The Orch OR Theory of Consciousness and Quantum Information: Limits on the Speed of Switching of Quantum States allow Coherence over the Length Scales of Cellular Biology

Simon WW Manley

SimonWWManley@gmail.com

Abstract

The theory of Orchestrated Objective Reduction (Orch OR) can be reformulated using the Margolus-Levitin Theorem of conventional quantum mechanics, thereby preserving the essential predictions of Orch OR without invoking a theory of Quantum Gravity which still awaits satisfactory development. Further, we demonstrate that, at the energies encountered in biology, quantum states cannot evolve quickly enough to preclude causal interactions over length scales matching the dimensions of typical cells. The facile inference, often drawn, that decoherence of a quantum state in a heat bath at biological temperatures is too rapid to permit significant quantum effects is thereby shown to be fallacious.

Introduction

In the controversial theory of consciousness known as Orchestrated Objective Reduction (Orch OR), postulated quantum-mechanical effects in neuronal microtubules mediate computational activities underlying conscious awareness [Hameroff & Penrose, 2014]. Although often discussed as a unified package, Orch OR in fact consists of several distinct postulates:

1. Collapse of the wave function is a real physical process (Objective Reduction, OR).
2. The time to OR varies inversely as the gravitational energy difference between eigenstates, and is independent of "observation" or "measurement."
3. Quantum-mechanical effects can be significant in biological systems.
4. Neural microtubules process information by quantum computation.
5. Conscious awareness occurs when a superposition of quantum states in the brain collapses to a classical state.

Much criticism of this sweeping proposal centers on the apparent difficulty of maintaining quantum coherence in the "warm, wet and noisy" environment of biology [e.g. Tegmark, 1999]. Curiously however, despite information being central to any concept of consciousness, the constraints imposed by quantum information theory are seldom considered.

In this paper, we apply the Margolus-Levitin Theorem [1998] to the postulates of Orch OR. These considerations render OR plausible without invoking a theory of Quantum Gravity which has yet to be developed, and show that, at the typical energies observed in biology, quantum states cannot evolve quickly enough to preclude causal interactions over length scales of the same order as the dimensions of neuronal cell bodies.

Objective Reduction

A quantum system undergoing unitary evolution according to a deterministic Schrödinger equation may exist as a superposition of eigenstates, only one of which will be observed when a measurement of the system is made, forcing reduction of the state ("collapse of the wave-function"). No conceptual picture of this process is universally accepted, two of the best known being the *Copenhagen* and the *Many Worlds* interpretations. Recent work has focused on decoherence, where there is no assumption of a boundary between the quantum and classical domains, but instead the classical outcome of measurement is seen as a result of quantum coherence "leaking out" into the macroscopic environment [Zurek, 2003; Busse & Hornberger, 2009, 2010].

Penrose and colleagues propose that reduction of the quantum state is not merely a mathematical device for calculation, but instead is a real, objectively-occurring physical process [Penrose, 1996]. In this model, Objective Reduction (OR) is driven by the gravitational energy difference between eigenstates, and it is hoped that such a process will emerge naturally from a yet-to-be-developed theory of Quantum Gravity.

The time in which states with a gravitational energy difference, E_G, resolve from superposition is given in the Penrose formulation as

$$t = \hbar/E_G = h/2\pi E_G \qquad (1)$$

The mathematical form is strikingly similar to the calculation by Margolus & Levitin [1998] of the minimum time required for a quantum system of total energy, E, to evolve to a distinguishable (orthogonal) state, *i.e.* to write out one bit of information.

$$t \geq h/4E \qquad (2)$$

This calculation is the most universal among several analyses yielding similar relationships of the time of evolution to the energy of states (or to the energy difference between eigenstates), and appears to be highly generalizable [Cao, Chen & Li, 2008].

The analogy between equations (1) and (2) suggests an alternate formulation of the OR proposal. Instead of the Penrose concept of gravitational energy driving reduction of the quantum state, we instead postulate that a superposition will collapse when energy and time constraints permit the write-out of information. If the write-out were to an environment with many degrees of freedom, the process would be seen as *decoherence*: if to a suitable experimental apparatus with few degrees of freedom, it could be described as *measurement* [Zurek, 2003].

