Active Agents, Intelligence and Quantum Computing

Subhash Kak
Department of Electrical & Computer Engineering
Louisiana State University
Baton Rouge, LA 70803-5901, USA
FAX: 225.388.5200; Email: kak@ee.lsu.edu

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Abstract

This paper reviews evidence from neuroscience and quantum computing theory in support of the notion of autonomy in the workings of cognitive processes. Deficits in speech, vision, and motor abilities are described to show how cognitive behaviour is not based just on incoming sensory data. Active agents, to which the conscious mind may not have access, are described. Recent developments in quantum computing, of relevance to machine intelligence, are also examined.

1 Introduction

In the naive view, the mind processes the signals coming into the brain and obtains its understandings in the domains of seeing, hearing, touching, tasting, and so on using its store of memories. But in reality, a cognitive act is an active process where the selectivity of the sensors and the accompanying processing in the brain is organized based on the expectation of the cognitive task and on effort, will and intention. It is now generally agreed that intelligence must be seen as a result of the workings of numerous active cognitive agents. If we could properly assess the capacities of these agents, it would help us better appreciate the power of natural intelligence and provide directions for future research in machine intelligence.

The reductionist approach to artificial intelligence (AI) emerged out of an attempt to mechanize logic in the 1930s. In turn, AI and computer science influenced research in psychology and neuroscience and the view developed that a cognitive act should be viewed as a logical computation. This seemed reasonable as long as classical computing was the only model of effective computation. But with the advent of quantum computing theory, we know that the mechanistic model of computing does not capture all the power of natural computation[32, 23, 19].

Classical computers work on classical logic and they may be viewed as an embodiment of classical physics. Quantum computers, on the other hand, are based on the superpositional logic of quantum mechanics, which is a different paradigm. Conventional explanation sees consciousness arising as an emergent property of the classical computations taking place in the circuits of the brain, but this does not address the question of how thoughts and feelings arise.

The other view is to consider consciousness as one of the grounds of reality, together with space, time and matter. Consciousness and space-time-matter are complementary because consciousness needs the support of matter and without observers it is meaningless to speak of a universe. Also remember that our idea of the physical world is constructed out of mental experiences. If I give primacy to this mental experience then I am an idealist, but if I give primacy to the contents of this mental experience then I am a materialist. If I believe that both these have an independent existence then I am a dualist.

In going beyond reductionism it is assumed that quantum processing in the brain, given appropriate neural hardware, leads to awareness. This model is similar to the classical model in that computational structures of a certain complexity are required before awareness can emerge. But there is a basic difference in the nature of processing in the two models.

It is useful to note that there exist several states of consciousness: wakefulness, sleep, dream-sleep, coma, hunger and thirst, love and anger, interest and boredom which have distinct neurochemical signatures. These different states may be taken to be modifications caused by the neural hardware of a universal state. The contents of consciousness are our perceptions. Due to the subjective nature of perceptions, often one eschews this term and speaks only of attention.

The case that quantum computing is at the basis of biological information processing and, consequently, the explanation for the power of animal intelligence, is based on the following elements:

- *Philosophical.* At the deepest level of description nature is quantum-mechanical. The world of mathematics, as a product of the human mind, sits on top of the sequence physical → chemical → mental → ideational (mathematical). Since our ideas (dressed in a mathematical form) are able to describe the quantum-mechanical physical reality, the power of information processing in the brain should equal the power of quantum mechanics[23]. Another argument is that quantum mechanics as a universal theory should apply to information and organization and so the information processing of the brain cannot be understood but in quantum mechanical terms[12, 13, 14, 15].

- *Neurophysiological.* The interior of living cells is organized around the cytoskeleton which is a web of protein polymers. The major components of the cytoskeleton are the microtubules, that are hollow tubes 25nm in diameter, consisting of 13 columns of tubulin dimers arranged in a skewed hexagonal lattice. Researchers have argued that the microtubules support coherent, macroscopic quantum states. They see brain processing as a hybrid quantum/classical computation[10].

