

Chaos, Quantum-transactions and Consciousness
A Biophysical Model of the Intentional Mind
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Abstract: *The nature of subjective conscious experience, and its consequences in intentionality, remain the central unsolved problem in science and one of critical importance to humanity's future as sentient observers and autonomous participants in a world history we are coming to have ever more pivotal influence upon. Each of us who read this paper are subjective conscious observers, making an autonomous decision to carry out a volitional action. All our knowledge of the physical universe is gained through the immediate conduit of our subjective experience and our intentionality in turn has major impacts on the physical world around us.*

To understand how the subjective aspect arises requires both a radical investigation down to the foundations of physics and an understanding of how subjective awareness, as opposed to mere computational capacity, may have become elaborated by Darwinian natural selection. We thus have to find reasons why subjectivity itself, rather than computation alone, is of pivotal importance in organismic survival. The answer lies in its capacity to anticipate situations crucial to survival. For this to be possible, the foundations of physics must contain a principle of space-time anticipation not covered by any mechanism of computation alone, or subjectivity would become superfluous and would have never been selected for in evolution. This paper sets out to demonstrate how quantum transactions universal to all quantum phenomena may fulfil this pivotal role.

The role of dynamical chaos¹ and bifurcation² in neurodynamics has been the subject of an increasing volume of theoretical and experimental research in which transition from chaos to order may form a key process in perception and cognition. There has also been a continuing interest in the possible link between quantum non-locality³ and consciousness. This paper presents a two-part theory in which: (a) a fractal link between neurodynamical chaos and quantum non-locality; and (b) a complex system theory of the sub-quantum world; together provide a physical solution to the mind-brain paradoxes of subjective consciousness and free-will.

The fractal link between dynamical chaos and quantum uncertainty is proposed to be made through overlapping non-linearities capable of chaos, running from the neurosystems level down through the neuron, synapse, to the ion channel. Chaotic systems possess sensitive dependence, and brain states also contain features of self-organized criticality. In a critically poised brain state representing uncertainty of outcome, it is proposed that sensitive dependence opens the brain to quantum processes. In the transactional interpretation of quantum mechanics, future states form part of the boundary condition of reduction of the wave packet⁴. Transactional supercausality may allow a form of prediction in the excitable cell which bypasses and complements formal computation. The selective advantage of such a process would explain the emergence of consciousness in organismic evolution (King 1996a, 1996b).

1 Introduction

The nature of subjective consciousness and its relationship with brain function remains the most challenging problem facing modern science, and one whose principles remain elusive, despite major conceptual advances in

¹ A *chaotic* system is arbitrarily sensitive to initial conditions, mixes spatial regions, and has a dense set of periodicities.

² A sudden change in dynamical structure resulting from a continuous change in the underlying parameters.

³ The capacity of a quantum system to maintain a global coherence between all regions of its wave function when the state of any of its particles is subjected to measurement.

⁴ The reduction of the set of probabilities in any quantum prediction to a single realized outcome.

other fields. This suggests a progress in understanding the mind-brain relation requires a further biophysical discovery. This paper presents a model in which chaos and novel quantum mechanical principles combine to give a physical description in which mind can interact with brain and in addition provide a potential predictive advantage of evolutionary significance for the organism.

The possible involvement of chaos in consciousness has been raised by a variety of researchers from Skarda and Freeman (1987) to Hardcastle (1994) and in several of my own papers King (1991, 1996) based on the usual process of neurons, synapses, and ion channels. Hameroff (1994) has also discussed the potentiality of microtubules⁵ to use Bose-Einstein condensates⁶ as a quantum computer⁷ possibly in the form of cellular automata⁸ operating on the microtubule's protein subunits, coupling these to global brain states through coherence⁹.

The current model also develops from properties of the single cell but utilizes the central electrochemical properties of cell membrane excitations, broad neurodynamical features including coherence and chaos, and a potentially predictive property of quantum-nonlocality universal to all quantum interactions.

The model consists of two parts:

(1) A *polyfractal* linkage between chaotic neurosystems, the excitable cell, and the molecular level of the synapse and ion channel. Rather than being a simple self-similar process, this linkage involves biological structures with fractal dynamics which interact on a discrete series of descending scales, neurodynamic, cellular and molecular.

(2) A *transactional* interpretation of quantum mechanics, providing a space-time supercausality, which may be able to be utilized by the excitable cell, and consequently the dynamical nervous system, to provide an implicit form of anticipation of events which complements the predictive capacity of formal computation.

The paper is organized as follows: 2: The problems of consciousness and free-will. 3: A synopsis of the polyfractal and supercausal aspects of the model. 4: The polyfractal linkage between global neurodynamics, cellular and molecular levels. 5: Transactional supercausality as a basis for implicit anticipation in the excitable cell and brain. 6: Evolutionary origins of chaos and consciousness. Supporting evidence and detailed theory are postponed to the appendices so that the general reader can more easily understand the overall nature of the model. Appendix A: Fractal neurodynamics. Appendix B: Quantum mechanics and transactions. Appendix C: The role of global brain structures in consciousness. Experimental evidence remains suggestive rather than conclusive because of limitations of the current state of experimental research.

2 Consciousness and free-will: Two aspects of the subjective mind

The subjective mind presents both an existential dilemma and a two-fold interactive problem in relation to the physical world. While consciousness research has become a fashionable scientific area, the inverse interaction, free-will, raises acute scientific problems, because it invokes the spectre of causal interference in the physical determinism required for computation in the brain. In this paper I will advance a *complementarity* perspective in which mind and universe are *aspects of a complementary totality*. *The supercausal theory will solve the mind-*

⁵ Subcellular organelles, forming subunits of the eucaryote flagellum, spindle apparatus of chromosome separation and serving cellular structural and transport functions.

⁶ Many particles [bosons] existing in one wave function, illustrated by the laser and superconductors.

⁷ A formal computer using superimposed quantum states rather than discrete states.

⁸ A simple algorithm evaluating the state each cell in a grid in terms of its neighbouring states.

⁹ Two oscillations are *coherent* if their waves match phase, e.g. laser light.

brain paradox in so far as it provides a physical explanation supporting an interaction between mind and brain. Subjective consciousness remains qualitatively distinct from and complementary to any objective description of its possible role, whether by transactional or other means.

Because consciousness and free-will are subject to multiple interpretations, I will make the following informal definitions:

Consciousness – Brain acts on mind: subjective awareness accompanying attentive brain function.

Free-will – Mind acts on brain: mental will, or intent, acting on brain function.

2.1 The primacy of subjective consciousness

Although scientific description is based exclusively on the physical universe, our contact with reality is entirely through our subjective experience, whose consensus of stable representations we assemble into the physical world view. This subjective aspect of reality is often referred to as the conscious mind. Because its subjective nature makes it unavailable to objective investigation, reductionist descriptions identify it merely with functional attributes of the brain, inferring computational machines might also possess consciousness. However it remains unclear whether a physical universe without conscious observers could exist in any more than a purely conceptual or theoretical sense. Subjective consciousness may be necessary for the actualization of physical reality, and thus fundamental to physical existence (Barrow & Tipler 1988).

The conscious mind can also be described functionally as an *internal model of reality*. While such an explanation does not address the basis of subjectivity, it does help explain some of the more bizarre states of consciousness and is supported by many actively constructive aspects of sensory processing. Such an internal model can be described in terms of dynamical brain processes which undergo unstable transitions to and from chaos. Dynamical resonance also provides a direct means to solve the 'binding problem', how the unitary nature of mind emerges from distributed parallel processing (Hardcastle 1994).

2.2 The causal paradox of free-will

A second critical property of mind comes into play as we move from perception into action. To quote Sir John Eccles: "It is a psychological fact that we believe we have the ability to control and modify our actions by the exercise of 'will', and in practical life all sane men will assume they have this ability" (Hooper & Teresi 1986). However this premise, which is basic to all human action, contradicts physical determinism, because any action of mind on brain contradicts the brain functioning as a deterministic computational machine.

A confluence of ideas between quantum physics and the science of mind may resolve this apparent paradox. Firstly physics has difficulty determining when collapse of the wave function from a set of probabilities into an actual choice takes place, leading to some interpretations in which the conscious observer collapses the wave function. Secondly quantum uncertainty and non-locality provide exactly the types of explanation which could enable the subjective experience of free-will to be consistent with a non-deterministic model of brain function. The unpredictability of chaos could in turn provide a means to link quantum indeterminacy to global brain states.

3 The polyfractal-supercausal model: a synopsis

3.1 The chaotically-excitable cell

Chaotic excitation may have provided key advantages for the first cells, including sensitivity to light, vibration and chemical factors, through sensitive dependence on initial conditions, the capacity to generate electromagnetic fields and use them to sense other cells, to respond to internal changes and to utilize bifurcation in cellular decision-making.

A chaotic or unstable system can dynamically inflate arbitrarily small perturbations into global fluctuations. In the case of the cell, the underlying limit of such perturbations is the molecular level of the quantum. A cell in a chaotic state, or tuned to its own threshold of excitation could thus in principle be sensitive to a single quantum, as is the case for retinal cells fig 4(a). This could result from opening of an ion-channel, the release of a single synaptic vesicle or other processes. The effects of a single quantum fluctuation could thus become inflated into a burst of excitation of the cell.

Transactional supercausality asserts that all quantum wave reductions possess an anticipation of the future state of their absorbers, providing an implicit form of prediction in a sensitively excitable cell. By coupling related emissions and absorptions, the chaotically excitable cell may have thus gained access to anticipatory information about its immediate environment, providing a critical evolutionary advantage.

3.2 The polyfractal brain

The idea is that this evolutionary advantage is then incorporated into the nervous systems of multi-cellular organisms, in which parallel organization, chaotic excitability and the capacity for coherence provide for the expansion of the existing cellular properties into global neurodynamics. The excitable cell, rather than neural net architecture alone, thus becomes pivotal in the evolution of the conscious brain.

The brain is conceived of as a *polyfractal*, a fractal complex of three distinct units: global neurosystem, cell and molecular complex, each capable of controlled chaos and interlocked structurally by a change of scale. Each is linked so that neurodynamical instabilities can be influenced by cellular instabilities which in turn can be influenced by quantum instabilities. Reciprocally, the nature of the global neurodynamic determines which cells are critical and each neuron can determine by its excitation and adaption which molecular organelles may be critical. This would provide a mutual scale interaction between global and quantum events.

