On Quantum Neural Computing

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Abstract

This paper examines the notion of quantum neural computing in the context of several new directions in neural network research. In particular, we consider new neuron and network models that lead to rapid training; chaotic dynamics in neuron assemblies; models of attention and awareness; cytoskeletal microtubule information processing; and quantum models. Recent discoveries in neuroscience that cannot be placed in the reductionist models of biological information processing are examined. We consider some characteristics of a quantum neural computer. We show that information is not a locally additive variable in a quantum computation; this property may be used to examine the nature of biological information structures.

1 Introduction

History tells us that paradigms of science and technology draw on each other. Thus Newton's conception of the universe was based on the clockworks of the day; thermodynamics followed the heat engines of the 19th century; and computers followed the development of telegraph and telephone. From another point of view, modern computers are based on classical physics. Since classical physics has been superseded by quantum mechanics in the microworld and animal behavior is being seen in terms of information processing by neural networks, one might ask the question if a new paradigm of computing based on quantum mechanics and neural networks can be constructed.

In recent years proposals have been made [3, 4, 12, 13, 14, 16, 42] for the development of computers based on quantum mechanics. In these schemes the quantum mechanical basis states are the logic states of the computer and the computation is a unitary mapping of these states into each other. Hermitian

Hamiltonians are specified that define the interactions. From another perspective these computers let the computation of several problems proceed simultaneously as in the evolution of a superimposition of states. By itself that is no better than several computers running in parallel. However, if one were to imagine a problem where the partially evolved computations of some of these superimposed states are used to find the solution then it can be shown that such a machine offers improved speed in the sense of complexity theory. In other words these proposals only deal with the question of the physics underlying basic computation; they do not consider the question of how a computation process leads to intelligence.

On the other hand, the mind, with its concomitant intelligence, is taken by some to be an emergent property of the complexity of the interconnections between the neurons. The concept of emergent property comes from chemistry, where the properties of water are taken to be "emerging" from the properties of hydrogen and oxygen. Although the properties of water could not originally be predicted from the properties of hydrogen and oxygen, it is assumed that in future, given the properties of atoms and the rules of their combinations, the properties of water would be completely explainable from the properties of its constituents. But the notion of an emergent property does not explain the rise of self-awareness.

Evidence for the unity of self-awareness or consciousness is provided by many neuropsychological experiments. These include split-brain research as well experiments on dissociation of behavior from its awareness as in prosopagnosia, amnesia, and blindsight. Schrödinger, Penrose and other scientists [26, 50, 52] have argued that as a unity consciousness should be described by a quantum mechanical type wavefunction. No representation in terms of networking of classical objects, such as threshold neurons, can model a wavefunction. Therefore, current computing machines, which are based on mechanistic laws of information processing, are unlikely to lead to machines that would match human intelligence.

It is sometimes argued that since quantum mechanics is not needed to describe neural processes, therefore it should not enter into any higher level descriptions of cognitive processes or of consciousness. The noisy environment characterizing nerve impulse flow should drown out any quantum mechanical behavior. In reality it has been experimentally determined that the retina does respond to single photons [1, 55] although the process that leads to such response is not understood. This was determined by directing dim flashes of light into one eye of a subject sitting in total darkness. The subject perceived a flash when only seven photons were absorbed. Since a population of about 500 rods in the eye absorbed the photons in a random spatial pattern, there was no likelihood that any single rod had absorbed more than one photon. The response itself is a macroscopic nerve signal.

Reductionist approaches to brain function do not capture the richness of biological information processing since they do not constitute a holistic paradigm.

Furthermore, according to quantum theory any indivisible phenomenon must be described by a wave function. This is why "elementary" particles, which in turn have "sub-particles" as constituents, are described by wavefunctions. One can even speak of a wavefunction for a macro-object and indeed for the entire universe. If consciousness is taken to be indivisible, one has no choice but to model it in a quantum mechanical fashion.

This paper presents several perspectives on this problem. For background we consider new neuron and network models that lead to rapid training, chaotic dynamics in neuron assemblies, models of attention and awareness, cytoskeletal microtubule information processing, and quantum models. Recent discoveries in neuroscience that cannot be placed in the reductionist models of biological information processing are examined. We learn from these studies that all biological systems cannot be viewed as connectionist circuits of components or systems; there exist dynamic structures whose definition is, in part, related to the environment and interaction with other similar systems. Nevertheless, there are biological structures that are well modelled by artificial neural networks. But in general biological systems define a concept of interdependence that is much stronger than the notion of connectionism that has been used in artificial neural networks. We call such interdependence as connectionism in its strong sense. One may postulate systems that are equivalent in their connectionist complexity to biological systems.