- *Self-awareness.* Awareness implies conscious choice and this has been compared with a reduction to one-out-of-many possibilities of quantum mechanics. More directly, since there is no credible reason that awareness is a result of the degree of complexity of neural mechanisms doing classical computing, it is reasonable to take it as a fundamental attribute of reality which is manifested by neural hardware running a quantum process.

The notion of "self", which provides a unity to experience, is then a consequence of favourable neural hardware tapping the ground consciousness[25, 23, 15].

- *Behavioral science.* Human and non-human animal intelligence appear to have features that lie beyond the capacity of the most powerful machines[14, 15]. Conceptualization is not unique to humans and ability to use language is not a pre-condition to cognition or abstract processing. Since we associate linguistic analysis with classical logic, one may presume that cognition is based upon some non-computable program[23]. Intelligent behavior may be viewed as adaptation to a changing environment. Paralleling adaptive behaviour is the continual self-organization in the brain. Analogously, a quantum system may be viewed as responding to its measuring apparatus (environment) by changing its state. Although non-quantum models for self-organization can be devised, only a quantum approach appears to satisfy different attributes of mental activity.

Many ancient cultures recognized the limitations of mechanistic logic in understanding the autonomy of individuals. The richest textual tradition on this field comes from India whose earliest literature called the Veda (before 2000 BC) which declares reality as transcending the subject-object distinction and then self-consciously describes itself as a narrative on the nature of consciousness. Specifically, the texts speak of the cognitive centers as individual, whole entities which are, nevertheless, a part of a greater unity. The cognitive centers are called the *devas* (gods), or points of light. The devas are visualized in a complex, hierarchical scheme, where some are closer to the autonomous processes of the body and others are nearer creative centers. Mirroring the topology of the outer reality, the inner space of consciousness is seen to have a structure. The Vedic texts divide the capacities of the mind in various dichotomies, such as high and low, left and right, and so on[16, 17, 18].

Parallels between the Vedic view and quantum theory are well known[15, 16]. For example, both suggest that reality is consistent only in its *primordial, implicate* form[2, 4]. The Vedas insist that speech and sense-associations cannot describe this reality completely. In quantum physics, use of ordinary logic or language leads to paradoxes such as present can influence the past, effects can travel instantaneously, and so on.

Various Indian philosophical schools describe the Vedic theories of mind in detail. In one of these schools called Vaisheshika, the mind is considered to be atomic and of point-like character, anticipating Leibniz's theory of monads.

The quantum mechanical approach to the study of consciousness has an old history and the creators of quantum theory were amongst the first to suggest it. More recently, Pribram[26], Stapp[32], Hameroff[10, 23], Penrose[23], Jibu and Yasue[11] and others have proposed specific quantum theoretic models of brain function. But there in no single model that has emerged as the favored one at this point. For the best grounding in neuroscience, one must look at the work of Karl Pribram who has argues[24, 27] that the brain performs Fourier processing of auditory, visual and somatic sensations in the synapses separating the neurons. In particular, the local circuit neurons, found most often in horizontal layers of neural tissue such as the retina and the cortex, which have no axons and display no nerve impulses appear to influence the polarizations of the spectral computation. Since this view does not ignore the phase information, Pribram has argued that information is stored by a holographic process in the brain. In our understanding, this information would be regarding the observational system that would be used later to extract the information from the quantum field.

Arguing for a monistic unity between brain and mind, Pribram summarizes[27]:

> [A]nother class of orders lies behind the level of organization we ordinarily perceive...When the potential is actualized, information (the form within) becomes unfolded into its ordinary space-time manifestation; in the other direction, the transformation enfolds and distributes the information much as this is done by the holographic process.

In my own work I have considered the connections between quantum theory and information for more than 25 years. More recently, I argued that brain's processing is organized in a hierarchy of languages: associative at the bottom, self-organizational in the middle, and quantum at the top[15]. Neural learning is associative and it proceeds to create necessary structures to "measure" the stimulus-space; at the higher level of multiple agents the response is by reorganizing the grosser levels of the neural hardware. Each cognitive agent is an abstract quantum system. The linkages amongst the agents are regulated by an appropriate quantum field. This allows the individual at the higher levels of abstraction to initiate cognition or action, leading to active behavior. In this paper, I review evidence regarding the activeness of agents from neuroscience and psychology and also sketch the elements of a quantum approach to active agents. This introduction is being written as a corrective to an overemphasis on the reductionist approach to intelligence.