The fractal branching structure of the neuron supports many-to-many connectivity enabling each successive processing stage to be an integral transform¹⁷ of the preceding one, just as a hologram is a many-to-many representation of an image. Models of the nervous system have been proposed in which neural layers develop chaotic excitation modulated by attention, with the capacity to represent each perception in a distributed manner across the cortex through phase coherence, again leading to spatial coherence within temporal chaos and bifurcation, as in the case of the cell.

In using controlled chaos, the brain could link the instabilities of neurosystem, cell and molecular complex so that choice is made by an inflated quantum reduction. Such instabilities can complement formal computation because they correspond to heuristic choices³¹, where computation anyway becomes probabilistic. It the brain uses global instabilities in the transition from chaos to order, unstable resonances may become linked with quantum anticipatory excitons. Again here there is a structural complementation between quantum computation and transactional exchange. The complex connectivity of the brain could then enable its global dynamics to provide a new emergent manifestation of quantum non-locality, reflected in turn in the form of subjective consciousness.

3.3 The interactive mind

The conscious mind would thus gain an anticipatory role in brain function, corresponding to the indeterminacies of the sensitively unstable brain. Free-will also gains a role, providing the choice made through collapse of the wave function. While an unstable brain might seem problematic, in dealing with the 'real' world, such instabilities are confined to sensitively forming a perception and making a decision already characterized by external circumstances. They are thus just those instabilities an active conscious mind requires.

4 Linking chaos and quantum mechanics.

Chaotic systems possess *sensitivity to initial conditions* and *computational unpredictability*, (Schuster 1986, Stewart 1989) because arbitrarily small perturbations exponentiate with time into global instabilities, the 'butterfly effect'¹⁰. Sensitivity makes a chaotic system responsive. It also prevents a chaotic system from being predicted because infinitesimal errors exponentiate. It is thus impossible for an observer outside the system to describe it precisely enough to predict its outcome. The mixing property of chaotic systems results in states which permeate phase space¹¹. They also generally contain an infinite number of distinct periodicities forming a rich internal

¹⁰ As originally described by Lorenz, a butterfly flying in Hawaii could trigger a subsequent hurricane elsewhere in the Pacific.

¹¹ The space of internal configurational states of a dynamical system.

structure which can be revealed by bifurcation out of chaos. Often this internal structure takes the form of a self-similar *fractal*, which may be an attractor¹², repeller or other invariant set. Fractals characteristically repeat their structure on ever diminishing scales, displaying a power law relation from which a non-integer fractal dimension can be derived. In the polyfractal model, global neurosystem, cell and molecular complex, are linked so that they have mutually interactive instabilities.

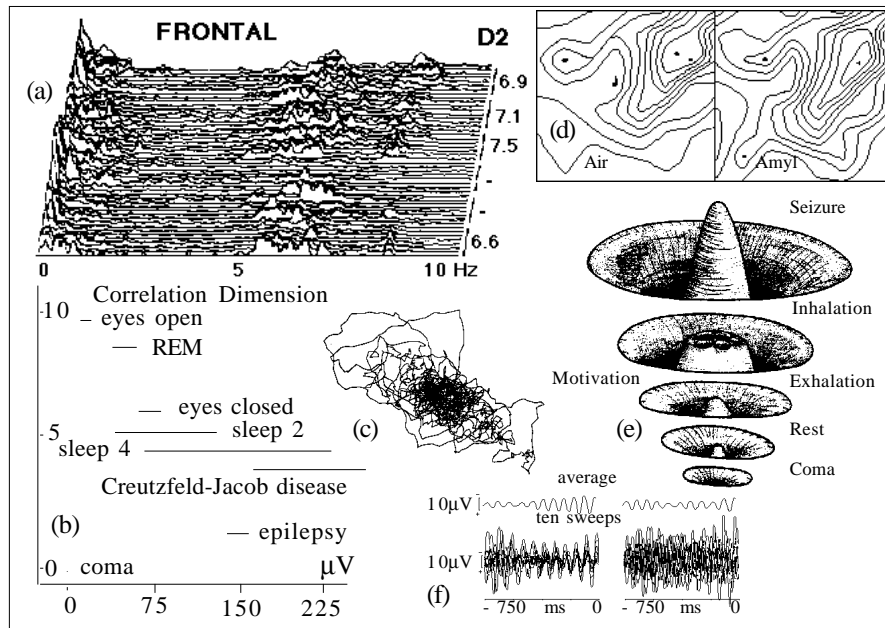


Fig 1: Chaotic neurosystems dynamics is illustrated by: (a) Time evolving EEG with broad frequency spectrum and associated correlation dimensions. (b) The low correlation dimensions of a variety of brain states. (c) Phase portrait of an EEG recording (Babloyantz & Salazar 1985). (d,e) Chaotic and distributed processing is combined in Walter Freeman's model of olfactory bulb processing. Recognition of a given odour by the bulb arises from the distributed pattern of activity, occurring in bursts phased with inhalation. The time-dependent dynamics supporting this consists of bifurcation from low-level chaos to higher level activity which settles into an existing attractor [recognition] or develops a new one [learning] after exploring phase space in higher level chaos. Chaotic neural nets based on neuroanatomy can perform pattern discrimination tasks competitively with other neural net designs (Skarda & Freeman 1987). (f) Phase decoherence in novel or unexpected stimuli is consistent with a distributed model of processing based on oscillatory phase, similar to a hologram.

NOTE: All diagrams are digitally processed by the author. Original sources are indicated in the text or captions.

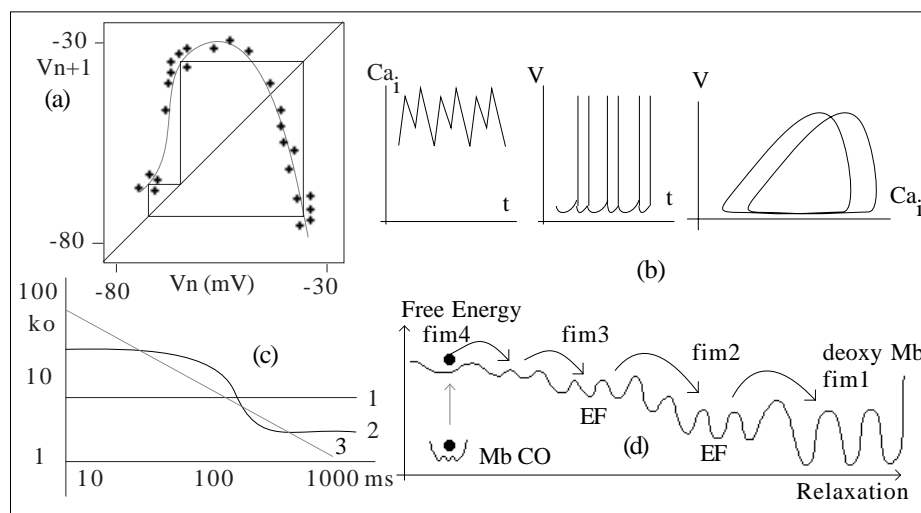


Fig 2: (a) Chay-Rinzel model (1985). Period 3 oscillations in *Nitella* indicate dynamics within the chaotic regime.

¹² A conserved set of states towards which all neighbouring states converge.

(b) Period doubling bifurcation in model. (c) Experimental behaviour of voltage gated K^+ -channel is consistent with a fractal model (3) rather than a one, or two step Markov chain (1,2) (Liebovitch et. al. 1987a,b). (d) Fractal dynamics of the excited muscle oxygen carrier protein myoglobin is illustrated in term of functionally important movements and equilibrium fluctuations involving a variety of quantum transitions on differing scales.

4.1 The scale link between neurosystems and cellular dynamics.

Appendix A outlines evidence for chaos and bifurcation in neurosystems, single cells and long-term adaption. Evidence for chaos, fig 1, has been detected in the electroencephalogram for a variety of natural and pathological states (a-c), although current techniques cannot distinguish chaotic and stochastic¹³ processes for active attention. Freeman's model of sensory perception (d,e) is based on spatially coherent oscillations which are chaotic in the time domain, thus combining concepts of coherence, chaos and bifurcation in a single dynamical model. Transition to high energy chaos accompanies inspiration, enabling the system to explore its phase space and avoid becoming locked in any particular state. Reduction of the level enables the system either to fall into a learned attractor, or bifurcate to form a new one in the case of a novel stimulus. The model is consistent with complex system dynamics at the edge of chaos¹⁴. The resonances of non-linear dynamics are capable of inducing the spatial phase coherence, which accompanies recognition and orientation in experimental studies (f).

Freeman's model has been traditionally applied to cell assemblies consisting of hundreds, or thousands of cells whose individual behaviour may not reflect the global dynamic. However reciprocal coupling between major cortical areas and individual neurons could provide the capacity for a global neurosystem dynamic, which is unstable or chaotic, to become sensitive to instabilities in a single critical cell or synapse, which could consequently be amplified into a global fluctuation or bifurcation¹⁵.

Conversely the stability of single cells would be modified by the global dynamic. This situation naturally includes decision-making processes in which critical states determine the outcome. Such fractal dynamics have been explored in experimental models (Bower 1992, Teich 1992). The central nervous system includes reciprocal linkages between neurosystem architecture and the single cell. One is illustrated in fig 5(b) where a single hippocampal CA1 pyramidal cell has inputs from distinct brain regions, the sensoria and the reticular activating system via distinct neurotransmitters and distinct anatomical regions of the cell.

4.2 The neuron as a fractal integral transform unit.

On a descending series of scales, the neuron is structurally and functionally a fractal processing system, fig 3, in terms of its dendritic and axonic trees (b), and subcellular processing in dendritic microcircuits (d) and synaptosynaptic junctions (e). It is capable of unstable bifurcations and chaos, properties possessed neither by formal McCulloch-Pitts neurons nor the analogue neurons in optimizing nets such as the Hopfield net (Tank & Hopfield 1987). Despite the approximate conformity to linearity of neuronal conduction over a restricted range above threshold (ai), the neuron also displays self-organized criticality¹⁶ in the form of tuning to its sigmoid threshold (aiii), limit-cycle bifurcation (aii), and chaotic dynamics as depicted by the Chay-Rinzel model, 7.1.2, fig 2(a,b), and found in a variety of experimental studies.

