

1. Introduction: The Sentience of Life

A natural question in response to the remarkable discoveries of quantum-based effects found within biological processes is considering just how quantum is Life? While the potential of finding novel quantum-based processes in biology is exciting, one cannot forget the many decades of biological knowledge that is predicated upon prosaic classical physics.

Thus, categorizing Life's functions into the classical and quantum domains would be an effective method of answering the question of how quantum is Life? Such an exercise would require a massive scope, as it would need to include the entirety of our current knowledge of standard classical biology, as well as summarizing the current evidence of quantum based phenomena. Necessity then calls for a sacrifice of precision and detail in favor of appealing to broad abstractive categorization. To this end, it should be the least controversial to ascribe, at minimum, the responsibilities of somatic structure, communicative signaling and molecular machinery as a crude generalization of the functional roles of classical biology. One can - and should - debate how functions of Life ought to be included in these classical or quantum categories.

Other functions of Life seem better classified as different adaptive means of ensuring the organisms survival - which can be either classical or quantum based. The commonly cited quantum examples include increased energy conversion efficiency within processes of photosynthesis due to quantum mechanical effects, or magnetoreception dependent on quantum spin within the eyes of birds to detect the earth's magnetic field for migratory navigation[1].

A lesser known adaptive advantage provided by quantum physics is the increased electrical conductivity in a cytoskeletal structure within cells and neurons called microtubules (MTs). The state of quantum coherence between the MT's tubulin proteins (of which the MT is composed) increases its conductivity and therefore, the efficiency of energy transfer, as measured by comparing the intrinsic conductivity of an individual tubulin protein with the conductivity of the collectively assembled MT[2]. The result is a non-linear increase of conductivity that exceeds what would be predicted with only classical physics - a quantum based phenomenon called "ballistic conductance". This has potential implications for neuroscience as neuronal connections (called axons) are composed of MTs, and the electrical "firing" of a neuron is passed along these connections.

Any such traits and advantages, quantum or otherwise, may be necessary in assisting the survival of a particular species, but not necessary to all life forms. Thus, neither the classical or quantum has sole claim to the functional ownership of 'adaptation' as such, which likewise may not be sufficient in defining what Life really is.

If you ask the average person about what it means for something to be considered alive, it typically involves the boundaries of some biological system - like a body, cell, or cluster of cells - working together to ensure its own survival via its adaptive traits and homeostatic processes, and to somehow reproduce to carry on the species survival. Life is also usually described as possessing the capability to responsively act by its own accord, rather than being inanimately inert or moved by purely deterministic processes (such as a rock rolling down a hill, or a refrigerator modulating its temperature homeostatically through its thermostatic setpoints and electrical processing).

However, the motivation for survival and reproduction do not seem sufficient in defining what Life is, as one can easily imagine a human who possesses neither of these traits to still be considered as living, and as the refrigerator example demonstrates, neither does computationally made adjustments or homeostatic processes themselves. Setting aside these functional tendencies of Life, what remains from the previous paragraph's definition is the ability for Life to act on its own accord - which implies some sense of sentience for the organism to initiate such intentional actions - as being a minimally sufficient definition of what could be characterized as living.

The sentience of Life may be best defined as a subjective form of phenomenological consciousness that is capable of exercising its own autonomous Will. This is what most people implicitly use as a heuristic to test if something has sentience - as seen in viral cultural shocks of alleged signs of artificial intelligence exhibiting its own autonomy, contrasted with its deterministic information processing based on classical computing algorithms. The capacity to override deterministic processes enables the ability to creatively

adapt; consciousness recognizes the need to do so and initiates the process. These functional traits of sentience intimately comprise the most important aspects of what it means to be alive.

A case will be made in this essay that these sentience-defining, functional traits of consciousness and Will, both categorically belong within the quantum biological domain. It follows that if these functions require quantum physics to mechanistically facilitate their emergence, then an answer to the question of how quantum is Life is: *the sentience of Life is necessarily quantum*.

2. Consciousness & Quantum Biology

While the scientific study of consciousness is usually concerned with identifying what is responsible for its generation, it must equally account for what is not conscious - down to the level of quantum mechanics governing subatomic particles, which constitute the atoms of the molecules that form organelles and proteins within classical cellular processes. While we call the collective summation of all such factors within a biological system (such as neurons) to be “Life”, the mystery is where exactly within these many levels does consciousness occur within the cellular milieu?

The connection between quantum physics, biology, and consciousness isn’t a new proposition of course. The flag of Quantum Biology was firmly planted in 1944 by the physicist Erwin Schrodinger with his influential book *What is Life?*[3] This frontier has since been built upon in the 1990’s by Sir Roger Penrose, partnering with the anesthesiologist and consciousness studies pioneer Dr. Stuart Hameroff, through their Orchestrated Objective Reduction (Orch OR) theory of a quantum-based consciousness[4].

