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Quantum Mechanics, Chaos and the Conscious Brain

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A model is described in which subjective consciousness is generated through an unusual property of quantum non-locality. Chaos and bifurcation serve to link quantum transactions to global brain dynamics through the fractal architecture and dynamics of the central nervous system. The resulting process operates at the boundary between quantum computation and wave-particle reduction, thus combining optimality and free-choice. It is concluded that subjective consciousness has an evolutionary role as a non-computational predictive faculty, first emerging from chaotic excitations in single-celled organisms; and that conscious anticipation, rather than computation, has been the principal factor promoting selective advantage in the development of the brain.

Despite the vast and diverse development of twentieth century science, one small dark cloud remains unchallenged and unsolved on the horizon of human understanding: the subjective nature of the conscious mind. One key to unravelling this paradox lies in our understanding of the principles of operation of the human brain. In this context, there has been a growing interest in both quantum mechanical ideas and chaos as possible answers.

Several of the pioneering quantum physicists, including Werner Heisenberg, noticed that the uncertainty principle provides a physical basis for the brain to manifest free-will. If the brain is a quantum system, rather than a classically deterministic one, its states are not entirely determined because of quantum uncertainty. A single particle can occur anywhere within its wave function, despite the behaviour of many particles settling into a probability distribution determined by the wave. In the same way, free-will in a single brain could correspond to quantum uncertainty in the ongoing brain state. Eddington (1935) showed for example that the uncertainty

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of position of a synaptic vesicle was as great as the width of the membrane thus constituting a possible trigger for an unstable cascade, leading to a global change in brain state.

Chaotic Neurodynamics

More recently, there has been interest in the idea that the brain may utilize transition in and out of *chaos* (Barton, 1994; King, 1991; Schuster, 1986; West, this issue) in its processing to form a *complex system* (Ruthen, 1993), displaying *self-organization* (Barton, 1994), capable of generating new types of structure through *bifurcation* — a sudden qualitative change in structure occurring at a critical value of a continuously varying parameter. Nonlinear systems including simple quadratic and piecewise linear functions generate chaos in their dynamics under suitable conditions. Experimental evidence for chaos has been found in the electroencephalogram (EEG) and in the excitation of individual cells. In Figure 1(a) a chaotic EEG trajectory is illustrated.

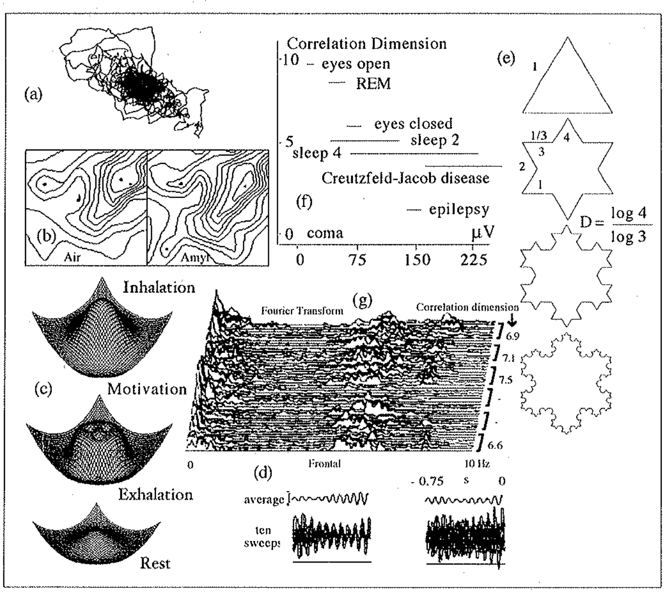

Figure 1: (a) Trajectory of a chaotic EEG recording. (b) Spatially-coherent chaotic wave patterns on olfactory bulb distinguish an odour (redrawn after Skarda and Freeman 1987). (c) Stages of chaotic olfactory excitation. (d) Phase decoherence in novel or unexpected stimuli (redrawn after Basar, Basar–Eroglu, Röschke, and Schütt, 1989). (e) A fractal reproduces itself on successively smaller scales. (f) Correlation dimensions of a variety of brain states. (g) Time evolving EEG with broad frequency spectrum and associated dimensions (redrawn after Basar, 1990).

On descending scales, studies of membrane, synapse and ion channel kinetics provide further support for such activity.

Freeman (1991) [see also Skarda and Freeman 1987] has formulated a chaotic model for olfactory sensory recognition. In the olfactory cortex, excitations are globally distributed wave forms, much like a hologram in which coupled cells oscillate together, however the cell assemblies can oscillate chaotically in time. Figure 1(b) illustrates two such distributed wave forms which distinguish an odour [amyl acetate] from a puff of air. During inhalation, transition into high energy chaos permits the exploration of dynamical or phase space without the system becoming locked in an inappropriate mode [see Figure 1(c)]. Sensitive dependence guarantees sensitivity to input. Subsequent lowering of the energy parameter during exhalation promotes bifurcation in which the system falls, either into an existing attractor if it is a recognised smell [illustrated by the little hollows in the centre of the second (middle) level of Figure 1(c)], or if it is a novel one, the system will eventually bifurcate to create a new attractor. In addition to ensuring plasticity, responsiveness and full exploration of the space of possibilities, the model is tuned so that a decisive end state is guaranteed.

The use of "holographic" distributed wave forms is also consistent with studies in which phase decoherence occurs with unexpected stimuli, to be replaced by coherent states once the brain has developed a stable representation of the situation. An example is illustrated in Figure 1(d) [Basar, Basar–Eroglu, Röschke, and Schütt 1989]. Here averaging of several EEG recordings to form an evoked potential of a randomly omitted regular stimulus displays decoherence when the pattern cannot be anticipated and coherence when the expected stimulus occurs. Chaotic systems can cohere through nonlinear coupling.

