



Reply to comment

## Reply to seven commentaries on “Consciousness in the universe: Review of the ‘Orch OR’ theory”

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Here we respond to seven commentaries [1–7] on “Consciousness in the universe: Review of the Orch OR theory” [8]. The eighth commentary by Reimers et al. [9] is discussed separately [10]. We thank authors of these seven commentaries, and reply to some of their key points.

### 1. Jack Tuszynski (‘JT’) [1]

“First, Orch OR appears to be decoupled from the animate/inanimate divide . . . Divorcing consciousness from life forms puts it back into the spiritual/dualistic type of reasoning that Orch OR rejects. How can one account for metabolism taking place in neurons, which would be a minimal requirement for making Orch OR account for life?”

### Stuart Hameroff and Roger Penrose (‘H&P’)

Orch OR doesn’t divorce life from consciousness, but marries them within non-polar ‘quantum channels’ inside microtubule cylindrical walls. Although life is commonly equated with some of its properties, e.g. metabolism, reproduction, adaptation and evolution, these phenomena also occur in inanimate complex systems. They do not define life.

In living cells, metabolism occurs in polar, aqueous environments from which non-polar, water-excluding ‘quantum channels’ are isolated [8]. Biological metabolism is no different than inanimate chemical activity ubiquitous in nature. While metabolism, reproduction, adaptation and evolution may be necessary for life and consciousness, they are not sufficient. As suggested by Schrödinger [11], life, as we know it, depends essentially on quantum processes, e.g. originating in non-polar quantum channels. In Orch OR, consciousness is a particular manifestation of life’s quantum activity in these channels, involving ‘orchestrated’ quantum coherent superpositions that persist sufficiently to reach the physical threshold for ‘objective reduction’.

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**JT**

“Second, the emphasis based on the gravitational interactions is difficult to accept within conventional physics. Gravitational interactions are many orders of magnitude weaker than even thermal noise [12].”

**H&P**

This is a frequent misunderstanding. The role of gravitation in Orch OR is quite different from that of other forces, and it is not in competition with them. The DP proposal, upon which Orch OR relies, is not even a form of “quantum gravity” in the normal sense of that term, where the rules of quantum (field) theory would be imposed upon classical gravitational theory. In DP (Diosi–Penrose objective reduction), we consider the opposite effect, where principles underlying Einstein’s gravitational theory (general relativity) have their effect on quantum mechanics itself. With regard to issues of energy balance, the extremely tiny contribution from gravitation would be merely at the level of basic *uncertainties* in energy conservation. It is good that, in the circumstances under consideration, the gravitational contributions *are* extremely tiny, since they represent only a minute *uncertainty* in the normal energy balance (called upon only when the quantum state reduces according to OR), this balance thereby holding to an enormous precision, *by virtue* of gravitational energy contributions *necessarily* being ignored, as is normal practice.

Indeed, we say in Section 5.1 of our review: “Owing to the extreme weakness of gravitational forces ... the energy  $E_G$  is liable to be *far* smaller than any energy that arises directly from biological processes. ...  $E_G$  is not to be thought of as being in direct competition with any of the usual biological energies, as it plays a completely different role, supplying a needed energy *uncertainty* that then allows a choice to be made between the separated space–time geometries ... This energy uncertainty is the key ingredient of the computation of the reduction time  $\tau$ , and ... it is appropriate that this energy uncertainty is indeed far smaller than the energies that are normally under consideration with regard to chemical energy balance etc. If it were not so, then there would be a danger of *conflict* with normal considerations of energy balance ... Nevertheless, the extreme weakness of gravity tells us there must be a considerable amount of material involved in the coherent mass displacement between superposed structures in order that  $\tau$  can be small enough to be playing its necessary role in the relevant OR processes in the brain.”

Microtubules may be thought of as “quantum switches”, acting within the quantum energy uncertainty that comes about through the influence of Einstein’s gravitational principles in a quantum context, thereby—according to Orch OR—enabling weak gravity-related influences to affect conscious thought and behavior.

**JT**

“I foresee major progress in bridging the gap between nanoscience and consciousness in the area of nano-neuroscience [13] where microtubules, actin filaments and motor proteins connect between neurophysiology and molecular biology. Studying the neural phenomena at a nanoscale will lead to monumental breakthroughs in science and medicine and aid in consciousness studies.”