2 Anomalous abilities

That cognitive ability cannot be viewed simply as a processing of sensory information by a central intelligence extraction system is confirmed by individuals with anomalous abilities. Idiot savants, or simply savants, who have serious mental handicaps, either from developmental disability or major mental illness, perform spectacularly at certain tasks. Anomalous performance has been noted in the areas of mathematical and calendar calculations; music; art, including painting, drawing or sculpting; mechanical ability; prodigious memory (mnemonism); unusual sensory discrimination or "extrasensory" perception. The abilities of these savants and of mnemonists cannot be understood in the framework of a monolithic mind.

Oliver Sacks, in his book *The Man Who Mistook His Wife for a Hat* (1985) describes two twenty-six year old twins, John and Michael, with IQs of sixty who are remarkable at calendrical calculations even though "they cannot do simple addition or subtraction with any accuracy, and cannot even comprehend what multiplication means." More impressive is their ability to factor numbers into primes since "primeness" is an abstract concept[28, 29]. Looking from an evolutionary perspective, it is hard to see that performing abstract numerical calculations related to primes would provide an advantage?

From a quantum (implicate) view of reality, one may assume that the senses *unpack* it in chunks of familiar associations, which look like scripts of a movie. The remarkable observations of the neurosurgeon Wilder Penfield nearly forty years ago[22], in which the patients undergoing brain surgery narrated their experience on the stimulation of the outer layer of the cortex at different points, may be interpreted as showing how the brain works in terms of gestalts. The stimulation appeared to evoke vivid memories. Subsequent stimulation of the same site did not necessarily produce the same memory, and stimulation of some other site could evoke the same memory. Furthermore, there was no evidence that these memories represented actual experiences in the patient's past. They had a dreamlike quality, as if they consisted of generic scripts out of which real memories are combined. When the patients heard music they could not generally recall the tune or they saw individuals who they could not identify and so on. The events did not appear to have a specific space-time locus.

It appears that generic scripts of this kind taken together form the stuff of real, waking experiences. The workings of the mind may be described in terms of the scripts and their relationships. The architecture of the brain provides clues to the relationships amongst the agents, and this architecture is illuminated by examining deficits in function caused by injury. In the next section we consider impairment of language function.

3 Aphasia, alexia, apraxia

One might expect aphasia to be accompanied by a general reduction in the capacity to talk, understand, read, write, as well as do mathematics and remember things. One might also suppose that the ability to read complex technical texts would be affected much more than the capacity to understand simple language and to follow commands.

In reality, the relationship between these capacities is very complex. In aphasia, many of these capacities, by themselves or in groups, can be destroyed or spared in isolation from the others. Historically, several capacities related to language have been examined. These include fluency in conversation, repetition, comprehension of spoken language, word-finding disability, and reading disturbances[1].

Broca's aphasia In expressive or Broca's aphasia there is a deficit involving the production of speech. There is deep subcortical pathology as well as damage to the frontal cortex. It is caused by injury to the Broca's area which is located just in front of the primary zone for speech musculature. These speech motor areas are spared in the case of classic Broca's aphasia. When the speech musculature itself is partially paralyzed leading to slurred speech that is called dysarthria.

In Broca's aphasia speech patterns are reduced to "content" words and the usage of the simplest, non-inflected froms of verbs. The production of speech is severly impaired but comprehension is relatively intact. Such speech is often telegraphic or agrammatic.

Wernicke's aphasia A lesion in the posterior portion of the left temporal lobe, the Wernicke area, causes a receptive aphasia in which the speech production is maintained but comprehension is much more seriously affected. Depending on the extent of damage, it may vary from being slightly odd to completely meaningless.