The obvious sophistication of typical central nervous neurons, with up to 100,000 synaptic junctions, having a

¹³ A system based on repeated application of probabilities and random variables.

¹⁴ Both continuous dynamical systems and cellular automata display enhanced complexity, including production of new structure and computational capacity [automata] when their parameters are close to, or traverse the boundary between chaos and order. Publications of the Santa Fe Institute discuss a variety of complex systems (e.g. Jen 1990).

¹⁵ This would effect only the existing instability, i.e. a single decision-making step at an uncertain point in computation.

¹⁶ A system which converges to a critical state. Threshold tuning takes the neuron towards critical sensitivity.

variety of anatomical forms fig 3(c), contrasts markedly with artificial neurons and nets. The variety of up to 12 distinct modes of locomotion of *hydra*, which has an undifferentiated nerve net, illustrates that complex behaviour may arise as much from cellular sophistication as from neural net complexity. Single-celled protozoa also display behavioural complexity, leading to the conclusion that subcellular organelles can coordinate and process information.

The fractal aspect provides the neuron with its second outstanding complex systems feature, that of a *fractal integral transform*¹⁷, as exemplified by the Fourier transform of the hologram. The many-to-many nature of the synaptic contacts arising from the neuron's fractal structure, when organized in layers enables the sequential formation of complex sensory fields and modular cortical regions fig 6. Oscillatory phase fronts allow for coherence and transform inversion supporting the retrieval of previous states in the form of a hologram as suggested by Pribram (1971) and consistent with decoherence in experimental studies fig 1(f).

4.3 Subcellular organelles, the scale link between cell and molecule.

Cell organelles can similarly provide a fractal link between cellular and molecular dynamics. The dynamics of the synapse fig 3(e) and membrane involves a rich diversity of non-linearities including quadratic sensitivity in touch receptors and bilinear dynamics in synapto-synaptic junctions, both of which can be chaotic.

In cortical synapses, there is no need for the large number of vesicles seen in the neuro-muscular junction. It has been proposed that in some cortical synapses, the release of the contents of a single vesicle is sufficient to traverse the threshold and elicit a post-synaptic response. A vesicle, releases around 10,000 acetyl-choline molecules, activating 2000 ion channels, causing discrete micro-potentials even at the neuro-muscular junction, which depolarize the membrane by about 1 mV, sufficient to result in an action potential if a cell is already at threshold, making it dynamically feasible for unstable fluctuation at the level of the synaptic vesicle to precipitate cellular instability and subsequent global neurosystem bifurcation.

Eddington (1935) and Eccles (1970) discussed the possibility of quantum-mechanical action of the vesicle and pointed out that the uncertainty of position of a vesicle of 400 Å diameter and mass 3×10^{-17} g is about 30 Å , comparable with the thickness of the membrane. Because of this, the vesicle can be regarded as a quantum object, which is at the same time capable of triggering cellular and hence global instability. The topological closure of the vesicle membrane thus results in the amplification of quantal instabilities from the level of the molecule to the larger level of the vesicle. The kinetics of vesicle association with the pre-synaptic membrane is determined by protein binding, making vesicle release a function of the kinetics of a single molecular complex.

Concentration dynamics is linear only for single molecule interactions, but ion channels such as the acetyl-choline channel require two molecules for activation, again having quadratic dynamics. In the fractal model of ion channel kinetics Liebovitch (1987a), as discussed in appendix A, fig 2(c), molecular conformation changes occur fractally on scales varying from larger functionally important global changes to a variety of smaller thermodynamic fluctuations. Large protein molecules are thus both structurally and functionally fractals. The chaotic nature of quantum kinetics, fig 4(h,i) finally allows the neurodynamic interface with the level of the quantum. Microtubules have also been proposed as functional cellular automata (Hameroff 1987, 1994) which could also be significant in nervous function. Similar considerations apply to proteins which are responsible for vesicle release which, like the microtubules, form a paracrystalline structure. Beck & Eccles (1992) have cited this interaction as a principal vector for quantum stochasticity. Any of these structures could enable quantum fluctuations in a way which could result in global neurodynamic changes.

¹⁷ The Fourier transform integrates the values of a function by multiplying each with an oscillating sine function to form a frequency representation of the time-dependent function. A hologram forms a physical realization through the sinusoidal phase fronts of coherent laser light. Both act by a many-to-many integration process [each point on the hologram corresponds to waves coming from every point on the image]. Each can be inverted to retrieve the original form.

4.4 Polyfractality

In the polyfractal model, global instabilities in brain dynamics are dynamically-linked to neuronal fluctuation. Threshold tuning similarly enables neuron to respond unstably to synaptic perturbations. Quantization at the level of the synaptic vesicle, ion channel and/or microtubule allows for capping off of the fractal process at the level of molecular complexes. Amplification of quantum fluctuations into micropotentials at the neuronal level could thus in principle, if the neurosystem is critically poised, lead to global bifurcation. Sensitive dependence and quantum amplification make the brain theoretically able to detect fluctuation at the quantum level, consistent with the sensitivity of sensory apparati which are all capable of detections at or close to single quanta, 8.1. It is thus possible for chaotic dynamics at the global, cellular, synaptic and molecular levels to combine to provide a fractal model in which global and quantum instabilities are linked by mutual interactions of scale.

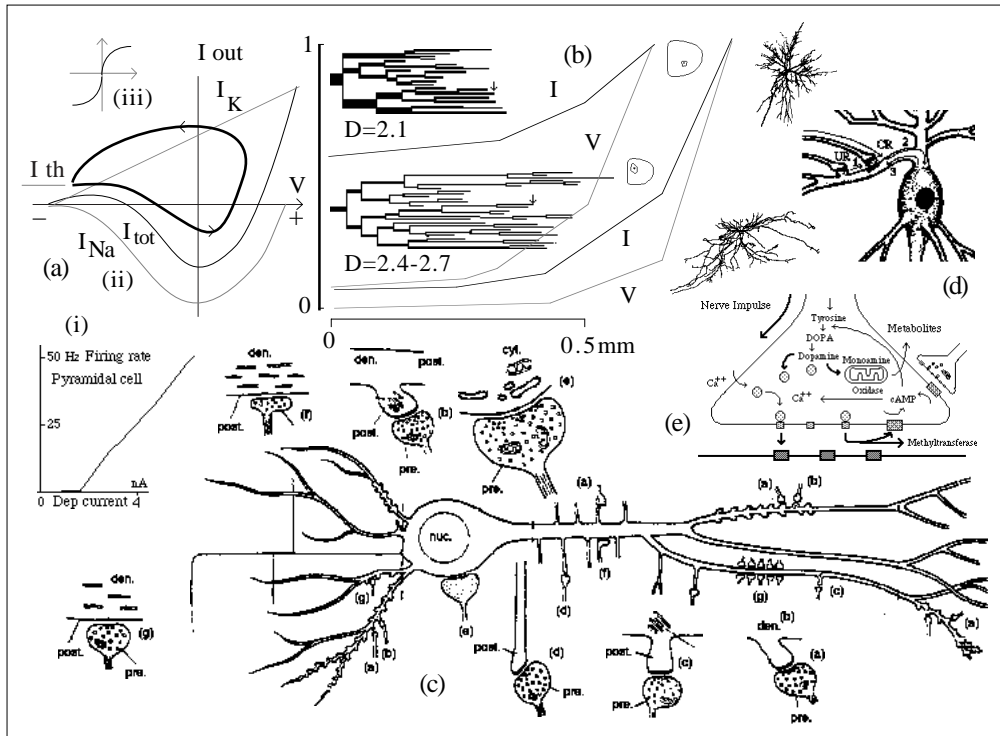


Fig 3: Non-linear and fractal aspects of the neuron. (a) Limit cycle at excitation threshold (ii) illustrates neuronal non-linearity, despite approximate linear relation between depolarization current and firing rate in a limited range (i). Sigmoid transmission curve (iii) and mechanoreceptive bulbs also have a non-linear response. (b) Fractal dimensions of dendrites of two cell types and their electrodynamics (Schierwagen 1986). (c) Anatomical complexity of the neuron illustrated by the structural variety of synaptic junctions, which also utilize distinct neurotransmitters. (d) Dendritic microcircuits and synapto-synaptic junctions (e) place the level of net organization one or two levels below the neuron. Synaptic conduction involves many feedbacks, some of which, including the two-molecule activation of the acetyl-choline ion channel have quadratic rather than linear concentration dynamics.

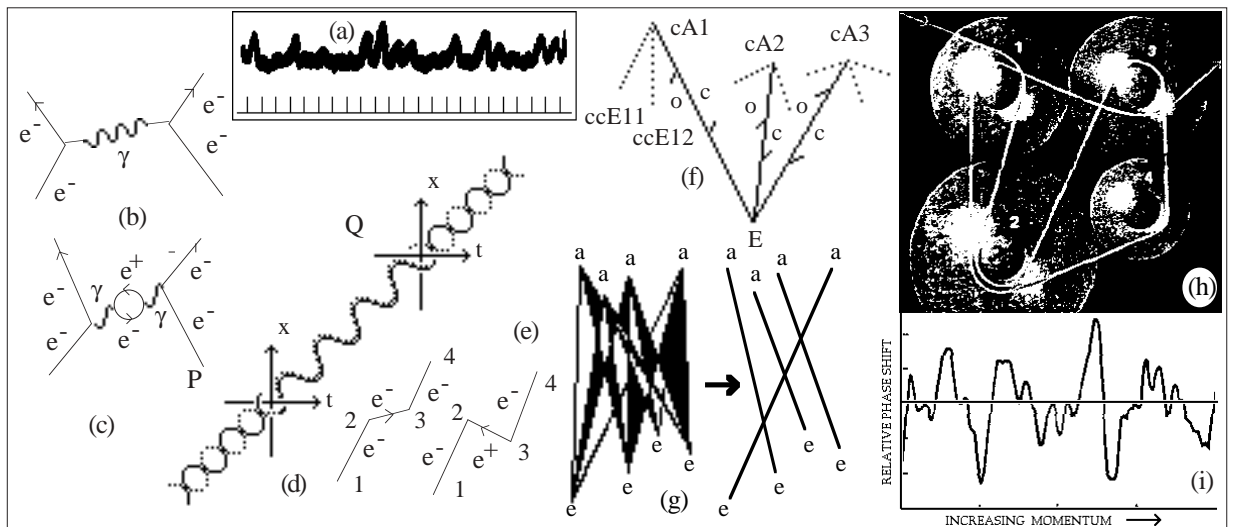


Fig 4: (a) Excitations of single rod cells show peaks with 0, 1, or 2 photons being registered, consistent with quantum statistics of photons being released very slowly at a rate corresponding to the marks below (Bailer & Lamb ex Blakemore 1991). (b) Feynman diagram of exchange of a photon, (c) higher-order diagram. (d) One-photon transaction involves interfering offer and confirmation waves. (e) Electron deflection and positron creation and annihilation. (f) Contingent emitters and absorbers as boundary of collapse.(g) Transactional reduction reduces to a combinatorial problem. At first all emitters and absorbers are correlated. Afterwards only the selected pairs. (h) Electron traversing a molecule has continuous variation of time [phase] with chaotic irregularity (i) (Gutzwiller 1992).