As a quick overview, ‘Orchestrated’ refers to quantum entanglement across the brain, and ‘Objective Reduction’ refers to Penrose’s proposal of how a quantum system ‘collapses’ its superpositioned wave-function into a classical state, generating with it a moment of conscious experience. Together with Hameroff, they propose that this occurs within the microtubules (MTs) of neurons, whose molecular properties are capable of hosting quantum coherence (see the Technical Endnotes section for an explanation of how this occurs).

While this aspect of wave-function collapse causing consciousness has yet to be verified, there is a growing body of experimental evidence suggesting that consciousness is rooted in quantum-based processes, rather than emerging from the machinery of classical physics. Intrinsically quantum effects have now been experimentally demonstrated in MTs; this was accomplished through detecting a quantum phenomenon called superradiance being emitted from them[5], as well as the previously discussed ‘ballistic conductance’ studies[2]. While this importantly establishes that quantum coherence is indeed possible within MTs, other separate studies support the link to this having a causal role in consciousness.

One way of experimentally testing consciousness is to investigate what stops it from occurring - such as anesthetic induced unconsciousness. If anesthesia disrupts consciousness from occurring, then finding the mechanism of anesthetic interaction points towards what processes are ultimately responsible for the generation of consciousness. While this has long been regarded as a scientific mystery, there’s compelling evidence that the primary site of interaction is within MTs. In a study involving tadpoles, anesthesia was shown to interact with MTs, leading the authors to explicitly conclude that this interaction was significant to the disruption of consciousness [6]. It’s been found that people (and rats) who take MT stabilizing drugs require a higher anesthetic dosage to achieve the same consciousness debilitating effects[7]. If one wants to contend that MTs aren’t the primary site of anesthetic interaction, then an alternative explanation needs to be provided as to why taking these drugs has such an effect.

While this likely establishes MTs as the primary interaction site of anesthesia, other studies go further in implicating that consciousness itself is quantum based, rather than being caused by classical processes such as the electrical currents that MTs are capable of hosting[2]. After the administration of anesthesia, quantum optical effects detected in MTs have been shown to be dampened[8], indicating that anesthesia disrupts the quantum state inherent to MTs; this suggests a link to consciousness occurring within that same quantum state too, as implied by this corresponding disruption.

It’s also been shown that the anesthesia xenon differs in its potency depending on its isotope; the authors conclude that this difference could only be due to differences in the intrinsically quantum property of nuclear spin between the different xenon isotopes[9]. Upon deeper technical analysis, this finding demonstrates that

the anesthetic interaction must be quantum based, implicating that consciousness itself is more likely to be a quantum-based phenomenon.

Unless alternative classical explanations can be provided for the above experimental findings, the current evidence supports the effect of anesthesia primarily occurring within MTs due to the disruption of its innate quantum state. It then follows that consciousness itself must be dependent on these same quantum processes, as a necessary pre-requisite condition for its functioning.

3. Quantum Physics and Determinism

Despite the overall uncertainty about the actual ontology of the quantum state - even in the field of physics - one thing that's fairly well accepted is its apparent probabilistic nature, as opposed to the deterministic physics of its classical counterpart. Such findings famously perturbed Einstein enough to say "God does not play dice with the Universe", suggesting that quantum mechanics is incomplete and there must be a "Hidden Variable" that deterministically guides the behaviour within the quantum state of supposed uncertainty. Nearly 100 years later, such a deterministic variable has yet to be confirmed.

It should be noted, as Schrodinger did in his book 'What is Life', that randomness in statistical physics is not necessarily the same as indeterminism. Rather, he uses the example of the probabilistic nature of thermodynamic entropy, which reflects the deterministic dynamics of countless microscopic interactions that, taken together, appear random at the macroscopic level[3]. Even in quantum mechanics, the Schrodinger equation governs the deterministic evolution of the quantum state and the probability distribution of where the particle can possibly 'collapse' to - out from its uncertain state of quantum superposition into what we can empirically "measure" in classical reality. However, while these probabilities can be computed deterministically, the location of where exactly the superpositioned particle ultimately collapses to is currently known as a 'non-computable' factor, highlighting the previously mentioned "incompleteness" of the current theoretical modelling of quantum mechanics[10]. Thus, until this matter is ultimately settled among physicists, any encompassing theory of quantum biology also rests on this fundamental ontological uncertainty.

Given that the heart of the matter involves what is deterministic and what isn't in quantum reality, then the answer to this dilemma will have implications on the question of: is there any room for subjective intentionality of Will to arise at all within our laws of physics?