Lorenz, the meteorologist who first described dynamical chaos in three dimensions, noted the example of the butterfly effect — the flap of a butterfly in Hawaii could, in principle, subsequently be amplified by a chaotic airflow into a hurricane in Tahiti. Because a chaotic system is *sensitively dependent* on its initial conditions, arbitrarily small perturbations are amplified into global fluctuations. Sensitive dependence also ensures that the eventual state of the system cannot in principle be predicted from outside, because any simulation will eventually become inaccurate as a result of the amplification of small errors. In this respect, the chaotic model has similarities to the quantum approach in that future states of the system cannot be determined from outside e.g., by simulation. Neurodynamic sensitive dependence ensures the brain remains optimally responsive both to the environment and its own evolving states. It also provides a basis for quantum perturbation to become inflated into global fluctuations when the neurodynamics is critically poised.

The Fractal Expression of Chaos in the Brain

Many chaotic systems contain *fractal* invariant sets, which are self-similar on descending scales of size, much like a snowflake. Any fractal has a non-integer fractal dimension associated with it. For example, the Koch snowflake of Figure 1(e) illustrates how the dimension

$$D = \frac{\log 4}{\log 3} = 1.26$$

is derived by a process of taking four times as many units of 1/3 the length at each stage. Fractals also arise from simple non-integer power law relationships (West, this issue). Much of the study of chaos in the electroencephalogram involves looking at the correlation dimension of a time-series of signals. The correlation dimension is another dimensional measure similar to the fractal dimension. In Figure 1(f) is shown the very low correlation dimensions of a variety of normal and pathological brain states. Bearing in mind that the number of synapses is as high as 10^{15} such a low dimension indicates globally-coupled chaotic dynamics. In Figure 1(g) a series of frequency [Fourier] spectra of an ongoing EEG are plotted along with their correlation dimensions (Basar, 1990). Both the broad frequency spectrum and the low correlation dimensions indicate the presence of chaos.

An added feature of the brain, which separates it from other potentially chaotic systems is that it is specifically constructed from the global level down to individual sub-molecular assemblies as a particular design of nonlinear geometric and dynamic fractal. The neuron, despite having an approximately linear firing rate with depolarization [Figure 2(a)(i)], displays a variety of nonlinearities capable of chaos. The development of the action potential arises from a nonlinear limit cycle that develops at threshold [Figure 2(a)(ii)]. Neuron–neuron transmission is modelled on a nonlinear sigmoidal function of threshold [Figure 2(a)(iii)]. Threshold tuning of a neuron to its input makes it an unstable bifurcator. The global many-to-many connections implicit in neural nets require the neuron to be a geometric fractal tree, as illustrated in Figure 2(b). The anatomical complexity of the pyramidal neuron is illustrated by the structural variety of up to 10^4 synaptic junctions, which also utilize several distinct neurotransmitters. The varying fractal dimension of distinct neuron types also determines their electrical conduction characteristics [see Figure 2(c)] (Schierwagen, 1986).

Furthermore, the dynamics, not just on a global scale but on descending orders of magnitude, from neurosystem, to cell, to synapse, to ion channel, vesicle or microtubule (Hameroff, 1994; Penrose, 1994), to protein subassembly and neurotransmitter molecule all display nonlinearities, chaos or fractal dynamics (King, 1991). The synapse, for example, contains complex feedbacks including nonlinear reactions [Figure 2(d)]. The acetyl-choline ion channel requires two molecules to activate it, thus having quadratic, rather than linear concentration dynamics. Large molecules such as proteins are structurally and dynamically fractals, as a result of interacting on several levels of scale, from atom, through individual amino acids and sub-assemblies such as the alpha helix to global conformation changes [Figure 2(e)]. Voltage-gated ion channels have a fractal time delay in the closed state, see Figure 2(f) [Liebovitch, Fischbarg, Konairek, Todorova, and Wang 1987].

The fractal architecture of the brain provides for a structured scale interaction, in which fluctuations at one level can be linked to instabilities at a higher one, if the system happens to be at unstable bifurcation or in chaos. The system can thus over-ride any micro-instabilities if it is evolving toward a stable outcome, but may become arbitrarily sensitive to them if it is unstable. This leads to the hypothesis that the brains of multi-celled organisms have evolved in response to the selective advantage of properties emerging from fractally-organized chaos. From the point of view of instability, the law of mass action not withstanding, such a fractal architecture provides unique possibilities for the entire neurosystem to become responsive to fluctuations at the level of a single quantum. What particular advantages could accrue from such an apparently noisy process? Noise would normally be an anathema which could corrupt a computational process. We know that artificial neural nets do have a use for random noise in terms of thermodynamic annealing. By