It is one thing to establish that fluctuations at the quantum level could become amplified into global instabilities in the brain, but quite another thing to explain why the brain should find it advantageous to allow seemingly disordered processes to intervene in its functioning. Normally noise is an anathema to computational precision. How then could quantum-chaotic processes have been selected in evolution and utilized in nervous system function?

5 Supercausality and the conscious brain

5.1 Transactions and correlations

Energetic interactions in the universe are based on real, positive energy particles. All quantum force field interactions are mediated by virtual particles which depend on the existence of both emitter and absorber because the exchanged particle can only be in existence for an interval determined by the uncertainty relations 8.3.2. A virtual particle can become real if it is given a real positive energy¹⁸, so real particles should behave likewise. The strict rule which prevents a single real particle being accidentally absorbed at two different places in a spatially extended wave function, indicates the absorber plays a significant role in wave function collapse, as do several famous experiments in which changing the configuration of the detection apparatus after emission has occurred changes the behaviour of the emitted particle (Horgan 1992). Heisenberg's idea that quantum mechanics describes our 'state of knowledge' of the system also places a formative emphasis on the detector as an absorber, in determining the rules of quantum collapse in any measurement. All particles may thus arise and demise in like manner out of the universe as a self-contained quantum system.

The transactional interpretation (Cramer 1986), appendix B, fig 4, is a formulation of quantum mechanics in which the emitter and absorber impose mutual time-symmetric boundary conditions on quantum interaction. This means that quantum non-locality, even in a one-particle wave function, is indirectly utilizing information about future states¹⁹ of the universe in collapse of the wave function. The basis of the transactional interpretation is as follows: The emitter radiates an *offer* wave indicating it can emit a photon. This offer wave permeates space-time. All potential absorbers of the prospective photon throughout the universe at more distant and later times in turn radiate similar *confirmation* waves indicating they can absorb a photon, but this wave radiates backwards in time, reaching the emission vertex at the same instant the offer wave is radiated. The emitter is thus made aware of the existence of all potential absorbers. Collapse of the wave function then results in reinforcement of only one of the many potential absorbers. The mutual interference of the chosen offer and confirmation waves results in the wave function of a real photon travelling between the chosen emitter and absorber.

¹⁸ Real particle interaction differs from virtual interaction in one important respect, all possible virtual particle interactions happen simultaneously in force interaction, but in real particle interaction only a single quantum is exchanged out of an envelope of possibilities, the choice of which constitutes reduction of the wave packet.

¹⁹ The transaction starts out in many worlds. The contingent absorbers may also be contingent future states of other interactions, existing only as a probability in terms of quantum mechanics. However in the completed transaction, which happens for the emitter as soon as emission occurs, the existence of the absorber is certain. The collapse of any wave packet is thus a collapse of the universal wave function. The entire historical process is a single collapse appearing in serial time, but actually occurring throughout space-time in a supercausally-coupled event, the 'infinite clockwork' of Maria Sabina (22).

The advent of Bell's theorem²⁰ and the pair-splitting experiments of Aspect et. al. (1982) among others, have demonstrated that in a splitting to form a quantum-correlated particle pair, non-locality ensures that, although neither is in a specific state to start with, when the state of one of the particles is measured, the other is immediately determined to have a complementary state. Although the information at each particle detector appears random, there is actually a correlation between the statistics of the two detectors which demonstrates non-locality. Because we can detect the correlation only when we examine both detectors, we cannot use the process to explicitly transfer information faster than the speed of light. The information is enfolded in the hidden²¹ *implicate order* (Bohm 1980) of the sub-quantum world.

5.2 Transactional supercausality and quantum inflation

Transactional supercausality or *transcausality* (King 1989) proposes a theory in which the temporal ordering of causal events is replaced below the quantum level by symmetric space-time transactions forming a *hidden* complex system. Rather than being random, quantum indeterminacy would arise from a non-local pseudo-random²² process. Because future states are part of the boundary conditions, a transaction cannot be reduced to a deterministic process in terms of increasing time²³. The absorbers may exist only as future probabilities arising from other future quantum interactions. A paradox in temporal determinism results. Transactional collapse thus carries predictive information in implicit form, which could be accessed by the emitter, for example through resonant excitations in which the brain emits and reabsorbs its own excitons.

In chaotic systems, sensitive dependence on arbitrarily small perturbations makes it possible for fluctuations on the quantum scale to eventually become amplified into global differences, something I will call *quantum inflation*. The interpenetration of classical and quantum chaos at the level of molecular kinetic processes²⁴ forms the lower scale limit where chaos and quantum non-locality merge, 8.4. This means that the underlying source of 'randomness' in kinetic processes is also quantum indeterminacy. In fact this is clear from quantum mechanics, in which evolution of the wave function is deterministic and reduction of the wave packet is the source of all natural 'randomness'²⁵. Since every natural stochastic process can thus be traced ultimately back to indeterminacy, transcausality may apply to a variety of evolutionary and historical processes.

A more systematic form of anticipation could arise from parallel transactions which may provide anticipatory

²⁰ Bell's theorem placed limits on the correlations between two particles in a single wave function if they were related in a local and causal manner. Experiments, including Aspect et. al. (1982) proved correlations exceeded these bounds, confirming the intrinsic non-locality of quantum mechanics.

²¹ Bohm (1952) originally described such sub-quantum theories as *hidden-variable* theories.

²² A [super]causal process is pseudo-random if successive values approximate those of a random distribution in that all values are equi-probable and there are no dominant periodicities. A system with many interacting parts such as a classical gas may return pseudo-random measurements because the position of any particle is a function of the positions of all the others.

²³ It is thus neither random nor predetermined, providing consciousness with a critical role.

This is a double-edged privilege however, as responsibility takes on cosmological proportions!

²⁴ Kinetic interactions of an electron with a molecule are an experimental example of quantum chaos, fig5(c).

²⁵ Transactions would also explain the occurrence of causally unrelated coincidences, Jung's *synchronicity* and the stochastic basis of the I Ching (Wilhelm 1951).

information in implicit form through correlated behaviour. The apparent randomness of quantum indeterminacy may conceal other types of correlation more general than those seen in correlated pairs or multi-particle Bose-Einstein condensates. It has been proposed that all particles in the universe are correlated by virtue of their emergence from the common universal wave function. There may thus be many other types of correlation occurring in the supposed randomness of quantum probabilities. Depending on the exact model for the correlations envisaged, such a population could be a looser collection, such as a set of contingent emitters and absorbers, like wave functions, or exchangeable particles.

A single cell with chaotic dynamic expressed globally via coherent excitation of the cell membrane might then access a form of prediction unavailable through classical computation. A collection of cells forming a neural net coupled in the form a global dynamical system could likewise experience linkage. The interaction could be based on coherent oscillations or on the quantum sensitivities of a chaotic system undergoing bifurcation. A variety of types of quantum exchange are possible such as photons, phonons or various excitons. The predictive interval would be related to the lifetime of the exchanged quanta. Long-lived quanta or reverberations might thus prove a predictive advantage. Emitters might function as quantum predictors for example through their interactive recoil (Storey 1994). Major oscillations of the electro-encephalogram, especially in the 10 Hz-100 Hz range might also form a basis for quantum linkage in the brain. Such oscillations could form a self-contained transactional system. Global resonances might form Bose-Einstein condensates as they become coherent, although doubt has been cast on the capacity of coupled molecular oscillators to do so Clarke (1994). Consciousness as a subjective manifestation of quantum non-locality may thus possess a predictive capacity that, like the pair-splitting experiments, comes in an implicate form which, although not formally computable, can emerge from an instability, subjectively experienced as a hunch or intuition.

5.3 Representation of time in the cortex and in conscious experience

Since Grey-Walter first made subjects witness movement of a slide show via a motor cortex probe and found they witnessed the slide change *before* they pressed a dummy button, the time properties of conscious experience have been a conceptual challenge. Two experiments outline some puzzling temporal properties of consciousness. In the first, (Kolars & von Grunau 1976) alternate lights of different colour flash for 150 ms with an intervening gap of 50 ms. Subjects report a single moving light which changes colour at the mid point, even on a first exposure, or random colour change. This creates an apparent paradox because the colour change apparently occurs *before* the second light has come on.

In a second class of experiment (Libet et. al. 1979), subject to repeated discussion (Libet 1985a,b,1987,1989, Churchland 1981 a,b, Honderich 1984, Snyder 1988) involves the subjective timing of stimulation of one hand [say the left, which excites the right somatosensory area] at the same time as direct stimulation of the opposite [left] somatosensory area. The genuine hand-tingle is perceived *before* the cortically induced one even if it actually occurred afterwards. Because of the considerable delay for the development of neuronal adequacy for the conscious experience [200 - 500ms] the time of the experience appears to be referred back to the primary evoked potential [10-20ms after stimulus]. Such temporal projection comes close to causal paradox. Libet comments “a dissociation between the timings of the corresponding mental’ and ‘physical’ events would seem to raise serious though not insurmountable difficulties for the ... theory of psychoneural identity”.

