1 The Path Ahead

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Summary. This chapter provides an introduction to the rest of the book, which has a multidisciplinary approach to the physics of consciousness. We summarize the various contributions and present our own point of view, which is that there are some deficiencies in defining higher-order consciousness in strict terms of classic physics. We favor a proposal that considers some aspects of quantum-mechanical operations among molecules involved with neurotransmission and mechanical transport of synaptic proteins. In our view, the wiring of the brain is not as complex, and certainly not as integrated, as commonly assumed. Instead, the wiring pattern redundantly obeys a few general principles focused on high resolution rather than crossmodal integration. Basing cognitive functions, such as higher-order consciousness, solely on electrophysiological responses in neural networks thus wired may not suffice. On the other hand, coherent quantum computing, executed by tubulins, the protein subunits of microtubules, may exert en masse influences over the transport of many receptor and scaffolding proteins to various activated synapses, thereby accounting for the unity of conscious experience. We discuss the potential problems of quantum computing, such as decoherence, and also present counterarguments, as well as recent empirical results consistent with the notion that quantum computing in the interiors of neurons, in particular, within the interiors of dendrites may indeed be possible.

1.1 Definition and Fundamentals

Consciousness is one of the major unsolved and poorly understood problems in biology. How do the elemental feelings and sensations making up conscious experience arise from the concerted actions of nerve cells and their associated subcellular, synaptic and molecular processes? Can such feelings be explained by modern molecular science, or is there an entirely different kind of explanation needed? How can this seemingly intractable problem possibly be investigated experimentally and what kind of theory is appropriate? How do the operations of the conscious mind emerge out of the specific interactions involving billions of neurons connected with thousands of neurons each? This multiauthor book seeks answers to these questions within a range of physically based frameworks. In other words, the underlying assumption is that consciousness should be understood using the combined intellectual potential of modern physics and the life sciences. We have gathered contributions from a number of scientists representing a spectrum of disciplines taking a biophysics-based approach to consciousness. Thus, we have attempted to provide the reader with a broad range of vantage points to choose from.

There are a number of theories of consciousness in existence, some of which are based on classical physics while others require the use of quantum concepts. Although quantum mechanics lie at the heart of the material realm, it remains to be determined if these seemingly peculiar phenomena contribute significantly to human cognition and consciousness. Quantum theory has invoked new perspectives of consciousness almost since its inception. Neuroscientists widely accept that cognition, and possibly consciousness, are correlated with the physiological behavior of the material brain (for example, membrane depolarizations and action potentials). Quantum theory is the most fundamental theory of matter known thus far; as such, it appears likely that quantum theory can help us to unravel the mysteries of consciousness. We will try to present the reader with a spectrum of opinions from both sides of this scientific divide letting him/her decide which of these approaches are most likely to succeed. While classical physics is easily grasped by our intuition, quantum theory often defies the common sense developed through everyday experiences. Therefore, a general introduction into quantum phenomena needs to be presented in this context to better understand detailed discussions presented in the chapters that follow.

1.1.1 Definition of Consciousness and the Classical Approach

There are several possible definitions of consciousness, but the general consensus is that the state of being conscious is a condition of being aware of one's surroundings and one's own existence or self-awareness. The status quo or the currently accepted view is that the substrate of consciousness emerges as a property of an ever-increasing computational complexity among neurons. This framework envisions neurons and synapses as the fundamental units of information processing hardware in the brain, acting much like chips manipulating information bits in a computer. It is often argued that although individual neurons are assumed to have only two different states, on when the neuron is firing and off when it is not, there is a critical level of complexity required such that when it is reached, many neurons interact with each other to form a conscious experience. While this appears to be the currently accepted approach to explaining consciousness, it may fall short, especially in cases where the apparent randomness of neural processing is represented simply as white noise.

Moreover, the fact that neuronal assemblies can be fully described by classical physics does not rule out significant quantum effects, especially at the level of subneuronal components such as individual proteins, or strands of DNA or RNA. The brain contains both electrical and chemical synapses, named according to the type of signal they transmit [30]. Although relatively sparse in the brain, electrical synapses, which are also called gap junctions, literally connect the cytoplasm of the presynaptic neuron with that of the postsynaptic cell. Although gap junctions conduct electrical impluses according to the laws of classical physics, these structures may be important for transmitting quantum states from neuron to neuron [73].

Chemical transmission is the much more prevalent type in the mammalian brain, but also operates much more slowly than electrical transmission. In chemical transmission there is release of a chemical neurotransmitter, such as glutamate or acetylcholine. Neurotransmitters are sequestered in presynaptic vesicles, which bind docking proteins that cause the vesicles to fuse with the presynaptic membrane and then release their contents. The neurotransmitter molecules then cross the synaptic cleft to bind with the exposed surface of specific receptor subtypes in the postsynaptic membrane. This results in the opening or closing of ion channels or in the initiation of signal-transduction cascade, some of which act on the cytoskeleton. Although these steps operate according to classical physics, quantum processes can come into play. As will be detailed later, a physical model developed by Beck and Eccles [6] proposes that quantum tunneling among vesicles occurs, which in turn regulates quantal neurotransmitter release and subsequently determines the state of consciousness.

In an approach based solely on classical physics, Flohr [14, 15] suggests chemical synapses using NMDA receptors are critical to perception and consciousness because NMDA receptors are involved in developmental plasticity and learning. That anesthetic agents block NMDA receptors and consequently lead to a loss of consciousness supports his theory to some extent. Nonetheless, not all synapses possess NMDA receptors. In contrast, the neuronal cytoskeleton is the most ubiquitous and basic cellular protein thus far proposed for quantum processes in consciousness. The cytoskeleton consists of three types of protein networks: microfilaments, intermediate filaments and microtubules. Microtubules are essential for axoplasmic transport, signaling and neuronal plasticity, among other key cellular processes within neurons. A growing number of researchers are focusing their attention on the biophysics of the cytoskeleton in order to better understand its role in neurophysiology and consciousness.

Another reason to look beyond classical models is that currently accepted models for consciousness are unable to properly explain the rather primitive consciousness in single-celled organisms. Single-celled organisms, such as the paramecium, have no neurons or synapses, but still exhibit protoconsciousness, an apparent awareness of and responsiveness to their environment [22]. One can conclude from this that the rudiments of consciousness lie someplace other than the complex interactions between neurons and synapses, although the latter are certain to contribute to the richness of sensory experience and the resulting behavioral repertoire. In many respects, the cytoskeleton can be viewed as the control center of the cell. Microtubules control cell division and cell migration (i. e. replication and motility). Microtubules also provide an ideal bridge between classical and quantum processing; moreover, these structures literally fill the interiors of neurons. They are composed of tubulin dimers arranged into longitudinal protofilaments. The interior milieu of tubulin can be likened to a caged qubit, capable of quantum computation, linked into a long polymer chain responsible for transmitting classical information. Substantial efforts have been made to fuse quantum theory with microtubules and consciousness, the result being one unified theory that still awaits experimental verification. This effort is considerably advanced from a mathematical point of view. According to this model, preconscious thought and experience exists in terms of multiple quantum states, and the conscious experience is realized when one of the many possible states prevails.

