Introduction

It's often said that proving any mathematical statement is either trivial or impossible. Ex ante a solution is unknowable, but usually ex post obvious. In the case of quantum biology, we face a situation where the essential question - how quantum is life? - is simultaneously trivial *and* impossible. This is because the answer depends entirely on one's semantic specification of what is meant by quantum effects in biology - it's not a *scale-invariant* question.

On the one hand, biology is built from chemistry. This in turn is described by quantum mechanics, so by the transitive property we may conclude life is quantum. But quantum's status squatting at the base of the reductionist hierarchy means that the same conclusion could be drawn with respect to any topic. It would for example be absurd to suggest quantum social science [1] - so what exactly is meant by the question? I believe a reasonable interpretation is as follows: do there exist phenomena at the biological scale which can only be explained quantum mechanically? By this I mean effects that require the language of non-commutative operators in Hilbert space, and no effective classical model offers equal explanatory power.

Lamentably, I must speak for orthodoxy and declare the only plausible answer to this question is negative. To make this case, I first outline the essential features of quantum theory distinguishing it from classical descriptions. Drawing on this, I demonstrate that quantum effects are rapidly suppressed by increasing system size. Beyond this I employ complexity scaling arguments to establish that even if such effects existed they would be empirically and computationally impossible to verify. I further argue that the efficacy and safety of medical imaging offers strong contraindicative evidence against the existence of any functional quantum effect at physiological scale [2]. The essay concludes with a reframing of the question, suggesting a more profitable perspective is not quantum but the broader mathematical formalism underpinning it: linear algebra.

A note on style. I do not intend to restrict myself to the bloodless prose of academic exposition. I think it much better to be wrong with honest force than to perform the academic theatre of insincere objectivity. There will inevitably be passages whose rhetorical reach exceeds my technical grasp. Hopefully you do not notice. But if you do, stick with me, and consider this an open invitation to nail me to my mistakes afterwards. It will be fun.

What Is Quantum?

We begin by outlining the key features of quantum theory. This formalism has been consistently abused by soft minded fantasists choosing quantum as the de rigueur ingredient for their word salads (often dressed in a vinaigrette of faux-Buddhist woo). It is vital from the outset to divorce quantum terminology from the phantom cultural mass it has acquired. I therefore ask the non-expert reader to unburden themselves of any preconceptions of quantum (and its quasi-mystical associations) and approach this *tabula rasa*.

The single most important fact about quantum dynamics is that it is a statistical theory. It is not unique in this regard, but is distinguished insofar as its randomness is *intrinsic*. This is the Heisenberg uncertainty principle, which bounds the minimal statistical uncertainty a quantum particle may have. Mathematically, this is equivalent to the postulate that there are non-commuting pairs of physical properties which we call observables. Physically, if two observables A and B are non-commuting, then the measured statistics of each observable may depend on the order they are measured. The canonical example is position and momentum, although more abstract conjugate pairs abound. Remarkably, non-commutation is provably responsible for the full-spectrum weirdness of quantum theory [3]. Exactly how this occurs is beyond the scope of our discussion, but we summarise the major observable consequences here.

The first of these is coherence, responsible for many canonical quantum effects. Its key signatures are interference patterns and extreme sensitivity to perturbation. Coherence and its measurement dependence often motivate the concept of wave-particle duality, but this is an unhelpful framing since the theory is statistical and probability distributions are neither-wave-nor-particle. Notably, the effects of coherence can be easily imitated by classical systems. Specifically, while a single coherent quantum system can yield statistics no classical single-particle theory can reproduce, a classical model with two interacting degrees of freedom can mimic the fringes and beats that coherence produces. There is a blunt lesson to be drawn from this. Interference by itself is a necessary but not sufficient witness of non-classical behaviour. Unless you independently certify quantumness, coherent effects alone admit explanation by an interacting classical model. These subtle and foundational issues should always be kept in mind: we cannot casually ascribe quantum causes to observed outcomes.

Truly inimitable quantum effects may occur only when two systems interact and are composed together. This correlates the statistics of the individual systems, and when coherence is present the subsystem correlations can exceed any classical bound derived from a joint probability distribution. This correlative surplus is known as entanglement. It is quintessentially quantum, since it provably cannot be explained by any classical theory without unphysical assumptions [4]. Any biological process functionally reliant on entanglement would therefore affirm the existence of non-trivial quantum biology. Its existence would however be in violent conflict with the *scaling* properties of quantum systems.