4. Quantum Biology Enables Will

The probabilistic and non-computable "loosening" of the strict determinism of classical physics is an advantage that the quantum ruleset potentially has to offer Life. If the capacity to assert any subjective intentionality - or Will - is to exist at all, then the corresponding mechanism for facilitating it will more likely be enabled by quantum physics rather than deterministic classical physics. The capacity for intentionality is evolutionarily advantageous because it allows for the adaptive adjustment of actions beyond only being bound to deterministic processing.

For any subjectively initiated factor to influence the unfolding of causality, definitionally speaking it has to be capable of overriding what otherwise would've just continued to evolve deterministically. When philosophers contend that we have no Free Will at all, it's usually based on the assertion that unconscious deterministic factors are responsible for the illusion of our conscious choices being made. A genuine act of intentional Will then must be capable of beginning from the phenomenology of a volitional act, which occurs within the experience of consciousness itself.

Whatever mechanism is responsible for consciousness then must necessarily be able to connect to, or become involved with, the mechanism for intentionality. As a criterion, the mechanism must be capable of influencing neuronal firing, as this can be detected and correlated with bodily behaviors and actions. The field of neuroscience has long studied such correlations of different parts of the brain firing alongside certain actions, but also generally subscribes to a deterministic model of what causes a neuron to fire an electrical signal - called an "action potential". The standard Hodgkin-Huxley (H&H) model of neuronal firing posits that neurons fire when their cellular membrane's "voltage potential" reaches a certain threshold of electrical charge within the cell (due to the flooding in of charged particles called ions)[11]. At this threshold, an

electrical impulse is then “fired” along its elongated axonal connection, which signals the release of chemical neurotransmitters to bind to the subsequent neuron’s receptors, controlling its ‘ion channels’ for the flooding of ions into its membrane where the process is to be repeated again. This is a classical deterministic process which seems to leave no room for Will to exert an influence on selecting which neurons should fire to carry out specific actions.

These classically based processes are clearly necessary to the functioning of the brain, but experimental findings show that they are insufficient in fully explaining all of the brain’s associated phenomena. For example, “anomalous” deviations from the standard calculable predictions made by H&H’s voltage thresholds have been detected in animals, which in practice actually “vary significantly” between each firing[4,12].

Additionally, such electrically transmissive mechanisms face challenges of completely explaining how neuronal synchrony initiates across the brain - which refers to how networks of neurons rhythmically fire within the same phase timing. This is an important pre-requisite criterion for enabling effective electrical communication between neurons (as pointed out by Pascal Fries in his Communication through Coherence theory[13]); if neurons aren’t within the same oscillatory phase, then the subsequent neurons are far less likely to fire together to carry out their associated functions. Brain electroencephalogram (EEG) technology is used to detect such phase synchrony, and classical electromagnetic (EM) fields can have a regulatory effect on timing the firing of neurons within the same synchronous phase (at the rate of Hz).

What isn’t as well known though is that this EM regulation similarly occurs down at the faster MHz, GHz and THz frequency speeds too - signatures of which have been detected in the neuron’s somatic (dendritic cell body rather than axonal) MTs prior to the initiation of an action potential firing[14,15]. Furthermore, it’s been found that removing these somatic MTs from neurons causes them to fire asynchronously “as if they had no neighbors”[15] - which is what H&H did with their initial membrane threshold experiments, leading them and the rest of neuroscience to believe that those MTs were not important to neuronal firing and could be ignored. At that time however, they did not know of the importance of neuronal synchrony, and to this day, mainstream neuroscience largely remains stuck in H&H’s old paradigm.

These are important findings, as it brings us closer to a mechanism of intentionality, given the precedence in the causal chain that MT EM frequencies have on synchronous neuronal firing, overriding the previously mentioned process of the deterministic H&H model. If the quantum processes within MTs are responsible for the generation of consciousness as per the previous section, then this could serve as a mechanistic pathway for intentionality of Will to begin within the experience of consciousness and then meet the criterion of influencing neuronal firing to carry out particular actions.

One might rightfully contend that these mentioned MT frequencies are classically based, but another anomalous finding in neuroscience suggests that the origin of the initiation of these EM frequencies begin within the quantum state. This anomalous finding is “zero-phase-delay synchrony”, where EEG synchrony has been shown to initiate and oscillate in synchronous phase across the entire brain without experiencing any delays in timing[16]. This phenomenon seems to evade a robust classical explanation, as electrical transmission times are too slow, and it’s been shown that EM fields are too weak and inaccurate to account for this precise occurrence across the brain.

Hameroff instead proposes that EEG originates within the MTs of neuronal dendrites, and gap junctions (which are connecting “gates” between neighbouring neurons) could enable quantum entanglement to occur across the brain[16]. This could explain how distal networks can fire in synchrony, without the inherent delay that occurs with classically based mechanisms. This “Orchestration” via entanglement also provides the advantage of solving the so-called “Binding problem of consciousness” - referring to how exactly various qualitative sensory inputs integrate into a unified conscious experience.