1.1.2 Quantum Theories

The physical term quantum means the smallest unit of a physical quantity the system is able to possess. The quantum world is the microworld of elementary particles, which are the fundamental building blocks of matter. The brain is made up of physical matter like all other living and nonliving systems. The ultimate pursuit for brain science is to give an explanation of how matter that comprises the physical structure of the brain gives rise to its functions, in particular higher cognition and consciousness. That the brain does give rise to consciousness is a key assumption of modern neuroscience and we will take it as a given, otherwise we would be compelled to seek these answers in the realm of religion or metaphysics. A search for that link has occupied numerous philosophers and scientists for at least two millennia [29]. In recent years some scientists have begun to probe the brain at the quantum level of physical description, facing considerable opposition from the traditionally inclined academics in both physics and neuroscience.

Perhaps the most bizarre quantum feature is the effect called superposition that implies that quantum particles can exist in multiple spatial locations or states being described by a mathematical superposition of pure state wave functions simultaneously. Such quantum superposition states can end when out of each multiplicity of the possible states the system selects one definite state or spatial location. Because quantum systems are described mathematically by a quantum wave function, and because quantum systems switch states they occupy very rapidly, the transition from quantum to classical states is often termed wave-function collapse (or sometimes state reduction). A number of experiments in the early 20th century demonstrated that quantum superpositions persisted until they were observed or measured by an experimentalist (observer). If a machine measured a quantum system, the results appeared to remain in superposition within the machine until actually viewed by experimenters. Therefore, the prevalent view in physics at that time (expressed within the famous Copenhagen interpretation) was that conscious observation led to a collapse of the wave function. To illustrate this paradox and the apparent absurdity of the notion, Erwin Schrödinger in 1935 described his celebrated thought experiment known as Schrödinger's cat. In this example, a cat is placed in a box with a vial of poison. Outside the box, a quantum event (e. g., passage/not passage of a single photon through a half-silvered mirror) is causally connected to the release of the poison inside the box. Since the photon is a quantum object in a superposition state, it both passes and does not pass through the mirror. Hence the poison is both triggered and not triggered. Therefore, by quantum logic, the cat must be both dead and alive until the box is opened and the cat observed. (Analogous to quantum logic, superposition of mental events is commonplace, further suggesting that the mind is a quantum system. Cognitively, we are simultaneously prepared for the cat being alive and prepared for the cat being dead until we open the box.) At the moment the box is opened, the system chooses either to reveal a dead cat or a live cat. Therefore, consciousness essentially selects reality. The precise choice in any given quantum collapse experiment was believed to be probabilistic, an idea Einstein found unsettling by proclaiming in a famous statement that: "God does not play dice with the universe."

Today the generally accepted view is that any interaction of a quantum superposition state with the classical environment causes decoherence. Due to these difficulties many physicists maintain that quantum theory is incomplete and that other approaches to the problem of collapse of the quantum wave function need to be found. One suggestion, called the multiple-worlds hypothesis, was put forward by Hugh Everett [13] and it holds that each collapse event is a branching of reality into parallel manifolds, so for example, a dead cat in this universe corresponds to a live cat in a newly formed parallel universe. If so, there must exist an infinity of parallel worlds, a bizarre notion to many. David Bohm's theory of quantum reality [8] avoids collapse altogether, while still other views hold out for an objective factor causing wave-function collapse. These latter ones are called objective reduction (OR) theories. For example, Ghirardi et al. [18] predicted that OR would occur at a critical number (on the order of 10^{17}) of superpositioned particles.

Complementarity and entanglement are quantum-level concepts with potential explanatory power with regard to some properties of consciousness [5]. A number of prominent figures in quantum physics, including Planck, Bohr, Schrödinger, and Pauli, argued for the irreconsilability of physical determinism and conscious free-will (for reviews see [4, 31, 60]). These early physicists sometimes used terms such as entanglement, superposition, collapse, and complementarity metaphorically without defining precisely how they should be applied to specific situations in cognition. Later, approaches were proposed that described neurophysiological and/or neuropsychological processes in some detail (e. g., [54, 62, 70, 72]. In his 1999 paper, Stapp addresses potential causal interactions, raising possibility that: "conscious intentions of a human being can influence the activities of his brain". Stapp further argues that the probabilities for eigenstates after collapse can be mentally influenced and that conscious mental events are assumed to correspond to quantum collapses of superposition states at the level of macroscopic brain activity.

Quantum field theory has been used in a preliminary way to describe memory. Ricciardi and Umezawa [49] emphasized many-particle systems and vacuum states of quantum fields as potential memory storage devices (see also [27, 63]). This type of memory would not be accessible to consciousness without external stimuli activating a neuronal assembly, however. The activation of coherent neuronal assemblies enables a conscious recollection of the content encoded in the vacuum state. Pessa and Vitiello [47] speculate that dissipation, chaos and quantum noise generate an arrow of time for the system. This would not be a plausible mechanism for long-term memory, however, because the model gives rise to a temporally limited memory [3].

Up until John Eccles' death in 1997, Beck and Eccles applied the principles of quantum mechanics to vesicular release at the synaptic cleft, hypothesizing that quantum indeterminacy was a factor in the all-or-none quantal release of neurotransmitter (see posthumous account in Beck and Eccles [6]). Chemical synapses depend upon vesicular release of transmitters from the presynaptic terminal, and this is triggered by a nerve impulse reaching the axon terminal. Although the biochemistry of vesicular docking and exocytosis is reasonably well understood, the trigger mechanism can also be viewed in a statistical way. In the latter case, either stochastic, thermodynamics or quantum mechanics should apply. Due to the nanometer size range of most proteins or macromolecules in the presynaptic terminal, quantum processes would be expected to prevail over thermal processes and purely stochastic release is less attractive as a correlate of consciousness. Beck and Eccles built their quantum concept of a release trigger on quasiparticle tunneling, which results in a probability of exocytosis in the range between 0 and 0.7, comparable to experimental observations. Beck and Eccles relied on theory worked out by Marcus [38] and Jortner [28], who similarly modeled quantum-based electron transfer between biomolecules.