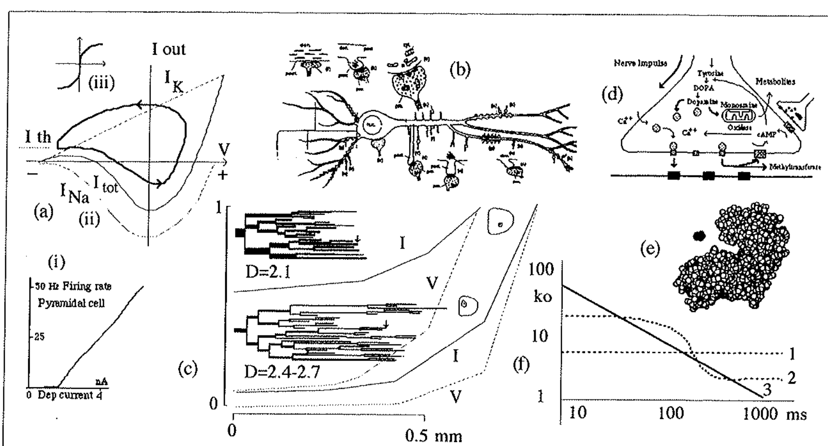

Figure 2: Non-linear and fractal aspects of the neuron. (a) Although depolarizing current causes a linear increase in firing rate (i), both (ii) formation of a limit cycle at excitation threshold and (iii) sigmoid neuron–neuron excitation curve are non-linear. (b) Anatomical complexity of the neuron. (c) Fractal dimensions of dendrites of two cell types and their electrodynamics (redrawn after Schierwagen, 1986). (d) Synaptic conduction involves many feedbacks. (e) Large molecules such as proteins are structurally and dynamically fractals. (f) Kinetics of a voltage-gated K^+ channel [3] is consistent with a fractal model, rather then a stochastic one [1,2].

shaking the system a little, one can jolt a sub-optimal state and cause it to roll down to a deeper hollow in the energy landscape, representing a better solution. A *combination* of fractal chaos and quantum mechanical fluctuation may provide qualitative advantages over such a primitive form of plasticity.

The Quantum Foundation of Chaotic and Statistical Fluctuation

At stake may be the very nature of statistical conceptions of the universe. What is the origin of randomness? Theories combining determinism and random variation arise in three contexts. The first is *quantum theory*, in which deterministic wave evolution is punctuated by reduction of the wave packet, giving a statistical distribution of states whose probabilities are determined by the wave amplitude. Quantum uncertainty thus represents the indeterminacy of a particle within its wave. The second arises from chemical kinetics and other examples of *statistical mechanics*. Partial information about individual trajectories of populations of interacting particles results in a description in which the positions and momenta are based on random variables and statistical probabilities. Biological evolution could be included as a sophisticated example. The third case consists of *chaotic dynamical systems*, whose evolution may be in principle deterministic, but cannot be predicted. Individual trajectories are often *ergodic*, wandering through phase space in a similar manner to a random variable.

When we come to consider a real world chaotic system based on molecules, we can see that Lorenz's butterfly effect extends naturally down in scale to a random kinetic encounter growing into a butterfly-sized fluctuation and hence a hurricane. So the underlying source of fluctuation in macroscopic chaos is kinetic randomness. However the matter does not stop there. All such molecular billiards are actually instances of quantum chaos (King, 1989). As illustrated in Figure 3(a,b), the transition time of an electron traversing a molecular medium varies chaotically with the energy arising from changes in the electron's trajectories (Gutzwiller, 1992). The quantum suppression of chaos noted in "scarring" of the wave function and other experimental results (Gutzwiller, 1992) carries quantum chaos to the edge of quasi-periodicity. This is where order-from-chaos computation becomes possible, as expressed neurodynamically in Freeman's model of perception, illustrated by Conway's game of life, an edge-of-chaos cellular automaton which is a universal computer (Dennett, 1995), and the superposition parallelism of quantum computation (Lloyd, 1995). Molecules are not simple classical billiard balls, but wave–particle assemblies which diffract according to their wave functions. The amino acid glycine at room temperature diffracts at an object its own width by about five degrees. Its uncertainty of position is chaotically amplified by its next encounter, just as classical billiards is chaotic (King, 1989), accentuated further by the nonlinear charge interactions determining the nature of electronic orbitals and chemical bonds. Quantum uncertainty of position is thus amplified by kinetic interaction to form the ultimate underlying source of global fluctuation in macroscopic chaotic systems. Collapse of the wave function thus lies at the core of chaotic fluctuation. I call this amplification *quantum inflation*.

The duality between deterministic and probabilistic processes extends to many levels of organization. Consider biological evolution: some traits, such as unusual plant alkaloids, are clearly the result of historical accident giving rise to unique and varied forms, which need not exist by necessity and have come about opportunistically. Many others, from the existence of photosynthesizers to the parallel forms of marsupial and placental carnivores, appear to be shaped by environmental factors which are influential enough that repeated mutation and selective advantage will almost inevitably lead to the adoption of the trait. The former case is like the behaviour of a single photon and the latter is like a large flux, forming an interference pattern. We thus have a distinction. On the one hand we have *historical processes*, in which one of many possible histories occurs. On the other, *necessary processes* in which causes precipitate effects, despite possibly having a statistical intermediate, through processes such as bifurcation. By extrapolation, one can argue that all historical processes, from flipping a coin to being picked up as a hitchhiker, are indirect consequences of quantum uncertainty and that we walk in an inflated quantum world. Supporting this world view is the fractal quantum nonlinearity of bio-molecular systems. We have already noted that large molecules such as proteins form fractals. The nonlinearity of electron charge interaction has, as a direct consequence, the development of a spectrum of bonding types from the strong covalent and ionic links down to the residual weak bond effects, which permit the formation of the complex supra-molecular assemblies seen in living organisms. These nonlinearities consequently support a fractal organization in which systems inherit *emergent* properties appearing on differing levels of scale.