Size Matters

Why does life occur at the scale of cells, rather than atoms? A succinct answer was offered by Schrodinger [5]: living organisms are highly ordered structures, which requires their constituent machinery to be predictable in their operation. How can this align with quantum theory? If our fundamental description of matter is a statistical theory defined by minimal uncertainties, how do highly predictable deterministic processes emerge?

Simply because *more is different* [6]. In large assemblages, the random fluctuations of individual particles will collectively cancel out. This is due to a minor miracle of statistical variance: the *central limit theorem*. This implies the uncertainty of measurement outcomes will shrink (relative to their average) with the square root of the number of particles. The uncertainty of quantum might be intrinsic, but it is not exempted from this collective self-averaging. Notably, while macroscopic quantum phenomena *do* exist, they typically require fine-tuned conditions far beyond the operating regime of physiology. Moreover macroscopic effects can always be well-characterised by a classical theory, with effective parameters ultimately determined by the underlying microscopic quantum model. An instructive example is magnetisation: in a paramagnet, applying a magnetic field tends to align atomic spins while thermal fluctuations oppose alignment; magnetisation increases either with stronger field or lower temperature.

Beyond this, we can be certain that scale erases the necessity of quantum description generically, because the entire edifice of computational physics and chemistry would be impossible otherwise. The reason for this lies in the relative complexity of quantum theory. Classically the state of a system is a point in *phase space*. The simplest model is a particle confined to one spatial dimension, which requires two phase space dimensions to describe - one each for position and momentum. If I wish to describe *N* particles classically, I must extend to *2N* dimensions. That is, the size of my problem scales linearly with number of particles.

Quantum theory differs insofar as states become points in *Hilbert space*. The details are unimportant, except insofar as quantum uncertainty necessitates that Hilbert space does not scale linearly with *N*, but *exponentially*. A single qubit *also* requires two dimensions, but adding another particle doesn't merely add dimensions - it doubles them. This means that even substituting a relatively modest *N=50*, the quantum state description requires eleven trillion times the dimensionality when compared to the classical case. Marvellous as computers are, they cannot feasibly store or process vectors of this size. And as N gets bigger, this only gets worse. Exponentially worse. It gets really big, really fast. Really big. Really fast. I simply must emphasise this point, because there is little in life as existentially terrifying as scaling laws.

The consequences of this scaling are profound. On the positive side of the ledger, this blow up in the relative internal complexity of quantum states underwrites the entire promise of quantum computing. More pertinent to us is the obverse implication: the simulation of quantum phenomena becomes *prima facie* intractable for more than a handful of quantum particles. If biology had functional dependence on large-scale quantum effects, it would be impossible to model it with classical computation. This mathematical wall is known as the curse of dimensionality : five minutes in the company of anyone working on the fermionic sign problem will convince you of the utter ruin it inflicts on those who struggle against it. This means that any claim for the necessity of large-scale quantum effects is effectively *undecidable*.

Of course, computationally intractable does not mean physically impossible. In practice however, we are supremely fortunate that these modelling problems aren't intractable. But only because nature apparently wants quantum at scale as little as we do. Even within computational quantum physics, approximations with 'almost-classical' models mean that laptops can produce quantitatively accurate simulations involving 10,000 particles, rather than 10. More broadly, an entire field has been built to navigate a hierarchy of simulation techniques across orders of magnitude. This is known as *multi-scale modelling*, and it aims to stitch together effective theories at the scales where relevant phenomena actually live. To glue them together, the results of the finer model are used to parametrise the next step up. From this you obtain models which incorporate all we know of the unbroken chain of being, but only *simulate* the minimum necessary. It's done this way because it works. If it didn't, it wouldn't have won a Nobel prize. The pharmaceutical research industry relies on it, as an approach which is accurate where it really counts. *It buys you drugs.* Absent any other consideration, it is hard to argue with this kind of success.

Finally, a word on decoherence. It is important to highlight that even an isolated system can self-decohere [7] at long times, effectively acting as its own environment. This cannot be loopholed by appeal to "special" biological environments, and provides a mechanism by which quantum systems become effectively classical at scale.

Ordering The Scales

So then, how quantum is life? We may answer this with a taxonomy of scales. We have already covered the quantum dependence of chemistry, but there is one more arena in which quantum matters to matter. Being made of atoms, biological tissue remains *susceptible* to quantum effects, and we routinely exploit this with imaging instruments. Take MRI: A strong RF pulse tips and synchronises nuclear spins. Different tissues then desynchronise at different rates, and an image is reconstructed by measuring the resulting magnetic field distortions. This relies on bona fide quantum effects, but all the action is on the instrument side. We are reading out passive responses of tissue under engineered fields, not witnessing biology harness macroscopic quantum resources to function.