More recently, Penrose [43, 44, 45] has claimed that the underlying reality itself, namely the fundamental space-time geometry, actually bifurcates during the superposition process. This is similar to the multiple-worlds view except the separations are unstable and hence they rapidly reduce to a single, undivided reality. Classical noncomputability is a key feature of conscious processes, which may also elevate our mental processes above that of mechanistic determinism that appears grossly inadequate. In Penrose's books "The Emperor's New Mind" and "Shadows of the Mind", he claims that the phenomenon of quantum collapse can explain the features of consciousness since the spontaneous wave function collapse is what distinguishes our thought processes from the behavior of completely deterministic classical computers (for a review, see [34]). According to Penrose, consciousness involves a time-ordered series of quantum-state reductions corresponding to individual thoughts. Although such ideas are controversial, the fact that quantum theory is being applied successfully to a new kind of computing (called quantum computing) where the collapse of multiple quantum possibilities to definite classical states is the key element lends credence to quantum approaches to consciousness. Applications of quantum physics to new modes of computation are currently being hotly pursued in the hope of finding a more powerful technology where the possibility of manipulating quantum states gives rise to the ultimate miniaturization of computer chips that would ultimately represent individual atoms or particles. While in classical computation, elementary units of information are the discrete bits (1 or 0), the basic units of quantum computation are quantum superposition states called qubits, where both 1 and 0 are represented simultaneously with arbitrary relative amplitudes. While qubits interact (or compute) with each other, they then reduce or collapse to a particular set of measurable states. Quantum computers would offer enormous potential advantages for certain applications, and prototype devices have already been constructed. Hence, comparisons involving the brain, mind, and quantum computers are logically linked and worth further investigation.

Other quantum properties of microscopic physical systems offer possible explanations of various aspects of consciousness. Because of a physical property called quantum coherence, individual particles lose their separate identity and become part of a common unit described by one wave function, as is the case with lasers where they produce optical coherence. Hameroff [24], Vitiello [69], Jibu and Yasui [27] and others have suggested this type of quantum coherence as an explanation for the unitary nature of self and the binding property in conscious experience. In nonlocal quantum entanglement, particles once unified in a common quantum state remain physically connected at a distance [17]. When one particle is measured, its quantum entangled partner particle reacts instantaneously, regardless of its location. This quantum interaction-over-distance has been proposed to provide a basis for associative memory, as well as an explanation of emotional connections between conscious individuals [73].

If validated, these speculations would indicate that biological evolution has taken advantage of quantum processes, one use being quantum computation in the brain. Indeed, modern biochemistry can easily identify molecules in the brain that operate at least partially in a quantum manner at the subneuronal level. Examples include various receptor proteins, enzymes, membrane lipids, presynaptic vesicle structures, gap junctions, neurotransmitter molecules, calcium ions, DNA, RNA, and microtubules and other protein filaments. The key question still remains: At what level of organization do quantum effects cease to exist, or become thermalized in a noisy system like the brain? In other words, where can we place the quantum/classical boundary? Conservative scientists argue that quantum effects are destroyed already at the level of individual molecules and ions in a thermal environment. On the other hand, advocates of quantum consciousness theories see more highly organized and spatially extended quantum states, for example, involving a number of different microtubules in the same neuron or even in several neurons forming a coherent cluster. Penrose and Hameroff [46] have put forth a highly original model of consciousness based on quantum computation in microtubules within the brain's neurons. This and other quantum models elucidate a number of enigmatic features of consciousness; however, a few hurdles remain in establishing their likelihood. Some of these difficulties are identified when designing prototype quantum computers. One such obstacle is that quantum computers will require a high degree of isolation from decoherence effects of the local environment, or alternatively some kind of fault-tolerant architecture that permits delicate quantum computing in the presence of realistic levels of decoherence [36]. The brain operates at body temperature, its mass comprises 60 percent water, and is electromagnetically, chemically and mechanically noisy, all of which would seem to severely shorten the time allowed for quantum computation. Long-lasting, large-scale quantum states are deemed to be impossible in the brain because a single ion, photon, or thermal vibration can cause decoherence and hence random reduction to classical states. On the other hand, proponents of a quantum approach to consciousness point to a number of physical mechanisms in the brain that may lengthen the time of quantum coherence and provide necessary quantum isolation. Firstly, microtubules may be able to perform quantum computations at room temperature because basic maintenance of microtubules is energy dependent, resulting in energy being continuously pumped in and out. This situation is analogous to that of lasers, which work according to quantum optical principles at room temperature [21, 39]. Secondly, the water of hydration surrounding microtubules appears to be in an ordered state, which decreases noise [21]. Thirdly, topological error correction (in a manner similar to that of the fault-tolerant architecture described above) may protect delicate quantum states [21].

1.1.3 Quantum Processing by Microtubules and Neurocognition

It is tantalizing to pursue the idea of subneuronal information processing since information processing at the level of microtubules within each neuron would provide an enormous increase in the brain's computing power. The currently accepted scientific model suggests that consciousness arises as a result of computational complexity among the approximately 10^{11} neurons in the brain. There are on the order of 10^4 synapses per large neuron, which switch their states at a rate of some 10^3 switches per second, so that we arrive at a number of 10^{18} operations per second in the brain on average. While this is a truly huge number, it may pale by comparison with the yield given by the brain if neuronal microtubules were actively involved in computational processes. Consider that at the cytoskeletal level there are roughly 10^7 microtubule–tubulin dimers in each neuron that can switch their conformational states on the order of nanoseconds resulting in on the order of 10^{16}

operations per second per neuron or 10^{27} operations per second in an entire brain instead of 10^{18} operations per second estimated for the coarse-grained approach where neurons are taken as the smallest computational units. Moreover, if each tubulin dimer does function as a qubit and not a classical bit processor, then the computational power becomes almost unimaginably vast. It has been claimed that as few as 300 qubits have the same computational power as a hypothetical classical computer comprised of as many processing units as there are particles in the universe.

Classical flow of information along the microtubule length putatively links tubulin qubits together. Indeed, some experimental evidence shows that microtubules do propagate signals in cells, as will be discussed in this book. Moreover, several types of interactions between microtubules and membrane activities are clearly recognized. That computations are carried out by microtubule subunits may imply that one of the brain's fundamental units of information is tubulin's protein conformational state. Other processes involved in the functioning of the brain, such as ion channels opening and closing, enzymes catalyzing, motor proteins moving cargo inside cells, and the propagation of ionic waves along filaments, may be inextricably linked to, or even determined by, tubulin's conformational changes, as will be detailed later in this chapter and in various other chapters of this volume. Tubulin consumes a large amount of chemical and thermal energy in the process of microtubule assembly, and is only marginally stable. Consequently, tubulin's conformation must strike a balance in response to delicate countervailing forces. The nature of tubulin and of these complex and opposing forces may confer a functional advantage and lie at the core of microtubules being able to carry out computations by component units.