Computational Intractability and Freedom of Choice

The evolving nervous system has a two-fold computational dilemma. Firstly, predicting the open-environment, the key to survival, leads to *computationally intractable* problems in which conventional computation requires exponentiating time, clearly impractical to an organism confronting immediate life-or-death decisions. The travelling salesman problem — finding the shortest route around n cities — is an example which theoretically grows super-exponentially like

$$\frac{(n-1)!}{2}$$

Probabilistic, dynamic or distributed processing approaches are required for even approximate solution in polynomial time. Certain logical propositions can also be formally *undecidable*. Chaotic dynamical systems are also classically *unpredictable*. Although they can be simulated over short time scales, and sometimes more rapidly than the original process (*rapid simulations*), sensitive dependence will ultimately cause a divergence between simulation and reality. Consequently it is very likely that biological nervous systems have found alternatives to conventional computation which do not involve temporal impasse. Recently an efficient form of quantum parallel computing involving wave function superposition has been devised, which is pertinent to the model here (Brown, 1994). In this approach wave functions are made to interfere so that they represent the results of numerical or logical calculations. Measurements of the wave function averaged over a number of reduction events lead to a calculation of a superposition of states. A large number could in principle be factorized in a few superimposed steps, through periodicities in the wave function, which would otherwise require vast and time-consuming classical computer power.

Secondly there is no *single* strategy for survival — the problem does not have a *unique* solution. Although survival of each individual is a unique historical process, it has at every point *many* potential avenues, some of which will be productive and some unproductive. Survival thus has more to do with deciding *a* viable course of action than finding *the* optimal solution to a problem. Antonio Damasio's (1994) Elliot with prefrontal damage affecting decision-making, planning and prediction with no other cognitive impairment illustrates this difference dramatically. Despite scoring normal on brain function and personality tests, his decision-making deficit had led to severe social problems.

Returning to quantum mechanics, we have a fundamental problem. Because quantum mechanics can only predict outcomes as probabilities, the theory cannot determine what actually happens. Schrödinger's cat paradox illustrates that we experience what I would term the *principle of choice*. When a cat is subjected to a Geiger counter device which could trigger its demise from a radioactive decay, we always find the cat either alive or dead. Quantum theory, by contrast, finds it both alive and dead with differing probabilities. The Everett *many-worlds* interpretation puts this position at its clear extreme by saying all quantum outcomes become probability universes and all happen. All quantum calculations then become descriptions of a bifurcating universal wave function. There is then no collapse of the wave function, and no principle of choice. However our experience depends on unique histories which are the consequence of choices. We do not experience all the probability universes, but only that the cat is either *alive* or *dead*. Our subjective world thus looks like collapse of the wave function does occur. This suggests that, to fully understand the nature of the conscious mind, we may require a deeper theory of the quantum world which unravels the principle of choice. Without this, quantum theory, despite its potentiality for parallel computing, may not help us understand the mind, because it claims free-will is merely a random variable. Although this might coincide with Edelman's Darwinian view of neural selection, it provides no hint of an answer to the relation between consciousness, cognition, intention and quantum uncertainty.

Transactional Supercausality

Several so-called *hidden-variable* theories have been developed, which attempt to explain the probabilistic aspect of quantum theory in terms of a deeper causality. *Quantum non-locality* remains a hot topic in physics in the light of the Bell's theorem experiments. In such experiments, a pair of spatially separated particles in a single wave, display correlations which cannot be maintained by information exchanged at the speed of light (Aspect, Dalibard, and Roger, 1982; Clauser and Shimony, 1978). Once we know, for example, the polarization of one of two correlated photons, the other immediately (without requiring the time light takes to cross the apparatus) has complementary polarization. However neither has their polarization defined until the first measurement takes place, because the statistics violate Bell's inequalities governing all locally-causal processes. This gives rise to the pos-

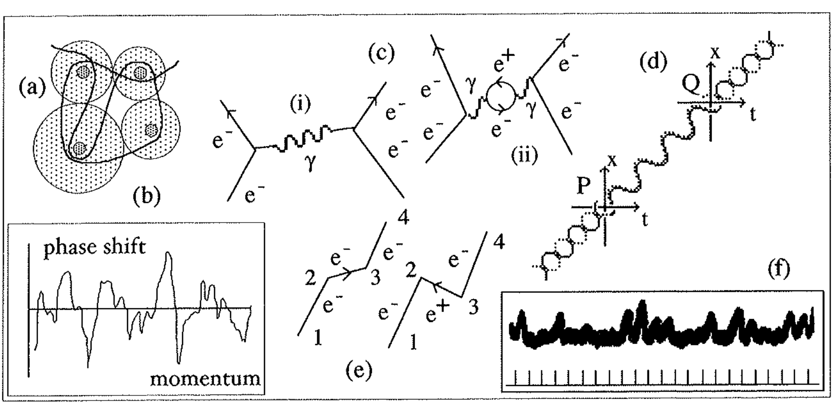

Figure 3: (a) Trajectory of an electron passing through a molecular medium illustrates quantum chaos in transmission times (b). (c) Two Feynman diagrams for the repulsion of two electrons. (d) A transaction consists of offer and confirmation waves interfering to form a single particle. (e) Time-reversed electron scattering is the same as anti-electron creation–annihilation. (f) Quantum sensitivity of frog rod cells to single photons illustrated in output recordings showing response to an average of one photon per second.

sibility that there are many types of non-local association hidden in the probabilities of quantum mechanical predictions.

I am going to illustrate an approach which I believe shows what the conscious brain may be doing, based on the *transactional* interpretation of quantum mechanics (Cramer, 1986; King, 1989). This will require us to explore how space–time may be linked so that information is mutually shared between future and past in a relatively symmetrical hand-shaking way which underlies the sequential nature of time we are familiar with. It will involve some elementary modern physics.