The Wernicke patient may speak at a abnormally fast pace and augment additional syllables to the end of words or additional worlds or phrases to the end of sentences. The speech is effortless, the phrase length is normal, and generally there is an acceptable grammatical structure and no problems of either articulation or prosody. But the speech shows a deficiency of meaningful, substantive words, so that despite the torrent of words ideas are not meaningfully conveyed, a phenomenon called empty speech. Paraphasia is another characteristic of Wernicke's aphasia. Here words from the same general class may be inappropriately substituted, or syllables in the wrong order generated, or an utterance produced which is somewhat similar to the correct word. For example, the patient may call a table a "chair" or an elbow a "knee" or butter as "tubber" and so on.

There exist other aphasias such as anomic (with word-finding difficulty), conduction (with good comprehension but difficulty with repetition), and transcortical (with varying degree of comprehension byt excellent repetition). In agraphia there is a loss or an impairment of the ability to produce written language.

Alexia In alexia, the subject is able to write while unable to read; in alexia combined with agraphia, the subject is unable to write or read while retaining other language faculties; in acalculia, the subject has selective difficulty in dealing with numbers.

Alexia has been known for a long time, but its first clinical description was made over a hundred years ago. One of these patients had suffered a cerebral vascular accident after which he could no longer read. Originally, the patient also suffered from some aphasia and agraphia but the aphasia cleared in due course. The other patient suddenly lost the ability to read but had no other language deficit. This patient, although unable to read except for some individual letters, could write adequately.

Three major varieties of alexia have been described: parietal-temporal, occipital, and frontal. In occipital alexia, there is no accompanying agraphia. In this spectacular condition, there is a serious inability to read contrasted with an almost uncanny preservation of writing ability.

Apraxia Our movements are almost automatic. These movements involve a whole sequence of intermediate steps which are performed in the right order with the correct timing. These movements may be considered an expression of a body language and, therefore, in parallel with aphasia, one would expect to see disorders related to body movements. Apraxia is the inability to perform certain learned or purposeful movements despite the absence of paralysis or sensory loss. Several types of apraxia have been described in the literature.

In kinetic or motor apraxia there is an impairment in the finer movements of one upper extremity, as in holding a pen or placing a letter in an envelope. This is a result of injury in the premotor area of the frontal lobe on the side opposite to the affected side of the body. Kinetic apraxia is thought to be a result of a breakdown in the program of the motor sequence necessary to execute a certain act.

In ideomotor apraxia the patient is unable to perform certain complex acts on command, although they will be performed spontaneously in appropriate situations. Thus the patient will be unable to mime the act of brushing the teeth although the actual brushing will be easily done. It is believed that this apraxia is caused by the disconnection of the center of verbal formulation and the motor areas of the frotal lobe.

When the sequence of actions for an act are not performed appropriately, this is called ideational apraxia. The individual movements can be performed correctly but there is difficulty in putting these together. Rather than using a match, the patient may strike the cover of a matchbox with the candletip.

Constructional apraxia is the loss in the ability to construct or reproduce figures by assembling or drawing. It seems to be a result of a loss of visual guidance or an impairment in visualizing a manipulative output. This apraxia is a result of a variety of lesions in either one or both of the hemispheres.

The complex manner in which these aphasias manifest establishes that language production is a very intricate process. More specifically, it means that at least certain components of the language functioning process operate in a yes/no fashion. These components include comprehension, production, repetition, and various abstract processes. But to view each as a separate module only tells half the story. There exists very subtle interrelationships between these capabilities which all come into operation in normal behavior.

Attempts to find neuroanatomical localization of individual language functions have not been successful. In fact critique of the approach of the localizationists led to a holistic attitudes to brain's function. The anatomical centers, such as the areas of Broca or Wernicke, for the various syndromes are to be viewed as "focus" areas at a lower level and not exclusive processing centers. The actual centers are defined at some higher levels of abstraction.

4 Blindsight

There are anecdotal accounts of blind people who can see sometime and deaf people who can likewise hear. In the 1970s, Larry Weiskrantz was working with brain damaged subjects who could not consciously see an object in front of them in certain places within their field of vision. Yet when asked to guess if a light had flashed in their region of blindness, the subjects "guessed" right at a probability much above that of chance.