There is accumulated evidence that microtubules are computationally relevant to neurocognition. Early work by Cronly-Dillon and Perry [10] showed that neurons in the visual cortex produce massive amounts of tubulin during the critical period (from the day the eyes open to postnatal day 35). The critical period is the time during which synaptogenesis and visual learning occur at highest rates. Thus, tubulin is implicated in these developmental cognitive processes. Aging is often viewed as the counterpart of postnatal development. In this regard, Alzheimer's disease, which is accompanied by deficits in intellect, memory and consciousness, has been linked to microtubule degradation [20]. Paired helical filaments are aberrant formations resulting from hyperphosphorylated microtubule-associated protein (MAP), tau. Axonal transport is compromised in Alzheimer's disease, not unexpectedly, given that microtubules are responsible for the transport of nutrients and other important substances from the cell body to the axon terminal [57]. Microtubules have been directly linked to consciousness because they provide a nonselective mechanism for general anesthesia. Anesthetics inhibit a number of neurotransmitter receptors, but differ from receptor inhibitors by having effects on the cytoskeleton, especially actin [7, 32]. Hameroff proposes that the most likely mechanism for general anesthetics acting upon microtubules is inhibition of electron movement within the hydrophobic pockets of tubulin dimers [23]. These oil-based hydrophobic pockets occupy approximately 1/30th to 1/250th the total volume of the protein, which works out to be less than one half of a cubic nanometer; nonetheless, these pockets control the overall protein conformation of tubulin. Moreover, the properties of these hydrophobic pockets create a suitable environment to support electron delocalization [26]. Electron motion or motility may well be the critical site of action for anesthetic gases. In the presence of an anesthetic gas, electron mobility that is required for protein conformation and quantum superposition is inhibited. Hence we should expect to see a loss of consciousness. Conversely, instead of inhibiting electron movement, hallucinogenic drugs such as LSD appear to be potent electron donors [59]. Thus, actions of both anesthetics and hallucinogens may involve alterations in electron states within hydrophobic pockets, which in turn affect the state of human consciousness.

Hameroff further proposes that microtubules are the place where reductions of quantum states can take place in an effective way [25]. Microtubules are, in theory, capable of extending coherent superposition states to adjacent microtubules by way of MAP bridges and to neighboring neurons by way of gap junctions or electromagnetic fields. The question has been raised whether quantum states can survive long enough in the thermal environment of the brain to affect neurocognition [64]. Tegmark estimated that decoherence caused by the noisy environment typical of the brain is likely to disrupt tubulin superpositions in under 10^{-12} s. Microtubule protein functions take on the order of nanoseconds; moreover, neurophysiologycial events range in the order of milliseconds. Hence, it was Tegmark's contention that tubulin superpositions are much too short to significantly contribute to neurophysiological processes in the brain. Hagan et al. [21] argue that Tegmark's criticism is misplaced and that the calculations he did were on a reformulation of the Hameroff–Penrose model of his own making. After adjusting to account for that error made by Tegmark, revised calculations produce decoherence times between 10 and 100 μs, which can be extended up to the neurophysiologically relevant range of 10 to 100 ms given that the particular physical mechanisms discussed earlier come into play.

In addition to exploring the potential for quantum approaches to consciousness (including quantum field theories), this multiauthor collection of chapters will discuss alternative theories that are based on physical and mathematical principles. In particular, an entirely classical formulation of the evolution of living systems culminating in the development of awareness and self-awareness is based on the idea of emergence. Emergent phenomena abound in the natural sciences and they are characterized by a higher level of complexity resulting from an aggregation of units whose individual properties differ from those of the aggregate. It is argued that while an individual neuron may only participate in information transfer, their clusters may collectively process information and clusters of neuronal clusters may achieve a yet higher level of complex behavior giving rise to the emergence of awareness eventually leading to consciousness. Indeed most accepted views within neuroscience see the brain as a nested hierarchy of information-processing subsystems. The firings of nerve cells and the transmissions between them via action potential propagation are at the bottom rung of the hierarchy – the fundamental units of information, analogous to bits in a digital computer. Unfortunately, these classical, deterministic activities, while explaining a number of neurophysiological phenomena, are unable to account for a number of key properties of conscious experience, most notably free-will, the unitary sense of self and many other enigmatic features of consciousness. Hence we may be again driven to delve more deeply inside the neuron, searching for a way to connect with the quantum level. However, most physicists would also argue that the rule of quantum effects ceases to exist in warm biological systems. Presumably that would make them unavailable to influence activities on the level of the neuron.

The challenge is to show how brain-cell firings and communication between cells may be influenced by weak and delicate, very small-scale quantum processes. To put it another way, we need to answer: At what level of organization are quantum effects required in order to explain biological phenomena? Can that level, in turn, influence activities at the neural level? The search for answers to these questions is, in a nutshell, the objective of this book. We have solicited contributions from a number of eminent scientists in the field, some very original thinkers, and several well-known science writers. We are hoping that this book will set the tone for future explorations in this field by new generations of scientists. It would be gratifying if this volume made many of its readers think about the concept of consciousness as a journey of scientific discovery.

1.2 Overview of the Contributions

We begin this volume with several experimental chapters. In the first chapter, Dick Bierman and Stephen Whitmarsh describe several recent experiments testing the subjective reduction interpretation of the measurement problem in quantum physics. These experiments investigate the proposition that consciousness acts as the ultimate measurement device, where a measurement is defined as the collapse of the statevector describing the external physical system, due to interaction with a conscious observer. To briefly summarize earlier work, auditory evoked potentials (AEPs) of subjects observing (previously unobserved) radioactive decay were recorded. The timing and peak amplitudes of these AEPs were compared with AEPs from events that were already observed and thus supposedly already collapsed into a singular state. In these earlier studies, significant differences in brain signals of the observer were found. In this chapter the authors report a further replication, which is improved upon the previous experiments by adding a nonquantum event as a control. Unfortunately, only marginal differences were found between the quantum and classical conditions. Possible explanations for the inability to replicate the previous findings are given in this chapter as well as suggestions for further research.

Nancy Woolf discusses the role that microtubules may play in neurocognition, in particular, how neurotransmitter receptors influence microtubules and how restructured microtubule/MAP networks could provide permanent memory storage in the subsynaptic zone underlying the synapse. She reviews her experimental work demonstrating that microtubules and microtubule-associated protein-2 (MAP2) are proteolyzed with learning, as exemplified in hippocampal neurons of rats with contextual fear conditioning. Corroborating data are discussed, including results indicating the critical involvement of MAP2 in contextual fear conditioning with knockout mice deficient for the N-terminus of MAP2 [33] and results that overexpression of the MAP, tau, disrupts memory in *Drosophila* ([40]; also see Mershin et al., this volume). The role of MAP2 and microtubules in kinesin-mediated transport is also reviewed and the participation of this motility in cognition in noted. Related to the issue of transport, local storage of mRNA within neuronal dendrites raises the possibility of rapid dispatch to synapses. Microtubules and actin filaments provide the needed tracks for protein cargo to reach synapses in response to increased synaptic activation. A number of researchers have proposed that the parameters of this transport result from microtubule-based computations, as opposed to the cytoskeleton acting as a system of passive cables. A model is presented in which microtubules compute on the basis of their protein conformational states determined by the binding of MAPs and motor proteins, such as kinesin. These computations are responsible for the mobilization of specific receptors to specific sites. Rather than synapses or spines being the locus of permanent memory storage, the microtubules that carry cargo to the synapse or spine are proposed as the storage site. The overall pattern is stored at multiple neural locations, such that it can be reconstructed as the proteins involved turnover. Finally, it is argued that microtubules possess the capability of self-organization, and that through this capacity; microtubules initiate mobilization of receptors and postsynaptic density proteins to synapses on spine heads. Thus, the model is able to account for the fact that ideas can occur spontaneously and can exist independently from sensory inputs. Other chapters in this volume elaborate on the key physical properties of microtubules mentioned above; in particular, the chapter by Priel et al. is devoted to microtubule computations.