The four forces of nature are known to be mediated by radiation-particles or *bosons* which are termed *virtual* because they exist only for an interval determined by the uncertainty principle. The electromagnetic repulsion between a pair of electrons is mediated by virtual photons bouncing between them as depicted in the Feynman diagram in Figure 3(c)(i). Such diagrams also involve virtual matter-particles or *fermions*, because a photon can briefly split by uncertainty to form an *electron–anti-electron* pair [Figure 3(c)(ii)] and so on to form an infinite sequence of such diagrams. Just like the many-worlds explanation, all possible virtual particles exchanged between the charged electrons add up exactly to the force between them. By contrast, with a *real* photon, like the ones we see, the boundary conditions require a single particle of positive energy to be exchanged. The collection of all possible interactions thus reduces to one real interaction upon measurement.

In addition to representing the force between the two electrons, each virtual photon must have both an emitter and an absorber to satisfy the uncertainty relation in a finite space–time interval. A real photon of positive energy can be created from a virtual one, if energy is pumped into the electromagnetic field, for example by oscillating it as in a radio transmitter. Since virtual particles can become real ones, real particles should also be subject to the same rules requiring both an emitter and an absorber. This is consistent with the universe emerging from a single wave function as a quantum fluctuation through the cosmic inflation arising with symmetry-breaking of the forces of nature.

One way of explaining quantum non-locality is through a hand-shaking space–time interaction between an emitter and its potential absorbers. The transactional interpretation does just this by postulating an *advanced* wave travelling back in time from the [future] absorber to the emitter. This interferes with the *retarded* wave, travelling in the usual direction from emitter to absorber to form the exchanged particle, see Figure 3(d). Because both waves are zero-energy crossed phase waves, they interfere destructively outside the particle path but constructively between the emitter and absorber. The emitter sends out an *offer* wave and the absorber responds with a *confirmation* wave. Together they form a photon, just as an anti-electron (positron) travelling backwards in time is the same as an electron travelling forwards. Figure 3(e) illustrates that electron scattering and electron–positron creation–annihilation are actually advanced and retarded solutions to the same interaction.

Although the transactional interpretation is completely consistent with quantum mechanics, it leads to some very counter-intuitive ideas. When I see a distant quasar, in a sense the quasar radiated the photon I see long ago, only because my eye is also here to perceive it. In this sense the quasar anticipated my presence and, despite its vastly greater energy, it may not be able to radiate without the presence of myself and the other potential absorbers in its very distant future. This would imply that non-locality is observer dependent in a way which prevents any single observer having access to all the boundary conditions and hence logical prediction of the outcomes. This would prevent the universe from being computationally or deterministically predicted, but it would not prevent quantum non-locality from displaying relationships in which future states had an influence through being boundary conditions.

In the transactional interpretation, wave function collapse corresponds to a collapse of a transaction between all potential emitters and absorbers to a single transaction between the emitter and the selected absorber. Although this hand-shaking interaction looks "random" to the observer, it may really be a complex system interaction manifesting the principle of choice, which varies in a *pseudo-random* manner because it is linked to many other space–time states of the universe. Because it has boundary conditions involving future states of the system, it cannot be predicted from the initial conditions and temporal determinism fails. We are left with a description in which correlations in wave–particle reductions operating in a manner consistent with quantum computation schemes (Lloyd, 1995) may display an indirect predictive feature, which is unavailable to classical systems, because the initial conditions are insufficient to determine the quantum outcomes. I denote this *transactional supercausality*, or transcausality. Transcausality differs from Clerk Maxwell's proverbial kinetic demon in that it conforms to the probability interpretation of quantum mechanics for each measurement, despite possibly reflecting non-local correlations. It thus does not violate any physical laws, such as making one side of a barrier hotter and another cooler by selectively letting through the fast molecules (which is anyway made impossible for a Maxwell's demon by quantum uncertainty). Neither can such non-local processes be regarded as computations, because the initial conditions provided any observer are incomplete boundary conditions.

The Evolutionary Origin of Conscious Brains

Nervous systems may thus have evolved in the following steps (King, 1996), as presented below.

(1) *Chaotic excitation as a universal sense organ.* In terms of the theory, the single eucaryote cell became chaotically excitable, because this provided a universal sense organ, responsive to quantum perturbations by chemical orbital interactions (smell), membrane solitons and phonons (sound) and incident photons (light). Quantum sensitivity is well known in the senses of modern nervous systems as illustrated for vision in Figure 3(f). Here the responses to individual photons are discrete and of 0, 1 or 2 photon magnitudes, in line with the probability interpretation for very infrequent photons. The quietest sounds we hear move the membrane of cochlear cells by only the radius of a hydrogen atom, far less than thermodynamic fluctuations. Coherent excitations below the energy level of kinetic interactions are thus detected as sound. Similar arguments apply to the smell, for example in the detection of pheromones, where a single molecule may be sufficient to provoke a response in the organism. Chaotic excitability would have made the single cell in a direct sense *conscious* of its surroundings in the sense that its global dynamical state would be sensitively responsive to its environment, however the theory also hypothesizes that chaotic excitation provided access to a non-computational form of *predictivity* based on quantum non-locality, in which future states of the system leave their mark on a pattern of related transactions in a coherently excited cell, with a time scale determined by the lifetime of exchanged excitations. Even a time scale in milliseconds would provide a critical advantage. Consciousness thus also becomes *conscious anticipation.*

(2) *Space–time anticipation in nervous systems.* Multi-celled nervous systems would then have evolved to utilize this form of space–time anticipation in a manner compatible with and complementing computation. The basis of this is the many-to-many neuron tree structure which provides a holographic transform of the information, and fractal rendering of the system and its instabilities down to the level of the synapse and ion channel. Chaotic neurosystem oscillations allow for linked sub-populations of neurons to enter a coherent oscillation through bifurcation. Bifurcation into a particular stable or chaotic attractor could thus perform a computation through a superposition of states as outlined in the previous discussion on quantum computation. In the indeterminate or unstable case it could go further and generate a unique anticipatory choice through quantum non-locality.