Although this seems a radical reformulation of the theory of OR, its quantitative predictions remain essentially unchanged, the times agreeing within a small constant ($\pi/2$). We note that the Margolus-Levitin relationship is an application of orthodox quantum mechanics. Unlike the Penrose OR proposal, it makes no appeal to theories still awaiting development.

Time and Distance Scales of Superpositions

The Orch OR theory demands that a quantum superposition be maintained over distances at least comparable to the dimensions of neuron cell bodies. This proposition has been criticized on the grounds that such dimensions are many orders of magnitude larger than the atomic systems typically encountered in quantum experiments.

Tegmark [1999] calculates that decoherence in a biological system may occur within 10^{-20} seconds, a time far too short to be relevant to biological processes. Such values, however, are in conflict with the requirements of causality and energetics. Since light travels only 3×10^{-12} m in 10^{-20} s, a distance far smaller than an atomic radius (*circa* 10^{-10} m), it is apparent that no interaction between atoms or molecules could possibly occur on this timescale. Further, the energetic considerations of equation (2) indicate that an entity changing state in such short a time must possess energy *circa* 10^5 eV, vastly in excess of biochemical energy scales around 1 eV.

The time and distance constraints dictated by considerations of energetics and causality are sketched in Figure 1. The most energetic reaction commonly encountered in biology is the hydrolysis of the γ–phosphate group of ATP, yielding 48 kJ/mole, corresponding to a quantum energy state *circa* 0.5 eV. Such an energy implies a switching time of not less than *circa* 2 fs (equation 2). On this timescale, causal interactions are permitted by velocity of light considerations over distances of up to *circa* 0.6 µm (about the diameter of a small nerve axon).

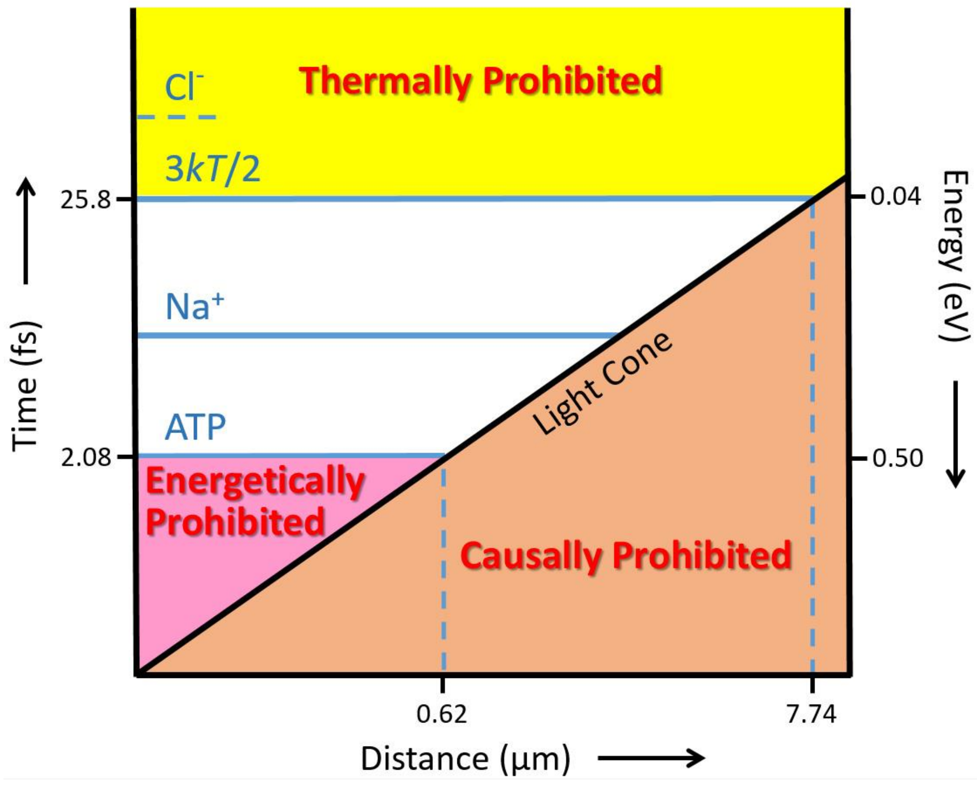

Figure 1. Minimal switching times for transition to an orthogonal state are determined by the energy of quantum entities. Time-energy-distance scales are shown for biologically-relevant processes. The permitted zone is in white. States could persist for longer times if isolated from the surrounding heat bath, but shorter times are excluded by the Margolus-Levitin Theorem [1998], which sets the minimum time required for a quantum entity to switch between orthogonal states, $t \geq h/4E$.