**H&P**

Agreed. Anirban Bandyopadhyay’s group has used nano-neuroscience to find quantum resonances at multiple gigahertz, megahertz and kilohertz frequencies in single brain microtubules at warm temperatures [14,15].

## 2. Deepak Chopra (‘DC’) [2]

“The choice is between two non-dual explanations for how mind came into being. [The Eastern spiritual tradition of] Vedanta says that mind is innate in creation. To be viable, this brand of monism must show how mind created matter and energy. The challenge from the Penrose–Hameroff side is to show how matter and energy created mind. Of the two, Vedanta, in my view, has the upper hand. Mind creates matter every time we have thoughts that generate unique electrochemical activity in the brain. But no one has credibly shown how molecules learned to think.”

**H&P**

DC is espousing ‘View B’ in Section 1 of our review, that ‘*Consciousness is a separate quality, distinct from physical actions and not controlled by physical laws, that has always been in the universe.*’ This is in marked contradiction to the conventional ‘View A’ that ‘*Consciousness is not an independent quality but arose, in terms of*

*conventional physical processes, as a natural evolutionary consequence of the biological adaptation of brains and nervous systems.*

We agree with DC that ‘View A’ fails to show how matter and energy create mind, how molecules can ‘think’ (i.e. perform cognition accompanied by conscious experience). But we also recognize the shortcomings of his ‘View B’, e.g. how can mind create energy and matter? Orch OR and ‘View C’ bridge these two views, and, in principle, point to a solution for both their problems: (C) *Consciousness results from discrete physical events [objective reductions, ‘OR’]; such events have always existed in the universe as non-cognitive, proto-conscious events, these acting as part of precise physical laws not yet fully understood.* Thus, in our view, a ‘proto-conscious’ source of mind is omnipresent in the universe as OR events which shape reality (as in ‘View B’). However experientially rich, human-like consciousness required biological evolution of a mechanism to ‘orchestrate’ OR events, and couple them to brain neuronal activity (as in ‘View A’).

## DC

“Orch OR provides a credible, testable model for how mental activity enters the physical world. I would take its optimism and turn it around: the mind-brain problem is indeed closer to being solved, not because quantum events give rise to mind but because these events indicate that an invisible agency (consciousness) is producing orderly, intelligent, information-infused activity at the very interface where spacetime emerges.

## H&P

In Orch OR, fundamental Planck scale geometry (“where spacetime emerges”) is indeed considered to contain Platonic values producing such activity. Orch OR, and View C, embrace and connect View A and View B.

### 3. Subrata Ghosh, Satyajit Sahu and Anirban Bandyopadhyay (‘SSA’) [3]

The blind faith that Hodgkin–Huxley type neuron bursts explain neural information processing completely will collapse soon, and then brain building projects [16] all over the world will face the danger of banking on an incomplete picture of a neuron.

## H&P

SSA are alluding to the assumptions that (1) Hodgkin–Huxley ‘integrate-and-fire’ neuron models adequately represent neuronal functions, and (2) mapping and simulating such functions will capture essential brain features including consciousness. We completely agree with SSA that these assumptions are wrong, as they ignore intra-neuronal classical and quantum computation in microtubules, and non-computability necessary for consciousness, memory and synaptic regulation.

## SSA

The recent finding of microtubule resonant oscillations [14,15] that could vibrate [the neuronal] axon brings Orch-OR into the picture as an extremely essential concept to fill the vacuum.

## H&P

SSA refer to their own landmark discovery of gigahertz, megahertz and kilohertz quantum vibrations in single microtubules, experimental findings which strongly support theoretical assertions of Orch OR. They imply that such finer scale, deeper order processes are needed for a proper picture of neuronal function. We agree.

## SSA

Stuart and Roger have rightly argued here [8] that the wireless communication of axons via resonant vibrations around a hundred micrometers diameter domain alleviates the biggest criticism of the Orch-OR proposal. The orchestration of resonant vibrations can occur globally among all neurons across the entire brain . . . . This article therefore closes the series of historical argument/counterargument on the “gap junction” forever [17].