(3) *The quantum-inflated brain.* The subjectively conscious brain then emerges from the unusual non-local space–time properties of quantum chaos. The structure of the brain can be described in terms of three dynamically-interacting components. (1) The entire cortex is activated by *basal brain*

centres, whose ascending distributed pathways fan out across the cortex and provide the activation that supports waking alertness and modulates light and dreaming sleep. These act in very much the way an energy parameter does in any dynamical system. (2) The *cerebral cortex* along with its connections to the *thalamus*. The cortex is broadly divided by the Sylvian fissure between parietal and temporal sensory and association areas on the one hand and the frontal areas on the other, which involve motor action and its abstraction in terms of intentionality, decision-making and survival aims — all future-directed. (3) Linking these is a set of feedback loops, broadly termed the *limbic system*, which provides a central connection between the frontal areas, emotion and the capacity to store and access experiences in sequential memory as realized in the hippocampus.

The mammalian cerebral cortex supports a distributed representation of reality, in which different aspects of experience are processed in parallel in a modular manner. The independent representation of movement and colour (Zeki, 1992), as well as modular representation of specific attributes such as facial expressions, music, verbal articulacy and semantics, along with the capacity of such areas to adapt and change their functional assignments under stimulation, illustrates how the cortex is organised as a distributed dynamical processing system. Just as spatial representations and sensory impressions are part of an internal model of reality constructed by the brain, our experience of time is similarly a constructive process. This is illustrated by the experiments of Libet (1989), in which the subjective timing of a conscious sensation refers it backwards in time to the initial sensory stimulus, a short interval *before* the cortex actually became activated.

The use of phase coherence in central nervous processing is essentially similar to making a quantum measurement through beats, the basis of the uncertainty principle. Phase coherence could thus provide globally the space–time relationship implied by the transactional interpretation.

Much of cortical structure, particularly including the role of the frontal lobes, can be explained in terms of developing a space–time model of reality, in which time is represented in terms of the past in memory systems, and the future in terms of much of prefrontal organization, forming a dynamic model of will, action and choice in much the same way sensory association areas abstract sensory input. A critical aspect of this space–time modelling is being able to consciously anticipate a prospective situation and comprehend it as a sequential event, spanning past, present and future. Some of this involves planning and logical choice, but a considerable part is involved in being able to run a smooth simulation of experience from the past, through the present, into the future. MacLean (1991) describes this as follows: "It was as though premeditation required not only the ability to plan, but also the step by step memory of what is planned, or as one might say a 'memory of the future'" (p. 5).

MacLean suggests that the cerebellum might function in coordination with the cerebral cortex as a rapid dynamical simulator. These principles however extend to the cerebral cortex itself just as meaningfully.

The nature of choice and decision-making in transactional supercausality requires detailed philosophical investigation. The system is physically indeterminate, and possesses the basis for free-will in the principle of choice. However, in the transactional interpretation, quantum non-locality allows contingent future states to form part of the boundary conditions. Free-will may thus involve a mixture of genuine freedom to determine future outcomes as a watershed decision is made and a type of temporal sensitivity for the future contingencies in which free-will is another kind of temporal sense, feeling for the possibilities already laid out by the non-local interaction. The nature of such free-will may remain causally paradoxical for a given observer, because free-will is not simply a random variable but a non-local phenomenon partly dependent on contingent future states.

Cognition can be modelled in the following way, which is similar to Freeman's model for olfaction. The problem sets up stable boundary conditions, just as sensory input does in sensory recognition. The brain then generates a chaotic excitation which explores the space of possible configurations. A solution arises when the resulting chaotic excitation bifurcates to form a stable self-consistent attractor. If a series of small bifurcations occurs resulting from successive [quantum] computational steps, we would say the conclusion was arrived at deductively, but if however a major global bifurcation is required to reach self-consistency, an intuitive leap of understanding may result. The transition from chaos thus models the sudden moment of insight — the "eureka" — of deductive cognition, sensory recognition and decision-making. Computational predictivity is thus complemented by conscious anticipation enabled through quantum transaction and manifested in the transition from chaos.

Conclusion: Conscious Anticipation and the Physical Universe

Consciousness is not just a globally-modulated functional monitor of attention as Crick (1994) might have us believe, but a dual aspect to physical reality. Although subjective consciousness, by necessity, reflects the constructive model of reality the brain adopts in its sensory processing and associative areas, the internal model is not *sufficient* to explain the subjective aspect of conscious experience. Conscious experience *underlies* and is a necessary foundation for the physical world view. Without subjective conscious experience, it remains doubtful whether the physical world would have an actual existence. It is only through *stabilities* of subjective conscious experience that we come to infer the objective physical world model of science as an *indirect* consequence. For this reason, subjective consciousness may be too fundamental a property to be explained, except in terms of fundamental physical principles, as a dual manifestation of quantum non-locality, which directly manifests the principle of *choice* in free-will.