We define a quantum neural computer as a strongly connectionist system that is nevertheless characterized by a wavefunction. In contrast to a quantum computer [13, 14], which consists of quantum gates as components, a quantum neural computer consists of a neural network where quantum processes are supported. We consider some characteristics of a quantum neural computer and show that information is not a locally additive variable in such a computer.

2 Review Of New Directions In Neural Networks

The two opposite approaches of large scale modeling of the brain and investigating novel neural network structures that could explain the behavior of different neurophysiological structures have provided important new discoveries. Those who seek computer models of the brain have suggested that it may be viewed as a complex hierarchy of specialized processors with the highest or intermediate levels defining the conscious mind. But no centers where such consciousness resides have been found.

Considering visual perception, there exist an unlimited number of objects that one is capable of seeing. Early theories postulated "grandmother neurons," one for each image; this concept leads to a homunculus—the person's representation inside the brain which observes and controls, and also represents the self.

The postulation of grandmother neurons leads to logical problems: How can we have a number that would exhaust all possible objects, and how does the homunculus organize all the sensory input that is received? Thus grandmother neurons cannot exist, although there might exist some specialized structures for certain features. If a large number of neurons fire in response to an image, the problem of how this set fires in unison, defining the perception of the image, is called the "binding problem." No satisfactory solution to the binding problem is known at this time.

In reality the problem is much worse than the binding problem as stated above. The bound sets are in turn bound at a higher level of abstraction to define deeper relationships.

The reductionist approach seeks explanations of brain behavior in terms of a sum of the behaviors of lower level elements. Brain behavior has traditionally been examined at three different levels of hierarchy: (i) synaptic level or in terms of biochemical changes; (ii) neuron level as in maps of the retina in the visual cortex; (iii) that of neural networks where the information is distributed over entire neuron cell assemblies. But the explanation of brain function in terms of behavior at these levels has proved to be inadequate.

Skarda and Freeman [58] have argued that while reductionist models have an important function, they suffer from severe limitations. They claim that "perceptual processing is not a passive process of reaction, like a reflex, in which whatever hits the receptors is registered inside the brain. Perception does not begin with causal impact on receptors; it begins within the organism with internally generated (self-organized) neural activity that, by re-afference, lays the ground for processing of future receptor input... Perception is a self-organized dynamic process of interchange inaugurated by the brain in which the brain fails to respond to irrelevant input, opens itself to the input it accepts, reorganizes itself, and then reaches out to change its input ([58], page 279)." In other words, the neural networks that perform the perceptual processing function together within a holistic framework that defines the self-organizing principle.

There also exist speculations regarding consciousness in quantum physics [30, 52]. It has been argued that the collapse of the wavefunction occurs owing to its interaction with consciousness. Many physicists believe that science, as it stands now, is incomplete since it does not include consciousness. Another issue of relevance here is that of limits of computation. Computation in quantum mechanical Hamiltonian systems was described by Benioff, Feynman, Deutsch and others and it is reviewed in Landauer [42, 43]. A convergence of these questions will occur as quantum mechanical limits of computation are compared to the corresponding biological ones. In addition there exists the ancient Vedic tradition of meditation, or consciousness examining itself, that has led to a rich conceptual structure [20, 36, 38, 51]. How these structures might be related to current neurophysiological discoveries needs to be determined. It is significant that these studies claim to define a science of consciousness and that they speak in categories that are reminiscent of those of quantum mechanics. It is also remarkable that at least for Schrödinger, one of the creators of quantum mechanics, Vedic ideas were a direct source of inspiration [45, pages 170-3]. For a review of these parallels see [36, 38].

Certain specific directions in the problem areas listed above are now summarized.

On Some Recent Neuron And Network Models

Much of the neural network research done in the context of electrical engineering and computer science has been investigation of networks of McCulloch-Pitts type neurons, their training, and their applications. The limitations of such networks are now well-known. Their main use appears to be in pattern recognition and signal processing where they are competitive with statistical techniques.

Paralleling the generalization underlying the passage from classical to quantum mechanics, where the latter requires an additional imaginary dimension, it was argued [33, 35] that we need complex valued network models where the additional component carries global information. It was speculated that the neurophysiological analog of the additional component may lie in the timing information of the neurons. Another possibility is to locate it in the microtubule information [27].