Andreas Mershin et al. in their chapter entitled “Towards Experimental Tests of Quantum Effects in Cytoskeletal Proteins” emphasize the absolute need for properly controlled and replicable experimental work if one is to take seriously any proposed quantum phenomena in biological matter, let alone consciousness. These authors detail the critical kinds of experiments that one must devise to test hypotheses that quantum effects have a fundamental place in the phenomenon of consciousness. These authors astutely identify that the three different scale ranges to address are: (1) tissue-to-cell, (2) cell-to-protein and (3) protein-to-atom. The authors exclude experiments that aim to detect quantum effects at larger levels arguing negative results and inconsistencies. Mershin and coauthors pay particular attention to those consciousness experiments belonging to the tissue-to-cell scale frequently utilizing techniques such as electroencephalography (EEG) or magnetic resonance imaging (MRI) to track the activity of living, conscious human brains. They point to experiments by Christoff Koch's group, for example, designed to elucidate the multi- and single-cellular substrate of visual consciousness and likely to lead to profound insights into the working human brain. Nonetheless, because of the large spatial and long temporal resolution of these methods, Mershin et al. argue it is unclear whether they can reveal possible underlying quantum behavior (unless of course classical physics is obviously violated in some manner such as with nonlocality of neural firing). Mershin and co-authors argue that the second size scale that is explored for evidence of quantum behavior related to aspects of consciousness (memory in particular) is that between a single cell and a protein. They point to experimental work done by Nancy Woolf on dendritic expression of MAP2 in rats followed by significant experiments from their own laboratory on MAP-tau overexpression on the learning and memory of transgenic *Drosophila*. They argue the merits of such approaches, while specifying that it is still hard to see how experiments involving tracking the memory phenotypes and intracellular redistribution of proteins can show a direct quantum connection. These authors conclude that experimentation at the cell-to-protein size scale can at best provide evidence that is consistent with quantum consciousness. Lastly, these authors spend a great deal of time discussing the protein-to-atom scale, where quantum effects are likely to play a significant role in whole-protein function, It is at this level that the authors give an overview of their theoretical quantum electrodynamics (QED) model of microtubules and the extensive experimental work undertaken.

Alwyn Scott in his chapter entitled: "Physicalism, Chaos and Reductionism" strongly argues against the need for quantum basis of consciousness using a number of examples such as the decoherence issue. Instead, he puts forward an argument that the concept of emergence is sufficient to explain the onset of consciousness as an evolutionary development.

Stuart Hameroff, on the other hand, equally vigorously stresses the presence of connections between consciousness, neurobiology and quantum mechanics. This chapter enumerates and discusses the crucial unresolved problems in consciousness research ranging from those related to the neural correlates of conscious perception to the binding problem, to the electrophysiological correlates and their properties to the distinction between conscious and unconscious behavior and finally, to the hard problem. The author then states that prevalent approaches assume that consciousness arises from information processing in the brain, with the level of relevant detail varying among philosophical stances. Hameroff strongly disagrees that all-or-none firings of axonal action potentials (spikes) could alone account for higher brain functions. Moreover, these simple binary states are comparable to unitary information states and switches in classical computers, which may not suffice in recapitulating consciousness given that consciousness presumably emerges from nonlinear dynamics of neuronal networks. Hameroff further argues that conscious states are sculpted by the modulation of electrochemical synapses and form metastable patterns identified with conscious experience (e. g. [16, 55]). Hameroff applies his analogy to a nonliving robot, and argues that if a robot were precisely constructed to mimic the brain activities, which modern neuroscience assumes to be relevant to consciousness, then the robot would be conscious regardless of its material basis. Lastly, Hameroff presents an overview of the elegant Orch OR model he and coauthor Roger Penrose have been working on over the last decade. Hameroff provides support for his own model, which has had a major impact on current thinking in consciousness studies, and goes on to further define the need for quantum approaches to consciousness studies.

Christopher Davia in his chapter entitled: “Life, Catalysis and Excitable Media: A Dynamic Systems Approach to Metabolism and Cognition” examines how life maintains its organization and describes an entirely novel principle that unites all living processes, from protein folding to macroprocesses. Davia’s hypothesis is that the same excitable media principle applies at every scale: living processes involve catalysis, biological processes mediate transitions in their environments, and enzymatic reactions act accordingly. By pinpointing enzyme catalysis as a prototypical process, Davia identifies energy dissipation as playing a major role in biology. Possible mechanisms contributing to excitable media are identified, including solitons and traveling waves, nondissipative and robust waves, all of which maintain their energy and structure in their biologically relevant environments. Particular emphasis is placed upon the relationship between microscopic instances of catalysis and traveling waves in excitable media. Pertinently to the topic of this volume, it is suggested that the brain is an excitable medium, and that cognition and possibly consciousness correlate with the spatiotemporal pattern of traveling waves in the brain. Davia offers this theory as an alternative to the functionalist perspective that underlies much of current theoretical biology. A key strength of his theory is that the same principle applies at multiple scales, potentially explaining how many biological processes that comprise an organism work and cooperate.

Avner Priel, Jack Tuszynski and Horacio Cantiello, discuss the biophysical model representing the dendritic cytoskeleton as a computational device. This chapter presents a molecular dynamical description of the functional role of cytoskeletal elements within the dendrites of a neuron. These authors present the working hypothesis that the dendritic cytoskeleton, which includes both microtubules and actin filaments, plays an active role in computations affecting neuronal function. Critical to their model is the assumption that cytoskeletal elements are affected by, and in turn regulate, a number of processes inside the neuron. Ion channel activity, MAPs and other cytoskeletal motors such as kinesin, for example, are viewed in terms of their interface with microtubules. Priel and coauthors go on to advance the novel and specific hypothesis that it is the C-termini protruding from the surface of a microtubule, existing in several conformational states, which lead to collective dynamical properties of the neuronal cytoskeleton. From a physics point of view, these collective states of the C-termini on microtubules have a significant effect on the ionic condensation and ion-cloud propagation. This is similar to what has been found recently for actin filaments. The authors provide an integrated view of their model using a bottom-up scheme. They marshal considerable evidence to support their model of ionic wave propagation along cytoskeletal structures impacting on channel function and computational capabilities of whole dendrites and entire neurons. The theoretical approach advanced in this chapter is conceptually consistent with the experimental evidence put forth by Nancy Woolf in her chapter.