In a typical case the subjects is completely blind in the left or right visual field after undergoing brain surgery yet he performs very well in reaching for objects. "Needless to say, [the patient DB] was questioned repeatedly about his vision in his left-half field, and his most common response was that he saw nothing at all...When he was shown the results, he expressed surprise and insisted several times that he thought he was just 'guessing.' When he was shown a video film of his reaching and judging orientation of lines, he was openly astonished."[33] Obviously, blindsight patients possess visual ability but it is not part of their conscious awareness.

Blindsight has been explained as being a process similar to that of implicit memory or it has been proposed that consciousness is a result of a dialog going on between different regions of the brain. When this dialog is disrupted, even if the sensory signals do reach the brain, the person will not be aware of the stimulus. In visual processing, it appears that motion and form are processed separately, in parallel. Semir Zeki[34] has shown that two critical parts of the cortex, regions V1 and V5, are involved in motion and its perception. If V5 is damaged there is no perception of motion. If V1 is damaged but V5 is intact, then signals in V5 are correlated with the stimulus, but the subject has no conscious awareness of that fact.

Zeki has proposed that the crucial factor for conscious vision is that the two areas V1 and V5 should be able to interact to carry on their dialog. The neurons in these two regions do not only respond to the motion of the object, but actually fire in synchrony, oscillating at the same frequency. This oscillation has been taken as a correlate of the conscious perception of movement.

Greenfield[9] has proposed that blindsight might be a result of the incoming signals being too weak due to some inhibitory chemical process. Flohr[5] has suggested that consciousness depends not so much on the extent of neurons recruited but, rather, on the the rate at which the recruitment occurs. This rate of recruitment may be inhibited due to some inhibitory process.

These explanations of blindsight in terms of the dialog within the regions V1 and V5 or neurons recruited therein do not exclude the possibility that simultaneous activity in other regions is essential for the feeling of consciousness. These simultaneous activity elsewhere need not be synchronized with the oscillations in the V1 and V5 regions.

Greenfield summarizes[9]: "We have two clues about the phenomenology of consciousness; first, that it depends on a focus that is literally or psychologically strong, and second, that it might depend spatially and/or temporally on the extensive, rapid recruitment of a population of brain cells. These brain cells would span different brain regions or different parts of the cortex to constitute a temporary working assembly where all member neurons resonated or discharged in the same way. The more powerful the recruiting signal, the greater the likelihood that such assemblies would be established and consciousness ensue."

This model is quite attractive but it has fundamental difficulties. First, the blindsight patient *is* conscious although he may not be conscious of certain images in his field of vision. Second, there are activities which are performed automatically of which we are not conscious. Some of these can be brought under the ambit of conscious control with varying degree of difficulty. As examples consider breathing or heartbeats, of which breathing is easily controlled and heartbeats can be controlled only by yogic adepts.

Why not consider that the injury in the brain leading to blindsight causes the vision in the stricken field to become automatic? Then through retraining it might be possible to regain the conscious experience of the images in this field. In the holistic explanation, the conscious awareness is a correlate of the activity in a complex set of regions in the brain. No region can be considered to be producing the function by itself although damage to a specific region will lead to the loss of a corresponding function.

5 Agnosia

Agnosia is a failure of recognition that is not due to impairment of the sensory input or a general intellectual impairment. A visual agnosic patient will be unable to tell what he is looking at, although it can be demonstrated that the patient can see the object. In visual agnosia the patient is unable to recognize objects for reasons other than that of loss of visual acuity or intellectual impairment. In auditory agnosia the patient with unimpaired hearing fails to recognize or distinguish speech. The patient can read without difficulty, both out loud and for comprehension. If words are presented slowly, the patient may comprehend fairly well; if presented at a normal or rapid speed, the patient will not comprehend. Other patients perceive vowels and/or consonants but not entire words, or some words but not vowels or consonants. These patients have little difficulty with naming, reading or writing; all language functions except auditory comprehension are performed with ease. Astereognosis is a breakdown in tactile form perception so that the patient cannot recognize familiar objects through touch although the sensations in the hands appear to be normal.

Prosopagnosia literally means a failure to recognize faces. Prosopagnosic patients are neither blind nor intellectually impaired; they can interpret facial expressions and they can can recognize their friends and relations by name or voice. Yet they do not recognize specific faces, not even their own in a mirror!