The thermal energy background at biological temperatures (37 C ≈ 310 K), $3kT/2 = 0.040$ eV, sets a limit below which a quantum state might be expected to undergo rapid decoherence through interaction with the environmental heat bath. An entity at this limiting energy would require 25.8 fs to switch states, during which time light and causal interactions could propagate a distance of 7.74 μm (about the diameter of a red blood cell or the cell body of the "granule cell" neurons which are extremely numerous in the central nervous system of mammals). A sodium ion crossing a neuron plasma membrane yields *circa* 0.1 eV, well clear of the thermal background, and might exist in a superposition of states for significant times. Chloride ions, however, are usually close to equilibrium across membranes, with energies of the order of 0.01 eV, and are well down in the thermal background.

It is clear from Figure 1 that a zone of time-energy-distance relationships exists at biological temperatures and energies where the rate of switching of quantum entities between orthogonal states must be slow enough to permit causal interactions over distances matching the dimensions of cells. The times indicated are the minima dictated by energetic considerations. Maxima may be considerably greater, if the coupling of the quantum entity to its environment is limited.

Coherent states can be maintained for long periods when suitably isolated. Quantum experiments commonly employ vacuum technology and cryogenic temperatures, however decoupling can also be achieved in the rigid structure of perfect crystals. A spectacular example is given by the NV color center in isotopically-pure diamond [Doherty *et al*., 2013], where qubits maintain coherence at room temperature on a timescale of seconds [Maurer *et al*., 2012]. Among biological systems, photosynthesis provides a well-characterized example of quantum coherence at ordinary temperatures over time and distance scales concordant with the dimensions of molecules and supra-molecular complexes [Hildner *et al*., 2013].

The nature of the entities most plausibly involved in quantum coherent effects in neural microtubules remained a subject of debate as the theory of Orch OR evolved in the literature over the last two decades [Hameroff & Penrose, 2014]. The gravitational focus of the theory of OR suggests involvement of the massive components, the atomic nuclei.

The more massive an entity, however, the more rapidly will decoherence of a superposition proceed in a thermal environment (other factors being equal). In the master equation approach of Zurek [2003], the time course of decoherence is determined by the dynamical relaxation rate of the system and the square of the separation distance measured in units of thermal de Broglie wavelength, $\lambda_T = \hbar/(2mkT)^{½}$. At biological temperature (310 K), a sodium ion (22.99 a.m.u.) has a thermal wavelength of 5.8×10^{-12} m, an order of magnitude less than atomic radii (*circa* 10^{-10} m), a proton has 2.79×10^{-11} m, while an electron has a thermal wavelength of 1.19×10^{-9} m, an order of magnitude larger than atomic radii. On these grounds, electrons seem more likely candidates than atomic nuclei for the species existing in a superposition of states.

In the informational formulation outlined herein, the gravitational energy difference between eigenstates in superposition is no longer important: rather it is the total energy of the state, which will be predominantly electromagnetic in the case of electrons. An electron may change its energy state if it is spatially displaced, if the surrounding potential field varies by movement of other charges, or if the electron's spin is flipped.

Neurons perform logical operations, receiving inputs from stimulatory and inhibitory synapses on their dendritic processes. The resulting currents are summed in the cell body and if the potential difference across the cell membrane in the zone known as the "axon hillock" reaches a threshold, an action potential (nerve spike) will be triggered and propagate along the fiber. The excitatory and inhibitory currents arising in the dendrites are conventionally considered to reach the cell body by drift of ions in the electrically conductive fluid of the cell interior.

Neural microtubules, however, are well placed to mediate current flow from dendrites to the axon hillock as they extend stably throughout the body and processes of the neuron. Their measured electrical conductivity is high [Minoura & Muto, 2006]. Theoretical calculations indicate that a quantum mechanism for signal propagation along microtubules is plausible [Craddock *et al*. 2014]. Using atomic force microscopy and sophisticated electronics, Sahu *et al*. [2013] demonstrated electrical switching properties in microtubules analogous to those of semiconductor memory devices.