It has been shown how memories may be retrieved from small fragments in a feedback network model [39, 32, 35]. Such models can be the basis of biological recall. But the question remains there: How are the fragments generated?

To consider the problem of the slowness of the backpropagation training algorithm for feedforward neural networks, a new network has been proposed [34, 37] that can be trained to yield a desired input-output mapping for binary patterns by inspection. Adding random noise values to the weights thus obtained enables such a network to generalize. Characteristics of this model are summarized in the work of Madineni [46] and Raina [53].

The speed of learning, and the simplicity of this procedure make the new model a plausible mechanism for biological learning in certain structures. Interesting issues that remain to be investigated include further development of this approach so that one can obtain continuous valued outputs and the development of competitive learning. But we cannot expect such models to provide any insight regarding holistic behavior.

Chaotic Dynamics

Freeman and his associates (e.g. [17, 19]) have argued that neuron populations are predisposed to instability and bifurcations that depend on external input and internal parameters. Freeman claims that chaotic dynamics makes it "possible for microscopic sensory input that is received by the cortex to control the macroscopic activity that constitutes cortical output, owing to the the selective sensitivity of chaotic systems to small fluctuations and their capacity for rapid state transitions."

One significance of this work is to point out the gulf that separates simple input-output mapping networks used in engineering research from the complexity of biological reality. But the claim that chaotic dynamics in themselves somehow carry the potential to explain macroscopic cortical activity relating to the binding problem seems to be without foundation.

The nonlinearities at the basis of chaos are seen as the basis of a self-organizing principle [58]. Considering these ideas for the olfaction in a rabbit, Freeman [18] says: "The olfactory system maintains a global chaotic attractor with multiple wings or side lobes, one for each odor that a subject has learned to discriminate. Each lobe is formed by a bifurcation during learning, which changes the entire structure of the attractor, including the pre-existing lobes and their modes of access through basins of attraction. During an act of perception the act of sampling a stimulus destabilizes the olfactory bulbar mechanism, drives it from the core of its basal chaotic attractor by a state transition, and constrains it into a lobe that is selected by the stimulus for as long as the stimulus lasts, on the order of a tenth of a second... In this way the cortical response to a stimulus is "newly constructed"... rather than retrieved from a dead store."

The above theory is very attractive for the olfactory system but it remains very limited in its scope. It is hard to see how it could be generalized for more complex information processing.

Attention, Awareness, Consciousness

Milner [49] speculated that neurons responding to a "figure" fire synchronously in time, whereas neurons responding to the background fire randomly. More recently von der Malsburg and Schneider [47] have proposed a correlation theory to explain a temporal segregation of patterns.

Crick and Koch [10] have considered the problem of visual awareness. They distinguish between two kinds of memory: "very short term" or "iconic," and a slower "short term" or working memory. Iconic memory appears to involve visual primitives, such as orientation and movement, and it appears to last half a second or less. On the other hand, short term or working memory lasts for a few seconds, and it deals with more abstract representations. This memory also has a limited capacity and it has been claimed that this capacity is about seven items.

For the "short term" memory Crick and Koch postulate an attentional mechanism that transiently binds together all those neurons whose activity relates to the different features of the visual object. They argue that semi-synchronous coherent oscillations in the 40–70 Hz range are an expression of this mechanism. These oscillations are sensory-evoked in response to auditory or visual stimuli. But postulating such a mechanism merely trade one problem for another: how the neurons that participate in these oscillations get bound is still not explained.

This theory is an extension of the earlier "searchlight" hypothesis relating to awareness. It shifts the basis of awareness to a more abstract mechanism of attention.

This work has led to an interesting re-examination of the question of what may be taken to define the loss of consciousness. In the standard view, anesthesia leads to four distinct effects: motionlessness in the face of surgery, attenuation or abolition of the autonomic responses like tachycardia, hypertension, and so on that would normally accompany surgery, lack of pain, and lack of recall. Use of EEG's shows little difference between natural sleep and the anesthetized state. On the other hand, Kulli and Koch [41] argue that the loss of consciousness, as defined by these four effects, is best represented by the loss of the 40 Hz sensory-evoked oscillations. On the other hand, deepening anesthesia has been seen as progressive loss of complexity of the EEG phase plot [21]. From a functional point of view one may see a prevention of memory consolidation from input to long-term memory storage as one of the consequences of anesthesia; other cognitive and motor functions may be similarly inhibited.