Moving up the scale hierarchy we hit the fuzzy edge of plausibility for "quantum biology". Into this bucket goes enzymatic tunnelling, avian magnetoreception, and photosynthetic light harvesting complexes. This is all unquestionably serious science, but its framing is seriously questionable. First, the tunnelling-assisted hydrogen-transfer reactions in enzymatic processes are standard, well-quantified correction within quantum chemistry [8] (and an example of multiscale modelling). It provides no evidence for long-lived coherence or any macroscopic "quantum advantage" specific to the context of living organisms. To claim this as quantum biology would surely trivialise the concept. A more interesting case is magnetoreception: the radical-pair account in retinal cryptochromes is chemically well-posed, but the *in vivo*receptor remains unproven, and magnetite-based mechanisms have not been ruled out [9]. Either way, while cryptochromes are described by spin chemistry, the presence of entanglement has been shown to have "little practical relevance" [10] to their proposed function. Again, it appears the claim can be reduced to a particular branch of chemistry. What *exactly* does the label quantum biology buy us then? Unless we have decided to stop shaving with Occam, I see no good reason to call this anything other than chemistry.

Well, perhaps there is a good reason. Just not a principled one. We live in a world in which the sociology of science cannot be separated from the science itself. Academia is sick with perverse incentives that control time, attention, and money. In the zero sum game of funding, the pursuit of one research agenda necessarily comes at the expense of another, and academics are forced to chase trends like a pack of starving rats. No one is to blame for this, it is just the dismal reality of industrial science. Nevertheless, we should always be cognisant of the imperatives a buzzy label creates, and that the best marketing does not necessarily equate to the best science. For this reason, it is not enough for quantum biology to simply be a rebrand of biochemistry. It needs to sing for its supper, and commit to some rigorous definitional criteria. I would suggest it requires (i) a mechanistic claim tested *in vivo* under physiological conditions; (ii) a falsifiable prediction that cleanly separates nonclassical dynamics from classical surrogates; and (iii) evidence of a bona fide performance differential (a measurable "quantum advantage") against that surrogate baseline.

This sets a high bar, but is necessary to prevent argumentative retreat across a rhetorical drawbridge. It is not meant to deny subtle effects, but check premature proclamations of paradigm shifts. Given the overwhelming *a priori* reasons to be sceptical, I do not think it is too much to demand evidence that *meaningfully* distinguishes quantum biology from its sibling studies. Absent this, we are simply dislocating real scientific debate into semantic territory, and rewarding whoever stakes the most marketable claim. Moreover, if your work is funded on the promise of revolutionary results, you are highly incentivised to make the case for positive results come hell or high water. We are only human, and this kind of pressure invites a confirmatory bias in everything you study. It creates an expectation gradient against which it is extraordinarily hard to do good science. The consequences of this kind of frame-chasing are easily identified. It has been suggested photosynthesis relies on quantum effects, based on an interpretation of observed spectroscopic oscillations as durable electronic coherence. These are now well accounted for by vibrational modes [11, 12], with no demonstrated functional quantum advantage under physiological conditions [13,14]. Despite this, popular science leapt immediately to the absurdity that plants perform "quantum computation" [15]. Again this is not a problem of the intrinsic science but its packaging, and an example of *why* messaging matters!

We can cap our taxonomy with those theories that assert that life is *essentially* quantum at the macroscale. I take quantum consciousness as synecdoche for this category. Let us dispense with the polite fiction that these proposals are merely controversial, and make our view plain. These are not theories, but magical thinking clothed in scientific language. Refuting them is almost too easy, given the veritable arsenal of devastating counter-arguments available. At minimum we can assert that *even* if brain-scale entanglement existed and were verified, it offers no explanatory power for the quality of internal experience. This is because despite their popular misrepresentations, quantum effects do not violate causality. An immediate consequence of this is that no matter how entangled two systems are, *no* information is transmitted between them. Entanglement is provably non-signalling. As the saying goes, correlation does not imply communication! Consequently there is no meaningful sense in which a quantum effect helps explain consciousness. It's called *the hard problem* for a reason