Dennett (1991) disavows such features as looping of the subjective time sequence out of the physical sequence, because the order of consciously perceived events does not have to be coincident with the physical or apparent physiological order when parallel processing builds up a global model of a time sequence from partial constructs. This approach implies that the completed representation cannot be formed until *after* the sequence ends. It is not clear this is the case with the first experiment.

As discussed in appendix C, the frontal cortex appears to be a distributed modular representation of intention and action in the same way the sensory areas are for perception, including both the capacity to anticipate the outcome of an evolving event and to utilize previous experience. Because it requires integration of past memories, present experience and future intentions and survival strategies, and because its functional basis may be phase coherence, our subjective internal model of time may more closely resemble a holographic image of space-time than merely a mechanical representation of time based exclusively on past data. Damage to prefrontal areas effects predictive sensory tracking tasks 9.4, in which the prefrontal cortex appears to utilize a modular representation of the phases of

a predicted action. The separate processing of movement in visual perception constitutes a similar temporal representation. A transform representation of time may provide better integration of past experience and future needs in response to situational demands than a time-consuming computation based only on past data 6.1. It is easy to see that visual perception constructs an external spatial reality, but is more difficult to accept time as a similar internal construct, in which the subjective experience of free-will or intent arises because the function of consciousness is to *anticipate*, forming an “ill-posed” problem in time whose outcome is not fully determined by the initial conditions.

The central task of the brain is the representation of the activity of the organism in terms of past and future actions. The likely basis for such a model is populations of dynamically coupled cells with chaotic excitation, bifurcating into coherently oscillating populations which induce Hebbian²⁶ reinforcement and hence synaptic adaption. Although these may include forms of time-coding, possibly provided by the hippocampus, coherent oscillations measure a circular phase-shift, i.e. an angle, and not a specific direction in time. Counting beats to determine frequency or wavelength also requires a reciprocal time or distance corresponding to the uncertainty relations, 8.3.3²⁷. The use of coherence is thus formally equivalent to quantum measurement. Quantum decoherence has also been proposed as a basis for wave function collapse (Zurek 1991). Cortical oscillations and their corresponding mental states may thus be inflated quanta reverberating through the brain. The subjective experience of the present may consequently be an extended *quantum of the present*, forming an envelope of immediate past and future states linked by transaction. This coincides with the way we generally deal with the present as a contextual flow of events linking past and future in integral attention spans of around half to one second duration.

When the the attention process is fixed on itself and sensory and/or cognitive processes are suspended, a variety of unusual reflexive mental states result, demonstrating that the mind is capable of self-generative behaviour in which unusual *anticipatory* space-time properties have been reported. These include the bizarre subjective realities of dreaming²⁸, lucid dreaming (La Berge 1990), sensory deprivation, meditative trance and hallucinogenic visions²⁹.

²⁶ Hebb proposed that connected neurons which fire synchronously increase their synaptic strength.

²⁷ The uncertainty Δv in a frequency measured by counting beats against a known wave for time Δt is $\Delta t \cdot \Delta v \geq 1$. Einstein's law $E = h \cdot v$ immediately returns the uncertainty relation 8.3.3. This suggests quanta apply the same discrete process.

²⁸ Dreaming has been reported to have unusual space-time properties, associated as much with future as with past experiences (Dunne c1935). Many traditional cultures report the use of dreams to anticipate future problems and events. The dreaming state is not viewed as an illusory representation of the ‘real world’. In the shaman's description, the *dreaming* aspect of reality underlies the physical, so that the waking experience of the physical world is a restricted aspect of a wider and more fundamental totality. After reading Dunne, I had a double nightmare that I was being stung. I awoke at eight and told my wife the dream. At nine I was stung wide awake by a wasp. I have been chasing the tail of that sting ever since! The night before I delivered a lecture on this subject at Oxford, I dreamed that I was being attacked in the shoulder by nurses. Next morning, as a result of unexpectedly accompanying a friend to a doctor, I was vaccinated in both shoulders by his nurses.

²⁹ Five aspects of visionary states are noted in societies making ritual shamanic use of hallucinogens; geometrical illusions, visions of animals and demons, separation of the mind from the body, clairvoyant visions of distant places, and divination of past or future events (Harner 1973). “*On the day following one ayahuasca party, six of nine men informed me of seeing the death of my ‘chai’, my mother's father. This occurred two days before I was informed by radio of his death*”. The mushroom shamaness Maria Sabina avowed “*The more you go inside the world of teonanacatl the more things are seen. And you also see our past and our future, which are there together as a single thing already achieved, already happened . . . Millions of things I saw and knew. I knew and saw God: an immense clock that ticks, the spheres that go slowly around, and inside the stars, the earth, the entire universe, the day and the*

Such reflexive conscious states may show us deeper features of how the conscious mind interacts with quantum supercausality than can be accessed from everyday waking experience, which is dominated by stable sensory representations of the ‘classical’ macroscopic world. They may thus be a unique avenue to discovering the implicate nature of quantum reality.

The problem of temporal representation is central to how attention and intention interact in the conscious moment. Attention is intentional as well as perceptual. The problem of the “ghost in the machine” (Koestler 1967) is essentially a problem of how such *intentional attention* is organised. As well as being an issue of control, this problem may be paradoxical in terms of any mechanistic description, because the boundary conditions of supercausality violate temporal determinism by including future states. The brain may thus be *intuitively conscious of the future* in a manner prohibited from deterministic description with increasing time.

6 Evolutionary origins

6.1 The computational intractability of survival in the open environment.

The principal task of the brain of is to optimize the survival strategy most likely to enable the organism to evade death and produce viable offspring. A computational problem is *intractable* if the number of computational steps required grows super-exponentially with the complexity of the problem, or *formally undecidable*. The *travelling salesman* problem (Bern & Graham 1989), finding the shortest route round n cities illustrates this, growing super-exponentially.³⁰ Many adaption-survival problems in the open environment are intractable because the number of options in an open environment rapidly exponentiates, or undecidable because the problem becomes indeterminate. Some intractable problems can be solved approximately by probabilistic methods. Neural nets also utilize random fluctuations of gradually reducing energy to carry the net from local optima into a semi-global optimum. Chaotic ergodicity may function similarly in biological neurosystems.

An active organism must complete a processing task within 0.1-1 second if it is going to have survival utility, regardless of its complexity. This makes it clear why parallel processing is an integral feature of vertebrate nervous systems. The modular features found in sensory processing realize a type of fractal algorithm (Penrose 1989, Dewdney 1989) which in addition to parallelism, features fractal task assignment. Chaos and bifurcation provide additional attributes of sensitive dependence, ergodic phase space pervasion, and the capacity to form new symbolic structures through bifurcation.

A dynamical model for cognition would function as follows: The initial conditions determining a problem result in a series of bifurcations generating accumulating attractors which form stable ‘symbolic’ representations of those aspects of a problem which have been modelled. The complementary unstable component of the dynamic, representing the unsolved aspects, continues to chaotically explore phase space, either bifurcating to stability, or forming fractal and consequently quantum instabilities. The final resolution of such instabilities into a global attractor determines the solution to the original problem. If either the initial conditions or subsequent bifurcations prove incompatible, the dynamic may fail to cohere, precipitating a global rearrangement in which some of the intermediate stabilities are removed or replaced.

Decision-making, which might be solved heuristically³¹ in a computer by making a random choice based on probabilities, corresponds to an unstable system poised at bifurcation. This might correspond to two interpenetrating assemblies of cells with differing coherent attractors, with a critical population of chaotically desynchronised cells. Developing a new learned perception can be realized a little differently. The neurosystem

night, the cry and the smile, the happiness and the pain. He who knows to the end the secret of teonanacatl can even see that infinite clockwork” (Schultes 1979, Guzman et. al. 1991,93).

³⁰ Given two directions and $n-1$ choices for the second city etc. we have $(n-1)!/2$ steps, where $n!=n.(n-1).(n-2). \dots$

.3.2.1

³¹ Inclusion of many possible strategies with probabilistic decisions based on success rates.

enters high-level chaos, exploring its phase space and as the energy is reduced a bifurcation out of high-level chaos occurs into a new lower level attractor. We thus have bifurcation out of chaos to form new structure. Such indeterminacies can complement formal computation because the instabilities correspond to heuristic choices where computation is anyway probabilistic. For the same reason any predictive capacity resulting from transcausality complements formal computation.

6.2 Chaotic excitability as a founding eucaryote characteristic.

Chaotic excitability may originate deep in evolutionary history, representing one of the oldest features of eucaryote³² cells (King 1978, 1990). Hameroff (1994) has suggested that microtubules may have provided a basis for consciousness in single celled eucaryotes such as *paramecium*. While not wishing to under-play the significance of microtubules, the current model envisages a more comprehensive basis for the origin of consciousness in single celled eucaryotes centred around chaotic membrane excitation and its sensory potential. This would apply to all eucaryote cells including ciliated and unciliated forms.

The Piezo-electric nature and high voltage gradient of the membrane provides an excitable single cell with a generalized sense organ. Sensitive dependence would enable the cell to gain active feedback about the external environment without becoming locked in a any mode. Excitation could be perturbed through photons, phonons or weak bond interactions, making the membrane sensitive to light, vibration, and chemical stimuli. The effects of the fluctuating fields generated by the excitations would provide an electromagnetic sense organ. The topological closure of the cell membrane would provide local excitations with a capacity for coherence and global dynamics. Bifurcation would also provide a global means for decision-making.

Such excitability would significantly predate the computational role of neural nets, making chaos fundamental to the evolution of neuronal computing rather than emerging later from neural net organization. Chemical modifiers may have included precursors of the amine-based neurotransmitters which span acetyl-choline, serotonin, catecholamines and the amino acids such as glutamate and GABA, (Cooper et. al. 1982) several of which could have a primal status chemically. The use of positive amines may have chemically complemented the negatively charged phosphate-based lipids in modulating membrane excitability without requiring complex proteins (King 1990), supporting an early origin for excitability in the RNA era. Protein receptors could thus be a subsequent adaption.