The structuring of events in dreams gives us important clues regarding sequencing of events by the mind. My father explained to me in 1955 that certain dreams run as scripts. Thus a foot slipping off another in sleep may be accompanied by a dream about falling off a precipice. That such a script includes an appropriate sequence of events preceding the climax indicates that the mind rearranges the events so that the dream appears to have started before the slipping of the foot.

Experiments focusing on time delays and rearrangement of events by consciousness have been performed by H.H. Kornhuber and his associates and by Benjamin Libet. Kornhuber and his associates [11] found that the readiness potential, the averaged EEG trace from the precentral and parietal cortex, of a subject who was asked to flex his finger built up gradually for a second to a second and a half before the finger was actually flexed. This slow build-up of the readiness potential may be viewed as a response of the unconscious mind before it it passes into the conscious mind and is expressed as a voluntary movement. In Libet's work [45] the subjects were undergoing brain surgery for some reason unconnected to the experiment and they agreed to electrodes being placed at points in the brain, in the somato-sensory cortex. It was found that when a stimulus was applied to the skin, the patient became aware of this half a second later although the brain would have received the signal of the stimulus in barely a hundredth of a second. Furthermore, the patients themselves believed that no delay had taken place in their becoming aware of the stimulus!

In further experimentation the somatosensory cortex was electrically stimulated within half a second of skin stimulus. A backward masking phenomenon occurred and the patient did not become aware of the earlier skin sensation. Now Libet initiated a persistent cortical stimulation first and then within half a second he also touched the skin. The patient now was aware of both the stimulations but he believed that the skin stimulation preceded that of the cortex. In other words, this established that the subject did extrapolate the skin-touching sensation backwards in time by about half a second. These experiments also demonstrate how brain works as an active agent, reorganizing itself as well as the information.

Cytoskeletal Networks

Recursive definition is one of the fascinating characteristics of life. For example, natural selection does not work only at the level of species but also at the level of the individual and that of the nerve cells of the developing organism [9]. Purposive behavior characterizes human societies as also the societies of other animals such as ants. Recursion may be seen regarding information processing as well down from animal societies to the neural structures of the individual or perhaps further down to the cytoskeleton of the cell. C.S. Sherrington [57] argued that even single cells possess what might be called minds: "Many forms of motile single cells lead their own independent lives. They swim and crawl, they secure food, they conjugate, they multiply. The observer at once says 'they are alive'; the amoeba, paramaecium, vorticella, and so on. They have specialized parts for movement, hair-like, whip-like, spiral, and spring-like... [Of] sense organs ... and nerves there is no trace. But the cell framework, the cyto-skeleton, might serve."

Hameroff and his associates [23, 27] have argued that microtubules that are the cytoskeletal filamentous polymers to be found in most cells, perform information processing. Microtubules are hollow cylinders 25 nm across. In [27, 22] interactions between the electric dipole field of water molecules confined within the hollow core of microtubules and the quantized electromagnetic radiation field were considered. These and Bose-Einstein condensates in hydrophobic pockets of microtubule subunits were taken to be responsible for microtubule quantum coherence. It was suggested that optical signalling in microtubules would be free from both thermal noise and loss, and that this may provide a basis for biomolecular cognition and a substrate for consciousness. But even if this were the mechanism, it is not explained how quantum coherence transforms into or represents consciousness.

The microtubule information may carry global features that seem to be essential for biological information processing.

Quantum Models, Binding Of Patterns, Wholeness

It is the notion of unity that awareness appears to possess that has driven the search for quantum neural models. Also many aspects of consciousness are distributed over wide areas of the brain. These issues are summarized in [36] and [52]. But the presence of noise and dissipation inside the brain makes the development of such models a daunting task. There exist other quantum models of computation, defined more by possibility rather than practical considerations [43].

Artificial neural network research has stressed pattern recognition and input-output maps. The development of machines that can match biological information processing requires much more than just pattern recognition. Corresponding to an input not only are many sub-patterns bound together, but there is also generated other relevant information defining the background and the context. This is the analog of the binding problem for biological neurons and therefore further progress in the design of artificial neural networks appears to depend on the advances in understanding brain behavior.

From the perspective of wholeness it appears that a drastic change of perspective may be necessary to solve the current problems. Consciousness is a recursive phenomenon: not only is the subject aware but he is also aware of this awareness. If one were to postulate a certain region inside the brain from where the searchlight is shown on the rest of the brain and which provides the unity and wholeness to the human experience, the question of what would happen if this searchlight were to be turned on itself arises.