Laxmidhar Behera and colleagues develop a theoretical brain model using a nonlinear Schrödinger equation. In the general scope, their model proposes the existence of a quantum process that mediates the collective response of a neural lattice representing the classical brain. The specific example used in their model is eye movements when tracking moving targets. By using a recurrent quantum neural network while simulating the quantum brain model, the authors find two novel phenomena. The first is that eyesensor data are processed in the classical brain, while a wave packet is triggered in the quantum brain. The second is that when the eye tracks a fixed target, the wave packet moves in a discrete mode, with jumps and rest periods reproducing experimental observations very accurately. These authors have accomplished a great deal and offer a very interesting theoretical development that combines the robustness of classical approaches with the quirkiness of quantum theories.

Elizabeth Behrman and her collaborators present a mathematical model of microtubules as a quantum Hopfield neural network. The motivation behind this work is the suggested existence of quantum computation in microtubule protein assemblies inside living cells as proposed by Hameroff and Penrose. The authors set up their equations within the constraints of a quantum Hopfield network with qubits representing tubulins interacting electrostatically by Coulomb forces. Simulations presented in this work focus on the existence of stable states, such as local minima, of the network. The authors report quantum information processing in microtubules is feasible, though at temperatures much lower than physiological temperatures. They conclude that microtubules can be used as information storage devices but not as quantum information devices at physiological temperatures.

Gordon Globus, in his chapter entitled "Consciousness and Quantum Brain Dynamics" argues that the opposition to quantum brain theory is deconstructed. The author refers back to quantum brain theory originated by Umezawa and coworkers, reiterating the differences between unimode quantum brain dynamics (QBD), a Hermitean-dual mode QBD and a non-Hermitean dual-mode QBD. Globus argues that unlike the non-Hermitean version, the Riemann hypothesis offers a unique approach. This chapter is rich in philosophical discussion and traces interesting connections to advanced mathematics.

Johnjoe McFadden outlines conscious electromagnetic field theory (CEMI) revealing seven clues to the nature of consciousness. The author argues that if consciousness is an epiphenomenon then, as scientists, we must turn aside and leave the topic to the philosophers and theologians to make sense of. However, consciousness does generate observable phenomena and thus belongs to the realm of empirical science. One undeniable example is that consciousness has had a major impact on the lives of philosophers, scientists and theologians who have studied the subject. In his chapter, McFadden examines the seven clues to the nature of consciousness and discusses how the conscious electromagnetic field theory (CEMI field theory) makes sense of them. As McFadden cogently argues, any successful theory of consciousness needs to include a physical mechanism enabling our conscious mind to interact with the matter of our brain.

Chris King, through the use of quantum cosmology addresses the hard problem of the conscious brain. The author explores a model resolving many aspects of the hard problem in consciousness research through cosmic subject–object complementarity. King's model combines a number of mathematical topics, including: transactional quantum theory, chaos, and fractal dynamics. These serve as a basis for a direct relationship between phase coherence in global brain states and anticipatory boundary conditions in quantum systems, which complement conscious perception and intentional will. King's aim is to describe unusual physical properties of excitable cells, which may form a basis for the evolutionary selection of subjective consciousness.

Paola Zizzi ambitiously deals with the issue of consciousness and logic in a model of a quantum-computing universe. The universe is described at various stages. The early inflationary universe is seen as a superposed state of quantum registers. In the end, at the close of the inflationary period, one universe is selected out of a superposition of many by a self-reduction mechanism. This kind of reduction is similar to Penrose's objective reduction (OR) model; moreover, it depends on gravity and can be numerically specified in terms of quantum registers (10^9 quantum registers). Zizzi then draws an analogy between the very early quantum-computing universe and our mind. Zizzi argues that events at the end of inflation of the universe (the so-called "Big Wow") acted to indelibly imprint on future minds to come, dictating future modes of computation, consciousness and logic. From this point on, the universe organized itself according to two computational modes: quantum and classical, like the two conformations assumed by the cellular automaton of tubulins in our brain, as in Hameroff's model. Zizzi speculates that the universe uses, as subroutines, black holes – quantum computers and quantum minds, which operate in parallel. He further suggests that the outcomes of the overall quantum computation are universal attributes endowed with subjective meaning. In other words, qualia are related to Planckian black holes. The author then considers two aspects of the quantum mind that are not algorithmic in the usual sense: the self and mathematical intuition. Zizzi argues the self corresponds to a self-measurement of a quantum state of superposed tubulins and that mathematical intuition is due to the consistent pattern of logic of the internal observer in a quantum-computing universe.

1.3 New and Notable Developments

In accordance with suggestions made in this book, it is imperative first to unequivocally demonstrate both theoretically and experimentally that quantum interactions exist at the atomic/molecular level. Only then is it possible to credibly build up to mesoscopic and macroscopic dimensions. One need not look to phenomena that are exceedingly difficult or impossible to measure to assess possible quantum level involvement. Electromagnetic and electrochemical energies are known to exist in neurons. Increased transport of proteins and receptors is likely to have an electromagnetic basis to the extent that this function is a result of microtubule computations. Electromagnetic events in the form of individual photons obey the principles of quantum mechanics and thus potentially bring with them intriguing phenomena such as wave propagation, wave interference, quantum entanglement, and collapse of the wave function.

1.3.1 An Electromagnetic Fingerprint of Transport Along Microtubules

Each chapter in this volume presents a viewpoint or model that provides a unique window into how a biophysical state might correlate with higher cognition. The perspective advanced in this introductory chapter is that a specific fingerprint defined by a particular electromagnetic state of a microtubular array potentially corresponds to a unique unit of cognition (e. g., a basic visual parameter, a sound, an irreducible idea, a morpheme, etc.). Recently, it has been shown that visual components can be represented musically [11]; hence the idea that there is one common type of energy underlying divergent percepts or qualia appears likely. Activation of one electromagnetic fingerprint could, in turn, activate another electromagnetic fingerprint, irrespective of sensory input. Thus, the model is able to account for the stream of consciousness and the fact that ideas self-perpetuate with their existence becoming increasingly abstract and independent from sensory inputs over time. Lastly, the subjective feels of this widespread pattern of electromagnetic energy can be specified according to those key physical properties of microtubules that influence the transport of proteins to synapses. Factors influencing kinesin-mediated transport include the protein conformation of tubulin and the nature of the C-termini (see [58]; Priel et al., this volume).

Not only is the protein conformation of tubulin critical to effective transport, motor proteins appear to alter the conformation of tubulin. Kinesin binding and that of the low molecular weight MAP, tau, significantly alter the direction of the protruding protofilament ridges along microtubules, which in turn influences their further binding abilities [52]. More than mere local adaptation to binding, microtubules may alter their conformation ahead of kinesin processivity [35], supporting the notion of long-range cooperative effects between tubulin dimers located along longitudinal protofilaments of microtubules. These biochemical relationships have consequences for electromagnetic fields. The dipole moment of tubulin depends on its configuration in the microtubule [21, 39, 40]. Thus, electromagnetic fields (and possibly quantum coherence) among microtubules could, in theory, be induced or inhibited by synaptic inputs that affect the protein conformation of tubulin directly or through alterations in kinesin or MAP binding. Synaptic effects upon microtubules could be mediated through ionic currents, by propagation via actin filaments [68], or by signal transduction cascades resulting in the phosphorylation of MAPs [51].