6.3 Consciousness as an evolutionary manifestation of chaotic neurodynamics.

In the supercausal model, an excitable cell, which evolved initially to achieve perceptual sensitivity or constrained optimization through chaotic excitation, would also inherit a capacity for prediction through non-local quantum interactions. This anticipatory capacity associated with quantum reduction would then constitute cellular consciousness. The evolution of the excitable cell and subsequently the sensitively-dependent brain may thus have been driven by the combined advantages of chaotic sensitivity and quantum anticipation.

Far from being an epiphenomenon, consciousness may thus have been elaborated and conserved throughout evolution, contrary to Jaynes (1976), because it has had survival value from the single cell to the brain. In the evolutionary perspective, consciousness first developed as a cellular process and then evolved into a neurosystems property as a result of global neurodynamical coupling of chaotically excitable nerve cells. Consciousness as we know it is thus an *emergent* property of neurosystems which is already partially expressed in single cells. It is a logical conclusion that the conscious brain has been selected by evolution because its biophysical properties provide access to an additional principle of anticipation not possessed by formal computational systems.

The objective manifestations of consciousness and free-will are intrinsic to the quantum - a form of *panpsychism*. Consciousness can be associated with a quantum by virtue of the capacity of the wave function to form a global space-time model of the diverse features of the universe including its future states. Free-will is expressed in the unique choice occurring in each reduction of the wave packet. Connectivity and coherence gives the brain a degree

³² All cells with nuclei, including protozoa, fungi, plants and animals are eucaryotes.

of cooperative indeterminacy which is undeveloped in a single quantum, or a simple Bose-Einstein condensate like a laser, leading to our contextually elaborate experience of consciousness and free will.

7 : Appendix A: Non-linear dynamics in the central nervous system

Experimental evidence for chaotic dynamics in a variety of aspects of central nervous system function has accumulated in recent years. Chaotic has been experimentally detected both at the neurosystems level and in the dynamics of single excitable cells, and ion channels have been shown to have fractal kinetics (King 1991). Although these results provide circumstantial support for the model, experimental research cannot establish more than suggestive consistency at this point in time.

7.1 Electrodynamics.

7.1.1 *Neurosystems Dynamics:* Evidence has been presented for chaos in the electroencephalograms of several phases of cortical activity, including sleep, resting wakefulness and pathological states such as epilepsy (Babloyantz 1985, 1989, Basar 1990). The low correlation dimensions³³ of these states is consistent with chaotic neurodynamics rather than stochastic, or locally programmed behaviour, fig 1(a,b). Active mental states have slightly higher dimensions, consistent with both chaotic and stochastic models. Evoked potentials display desynchronization on unexpected input, consistent both with cognitive instability, and with phase coherence being utilized in recognition and orientation (Basar et.al. 1989, Hoke et.al. 1989), fig 1(f). Crick and Koch (1990,1992) have suggested consciousness is associated with neuron populations associated by phase coherence in the 40 Hz range, where there is evidence of attention-related change. Coherence is a property of non-linear systems.

The model of burst dynamics in the olfactory bulb advanced by Walter Freeman fig 1(d,e) combines these two aspects into a single model based on bifurcations of the chaotic temporal dynamics of coherent spatially distributed waves, which closely follows the neurophysiology and also permits real tests of pattern discrimination of neural nets displaying comparable dynamics (Freeman & Baird 1987, Skarda & Freeman 1987, Freeman 1991, Yao et.al. 1991). In this model, low level chaos is lifted into a higher energy state by inspiration associated with an animal sniffing. Chaos in this state then enables the system to explore its phase space, subsequently falling into an existing attractor in the case of a recognised odour as the breath moves to expiration, or bifurcating to form a new attractor in the case of a newly learned stimulus. The transition into chaos may thus provide sensitive dependence on input, 'randomizing' ergodic phase space exploration, parametric bifurcation to form new symbols, and possible quantum amplification. Bifurcation from high-level chaos may in turn create new structures.

7.1.2 *Single Cell Dynamics:* Similar experimental evidence has accumulated for chaos in a variety of excitable cell types, supported by the chaotic models of Chay and Rinzel (1985), fig 2(a,b). These extend the Hodgkin-Huxley equations (1952) to take account of calcium ion pumping, displaying a variety of dynamical features, including period doubling bifurcations and period three oscillations characteristic of the chaotic regime. Chaotic dynamics well-model the excitations of *Nitella* pancreas cells and excitations in neurons and heart pacemaker cells. The irregular behaviour of controlling cells in small ganglia such as in the mollusc *Aplysia* is also consistent with sensitive dependence and chaos, by contrast with the more regular beating of subordinate neurons. Single-cell chaos has also been recorded in both isolated and *in-situ* neurons.

7.1.3 *Fractal Ion-Channel Kinetics :* A Markov chain model is commonly used for ion channel kinetics³⁴, however the likelihood that a closed channel will open behaves fractally with increasing time scales according to fig 2(c) (Liebovitch et. al. 1987a,b, 1991). This is consistent with bio-molecular structures behaving fractally, not only in a geometrical sense, but also dynamically as shown for myoglobin in (d) (Ansari et. al. 1985). The dynamics of many important biological molecules may be fractal in this way, which involves the linkage between a variety of quantum

³³ A dimension similar to the fractal dimension but based on relationships between pairs of points in the dynamic.

³⁴ A stochastic model with a finite set of states with fixed transition probabilities.

In the Markov ion channel an open state is linked to one or more closed states.

excitations of differing energies and scales, and feedback between tertiary structures and active sites.

7.2 Long-term adaption and development.

The developmental organization of sensory areas of the cortex appears to be dependent on sensory innervation and stimulation, consistent with an attractor-bifurcation model founded on general genetic principles. The spatial distributions corresponding to olfactory stimuli, fig 1(d) adopt new forms on relearning the same stimulus a second time, consistent with bifurcation. Phase desynchronization of cortical evoked potentials is consistent with unstable dynamics. Adaptive reorganization e.g. of ocular dominance regions on the cortex on covering a dominant eye, and somatosensory barrels of the rodent on removing a whisker, indicate major sensory structures may arise as dynamical systems induced through bifurcation.

8 : Appendix B : Quantum mechanics and transactions

8.1 Quantum sensitivity in the sense modes.

Limits on the sensitivity of nervous systems arise from quantum physics rather than biology. This is exemplified in fig 4(a) by the capacity of retinal cells to record single quanta, and by the fact that membranes of cochlear cells oscillate by only about one hydrogen atom radius at the threshold of hearing, well below the level of thermodynamic fluctuations. Moth pheromones³⁵ are effective at concentrations at which only one molecule must be active, as are the olfactory sensitivities of some mammals.

Despite the apparently similar electrochemical activity of their cortical areas, both the subjective natures of vision, hearing, touch and smell, and their quantum modes, namely photons, phonons and weak bonding interactions are qualitatively quite distinct. It is possible such modes may also function in the cortex in representing senses as outlined in, 6.1. All could thus occur simultaneously in membrane excitation, resulting in *synesthesia*³⁶, in which perception has cross-sensory effects. Hameroff (1994, p96) has suggested a similar sensory role for Bose-Einstein condensates.

8.3 Quantum mechanics and wave packet reduction.

Quantum systems differ fundamentally from the classical case. While the time evolution of the system proceeds according to a deterministic Hamiltonian wave equation, e.g.

$$(\partial^2/\partial t^2 - \nabla^2 + m^2) \phi = 0, \quad [8.3.1]$$

in the measurement process, reduction of the wave packet prevents a causal description because the probability interpretation

$$P = \phi^* \cdot \phi \quad [8.3.2]$$

determines the limits on our knowledge of the system, resulting in a *stochastic-causal* model. Measurement collapses the wave function from a superposition of possible states into one of these states. While quantum-mechanics predicts each outcome only as a probability, the universe appears to have a means to resolve each reduction of the wave-packet uniquely, which I will call the *principle of choice*, the subject of Schrödinger's famous cat paradox³⁷. The indeterminacy of [8.3.2] is also reflected in Heisenberg uncertainty

$$\Delta E \cdot \Delta t \sim \frac{h}{2\pi} \quad \Delta p_x \cdot \Delta x \sim \frac{h}{2\pi} \quad [8.3.3]$$

in which we cannot know simultaneously all the dynamical aspects of a particle's state.

Reduction of the wave packet in a measurement can most simply be described in terms of a system with a series of distinct eigenvalues such as the energy levels of an atomic electron. The state of the system is represented by a state

³⁵ Hormone-like sexual attractants detected by sense of smell during mating.

³⁶ The experience of one sense, say a colour in relation to input of another sense, say a sound.

³⁷ Quantum mechanics predicts a cat in a closed box which could be killed as a result of a radioactive decay is both alive and dead with certain probabilities, while we find when we open the box it is only one : alive! or dead!

vector $|\varphi\rangle$ which evolves in time according to the wave equation. An observable quantity A is represented by an operator with a set of eigenvectors $\{|\varphi_r\rangle\}$, with $|\varphi\rangle = \sum_r \alpha_r |\varphi_r\rangle$. The probability (see 8.3.2) that an observation of A will give the eigenvalue φ_r is

$$P = \sum |\langle \varphi_r | \varphi \rangle|^2 \quad [8.3.4]$$

Before measurement the state vector is $|\varphi\rangle$, but afterwards it has collapsed to one of the eigenvectors $|\varphi_r\rangle$. Similarly a photon in an interference experiment could be anywhere in its wave function, but is absorbed by one atom on the photographic film.

8.4 Quantum chaos versus uncertainty as a substrate for classical chaos.

Repeated attempts to model a variety of quantum analogues of classical chaotic systems have revealed significant differences which may inhibit the full development of chaotic dynamics in at least some of the quantum analogues (Peterson 1991, Gutzwiller 1992). The wave aspect of the quantum effectively blurs the fractal structure and has greater amplitude around the hidden periodic orbits. Such quantum inhibition may result in edge-of-chaos dynamics consistent with quantum computation paradigms (Brown 1994). The particle traversing a molecule fig 4(h,i) gives an illustration of chaos in molecular kinetics (Gutzwiller 1992) displaying chaotic variation in transition time [phase]. This supports a model in which molecular complexes form an interface between chaos and quantum nonlocality as portrayed in the fractal models illustrated in fig 2(d,e).