These several sets of recent data are consistent with the postulate that microtubules play a key role in the computational activities underlying conscious awareness. The analysis in the present paper, showing the plausibility of quantum coherence being maintained over time and distance scales concordant with cellular dimensions, further strengthens this hypothesis. We make no inferences about whether significant quantum phenomena might be manifest on larger scales, such as having an entire brain in a superposition of states.

Conclusions

Applying the Margolus-Levitin Theorem to the postulates of Orch OR leads to the suggestion of an alternative causal mechanism for Objective Reduction of the quantum state: *i.e.* reduction occurs when energy-time constraints permit the write-out of information. The predicted time-course for OR is identical (up to a small constant) with the original gravitational proposal, however electromagnetic forces can now be accommodated. The influence of particle mass on rates of decoherence in a heat bath suggests that electrons would be a more favorable candidate than atomic nuclei to remain in a superposition of states for significant times. Considerations of energetics and light-cone causality demonstrate the fallacy of claims that decoherence is too rapid to permit superposition of states over biologically relevant distance scales. Although changing one of its fundamental postulates, the proposals in this paper do not degrade the significance of the Orch OR theory. Rather, they render the theory more plausible by eliminating its dependence on a theory of Quantum Gravity which still awaits satisfactory development.

References

Busse, M. & Hornberger, K. (2009). Emergence of pointer states in a non-perturbative environment. ***J. Phys. A: Math. Theor.*** **42**, 362001. ***arXiv***:0905.4609 [quant-ph]

Busse, M. & Hornberger, K. (2010). Pointer basis induced by collisional decoherence. ***J. Phys. A: Math. Theor.*** **43**, 015303. ***arXiv***:0910.1062 [quant-ph]

Cao, Q., Chen, Y.X. & Li, J.L. (2008). Covariant versions of Margolus-Levitin Theorem. ***arXiv***:0805.4250 [hep-th]

Craddock, T.J.A., Friesen, D., Mane, J., Hameroff, S. & Tuszynski, J.A. (2014). The Feasibility of Coherent Energy Transfer in Microtubules. ***arXiv***:1405.3170 [physics.bio-ph]

Doherty, M.W., Manson, N.B., Delaney, P., Jelezko, F., Wrachtrupe, J. & Hollenberg, L.C.L. (2013). The nitrogen-vacancy colour centre in diamond**.** ***arXiv***:1302.3288v1 [cond-mat.mtrl-sci]

Hameroff, S. & Penrose, R. (2014). Consciousness in the universe: A review of the 'Orch OR' theory. ***Physics of Life Reviews*** 11: 39–78.

Hildner, R., Brinks, D., Nieder, J.B., Cogdell, R.J. & Hulst, N.F. (2013). Quantum Coherent Energy Transfer over Varying Pathways in Single Light-Harvesting Complexes. ***Science*** **340** (6139), 1448-1451.

Margolus, N. & Levitin, L.B. (1998). The maximum speed of dynamical evolution. ***arXiv***:quant-ph/9710043.

Maurer, P.C., Kucsko, G., Latta, C., Jiang, L., Yao, N.Y., Bennett, S.D., Pastawski, F., Hunger, D., Chisholm, N., Markham, M., Twitchen, D.J., Cirac, J.I., Lukin, M.D. (2012). Room-temperature quantum bit memory exceeding one second. ***Science*** **336**(6086):1283-6.

Minoura, I. & Muto, E. (2006). Dielectric Measurement of Individual Microtubules Using the Electroorientation Method. ***Biophysical Journal*** **90**, 3739–3748

Penrose, R. (1996). On Gravity's role in Quantum State Reduction. ***General Relativity and Gravitation*** 28, 581-600.

Sahu, S., Ghosh, S., Hirata, K., Fujita, D. & Bandyopadhyay, A. (2013). Multi-level memory-switching properties of a single brain microtubule. ***Applied Physics Letters*** **102**, 123701.

Tegmark, M. (1999). The Importance of Quantum Decoherence in Brain Processes. ***arXiv***:quant-ph/9907009.

Zurek, W.H. (2003). Decoherence, einselection, and the quantum origins of the classical. ***Rev. Mod. Phys***. **75**, 715. ***arXiv***:quant-ph/0105127