schrödinger equation. Whitehead approached the problem of the "now" as the concrescence of actual occasions of experience. Bohm's view parallels Whitehead except that the experience of his moment contains sufficient ambiguity that the potential states of one moment necessarily overlaps the next. Moments are not point events but have an irreducible duration because of quantum uncertainty.

> The extension and duration of these moments is in general determined only in some broader context in which they are embedded. In the particular domain covered by the quantum theory, these features will depend on the quantum-mechanical wave function. And so we see that they are already an implicate order (in which each moment is subject to a certain lack of precise localizability over a region in which the wave function is appreciable). (Bohm, 1986, pp. 183–184)

The implicate order Bohm refers to here is like the fine grain of space-time described by Penrose and Hameroff. The loss of the fine grain information creates new information at the larger level of the qualia (Hameroff, 2003, p. 77) just as Bohm's implicate order unfolds from pre-space potentialities into an explicate moment. The process of unfolding from the implicate order is associated with fine-grain information loss so that each succeeding moment differs from the preceding moment (Bohm, 1986, p. 195). There is presumably a difference from moment to moment at the level of becoming beneath our subjective perception of the "now" which is on the order of a few hundredths of a second. Our experience of the now becomes the stream of consciousness much like the slightly different images on a filmstrip are perceived as a continuous movement by the audience.

This calls to mind the question of whether consciousness ultimately reduces to discrete events like links of a chain or to a continuous flow. The discussion above suggests that is the wrong question to ask. Instead we encounter an unfolding whole that incorporates a fine granularity of space-time, that contains information of a deeper pre-space and implicate order that is at least proto-phenomenal. The whole, undivided process yields explicate content from a background of implicate possibilities (Bohm, 1980, pp. 204–205).

Process rather than particle is fundamental replacing mechanization with a sub-quantal flow of information and a principle of no absolute mindlessness. Consciousness is not the fortuitous accident of the blind adventures of particles but a fundamental aspect of reality.

If consciousness is in fact intrinsic to nature, then physics, not to mention biology, requires fundamental revision. The research described in this paper suggests that consequential progress toward a new paradigm has already occurred. The emergence of a new paradigm must remain parsimonious with relativity and quantum theory but will no doubt extend both in new and remarkable ways. The fact that leading physicists and brain scientists are collaboratively and independently advancing scientific theories of consciousness is itself a profound development.

The challenge of integrating consciousness into science requires re-examination of the most fundamental assumptions of physical reality. Bohm has demonstrated that the assumptions that underlie orthodox quantum theory are not the only viable assumptions but elevating them to the level of unquestionable dogma limits the questions that can be asked and the interpretations of the data that are allowed. In Bohm's analysis the processes that give rise to the stream of consciousness mirror the unfolding of the particles of matter from implicate order. This too is consistent with Whitehead's process philosophy and may well become fundamental to twenty-first century physics. The theories and data reviewed in this paper strongly suggest that materialism is not a necessary assumption for modern science and that some form of quantum panpsychism is likely to emerge as a new basis for understanding consciousness.

The central challenge at present is to design experiments that enable testing of the theories of quantum consciousness. There are prominent critics who argue that even the attempt to evaluate theories of quantum consciousness is a waste of time and thoroughly reject any and all quantum approaches to consciousness. Nevertheless, the data must ultimately determine the place of consciousness in science. The work of Pribram, Bohm, Hameroff, and Penrose implies that understanding consciousness is central to the advancement of science itself. The extension of theories of perception, memory and consciousness to the level of nanoneurology and beyond may open a wide door into profound new territory.

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