However it is the stochastic wave-reduction aspect of quantum mechanics which generates the unpredictabilities found in chaotic physical systems and is the source of randomness in their statistical mechanics. For example molecular kinetics is made uncertain through diffraction of the wave aspect of a molecule by other molecules. An amino acid at room temperature has a self-diffraction angle of about 5° (King 1989), contributing initial condition uncertainty to each successive kinetic encounter when traversing a molecular medium. One of the important roles of classical chaos may thus be *quantum inflation*, the amplification of quantum fluctuation into global perturbations of the dynamic.

8.5 Quantum concepts and consciousness.

Interest in quantum concepts in brain function has had a considerable history Eddington (1935), Szent-Gyorgyi (1960), Eccles (1970) and Bohm (1980). Wigner (1961), Popper and Eccles (1977) and Margenau (1984) and among others have suggested that quantum reduction is precipitated by the consciousness of the observer³⁸. Quantum decoherence (Zurek 1991) or registering a classical record is also a possibility. Bohm's (1952) work on the Einstein-Podolsky-Rosen conjecture, the advent of Bell's theorem and the Aspect experiments (Clauser & Shimony 1978, Aspect et. al. 1982) which display spin-correlations between a split photon pair over space-like intervals have demonstrated that hidden variable theories cannot be locally-causal, i.e. depend on local interactions which are transmitted no faster than light.

The possible implications of quantum non-locality for consciousness depend on which interpretation of quantum mechanics is used. Some theorists who follow the Everett many-worlds interpretation assert that reduction of the wave packet never occurs and that the universe is continually branching into all of its possible quantum outcomes which are presumed to co-exist as parallel aspects of a cosmic wave function. In such a view every quantum calculation is a superposition of overlapping quantum states and the utility of quantum non-locality is reduced to forming a parallel computer using superimposed states instead of discrete logic.

It has been proposed that Bose-Einstein condensates could function as quantum computers in which correlated particles could perform a superposition type computation (Zohar 1991, Hameroff 1994). Hameroff has made the suggestion that microtubules could be a form of quantum computer possibly taking the form of a molecular cellular automaton. Cellular automata are capable of being formal computers. Deutch (1985) has analysed the potentiality

³⁸ In the Wigner's friend paradox, an observer's friend splits the wave function, and reports on the result. Multiple minds thus lead to ambiguities of splitting. One way around this paradox is to require mind to be a cosmic unity, another is that the *first* conscious observer in the chain collapses the wave function.

of a quantum computer utilizing superposition of states. Although several instances have been given in which a quantum computer might solve specific tasks more efficiently, (Lockwood 1989) there do not appear to provide qualitative advantages over parallel distributed processing.

The many-worlds interpretation contradicts the evidence of our conscious sensory processes which experience only one of the possible outcomes thus conforming to a single historical process. Other approaches depend directly of collapse of the wave packet. The mathematician Roger Penrose (1986,1989) has suggested that collapse of the wave function may be a deterministic process based on the interaction of the superimposed wave function with the gravitational field at the level of one graviton. He has also postulated the idea of non-locality correlating the activity of various parts of the brain (Penrose 1987). The supercausal model proposed earlier in this paper, 5.2 is similarly based on quantum reduction.

8.6 The transactional interpretation of quantum mechanics

The supercausal model is based on the transactional interpretation, which developed out of Feynman's absorber theory (Davies 1974), is a form of special-relativistic quantum mechanics, utilizing the Feynman propagator diagram, fig 4.

The basis of the transactional interpretation is that each real and virtual particle can exist only as a link between emission and absorption foci, as an instance of the self-interaction of the universe, and consequently that particles cannot be created only to disappear into empty space. It is consistent with the behaviour of all virtual particles which mediate the quantum fields of the fundamental forces such as electromagnetism and the nuclear forces, and gravity, because each virtual particle must have an emission and an absorption focus to ensure it exists only within the limits set by quantum uncertainty (18). It is also consistent with Feynman diagrams in which a particle travelling in the usual (*retarded*) direction can be equated with its anti-particle in the time-reversed (*advanced*) state. Time reversal is standard in Feynman diagrams, a time-reversed electron being equivalent to a positron fig 4(e)³⁹. For a photon, which is its own anti-particle, these reduce to *offer* and *confirmation* waves of the emission and absorption foci.

The relativistic energy-momentum equation

$$E^2 = \mathbf{p}^2 + m^2 \quad [8.6.1]$$

has two solutions

$$E = \pm \sqrt{\mathbf{p}^2 + m^2} \quad [8.6.2]$$

in which the negative energy solution has reversed temporal behaviour in space-time. For example, the Hamiltonian equation, 8.3.1 for a zero spin particle with mass m has elementary solutions:

$$\varphi_{+,k} = (2\pi)^{-3/2} e^{i(\mathbf{k}\cdot\mathbf{x} - \omega t)} \quad [8.6.3a]$$

$$\varphi_{-,k} = (2\pi)^{-3/2} e^{-i(\mathbf{k}\cdot\mathbf{x} - \omega t)} \quad [8.6.3b]$$

where

$$\omega = (k^2 + m^2)^{1/2} \quad [8.6.4]$$

In the transactional interpretation of quantum mechanics (Cramer 1986) fig 4(d), a mutual encounter between emitter and absorber is modelled by the release of crossed-phase advanced and retarded waves, each having zero-energy, the *offer* wave of the emitter and the *confirmation* wave of the absorber. The retarded portion of the offer wave travels with increasing time in the usual manner permeating space-time and meeting potential absorbers. Each potential absorber in turn releases a confirmation wave. The advanced portions of the confirmation waves back propagate in time, meeting simultaneously at the emission vertex. Collapse now occurs so that one absorber is associated with the emitter. The mutual interference of these advanced and retarded waves produces a real superposition (the photon) between the emission and absorption events in space-time. Transaction is represented also in the fundamental equation, 8.3.2 in which the two wave function terms φ and φ^* represent the offer and

³⁹ This correspondence enabled Dirac to predict the existence of the positron from the negative energy solutions to his electron wave equation.

confirmation waves, the * [complex conjugate] arising from time inversion of the advanced confirmation wave.

In the Feynman diagram fig 4(b), the force between electrons is determined by integrating all possible virtual photon and higher-order interactions (c). The photon is *virtual* because it exists only for an interval consistent with the uncertainty relations, 8.3.3, and is detected only by its secondary effects in the electric field. While in virtual exchange, the effects of all possible exchanged photons are integrated, in the case of a real photon, the boundary condition that only one particle is exchanged, forces quantum reduction of the set of all possible exchanges to one real exchange.

The Aspect experiments illustrate that correlations occur across space-like intervals which cannot be bridged at the speed of light. The transactional interpretation explains such correlations by the confirmation waves of both absorbers interfering at the emission focus thus producing a communication by backward referral to the time the photon was emitted. Transactions are also the basis of the decoherence model of wave function collapse (Zurek 1991).

8.7. Transactions and Quantum Computation

Quantum computation (Brown 1994) has become an exciting issue in physics and computing because it provides the potentiality to profoundly speed up parallel computational processes, and even possibly provide solutions to problems which may be classically intractable (Calude and Pavlov 2002). Quantum computational schemes suffer from the need to maintain isolation from disturbance during calculation, however various consciousness research programs seek to find biophysical evidence for coherent states and the potential capacity for quantum computation in nucleic acids and other structures.

The configurations used in posing quantum computational problems such as decryption have features in common with the configurations one would anticipate the brain using in transactional anticipation, raising the possibility of these two quantum processes interpenetrating. In a decryption context a set of quantum systems are partially excited so they enter a superposition of excited and unexcited states. The quantum system is divided into two parts L and R so that measurement of one part R collapses the other L to a solution to the decryption problem. The solution in L is then decoded by using quantum parallelism again to convert L into its own discrete Fourier transform thus displaying its periodicities and giving a pointer to the numerical solution.

Transactional decision making differs from quantum computation in that the boundary conditions, instead of being a superposition leading to a measurement of a computed solution are a superposition leading to an open-ended decision which does not have a precise computational answer but rather may anticipate a future state of the brain. However in other respects, the biological substrates providing capacity for quantum computation and transactional decision making would strongly overlap providing a potentially common and complementary functional design.

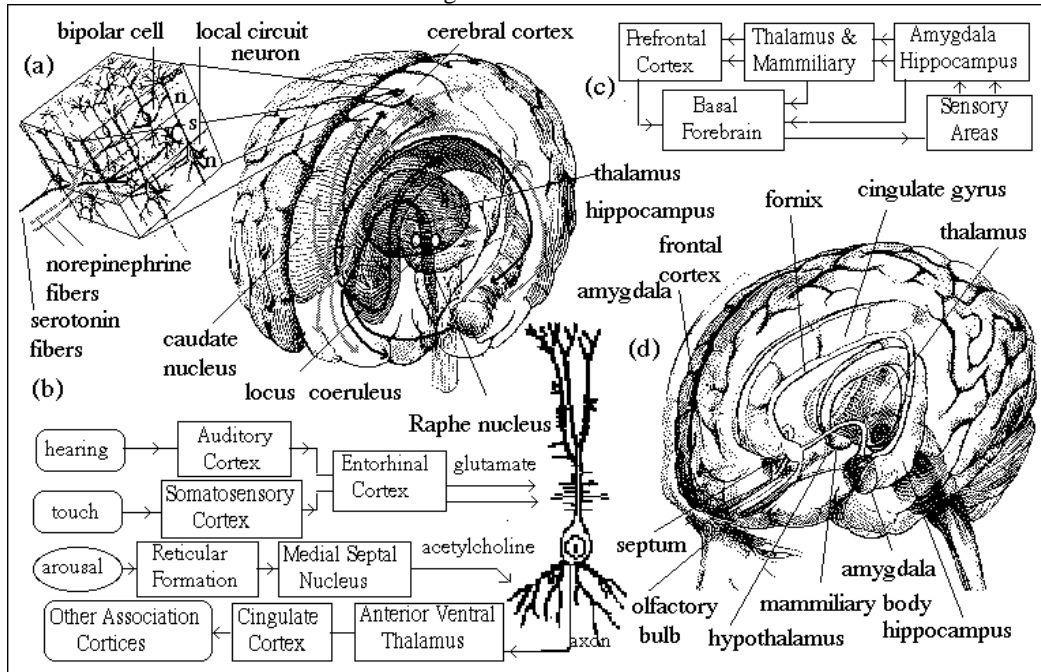


Fig 5: (a) Nor-epinephrine and serotonin pathways originating from mid-brain centres modulating light and dreaming sleep are distributed across wide areas of the cortex (Bloom et. al. 1985). (b) Inputs from different areas impinge on a single hippocampal CA1 neuron via distinct neurotransmitters, thus mapping neurosystems architecture on to single cells (Alkon 1989). (c) Looping circuits of the limbic system are involved in both affect and memory. (d) Limbic structures in brain section (Bloom et. al. 1985).