## H&P

SSA refer to the issue in Orch OR of how microtubule-based quantum coherence can extend globally in neurons throughout the brain, enabling sufficiently large  $E_G$  to reach OR threshold (by  $E_G \approx \hbar/\tau$ ) in times  $\tau$  brief enough

to be useful. Orch OR has previously suggested entanglement via window-like gap junctions (avoiding noisy membranes, synapses and neuropil). However SSA have shown ‘wireless’ communication among microtubules in different neurons, possibly obviating the need for gap junctions. This still does not properly explain the necessary *quantum* entanglements that would be needed between separated microtubules, however. In order for the respective ‘ $E_{GS}$ ’ of separated parts of a system to add up appropriately, in order to reach the required level for OR to occur, the entire mass displacement needs to be quantum-coherent, i.e. entangled. Quantum entanglements cannot be set up simply by classical communication. One might envisage gap junctions achieving the needed entanglements, but there does not appear to be any evidence, as yet, that SAA’s ‘wireless communication’ has this required quantum-coherent character. This would seem to be an important issue for future research.

As a further point, ‘wireless’ communication detected by the Bandyopadhyay group occurs between microtubule bundles in *axons* of different neurons. Orch OR has emphasized microtubule quantum computation in neuronal dendrites and cell bodies/soma (rather than those in axons) because dendritic–somatic processes correspond with integration in integrate-and-fire neurons, and such processes can trigger (or not trigger) axonal firings, thereby controlling behavior (Section 2.3 in our review). Microtubules in neuronal dendrites and soma are uniquely arrayed in mixed polarity networks of short, stabilized microtubules, whereas axonal microtubules extend continuously in unipolar bundles. The functional distinction for the two types of arrays is as yet unknown.

## SSA

... objective reduction also gets a new dimension because resonance frequency bands of brain materials cover a wide range. Therefore, the discovery of resonance and wireless processing lead to a layered architecture of multiple space–time metric stacked one above another [18]. This is exactly what Roger and Stuart have been arguing for as the foundation of brain information processing for decades ... This article [8] therefore marks the beginning of developing a comprehensive mathematical modeling of the brain. Hopefully, in the near future, with more experimental understanding of the space–time metric, Orch-OR would evolve to a complete deductive mathematical expression of consciousness,—a dream that entire mankind is eagerly waiting to see.

## H&P

SSA refer first to their own discovery of gigahertz, megahertz and kilohertz resonances in microtubules, vibrations whose frequencies appear to have a fractal-like relationship. Based on their results, we proposed that collective brain oscillations in the range of 4 to 100 hertz seen as the electro-encephalogram (EEG) are actually ‘beat frequencies’, interference patterns, of much faster microtubule vibrations inside neurons. Observed and recorded for over a century, EEG origins have never been understood.

In Orch OR, microtubule quantum events correlate with fluctuations in the structure of spacetime geometry (‘space–time metric’). SSA are referring to a scale-invariant conscious connection between brain processes and the structure of the universe. One must be careful about drawing too strong of a conclusion of this kind here. The Planck scale of quantum gravity is, indeed, a particular *scale* of size, and scale-invariance for such fluctuations is not to be expected.

## 4. Chanelle Jumper and Greg Scholes (J&S)

... A primary issue is decoherence, a process where the phases of quantum wavefunctions are randomized to reduce quantum phenomena to classical processes. Decoherence arises from dynamic disorder, or “energy noise”, and is expected to be extremely rapid in biological environments. For example, the Orch OR theory requires quantum superposition on a time scale that is not currently accepted for biological, or even chemical, systems [19].

## H&P

As J&S assert, avoidance of decoherence is critical to Orch OR and functional quantum biology. Previous versions of Orch OR called for microtubule coherence (avoidance of decoherence) for times  $\tau$  on the order of EEG frequency intervals, e.g.  $10^{-1}$  to  $10^{-2}$  secs, lengthy in terms of quantum systems, and too long for Bandyopadhyay’s measured coherence times [14,15] of  $10^{-4}$  secs (10 kilohertz resonance). However in the present updated version of Orch OR, EEG markers of consciousness are seen as beat frequencies of much faster microtubule resonances and Orch OR events, e.g. 10 megahertz with coherence times of a mere  $10^{-7}$  seconds. Given the Bandyopadhyay coherence times of  $10^{-4}$  seconds, Orch OR seems to now be on firm ground from the standpoint of decoherence.

The DP version of OR essentially replaces decoherence (or, rather, incorporates it within a broader objective scheme), as described in Section 4.5, but environmental interaction must still be avoided for significant times  $\tau$  to have cognitive and meaningful conscious moments.