In summary neural network research is now beginning to deal with questions of organization, awareness, and consciousness. This constitutes an important frontier where the concerns of neurophysiologists, computer scientists, psychologists have come together. But these studies have been largely unsuccessful in explaining the 'synthetic' part of cognition. On the other hand, quantum or holistic models related to a neural system have not been equally well studied.

3 Artificial Neural Networks, Indivisible Phenomena, And Animal Intelligence

To achieve the marvellous information processing ability of animals it is natural to investigate the neural structure of the brain and relate it to a hypothesized nature of the mind. If brain structure is neuronal then cognitive capabilities should be found for networks of neurons. But note the argument [54] that neuropsychology itself is flawed since it does not take into account the notion of self, which is why it is hard put to explain phenomena such as that of phantom limbs [48].

Artificial neural networks have almost exclusively used the threshold circuit model of the neuron [8], although there is evidence that the threshold model does not represent biological reality closely enough [44]. A threshold neuron is a device that functions like an electronic circuit and a network of such devices can only execute algorithms and not have true cognitive abilities that require awareness of constantly shifting context.

The study of neural computers was inspired by possible parallels with the information processing of the brain. It was proposed that artificial neural networks constituted a new computing paradigm. But our experience with these networks has shown that such a characterization is incorrect. When simulated they represent sequential computing. In hardware, they may be viewed as a particular style of parallel processing but as we know parallel computing is not a departure from the basic Turing model. Neither does the use of continuous values provide us any real advantage because such continuous values can always be quantized and processed on a digital machine. Artificial neural networks were assumed to offer a real advantage in the solution of optimization problems. However, the energy minimization technique, while sound in theory, fails in practice since the network gets stuck in local minima.

It has been argued that cognitive abilities arise from a continuing reflection on the perceived world. This question of reflection is central to the brain-mind problem and the problem of determinism and free-will (see for example [30, 52]). A dualist hypothesis (for example [15]) to explain brain-mind interaction or the process of reflection meets with the criticism that this violates the conservation laws of physics. On the other hand a brain-mind identity hypothesis, with a mechanistic or electronic representation of the brain processes, does not explain how self-awareness could arise. At the level of ordinary perception there exists a duality and complementarity between an autonomous (and reflexive) brain and a mind with intentionality. The notion of self seems to hinge on an indivisibility akin to that found in quantum mechanics. This was argued most forcefully by Bohr, Heisenberg, and Schrödinger (e.g. [50]).

The principle of complementarity, as a commonly used approach to the study of the individuality of quantum phenomena, goes beyond wave-particle duality. In the words of Bohr:

> The crucial point [is] the *impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear.* In fact, the individuality of the typical quantum effects finds its proper expression in the circumstance that any attempt of subdividing the phenomena will demand a change in the experimental arrangement introducing new possibilities of interaction between objects and measuring instruments which in principle cannot be controlled. Consequently, evidence obtained under different experimental conditions cannot be comprehended within a single picture, but must be regarded as complementary in the sense that only the totality of the phenomena exhausts the possible information about the objects ([7], page 39).

Observe that complementarity is required at different levels of description. But just as one might use a probabilistic interpretation instead of complementarity for atomic descriptions, a probabilistic description may also be used for cognitive behavior. However, such a probabilistic behavior is inadequate to describe the behavior of individual agents, just as notions of probability break down for individual objects.

According to complementarity, one can only speak of observations in relation to different experimental arrangements, and not an underlying reality. If such an underlying reality is sought then it is seen that the framework of quantum mechanics suffers from paradoxical characteristics. One of these is non-local correlations that appear in the manner of action at a distance [2, 56] . But quantum mechanics remains a very successful theory in its predictive power.

Consider again the similarity between the thought process and the classical limit of the quantum theory. The logical process corresponds to the most general type of thought process as the classical limit corresponds to the most general quantum process. In the logical process, we deal with classifications. These classifications are conceived as being completely separate but related by the rules of logic, which may be regarded as the analogue of the causal laws of classical physics. In any thought process, the component ideas are not separate but flow steadily and indivisibly. An attempt to analyze them into separate parts destroys or changes their meanings. Yet there are certain types of concepts, among which are those involving the classification of objects, in which we can, without producing any essential changes, neglect the indivisible and incompletely controllable connection with other ideas.