The evolution of the brain has depended not only on understanding the environment, but on competing with individuals of the same species and others for survival under unpredictable and changing situations. To quote Richard Leakey (1994):

> If . . . individuals were able to monitor their own behaviour, rather than merely operate as computerlike automatons . . . by extrapolation they might be able to predict the behaviour of others under the same circumstances. This monitoring ability . . . is one definition of consciousness, and it would confer considerable advantage in those individuals that possessed it. Chimpanzees . . . experience a significant degree of reflective consciousness . . . . In humans, mind reading goes beyond simply predicting what others will do under certain circumstances: it includes how others might feel. (pp. 157–159)

Survival in crisis depends as much on hunch, mind reading and quick reaction as on computational deduction. Despite emerging one and a half million years ago, the genus Homo took until approximately 35,000 years ago to begin the explosive manifestation of culture. From the unchanged toolmaking during the long intervening period, it is difficult to conclude that computation, as such, was even a feature of the human mind until culture developed, let alone a prominent aspect of animal behaviour. It is likewise difficult to reduce the hunting of a leopard or the flight of a gazelle to anything other than conscious anticipation. While one may acknowledge that computation is implicit in the functioning of all neural nets, even humans, despite having 10^{10} neurons and 10^{15} synapses and representing the pinnacle of cognitive evolution, are inefficient computers by comparison with a simple pocket calculator. The natural conclusion is that evolution has promoted conscious anticipation, rather than computation per se as its principal instrument of selective advantage.

The potential quantum basis of conscious anticipation leads to a stunning re-evaluation of our role in the universe. Far from being the most fragile and improbable of physical systems, the conscious brain may manifest the most fundamental aspects of quantum reality. Furthermore, these aspects arise from the re-interaction of the four wave–particle forces which originally emerged through cosmological symmetry-breaking, to form their ultimate nonlinear interactive structures, the large supra-molecular complexes of cell-biology. It may be that only in such structures can the cooperative effects of quantum non-locality be fully realized, making us, despite our long and tortuous evolutionary history, literally a manifestation of quantum cosmology.

> "We almost never think of the present, and when we do, it is only to see what light it throws on our plans for the future."
>
> (Pascal, 1662, p. 180)

References

Aspect, A., Dalibard J., and Roger G. (1982). Experimental tests of Bell's theorem using time-varying analysers. *Physical Review Letters*, *49*, 1804–1805.

Barton, S. (1994). Chaos, self-organization and psychology. *American Psychologist*, *49*, 5–14.

Basar, E. (1990). Chaotic dynamics and resonance phenomena in brain function: Progress, perspectives and thoughts. In E. Basar (Ed.), *Chaos in brain function* (pp. 1–30). Heidelberg: Springer–Verlag.

Basar, E., Basar–Eroglu, J., Röschke, J., and Schütt, A. (1989). The EEG is a quasi-deterministic signal anticipating sensory–cognitive tasks. In E. Basar and T.H. Bullock (Eds.), *Brain dynamics* (pp 43–71). Heidelberg: Springer–Verlag.

Brown, J. (1994, September 24). A quantum revolution for computing. *New Scientist*, *274*, 21–24.

Clauser, J.F., and Shimony, A. (1978). Bell's theorem: Experimental tests and implications. *Reports in the Progress of Physics*, *41*, 1881–1927.

Cramer, J.G. (1986). The transactional interpretation of quantum mechanics. *Reviews of Modern Physics*, *58*, 647–687.

Crick, F. (1994). *The astonishing hypothesis*. New York: Charles Scribner and Sons.

Damasio, A.R. (1994). *Descartes' error*. New York: G.P. Putnam's Sons.

Dennett, D. (1995). *Darwin's dangerous idea*. New York: Simon & Schuster.

Eddington, A.S. (1935). *New pathways in science*. Cambridge: Cambridge University Press.

Freeman, W. (1991, February). The physiology of perception. *Scientific American*, *264*, 35–41.

Gutzwiller, M.C. (1992, January). Quantum chaos. *Scientific American*, *266*, 78–84.

Hameroff, S.R. (1994). Quantum coherence in microtubules: A neural basis for emergent consciousness? *Journal of Consciousness Studies*, *1*, 91–118.

King, C.C. (1989). Dual-time supercausality. *Physics Essays*, *2*, 128–151.

King, C.C. (1991). Fractal and chaotic dynamics in the brain. *Progress in Neurobiology*, *36*, 279–308.

King, C.C. (1996). Fractal neurodyamics and quantum chaos: Resolving the mind–brain paradox through novel biophysics. In E. Mac Cormac and M. Stamenov (Eds.), *Fractals of brain, fractals of mind: In search of a secret symmetry bond, advances in consciousness research, Volume 7* (pp. 179–233). Amsterdam: John Benjamins.

Leakey, R. (1994). *The origin of humankind*. New York: Basic Books.

Libet, B. (1989). The timing of a subjective experience. *Behavioral and Brain Science*, *12*, 183–185.

Liebovitch, L.S., Fischbarg, J., Konairek, J.P., Todorova, I. and Wang, M. (1987). Fractal model of ion-channel kinetics. *Biochimie Biophysica Acta*, *896*, 173–180.

Lloyd, S. (1995, October). Quantum-mechanical computers. *Scientific American*, *273*, 140–145.

MacLean, P. (1991). Neofrontocerebellar evolution in regard to computation and prediction: Some fractal aspects of microgenesis. In R. Hanlon (Ed.), *Cognitive microgenesis: A new psychological perspective* (pp. 3–33). New York: Springer–Verlag.

Pascal B. (1662) *Pensées*. London: Walter Scott Ltd.

Penrose, R. (1994). *Shadows of the mind*. Oxford: Oxford University Press.

Ruthen, R. (1993, January) Adapting to complexity. *Scientific American*, *268*, 110–117.

Schierwagen, A.K. (1986). Dendritic branching patterns. In H. Degn, A.V. Holden, and L.F. Olsen (Eds.), *Chaos in biological systems* (pp. 191–193). New York: Plenum Press.

Schuster, H.J. (1986). *Deterministic chaos*. Berlin: Springer–Verlag.

Skarda, C.J., and Freeman, W.J. (1987). How brains make chaos in order to make sense of the world. *Behavioral and Brain Sciences*, *10*, 161–195.