If the initiation of a consciously intended action corresponds with zero-phase-delay EEG synchrony across the brain which can only be accounted for via quantum entanglement, and if consciousness also occurs within this quantum state, then it necessarily follows that intentionality of Will must begin within the quantum state too. Entanglement would need to precede these EM MT frequencies to account for the initiation of zero-phase-delay synchrony and neuronal firing; therefore, both consciousness and intentional Will must be quantum-based mechanisms, rather than classical.

5. Experimental Testing of a Quantum-based Will

While the above section arrives upon the conclusion that intentionality must be a quantum-based mechanism, additional experimental verification would be beneficial to further support this claim.

The parameters for testing the above conclusion should include the following: a subjectively initiated act of intentionality should be clearly differentiated against behaviour stemming from purely deterministic processes (eg. autonomic reflexes based on stimulus); MTs (which host these quantum processes) must be implicated as having a critical role for enabling this capability to occur. It follows then that neutralizing the influence of MTs on the operational dynamics of the cell should also prevent such agential acts of intention from occurring.

The ideal way to differentiate intentional acts from pre-determined behaviours is to introduce the organism into a novel situational challenge that their evolutionary hardware would not have prepared a reflexive adaptation for, and observe if they are able to successfully navigate and adapt to it. Given that all cells within complex life on earth have MTs - albeit in a less structured form than in neurons - there is a wide selection of organisms to potentially study and introduce novel challenges to, for microbiologists who are familiar with their normal behaviours and environmental contexts.

Test cases that meet the above criteria at the cellular level could be the pioneering experiments that've been conducted by the microbiologist Dr. Michael Levin studying cellular intelligence and problem solving in novel situations[17]. These experiments provide many possible examples that one could choose from, including apparent problem solving capabilities around obstacles introduced during embryonic developmental processes.

However, one particular experiment will be of focus here: the finding that a worm species called the planarian can selectively “switch on” specific genes in response to being exposed to a harmful novel chemical, barium chloride, which allows them to adapt and survive this exposure[17]. Throughout their evolutionary history, planarians would've never been exposed to this chemical in their natural environment which literally causes their heads to explode. However, they possess the capability to select a specific handful of genes to be up-regulated from tens of thousands of potential genes available, allowing them to survive exposure to this novel toxin. Remarkably, their heads regrow themselves and become resistant to the previous negative effects of being placed in the barium solution.

This is a prime candidate for testing intentionality, as no deterministic evolutionary scripts could've been drawn upon for this adaptation, and the specificity involved with correctly selecting the right genes for the job without any algorithmic trial and error process precludes the possibility of this remarkable finding being explained by random genetic mutation. This specificity implies that somewhere within the planarian, there's something with a sentient sense of understanding of not only the chemical problem it faces, but also what genes would be capable of providing the antidote, and is furthermore capable somehow of intentionally selecting these genes to be up-regulated.

If such a situational understanding is necessarily perceived within the phenomenology of conscious experience, and the gene selection requires an act of non-algorithmic intentionality, then perhaps the quantum effects within MTs could be responsible for mechanistically facilitating this? Neutralizing the planarian's MTs, or the quantum effects within them, and then observing whether these worms are still capable of making the adaptive switch to tolerate barium chloride, could then be possible a test case of the role that the quantum effects of MTs play in intentionality.

There seems to be at least two possible ways that MTs or their quantum effects can be “neutralized”: one already outlined in previous sections was the administration of an anesthetic dosage. Alternatively, experimental findings have found that applying pulses of certain THz ranged EMR frequencies has the effect of disassembling MTs within mere minutes[18]. If either method is applied to planarian worms before and/or during the barium chloride exposure process, and other potential contributing mechanisms are effectively ruled out, then observing whether planarians still possess the ability to adapt to the toxic novel solution would implicate and test for the role of MTs and their quantum effects for intentional acts of Will.

6. Conclusion

Part of the brilliance of Levin's approach to science is to propose experiments that test for what are normally considered to be metaphysical or philosophical issues; the same attitude could be applied with the above experimental proposals for philosophical arguments about intentional Will.

While the above experiments may narrow down the mechanism of intentionality to be quantum-based rather than classical, the work would only be just beginning, as there are a variety of different quantum phenomena to potentially choose from (eg. superposition, wave-function collapse, spin, retrocausality). The full causal chain would need to connect such a quantum variable with the capability to eventually modulate the firing of action potentials; Orch OR has a proposal for this which invokes quantum retrocausality and the collapse of the wave-function within MTs[4].

Regardless, the experimental results would serve as a significant step forward in understanding just how quantum Life is.