Investigations of subhuman animal intelligence present other riddles. It had long been thought that the cognitive capacities of the humans were to be credited in part to the mediating role of the inner linguistic discourse. Research has shown that animals do think but cannot master language, so the question arises as to how thinking can be done without language [59]. Herrnstein [24] summarizes the evidence thus:

> Pigeons and other animals can categorize photographs or drawings as complex as those encountered in ordinary human experience. The fundamental riddle posed by natural categorization is how organisms devoid of language, and presumably also of the associated higher cognitive capacities, can rapidly extract abstract invariances for some (but not all) stimulus classes containing instances so variable that we cannot physically describe either the class rule or the instances, let alone account for the underlying capacity.

Animal intelligence is based on processing of gestalts. Experiments on animals, such as the one done by Herrnstein [24] where pigeons were to discriminate scenes that contained trees from others that did not, can be used as models for testing artificial intelligence of computers. Current neural networks or AI programs cannot match such performance which is another reason one is entitled to examine the quantum paradigm in relation to neural structures.

Another useful perspective on animal behavior is its recursive nature. Considering this from the bottom up, animal societies have been viewed as "superorganisms". For example, the ants in an ant colony may be compared to cells, their castes to tissues and organs, the queen and her drones to the generative system, and the exchange of liquid food amongst the colony members to the circulation of blood and lymph. Furthermore, corresponding to morphogenesis in organisms the ant colony has sociogenesis, which consists of the processes by which the individuals undergo changes in caste and behavior. Such recursion has been viewed all the way up to the earth itself seen as a living entity. Parenthetically, it may be asked whether the earth itself, as a living but unconscious organism, may not be viewed like the unconscious brain. Paralleling this recursion is the individual who can be viewed as a collection of several "agents" where these agents have sub-agents which are the sensory mechanisms and so on. But these agents are bound together and this binding defines consciousness.

The model of *social computing*, described by the author several years ago [31], was an attempt to describe the processing that takes place in a society of individuals without a conscious notion of a collective self. What we seek now is a model where such a notion of identity exists.

4 Characteristics Of A Quantum Neural Computer

By a quantum neural computer we mean a (strongly) connectionist network which is nevertheless characterized by a wavefunction. The question of how such a wavefunction arises must be set aside for this paper since we are only interested in considering the computational potential of such a supposition. In parallel to the operational workings of a quantum model we can sketch the basic elements of the working of such a computer. Such a computer will start out with a wavefunction, reflecting the state of the self-organization of the connectionist structure, that is a sum of several different problem functions. After the evolution of the wavefunction the measurement operator will force the wavefunction to reduce to the correct eigenfunction with the corresponding measurement that represents the computation.

States of quantum systems are associated with unit vectors in an abstract vector space V, and observables are associated with self-adjoint linear operators on V. Consider the self-adjoint operator $\hat{f}$. We can write

$$\hat{f}\psi_i \;=\; f_i\psi_i$$

where ψ_i are the eigenvectors and f_i are the eigenvalues. The ψ_i are the wavefunctions and f_i represent the corresponding measurements. When ψ_i are a complete orthonormal set of vectors in V, we have $\psi_i\psi_j^* = \delta_{ij}$. Also any wavefunction ψ in V can be written as a linear combination of the ψ_i. Thus

$$\psi \;=\; \sum_i c_i\psi_i$$

where the complex coefficients are given by

$$c_i = \int \psi \psi_i^* dq$$

and q represents the configuration space. The sum of the probabilities of all possible values f_i equals unity:

$$\sum |c_i|^2 = 1$$

When an observation is made on an object characterized by a wavefunction ψ, the measurement process causes the wavefunction to collapse to the eigenfunction ψ_i that corresponds to the measurement f_i. This measurement itself is obtained with the probability $|c_i|^2$.

From a functional point of view this has parallels with the workings of a feedback neural computer. In such a computer the final measurement is one of the stored "eigenvectors" X_i where the neural computer is itself characterized by the synaptic interconnection weight matrix T, so that

$$sgm T X_i = X_i$$

where sgm is a nonlinear sigmoid function, so as to define a X with discrete component values.

The differences between the quantum mechanical framework and the above equation are the non-linearity introduced by the sigmoidal function and, more importantly, the fact that the matrix T is like one of the many measurement operators that would be defined in a quantum mechanical situation. In other words, a neural network is associated with a single measurement operator, whereas a quantum computer is associated with a variety of measurement operators.