Prosopagnosia may be regarded as the opposite of blindsight. In blindsight there is recognition without awareness, whereas in prosopagnosia there is awareness without recognition. But there is evidence that the two syndromes have underlying similarity. Electrodermal recordings show that the prosopagnosic responds to familiar faces although without awareness of this fact. It appears, therefore, that the patient is subconsciously registering the significance of the faces.

Prosopagnosia may be suppressed under conditions of associative priming. Thus if the patient is shown the picture of some other face it may trigger a recognition.

6 Split Brains

The two hemispheres of the brain are linked by the rich connections of the corpus callosum. The visual system is arranged so that each eye normally projects to both hemispheres. By cutting the optic-nerve crossing, the chiasm, the remaining fibers in the optic nerve transmit information to the hemisphere on the same side. Visual input to the left eye is sent only to the left hemisphere, and input to the right eye projects only to the right hemisphere. The visual areas also communicate through the corpus callosum. When these fibers are also severed, the patient is left with a split brain.

A classic experiment on cat with split brains was conducted by Ronald Myers and Roger Sperry in 1953[21], They showed that cats with split brains did as well as normal cats when it came to learning the task of discriminating between a circle and a square in order to obtain a food reward, while wearing a patch on one eye. This showed that one half of the brain did as well at the task as both the halves in communication. When the patch was transferred to the other eye, the split-brain cats behaved different from the normal cats, indicating that their previous learning had not been completely transferred to the other half of the brain.

Experiments on split-brain human patients[7] raised questions related to the nature and the seat of consciousness. For example, a patient with left-hemisphere speech does not know what his right hemisphere has seen through the right eye. The information in the right brain is unavailable to the left brain and vice versa. The left brain responds to the stimulus reaching it whereas the right brain responds to its own input. Each half brain learns, remembers, and carries out planned activities. It is as if each half brain works and functions outside the conscious realm of the other. Such behavior led Sperry to suggest that there are "two free wills in one cranial vault."

But there are other ways of looking at the situation. One may assume that the split-brain patient has lost conscious access to those cognitive functions which are regulated by the non-speech hemisphere. Or, one may say that nothing is changed as far as the awareness of the patient is considered and the cognitions of the right brain were linguistically isolated all along, even before the commissurotomy was performed. The procedure only disrupts the visual and other cognitive-processing pathways.

The patients themselves seem to support this second view. There seems to be no antagonism in the responses of the two hemispheres and the left hemisphere is able to fit the actions related to the information reaching the right hemisphere in a plausible theory.

For example, consider the test where the word "pink" is flashed to the right hemisphere and the word "bottle" is flashed to the left. Several bottles of different colors and shapes are placed before the patient and he is asked to choose one. He immediately picks the pink bottle explaining that pink is a nice colour. Although the patient is not consciously aware of the right eye having seen the word "pink" he, nevertheless, "feels" that pink is the right choice for the occasion. In this sense, this behavior is very similar to that of blindsight patients.

7 Modular circuits and unification

The brain has many modular circuits that mediate different functions. Not all of these functions are part of conscious experience. When these modules related to conscious sensations get "crosswired," this leads to synesthesia. One would expect that similar joining of other cognitions is also possible. A deliberate method of achieving such a transition from many to one is a part of some meditative traditions.

It is significant that patients with disrupted brains never claim to have anything other than a unique awareness. The reductionists opine that consciousness is nothing but the activity in the brain but this is mere semantic play which sheds no light on the problem. If shared activity was all there was to consciousness, then this would have been destroyed or multiplied by commissurotomy. Split brains should then represent two minds just as in freak births with one trunk and two heads we do have two minds.

Consciousness, viewed as a non-material entity characterized by holistic quantum-like theory, becomes more understandable. The various senses are projections of the mindfunction along different directions. Injury to a specific location in the brain destroys the corresponding hardware necessary to reduce the mindfunction in that direction. Mindfunction may be represented along many bases. Instead of aphasias and agnosias, one could have talked of other deficits. The architecture of mind adapts to the the environment. This adaptation makes it possible for the mind to compensate.