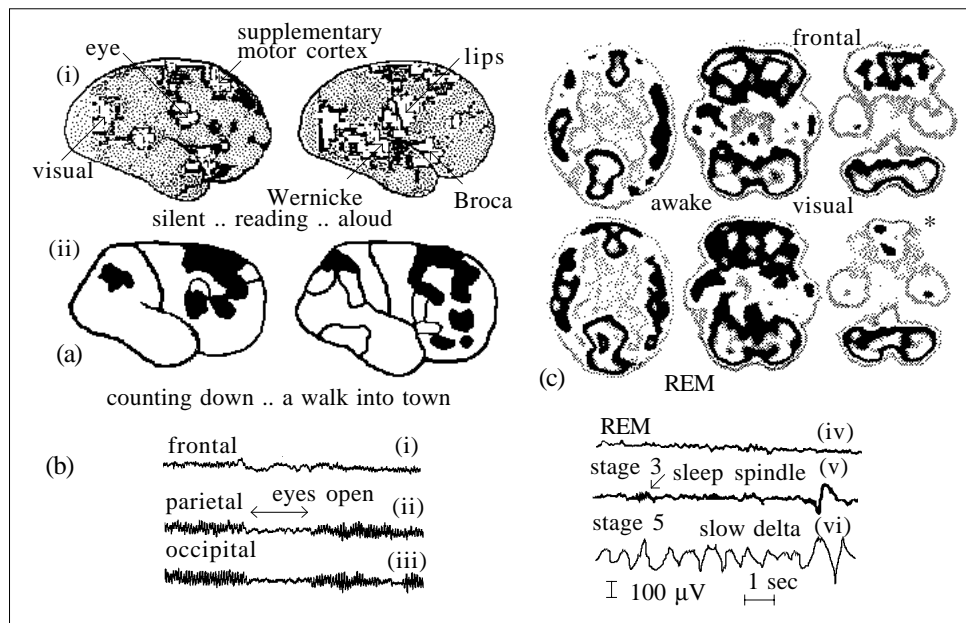


Fig 6: (a) Cortical modularity in PET scans. (i) Silent reading is contrasted with reading aloud, in which there is wider cortical involvement, including motor and somatosensory lips areas. (ii) Counting down is contrasted with visualizing a walk into town, stimulating a variety of frontal areas as well as the parietal cortex (P. Roland ex Blakemore 1991). The supplementary motor cortex is activated in all four views. (b) Similarity of the REM sleep EEG (iv) to the alert state [(i)-(iii) eyes open]. (c) REM sleep PET scan parallels the awake brain in activation of visual cortex and frontal lobes [dark], except for reduced REM inferior frontal activity (*), consistent with the lack of control in dream sequences.

9 Appendix C : The neurophysiological basis of mind

The experience of consciousness requires the global participation of the active brain. The ‘graceful degradation’ of function and subjective awareness that results from damage to a variety of cortical areas (Blakemore 1991) suggests the mind arises from distributed brain processes, rather than a specialized area. The major structures in the brain will be examined to indicate how each contributes to a global dynamical system representing the active conscious state.

9.1 Modular representations on the cortex.

Many different aspects of conscious experience can be associated with transform processing in which primary sensory inputs are transformed into an envelope of features including oriented lines, binocular dominance and the homunculus representing the body in the somatosensory cortex (Fodor 1983, Mountcastle 1978). *A variety of experiments confirm features such as written and spoken language, music, faces, spatial orientation etc. are all localized in a modular way, sometimes lateralized predominantly in one hemisphere, as is the case for language. Visual processing is clearly modular, with line orientation columns, and parallel processing of colour and movement in distinct areas (Zeki 1992). It remains unclear how these modular aspects are reintegrated except by diffuse connections as they have no common projection area. The PET scans in fig 6(a) illustrate the correspondence between different conscious activities and the activity of specific modular regions of the cortex, including Wernicke's and Broca's areas of linguistic interpretation and articulation, the supplementary motor cortex, and areas in the frontal lobes. Listening to ambiguous signals [time reversed recordings] can activate a majority of the cortex (Friberg 1992) suggesting activation is a product of instabilities in the process of forming a representation.*

Such studies support a modular distributed internal model, which may also be like a hologram in its use of distributed phase fronts and wave transforms. This aspect arises naturally from the many to many nature of synaptic connections, the simultaneity of the Hebbian response and the decomposition of sensoria into modular characteristics, forming a parallel representation in which each experience or memory is registered across the cortex in terms of its attributes.

9.2 Ascending distributed pathways.

A very important contribution to conscious activity comes from the distributed pathways ascending from the midbrain centres responsible for general arousal in the reticular activating system, and in regulating the modes of wakefulness, light and dreaming sleep. Two pathways, fig 5(a), involving the [inhibitory] neurotransmitters serotonin and nor-epinephrine, lead from the Raphe Nuclei and the Locus Coeruleus to diverse cortical areas. Methylated serotonin and catecholamine analogues constitute key hallucinogens. The onset of dreaming sleep is heralded by activity of cells in the Pons and silencing of cells in the Raphe Nuclei and Locus Coeruleus (Bloom et. al. 1985). Similar dopamine paths spread out from the Substantia Nigra into the frontal lobes and motor centres.

Dreaming sleep is one of the most singular phases of conscious activity in which feedback appears to be accentuated at the expense of external input, generating complete subjective realities. The nature and function of dreaming consciousness and its wealth of detail remains obscure. Dreaming states provide active PET scans and EEGs similar to the waking state, fig 6(b,c), reflecting the conscious intensity of dream experiences. One difference in dreams which may reflect their uncontrolled nature is the lower activity of the inferior frontal cortex (Madsen et.al. 1991). Hallucinogen action may also occur through the ascending distributed pathways, giving them the capacity to modulate excitability across the entire cortex. Alongside dreaming, they are responsible for some of the most remarkable changes discovered in the nature of consciousness.

9.3 The limbic system.

The *limbic system* fig 5(b-d), (Mishkin et.al.1988, Alkon 1989) forms a set of looping pathways combining sensoria, emotional states and episodic long-term memory. The hippocampus, which has an older three-layered structure than the six-layer neocortex has a pivotal role in long-term memory. It has projections from diverse sensory areas via the entorhinal cortex and feeds back into the thalamus and subsequently to cortical areas including prefrontal, cingulate gyrus, and basal forebrain (c). The amygdala has similar looping circuits linking sense modes and connecting to the thalamus and deeper emotional centres in the hypothalamus. Phase decoherence occurs in the hippocampus during orientation to unfamiliar stimuli. The limbic system thus forms a bridge between emotion, memory and representation of actions and goals in the frontal lobes, consistent with the emotional and motivational side-effects of frontal lobotomy and studies on time-delayed learning in damaged hippocampi.

9.4 The frontal cortex : Time and intentional action.

The frontal cortex forms representations of activities in time integrating future intentions and goals into time-directed actions based on past experiences. These may involve immediate memory, the central survival strategies figuratively described as the super-ego, and the capacity to anticipate and predict events in motion. Thus the frontal cortex may generate a spatially distributed representation of time in terms of the organization of both remembered

and planned actions spanning the past and future, utilizing oscillatory phase relations as seen in EEG and evoked potential studies.

Immediate short-term memory appears to be centred on the prefrontal cortex with reciprocal connections with both the parietal cortex and the limbic system. Prefrontal damage effects use of knowledge to guide behaviour in everyday situations, including predictive tracking e.g. of projectile movements (Goldman-Rakic 1992). When a monkey is trained to look at where a target has disappeared after a delay, selected cells in the prefrontal cortex fire on the target disappearing, others fire during the delay and others on the motor act. Such eye movement also involves feedback loops to the basal brain. Prefrontal action is modular with spatial and compound attributes active in different loci.

9.5 Global dynamics : Mind states and brain states.

Examination of the contributions to consciousness by the major structures of the brain confirms that all are required in interaction for consciousness as we know it to occur. This suggests that consciousness is a global product of the brain as a dynamical system. The reciprocal linkages between the cortex and thalamus provide for active dynamical coupling. Energetic activation by the ascending distributed pathways is essential for consciousness and function of the cortical dynamical system. These pathways play the role of adjusting parameters which can take the cortex through various modes of conscious activation or coma. The sensory and associative areas of the cortex can be seen to contribute in a modular manner to the envelope of features of conscious experience, representing both perception and action in time. The looping circuits of the limbic system are structured to provide feedback between cortical areas involved in emotional tone, sensory integration and accessing past experiences. The hippocampus appears to provide additional parameters which subsequently enable serial access to past experience in relation to a current stimulus. The major anatomical structures in the brain have their natural explanation in the way they form a global dynamical system whose interactive states correspond to our conscious awareness. The global dynamical system also explains the *binding problem*, the unitary nature of consciousness in a parallel distributed brain.

10 Conclusion

The importance of developing a model of brain function which gives a consistent description of mind, consciousness and free-will, is profound. The brain may provide a unique manifestation of the *supercausal* aspect of quantum reduction as a result of its unique connectivity, coherence and chaotic sensitivity. Cosmology is not simply a matter of vast energies, but also quantum laws. The diversity of wave-particles resulting from symmetry-breaking of the four fundamental forces finds its final interactional complexity in molecular systems, ultimately realized in the most delicate and complex of molecular systems known - the conscious brain. The brain may thus be a doorway between two complementary aspects of the physical universe, the time-directed nature of cosmic symmetry-breaking and the time-symmetric nature of the sub-quantum domain (King 1989). If so, consciousness and mind-brain duality may be central to cosmology.

It seems Einstein's god has had the foresight
to play with predictive dice. C.K.

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