Equivalently, we may view a quantum computer to be a collection of many neural computers that are "bound" together into a unity. The view of the cognitive process representing self-organized neural activity implies that each such process does set up what may be considered a different neural computer. The set of the self-organized states may then be viewed as representing a collection of neural structures that are bound together. The search for a local mechanism for this binding is as difficult as for the binding problem mentioned in Section 2. If on the other hand, we postulate a global function defining such a binding, then we speak of a quantum neural computer.

If the wavefunction was associated with several operators then the neural hardware for a specific problem will secure its solution. The measurement process will appear instantaneous after the decision to choose a specific measurement has been made. But how this choice might be made constitutes another problem.

Some of the characteristics of such a model are:

- It explains intuition, or the spontaneous computation of the kind performed in a creative moment, as has been reported by Poincaré, Hadamard, and Penrose [52].
- A wavefunction that is a sum of several component functions explains why the free-running mind is a succession of unconnected images or episodes. The classical neural model does not explain this behavior.
- One can admit the possibility of tunnelling through potential barriers. Such a computer can then compute global minima, which cannot be done by classical neural computer, unless by the artifice of simulated annealing. (The simulated annealing algorithms may not converge.)
- Non-local effects of quantum dynamics may be at the basis of the communication between conscious individuals.
- Being a linear sum of a large (or infinite) number of terms, the individual can shift the focus to any desired context by the application of an appropriate measurement hardware that has been designed through previous exposure (reinforcement) or through inheritance. Such a shifting focus is necessary in speech or image understanding.

5 On Quantum Information

That a quantum neural computer will have characteristics different from that of a collection of classical computers is seen from an examination of information. In contrast to classical systems, information in a quantum mechanical situation is affected by the process of measurement. If a linearly polarized photon strikes a polarizer oriented at 90° from its plane of polarization, the probability is zero that the photon will pass to the other side. If another polarizer tilted at 45° is placed before the first one, there is a 25 percent chance that a photon will pass both polarizers. By the process of measurement the 45° polarizer transforms the photons so that half of the initial photons can pass through it. The collapse of the wavefunction also causes non-local effects. These characteristics can be looked for in determining whether biological information systems should be considered quantum.

We consider the EPR experiment [2, 56] from an information theoretic viewpoint. In its Bohm variant, a pair of spin one-half particles, A and B, have formed somehow in the singlet spin state and they are moving freely in opposite directions. The wavefunction of this pair may be represented by

$$\frac{1}{\sqrt{2}}\left(V^+W^- \;-\; V^-W^+\right)$$

where V^+ and V^- represent the measurements of spin $+1/2$ and $-1/2$ for particle A and W^+ and W^- represent the measurement of $+1/2$ and $-1/2$ for particle B.

The EPR argument considers the particles A and B to have separated. Now if a measurement is made on A along a certain direction, it guarantees that a measurement made on B along the same direction will give the opposite spin. The important point here is that the spin is determined as soon as, but not before, one of the particles is measured. This has been interpreted to mean that knowledge about A somehow reduces the wavefunction for B in a specific sense. In other words, the EPR correlation has been taken to imply a non-local character for quantum mechanics, or instantaneous action at a distance. To reexamine these questions in an information-theoretic perspective, it is essential to determine the extent of information obtained in each measurement.

Given a spin one-half particle, an observation on it produces $\log_2 2 = 1$ bit of information. A further measurement made along a direction at an angle of θ to the previous measurement leads to a probability $cos^2\theta/2$ that the measurement would give the same sign of spin, and a probability $\sin^2\theta/2$ that it will give spin of the opposite sign. The information associated with the second measurement is

$$H(\theta) = -\cos^2\frac{\theta}{2}\log_2\cos^2\frac{\theta}{2} - \sin^2\frac{\theta}{2}\log_2\sin^2\frac{\theta}{2}$$

The average information considering all angles is:

$$H_{av} = \frac{1}{\pi}\int_0^\pi H(\theta)d\theta = 1 - \log_2\sqrt{e}\ \text{bits} = 0.27865\ \text{bits}.$$

In other words, the information obtained from the second measurement is somewhat less than a quarter of a bit. These sequential experiments are correlated. It is also important to consider that all further measurements provide exactly 0.27865 bits of information. This indicates that information in a quantum description is not a locally additive variable.

5.1 Information In The Experimental Setup

Now consider the information to be obtained from the measurement of spin of two half-spin particles that are correlated in the EPR sense. If information were additive then the first measurement provides one bit of information and after the end of the second measurement we have a total of 1.27865 *bits*.