Gazzaniga has said[8]: "consciousness is a feeling about specialized capacities." But why should this feeling of unity persist when the hemispheres are severed? I believe the fact that commisurotomy does not disrupt the cognitive or verbal intelligence of the patients is an argument against reductionism. One must grant that the severed hemispheres maintain a feeling of unity, which manifests as consciousness, by some fundamental field.

The argument that one of the two hemispheres does not have language and consciousness is uniquely associated with language fails when we consider split-brain patients who had language in both the hemispheres. Gazzaniga suggests that the right hemisphere, although possessing language, is very poor at making simple inferences. He reasons that the two hemispheres have very dissimilar conscious experience. But the fact that both the hemispheres have speech mitigates against that view. Furthermore, one would expect that the separated hemispheres will start a process of independent reorganization to all the sensory inputs. If the patient still is found to have a single awareness, as has been the case in all tests, then the only conclusion is that the mind remains whole although the brain has been sundered.

8 Quantum Agents

Quantum mechanics provides us a means of obtaining information about a system in the microworld associated with various attributes (component states). A quantum state is a linear superposition of its component states. Suppose the n component states are represented by $|S_0\rangle, |S_1\rangle, ..., |S_{n-1}\rangle$. In the special case of $n = 2$, these could be the two spin states of an elementary particle, "up" or "down"; or polarizations states of a photon, "horizontal" or "vertical". Then the general form of the superposition state, $|S\rangle$, will be:

$$|S\rangle = \sum_{i=0}^{n-1} a_i |S_i\rangle$$

The weights, a_i, are the probability amplitudes and they are, in general, complex numbers, subject to the condition that $\sum_i |a_i|^2 = 1$. The mod squares of the amplitude, $|a_i|^2$, is the probability of obtaining the ith component states upon observation.

Since the amplitudes are complex numbers, a quantum system cannot be effectively simulated by the Monte Carlo method using random numbers. One cannot run a physical process if its probability amplitude is negative or complex!

The counter-intuitive nature of quantum mechanics arises from the collapse of the state function by the observation. This renders the framework nonlinear, and irreversible if the time-variable is changed in sign. Philosophers of science have agonized over the many bizarre implications of quantum mechanics, such as an organism can be both dead and alive before it is observed (Schrödinger's cat paradox), present can influence the past (Wheeler's delayed-choice scenario), effects can propagate instantaneously in apparent violation of the ceiling of the speed of light (EPR paradox), and so on[30]. The strangeness of quantum mechanics is because it works contrary to the rules of classical logic.

Nevertheless, we must live by quantum mechanics because it is the most successful theory that we know of, and it provides us the ability to understand the microworld— including chemistry and biology— and devise electronics and computers. There is no a apriori reason why it should not apply to the macroscopic world as well.

The brain, as a system, may be viewed as a product of several subsystems which are entangled amongst themselves. This entanglement would explain why, in the absence of the output of a specific subsystem, it may still be possible to estimate it by using the information obtained from the other subsystems.

System Organization

We know that brain adapts its neural organization based on its experience. It appears proper to view this organization as the observational apparatus, $|V\rangle$, as well as the actual quantum information system, $|S\rangle$. The overalll system is the product $|S\rangle|V\rangle$. The organization changes to respond to its environment, which has two components: first, the outer environment to which the brain relates through its sensory extensions; second, the inner environment generated by mind's dialogue. It is this inner dialogue that makes the brain different from a machine.

Instead of considering the response of the system, we may examine the state of the organization, $|V_i\rangle$, and take it to have a quantum mechanical basis. Then the universe of all organizations can be expressed as:

$$|V\rangle = \sum_{i=0} a_i |V_i\rangle$$

This system can also be seen as the product of the states of the component systems, ψ_i, which could represent the various cognitive systems in the brain. In that case,

$$|S\rangle = \prod_i |\psi_i\rangle$$

The system changes with time and its behaviour reflects its experience. Why is it necessary to posit a quantum character to the system rather than taking it to be several classical systems running in synchrony, 'bound' together by 30-Hz oscillations? If they were separated classical systems just synchroncity of oscillations will not be able to explain the binding. The examples of aphasia and apraxia tell us that different physical structures come into play in determining cognitive behaviour. A phenomenological synchrony can only be an embodiment of a deeper unity.