Due to lengthwise electric dipoles of tubulin dimers, information in the form of traveling waves propagated along microtubular tracks can, in principle, be transmitted between synapses with high fidelity [67]. MAP2 bridges keep microtubular arrays within the dendritic core parallel and antiparallel by aligning portions of polarized microtubules. The antiparallel alignment of microtubules, which specifically occurs in dendrites, would severely attenuate any electromagnetic field generated by microtubules, at least under baseline conditions. However, during enhanced kinesin-mediated transport, as is likely to occur with heightened synaptic activity, MAP2 bound to the microtubule would be perturbed and may even temporarily detach from the microtubule. A similar phenomenon might also occur due to dynein-mediated transport, which occurs largely in the opposite direction to that of kinesin-mediated transport. Assuming that at least some MAP2 stays attached to the antiparallel microtubules, keeping the dendritic array intact, any net unidirectional transport along the microtubule array (via oppositely directed kinesin and dynein motors traveling on oppositely directed tracks) should increase the strength of the electromagnetic field associated with the fingerprint and should further result in the spread of that electromagnetic field to adjacent microtubules. Once a sufficient number of microtubules were engaged in dynamically sending and receiving complementary electromagnetic energies, whole neuronal compartments (e. g., dendrites) might be expected to interact. Due to the parallel/antiparallel arrangement of microtubules in cortical dendrites and the ability of electromagnetic fields to pass from one dendrite to adjacent dendrites, information could, in principle, pass between neurons when such electromagnetic fields were sufficiently amplified as a result of changes in the binding of MAPs or kinesin. Quantum effects at the level of electron movement across an energy barrier in a hydrophobic pocket of tubulin can be related to electromagnetic waves traveling down microtubules because the hydrophobic pocket determines the overall conformation of tubulin and the overall conformation of tubulin regulates its binding to kinesin and MAPs and thus its ability to transport.

Due to their topographical arrangement, one can build the argument that electrochemical synapses are unlikely candidates for permanent storage of information. The electrochemical synaptic wiring of the brain is an enormously complex network, or is it? Viewed another way, the system is massive, but nonetheless built upon a simple principle that is redundantly executed. Each cortical area provides a highly organized representation of each part of a sensory field (e. g., visuotopic, tonotopic, somatotopic, etc.). This topographic representation is carried over to the next higher sensory field (e. g., from V1 to V2; from A1 to A2). One might imagine a cartoon of the entire cerebral cortex as multiple video monitors, each of which faithfully represents the sensory field from which all information supplying that area ultimately derives. While it is true that there are some 20 billion neurons and some 100 trillion synapses in the human cerebral cortex, so too does each sensory field afford the luxury of extremely high resolution. The fovea of the retina, for example, contains roughly 1 million receptor cells that relay information to the cerebral cortex, diverging to eventually drive the synaptic activity of at least 1 billion cortical cells. So the mammalian cortex has many neurons, and even more synapses; nonetheless, its connectivity can be readily grasped by one recurrent theme, repetitive high-resolution topographic representation. Despite this simple organizational plan, cells in cortical areas, in particular cells in higher sensory or association areas, inexplicably show correlated responses during cognitive tasks. Does this mean that activity at electrochemical synapses is the sole basis? Not necessarily so. An idea that has been around a long time, and has not been ruled out, is that electromagnetic events in neurons contribute in an important way. Our best imaging techniques to date do not distinguish electrochemical from electromagnetic activities in neurons. Both types of events require metabolic energy. Moreover, the two types of activities are likely to induce each other, although these interactions may be highly filtered.

One can also construct the argument that synaptic activity is less likely to be available to perceptual awareness than are quantum-level intracelluar events in brain microtubules. Experience alters the basic structure of dendrites, and as a consequence, would also alter any electromagnetic fields generated by microtubules as a result of transport proteins moving along them. As described in the beginning of this chapter, a rearrangement of the cytoskeleton occurs during early development, with learning, and with neurodegeneration underlying dementia. Listed below are five arguments against changes in efficacy for electrochemical synapses, alone, being responsible for permanent memory.

1. The topographic organization of virtually all cortical circuits, exemplified by the visual cortex, is largely one of point-to-point representation of labeled line sensory fields, with only a very small percentage of divergently projecting neurons [56]. This organization scheme is predominantly vertical; information from a specific part of a sensory MAP projects to a vertical minicolumn of cortex and then to a higher vertical minicolumn of cortex, and so on [41]. With the possible exception of local pericolumnar inhibition, cortical spread of information along the horizontal axis may not be as widespread as would be needed to account for widely interconnected neural network models. Strictly synaptic models (electrochemical) suggest complex neural networks increase synaptic weights (i. e. neurons that fire together wire together). Nonetheless, visual cortical regions do not have massively random interconnections among all parts of the visuotopic map, thereby making many of the changes in synaptic efficacy necessary for encoding complex perceptual features impossible.
2. Probabilistically speaking, no stimulus is ever going to activate the same set of electrochemical synapses twice. Visual stimuli, for example, are never exactly the same distance away, presented at exactly the same angle, or strike exactly the same part of the retina. Nonetheless, to activate a memory, as in perceptual recognition, one needs to have a critical degree of matching between the stimulus input and the pattern of change in synaptic efficacy. It is unlikely that the critical degree of matching would be met in the vast majority of cases. In the case of storage by a fingerprint electromagnetic wave, however, future inputs need not directly activate circuits responsible for storage. There is more flexibility in finding a match to new inputs, because electromagnetic waves can, in principle, pass from microtubule to microtubule and from dendrite to dendrite.
3. We perceive the world differently from the actual inputs. There are countless examples: fill-in phenomena, attentional distortion and masking. As we view any stationary scene, our eyes quickly make saccadic movements. Yet we perceive the scene as stationary, and not darting about [50]. Current neural networks rely on top-down information to account for this; yet it is not clear how a network of cells connected according to a strict topography would be able to generate a concept such as stationarity.
4. Although models of changes in synaptic efficacy, e. g., long-term potentiation or depression (LTP or LTD), offer great potential as memory mechanisms [37], one often overlooked problem is that large numbers of synapses are affected in concert. If only a few synapses exhibited LTP or LTD with each learning experience, then the entire cortical system

might have a near unlimited capacity, but since many synapses are affected by LTP, there appears to be a serious ceiling effect. Explanations such as, a large number of synapses are potentiated initially but only a few synapses remain permanently altered, still fail to account for the fact that we are able to process new stimuli immediately after learning. This means that potentiated synapses most likely participate in unrelated perceptual tasks.