Zeki, S. (1992, September). The visual image in mind and brain. *Scientific American*, *267*, 43–50.

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Science of Consciousness and the Hard Problem

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Quantum theory can be regarded as a rationally coherent theory of the interaction of mind and matter, and it allows our conscious thoughts to play a causally efficacious and necessary role in brain dynamics. It therefore provides a natural basis, created by scientists, for the science of consciousness. As an illustration it is explained how the interaction of brain and consciousness can speed up brain processing, and thereby enhance the survival prospects of conscious organisms, as compared to similar organisms that lack consciousness. As a second illustration it is explained how, within the quantum framework, the consciously experienced "I" directs the actions of a human being. It is concluded that contemporary science already has an adequate framework for incorporating causally efficacious experiential events into the physical universe in a manner that: (1) puts the neural correlates of consciousness into the theory in a well defined way, (2) explains in principle how the effects of consciousness, per se, can enhance the survival prospects of organisms that possess it, (3) allows this survival effect to feed into phylogenetic development, and (4) explains how the consciously experienced "I" can direct human behavior.

"The Hard Problem" has dominated recent discussions of consciousness. Defined by Chalmers (1996), the problem basically is this: Why do our conscious experiences, which seem so totally different from the matter of which our brains are made, and which, according to the principles of classical mechanics can have no effect upon processes in our brain and bodies, exist at all. In this paper I address this problem within the context of the need to create an adequate theoretical foundation for the science of consciousness. Such a foundation must accommodate in a rational and useful way our

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knowledge of (1) our conscious experiences, (2) the physical processes in our brains, and (3) the tight relationship that exists between these seemingly disparate parts of nature.

The hard problem of consciousness arose at the dawn of modern science when Descartes suggested that the world be conceived to consist of two different kinds of stuff, mind and matter, which interacted in human brains. The difficulty was this: How one can rationally comprehend an interaction between two such different kinds of stuff. The problem was compounded by the development of classical mechanics, which entailed that the matter part of nature, by itself, is dynamically complete: classical mechanics asserted that the dynamical evolution of matter is completely controlled by matter alone. Thus mind, contrary to the idea of Descartes, was reduced to an impotent witness to the flow of material events: mind became epiphenomenal.

The problem was solved around 1930 by scientists led by Niels Bohr, Werner Heisenberg, and Wolfgang Pauli, and the mathematician John von Neumann. They went beyond classical mechanics, and created the practically useful and empirically successful quantum theory. This theory (in the Neuman/Wigner elaboration of the Bohr/Heisenberg formulation) is essentially a rationally coherent framework for the interaction of mind and matter and, as such, is the natural foundation for the science of consciousness.

The problem of the relationship of mind and matter is basically a physics problem: it is the problem of how two different aspects of nature are related to each other. Many of the problems about consciousness debated by philosophers fade away once the tacit physics assumptions are made manifest.

Take, for example, the zombie question that is being hotly debated at the moment (Sutherland, 1995). In those discussions a "zombie" is typically defined to be a creature that is just like a normal human being in every detail of behavior, down to the submicroscopic level, but has no conscious experiences. Can such a thing exist?

To avoid working in a theoretical vacuum, one should specify the underlying physics assumption. If one is referring to real human beings, then one is speaking about quantum systems, and in a quantum-mechanical description of a human being the interaction between mind and brain is a crucial part of the dynamics. Hence mind cannot be left out. But if one is tacitly assuming that a classical-mechanics conceptualization of the brain is adequate, then, since mind is epiphenomenal within classical mechanics, consciousness can be eliminated without affecting behavior at any level. The natural conclusion to be drawn from this is simply that the counterfactual classical-physics assumption is incorrect.

Purpose

My aim here is first to describe a quantum-mechanical approach to the mind/matter problem, and then show how this approach can resolve in principle some basic problems that arise from trying to employ counterfactual classical mechanics instead of empirically adequate quantum mechanics as the theoretical foundation of the science of consciousness. These problems are to understand how consciousness can aid survival — epiphenomenal consciousness certainly cannot do so! — and can evolve during phylogenetic and individual development, and to see how a satisfactory theory of "free will" pops out.

Experience Within Science

Classical mechanics purports to describe the physical world and how it functions, and claims to achieve this goal without bringing in thoughts, feelings, or any other experiential aspect of nature. For centuries this restriction to the purely physical was regarded as an important virtue of science: science had banished the primitive superstition that spirits were lurking everywhere, and causing things to happen. Instead, the physical world was asserted to be built out of nothing but quantifiable properties that could be localized in a space–time, and whose functioning was completely determined by rigid mathematical laws that referred to nothing but these physical properties themselves. Thus when the creators of quantum theory introduced "our experience" and "our knowledge" into the theory of atomic phenomena their move was initially opposed by the scientific community. Soon, however, this important enlargement of the scientific conception of basic physical theory came to be accepted, at least nominally, by most workers in the field.

Recently some quantum theorists have been trying to exorcise "the observer" from quantum theory. These attempts encounter difficulties that I shall mention below. But in any case the important point in our quest for a science of consciousness is not that our basic physical theory *might conceivably* some day be able to be formulated without introducing observers — it is rather that our basic theory of matter, in its contemporary orthodox form, has an explicit and dynamically efficacious place for conscious experiencings. Science already has in place the basis of a rationally coherent and practically useful theory of the interaction of mind and matter: there is no need to invent another one.

The focus of orthodox quantum theory on the experiential aspects of nature was emphasized in the opening words of Niels Bohr's (1934) principal book on the subject, *Atomic Theory and the Description of Nature*: "The task of science is both to extend the range of our experience and reduce it to order"