### J&S

... biological systems are purported to be “warm, wet and noisy” , . . . a messy business, incapable of supporting ‘delicate’ quantum processes . . . . On the contrary, it appears that living systems are governed by cycles and correlations, requiring massive cooperation across a large range of time and length scales . . . . Whether it is an acceptance of quantum behavior, or generating a foundation for the study of difficult questions in biology, should we reconsider the premise that living entities are founded on uncorrelated and chaotic machinery?

### H&P

Absolutely. Correlations over multiple spatiotemporal scales in living systems may be explained by a largely scale-invariant dynamics derived from quantum processes in non-polar, hydrophobic regions, e.g. quantum channels in microtubules (similar to quantum coherence in  $\pi$ -conjugated systems as described by Hwang and Scholes [20]).

Regarding the “warm, wet and noisy” description of the biological environment: warm, yes, biological systems are indeed warm compared to quantum systems developed in laboratory conditions. However as proposed by Fröhlich, biology can utilize thermal energy to drive coherence, in a manner roughly analogous to a laser. “Wet”? No, at least not in non-polar, hydrophobic ‘quantum channels’ within microtubules and other biomolecular interiors isolated from polar, aqueous portions of cell interiors and the extracellular milieu. These ‘dry’, non-polar regions are precisely where anesthetic gases bind to selectively erase consciousness. “Noisy?” Noise-like fluctuations in brain electrical activity appear to be globally correlated, and therefore not noise at all. Of course, J&S are merely pointing out flaws in the common criticisms of schemes like Orch OR that depend upon quantum processes, and with that, we heartily agree.

### J&S

... one of the next scientific revolutions will involve the evolution of a new framework for unraveling the extraordinary nature of life.

H&P Agreed. And microtubule-based quantum resonance may well be a major part of that framework.

## 5. Reply to John Lucas [5]

John Lucas [5,21,22] suggested in 1961 that Gödel’s incompleteness theorem indicates the human mind is non-computable, that some non-algorithmic factor is necessary. This anti-mechanistic argument was joined and elaborated by Penrose [18,23,24] who suggested ‘objective reduction’ as the non-computable factor, bringing quantum mechanics into the brain/mind picture. In his commentary, Lucas eloquently summarizes Orch OR positions, with particular reference to the thorny issue of freedom (‘free will’).

## 6. Reply to Charles Tandy [6]

Charles Tandy continues with Gödel non-computability (‘hyper-algorithmicity’, as Tandy calls it) a property which Lucas and Penrose have attributed to the conscious mind. Although non-computability has usually been taken as bad news for artificial intelligence (‘strong AI’) and ‘Singularity’ attempts to emulate conscious brain functions in computers, Tandy concludes that Orch OR and hyper-algorithmicity could in principle lead to such a goal—an Orch OR-based ‘artificial consciousness’.

## 7. Reply to Samanta Pino and Ernesto Di Mauro (P&D) [7]

Samanta Pino and Ernesto Di Mauro put Orch OR in a larger context, relating it, and the problem of consciousness, to issues raised by Popper, Descartes, Darwin, Jung, Pauli, Heisenberg and others. They suggest the failure of the Higgs boson to account for super-symmetry leaves the makeup of the universe as mysterious as ever, perhaps requiring consciousness to complete the picture. This is also the essential conclusion of our review.

## P&D

Hameroff and Penrose theory proposes an explanation by quantum physics of an intricately unapproachable phenomenon, of an *unknown*. To do this they feel comforted by the lack of different alternative explanations, possibly overinterpreting the possibilities and the role of quantum physics. However, this might after all not be that negative, potentially opening an experimental field to falsifiable verification.

## H&P

It is worth pointing out that the DP proposal may be fairly close to either experimental confirmation or refutation. Following on from an early proposal [25], Bouwmeester has recently intimated [26] that within 7 or 8 years we may well have an experimental answer to the viability of DP.

In closing, we refer back to the question of Cyclic Conformal Cosmology ('CCC') as discussed in Section 6 of our review. Ref. [175] in the review may now be updated [27]. An independent analysis of the WMAP satellite data [28] supports CCC, and groups are now analyzing the more recent (and precise) Planck satellite data [29]. Orch OR and consciousness may well have preceded the Big Bang!

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