The Power of Quantum Computing

We now take a brief look at the question of harnessing the power of quantum computing for the design of AI machines. The dynamics of an isolated quantum system are governed by the Schrödinger equation which can be cast in a form where the future states of the system are obtained by multiplication by a unitary matrix, U, (whose conjugate transpose is equal to its inverse):

$$|S_{t+1} = U|S_t\rangle$$

The task of the algorithm designer is to first find the unitary matrix for the given computing problem and then map the matrix into a sequential product of smaller matrix operations that can be implemented relatively easily. Effectively, a quantum computation is nothing more than matrix multiplication.

A quantum computer exploits the inherent parallelism that is provided by the superposition of the quantum state. A quantum register with n binary cells is able to store 2^n sequences simultaneously, in contrast to a classical register that can store only 1 of the 2^n sequences at a time. By its ability to simultaneously process very many problems, it becomes possible to devise new kinds of algorithms that provide substantial speedup over classical methods, which speedup, in principle, could be exponential[3].

A basic issue in quantum computing is to separate the "good" solution from the many other data sequences that are simultaneously present on the quantum register, and this must be done without "looking", because interaction with the contents of the register will cause the superposition state to collapse to one of its components. This separation is achieved by strengthening the amplitude of the desired (or, marked) state by changing the difference in the phase angles of the marked and the unmarked states.

Small implementations, at the level of proof-of-concept, of quantum computers have been made. The current problems with the technology of quantum computers are the problems of initialization, decoherence, and error correction. The problem of initialization arises from a fundamental uncertainty in the phase of the state, which can render the techniques for strengthening of the desired state useless. The problem of decoherence is the inability to completely shield the quantum system from unpredictable interaction with the environment causing the state function to lose its superposition; decoherence times range from fraction of a second to a few hundred seconds. Techniques for error correction of quantum bits have been proposed but these work under very artificial and unrealistic assumptions[20].

9 Conclusions

We have reviewed evidence from neuroscience showing how specific centers in the brain are dedicated to different cognitive tasks. But these centers do not merely do signal processing: each operates within the universe of its experience so that it is able to generalize individually. This generalization keeps up with new experience and is further related to other cognitive processes in the brain. It is in this manner that each cognitive ability is holistic and irreducible to a mechanistic computing algorithm. Viewed differently, each agent is an apparatus that taps into the universal field of consciousness. On the other hand, AI machines based on classical computing principles have a fixed universe of discourse[14] so they are unable to adapt in a flexible manner to a changing universe. This is why they cannot match biological intelligence.

Quantum computing has the potential to provide understanding of certain biological processes not amenable to classical explanation. Take the protein-folding problem. Proteins are sequences of large number of amino acids. Once a sequence is established, the protein folds up rapidly into a highly specific three-dimensional structure that determines its function in the organism, just as the three-dimensional structure of a drug defines its effectiveness. If three-dimensional structures could be studied on a computer, it would save a great deal of expense of test-tube experiments.

It has been estimated that a fast computer applying plausible rules for protein folding would need 10^{127} years to find the final folded form for even a very short sequence of just 100 amino acids. Such a mathematical formulation of the protein-folding problem shows that it is NP-complete[6]. Yet Nature solves this problem in a few seconds. Since quantum computing can be exponentially faster than conventional computing, it could very well be the explanation for Nature's speed. The anomalous efficiency of other biological optimization processes may provide indirect evidence of underlying quantum processing if no classical explanation is forthcoming.

In conclusion, we see that quantum computing ideas help understand puzzling problems of mind's agency. Awareness is seen to be a property related to certain neural hardware interacting with a quantum field. If these ideas are correct, then, in principle, new hardware could be devised that will embody intelligence to a degree unthinkable using reductionist approaches.

This review leaves several questions unaddressed: 1) What is the requirement for neural hardware that will support awareness? 2) Are different levels of awareness possible and, if yes, in what variety? 3) Can non-aware quantum mechanical intelligent systems be devised that match the intelligence of animals? 4) What are the mechanisms by which the mind controls the reorganizational processes in the brain?

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