5. Changes in the size and shape of synaptic spines following learning appear to be temporary, according to experimental observations [42]. This perhaps leaves us without much in the way of a biological correlate for permanent memory storage. The model presented here suggests that temporary changes in synaptic efficacy, which occur with learning or LTP, immediately induce permanent electromagnetic storage in the neuronal cytoskeleton, although that is fine tuned or expanded during memory considation. If, as predicted, the classical electromagnetic waves transmitted by microtubules, furthermore, bear a relationship to electron movements in the hydrophobic pockets of tubulin, then quantum entanglement provides a nearly unlimited storage capacity for associations.

The biophysical properties of microtubules are just beginning to be understood at the molecular and atomic levels and recent empirical evidence suggests quantum-based interactions occur between microtubules, at least under certain experimentally induced conditions. Two groups, one led by Watt Webb at Cornell and another led by Paul Campagnola and William Mohler at the University of Connecticut, observed that microtubules give rise to intense second-harmonic generation, a frequency doubling upon exposure to a sapphire laser in the 880 nm range. (Other frequencies were partially effective.) Microtubules were one of the few biological materials having electric dipoles that constructively interferred with the diploes of neighboring microtubules [9, 12]. This occurred for parallel microtubules in axons, but not for antiparallel microtubules in dendrites. This could be interpreted as a rudimentary kind of experimental evidence for quantum coherence among adjacent microtubules, because second-harmonic generation is a nonlinear quantum optics phenomenon. Webb noted that: "In sound waves, we can hear the second harmonic of a vibrating guitar string when the guitar body resonates and produces a tone twice as high in pitch as the original tone. The same thing happens with light waves, although no one knew it until lasers were invented, when a laser beam hits certain kinds of materials in our bodies."

Could such a phenomenon be expected to occur with natural learning or upon exposure to oscillatory input, an LTP-inducing tetanus or various pharmacological agents? To the extent that these induce electromagnetic energy, it is conceivable. In addition to being sensitive to electromagnetic radiation, microtubules may themselves produce this kind of energy. Second-harmonic generation by microtubules is consistent with their ferroelectric properties.

Materials with ferroelectric properties, i. e. exhibiting spontaneous symmetry breaking with respect to electrical polarization, are perhaps ideal for quantum computing and consciousness. Microtubules are implicated as generators of quantum electromagnetic radiation for the following reasons:

1. Materials that are nonlinear optically exhibit second-harmonic generation: microtubules are a salient example.
2. In second-harmonic generation, the most strongly enhanced wavelength is 880 nm, supporting the frequently overlooked reports of electromagnetic signaling by cells. Guenther Albrecht-Buehler [1] observed electromagnetic energy in the near-infrared region overlapping the 880 nm value that was generated by centrioles for the purpose of cell-to-cell communication, leading him to suggest that: "... one of the functions of microtubules may be to play the role of cellular 'nerves' ". Infrared light in this range of wavelengths also induces cell aggregation [2]. Since frequency (and hence wavelength) determines the long-range effect of dielectric polarization of a given microtubule, one would expect this effect to be length dependent just as the length of the guitar string determines the values of the harmonics. The distance between microtubules was shown to be critical in second-harmonic generation by microtubules.
3. Parallel orientations of microtubules in axons support frequency doubling, yet antiparallel orientations in dendrites do not. This may make sense in view of axial orientation of the net polarization vector. Whether this supports quantum coherence is not entirely clear. In principle it may, because this may be an example of a quantum of electromagnetic radiation propagating in a nonlinear medium. However, the medium (i. e. the microtubule) is not itself in a coherent state. That state is created by external means (i. e. by sending infrared radiation) and maintained as a coherent state. In other words, it is an induced coherent state. Moreover, it remains to be shown what holds true for living neurons that communicate with other neurons, with respect to the language of coherent states.
4. The role of motor proteins in this phenomenon may be crucial. The nonlinear polarized state of the microtubule depends on the conformations of tubulins, which depend on the interactions with kinesins, dyneins, and other motors. Microtubules may support a coherent state induced in them by external means depending on the conformational states. This may, in turn, regulate consciousness states.

1.3.2 Extrapolations to Mesoscopic and Macroscopic Levels

If quantum-mechanical properties of atoms can affect the behavior of whole proteins through the influence of electromagnetic waves, wave interference, and quantum entanglement, does this introduce the possibility of quantum nonlocal relationships at larger scales? There is some empirical evidence suggesting this may be possible.

A number of studies have been done using Faraday cages. These cages effectively block electromagnetic radiation. Hence correlations between electrophysiological activity in cells or in human subjects in different Faraday cages might be attributable to manifestations of quantum coupling or entanglement, bearing in mind that alternative explanations are possible.

Cultures of dopamine-containing ventral tegmental area cells derived from human stem cells and grown on circuit boards demonstrate an unusual nonlocal phenomenon that is not accounted for by classical physics [48]. Stimulating one culture with a 630 nm laser results in maximal levels of cross-correlational activity between the stimulated culture and another culture kept separate and shielded. Both cultures share the same nonlinear response properties. This effect is only seen in cells that derive from the same source. Thaheld [65] has proposed additional experiments to determine if there are Einstein–Podolsky–Rosen (EPR) nonlocal correlations between two neuron transistors. These experiments, which allude to quantum interactions in the whole brain, have the potential to explain a number of neural phenomena, including the binding problem, massively parallel searches, and associative memory.

It was during the mid-1990s that the first experiment was conducted indicating that a quantum nonlocal relationship might exist between the brains of different individuals [19]. Photostimulation causing a visual evoked potential (VEP) in one subject shielded in a Faraday cage, corresponded with a potential possessing a similar brain wave morphology in the brain of the nonstimulated subject located several meters away in another Faraday cage. This so-named transferred potential has been variously supported in some, but not all, subject pairs reported in the literature [61, 71]. Thaheld [66] has recently reviewed the earlier literature.

1.4 Conclusions

A number of authors in this book propose that quantum computing plays a role in human consciousness, although the counterview is also represented. A large number of contributors provide various arguments for microtubules being pivotal to consciousness, in particular, because they may well form the central nervous system of the cell. Quantum computations in microtubules, or in other brain proteins, may be a viable tenet, but how does the scientific community proceed to prove or disprove such an idea? Secondly, how does one extrapolate from essentially biophysical studies on brain proteins to assessments of higher cognitive functions in individuals alone or in groups? Within a single brain or mind, one might imagine that nonlocal quantum interactions occur in relation to neural connections or electromagnetic waves linking different neurons or brain areas. Considering small groups of individuals or large societies, we again have classical communication of information between individuals and the genetically determined similarity of neural tissue within the species. The resulting nonlocal phenomena may provide the basis for social psychological effects, such as emotional connection and empathy, as well as for group dynamics, such as polarization and unanimity. Both the nonlocal quantum effects and psychological effects described here are subtle, yet very real effects.

We hope that in assimilating these chapters we have posed some relevant questions and begun to address them.

Acknowledgement. The authors wish to thank the following individuals: Angela Lahee for encouragement, Adele Behar and Mike Weiner for constant support, Stuart Hameroff and Al Scott for inspiration and friendship, and Fred Thaheld for suggestions.

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