Since the EPR correlation reveals the spin of the particle B, as soon as the measurement of A has been made, one might infer that the information that the two arms of the experimental setup provide equals 0.27865 bits. But in reality we cannot do so as the calculus for information, in a quantum description, is unknown. Not being locally additive, the information in the experimental setup cannot be used in subsequent repetitions of the experiment.

In a study several years ago [28, 29] it was argued that the fundamental Heisenberg uncertainty was compensated by information in terms of new symmetries of the quantum description. A calculation of this information yielded plausible results regarding the number of such symmetries. The analysis given here provides further elaboration of that idea. Although we appear to be unable to use the information in the various measurements, it is clear that the experimental setup itself plays a fundamental role in our knowledge. From another perspective, information can be associated with the angular (as well as spatial) position of an object. Nevertheless, this information cannot be considered in a local fashion. Or in other words, this information cannot be considered separately for the components of the system. In the context of a quantum neural computer it means that certain behavioral characteristics of such a machine would depend on how the measurements on it are made. If such measurements are stored in the machine, then this experience can only be regarded as an *interaction* between the machine and the environment; this is precisely what characterizes the experience of biological organisms[5].

It has been argued that information in biological information processing exhibits other non-local characteristics as well. Such behavior may represent further parallels between the quantum mechanical paradigm and biological reality.

6 On Building A Quantum Neural Computer

In the previous sections we have argued that humans and other animals perform what might be called quantum neural computing. If we accept the reverse of this claim then a quantum neural computer would be characterized with life and consequently consciousness. On the other hand, ordinary machines cannot be conscious since they do not come with a set of potentialities that consciousness provides. Machines are therefore like the neural hardware that provides extension. A machine that is so designed so that it has infinite set of potentialities would be alive.

But where does consciousness then reside? As a field one cannot take it to be localized. Considering the parallel of the wavefunction, it is a unity and it cannot be taken to be identical to the physical body although it is associated with it. Recently Hameroff and his collaborators [23, 27] have suggested that the sub-neural structures called microtubules provide coherent information transmission that leads to the development of a quantized field that solves the "binding problem" and explains the unitary sense of self. These cytoskeletal microtubules, which provide structural support to cells, are hollow cylinders 25 nanometers in diameter whose walls are made of subunit proteins known as tubulin. Each tubulin subunit is a 8-nm dimer that is made up of two slightly different classes of 4-nm dimers known as *alpha* and *beta* tubulin. Hameroff has argued that the quantum dynamical system of water molecules and the quantized electromagnetic field confined inside the hollow microtubule core manifests a collective dynamics by which coherent photons are created inside the microtubule [15]. But the question of why consciousness characterizes only certain cells, although microtubules are to be found in all cells, is not answered by this theory.

It is possible also to see the microtubule information as providing the "imaginary" component in the complex neural information that was described in [33, 35]. If this is the mechanism that provides the simultaneous global and local information which is essential for artificial intelligence tasks then it is clearly not feasible to build such quantum neural computers at this time because microtubule information processing is still imperfectly understood.

7 Conclusions

This paper presents arguments for a holistic computing paradigm that has parallels with biological information processing and with quantum computing. In this paradigm inputs trigger an internal reorganization of the connectionist computer that makes it selective to the input. But such a holistic paradigm suffers from several paradoxical aspects. No wonder, the determination of the phenomenological correlates of the holistic function, and therefore the design of a computer that operates in this paradigm, remain perplexing problems.

A quantum neural computer represents an underlying quantum system that interacts with classical measurement structures composed of neural networks. This parallels the basic quantum theory framework where measurement is to be performed using macroscopic apparatus. Learning by a biological system then represents the development of the measuring instruments, which are the neural structures in the brain. This picture still needs to address other questions, such as how in response to a stimulus does the brain reorganize itseld so as to pick the appropriate neural network for measurement? And how does the unity of the wavefunction lead to self-awareness? Unless we consider all matter to be conscious, we must take consciousness to be an emergent property of a quantum system that requires a certain structural basis supporting specific neuronal activity.

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Notes

- *This is not the final version of the paper as it has appeared in the journal.* Check the journal printed copy. Note that the page numbers in the printed version are 143-160.

- For a much more comprehensive study of qnc see Subhash C. Kak, "Quantum neural computing", In *Advances in Imaging and Electron Physics.* Peter Hawkes (editor). Academic Press, 1995.