In any case, the above argument already concedes too much in not challenging the existence of non-explanatory quantum mechanisms. Time and again, natural selection has proved a ravenous optimiser under constraints. Given billions of years and countless lineages, if robust, physiological-scale quantum mechanisms existed and conferred a material fitness advantage, natural selection should have stumbled on them. But life has evolved in Earth's magnetic field, bathed in broadband electromagnetic fields and ceaselessly agitated by thermal shot noise. Any mechanism that functionally depends on fragile quantum phases at the cellular scale would be catastrophically brittle in this environment. Instead, organisms are famously robust. If quantum effects occur in biology, they can only do so as microscale phenomena that produce classically deterministic phenomenology - precisely the pattern robustness predicts. Even discounting this, we already perform a population-scale intervention that would obliterate any functional process dependent on coherence: MRI. This imposes static fields orders of magnitude greater than the Earth's, together with rapid RF pulses that forcibly align nuclear spins[16]. On the scale of quantum devices, these are overwhelming drives. Yet cognition is intact; subjects perform tasks in-scanner, with side-effects limited to benign sensations at high field. If essential neural function rode on long-lived coherence, we would not be so cavalier with the electromagnetic spectrum

With this established, we can list the implicit assumptions necessary to maintain that physiological-scale quantum resources drive function. It requires that evolution discovered large-scale quantum mechanisms in warm tissue, which deliver a clear fitness advantage in ordinary conditions and are *also* immune to perturbations far beyond the range of natural adaptive pressures. All this, while simultaneously pleading for the idea that otherwise vanishing quantum effects reassert themselves only at the most psychologically convenient scale. The genesis of these ideas is almost comically easy to infer: confronted with two concepts one does not understand, it is tempting to believe that there's really only *one* thing . A cheap trick in which genuinely hard problems are collapsed into highly technical abstractions. This is an argument by obfuscation, conflating a mystery (consciousness, agency, emergence), with something merely abstruse (quantum). That is not an explanation. It's intellectual fly-tipping. While I believe the creators and advocates of these theories are acting in good faith, the effect is the propagation of confused, misleading ontologies which do real damage to the public understanding of science. Presuming there is any substance left to academic debate beyond a mummer's game of tone policing and prestige optimisation, they *must* be contested in the most vigorous terms possible. Sorry mum, I had nothing nice to say, but still said it

Because I believe it matters. Our moment is one of accelerating discovery and epistemological crisis. Biologists are entirely correct to search every possible avenue for answers, but quantum is the last place they should be looking. Even professional physicists regularly and profoundly misunderstand it, and consequently often becoming unwitting purveyors of snake oil. Worst of all, none of this is even necessary! To find the answers we seek, I propose we turn to a different adjective. Life is not meaningfully quantum, but it is perhaps *algebraic*. # Algebra All The Way Up One of the central themes of this essay has been the importance of *scale*. On the scale of being, quantum is merely the root note, setting the key but not the melody. It offers no guide for how we may hope to understand emergent phenomena. In one sense this problem can be framed as the conceptual complement to that of infinite regress, each oppositely oriented to substrate or superstructure. Even the solutions are symmetric. In our case it is not turtles all the way down, but *algebra all the way up.*

What do I mean? The essential problem for almost all scientific inquiry is to find the *correct representation.* With the right mental lens, inexplicable phenomena become inevitable. The *impossible* becomes *trivial.* This naturally motivates the search for a scale-free, universal model of representation. We have had this tool for centuries, but are only now grasping its potency. It is called linear algebra. This story has a beautiful circularity to it. In the mid-twentieth century neuroscientists sought functional mathematical models to describe neuronal dynamics. From this emerged cybernetics [17], which formalised the mathematical study of goal-seeking and self-correcting behaviour. The bridge from this to machine learning came through physics, via the Hopfield network. This adapted a statistical mechanical model to a "neural circuit", which could be analysed with the toolkit of statistical physics. This has proven to be - in grand mathematical tradition - *unreasonably effective* [18].

This is exemplified by the fact its most dramatic advances have come in the past decade. The entire architecture underpinning generative AI arose not from elaboration but simplification of the underlying models [19]. The present frontier of transformer models consist of almost nothing but linear algebra, spiced with computationally trivial nonlinearities. Their power is derived not from conceptual complexity, but from *scaling laws* linking performance to model size. Setting aside the question of if general intelligence can be realised in this paradigm, it has already utterly transformed our understanding of what intelligence *is.* Ask yourself, when was the last time we spoke seriously of Turing tests?

Above all I sense a loop is closing. The addition of a thermodynamically inspired performance metric to mathematical learning echoes back to neuroscience through *the free energy principle.* This argues living systems that persist far from equilibrium can be interpreted as the outcome of an analogous optimisation, and posits that thermodynamic laws make life-like order inevitable [20,21]. To my mind, such resonances and assonances are becoming irresistible. One might still ask how it is that meat might mimic algebraic abstraction, but again we are discovering how little is required. Paradigms such as reservoir computing [22-25] and Koopman-von Neumann (KvN) dynamics have shown an equivalence between the algebraic models underpinning machine learning and the dynamics of nonlinear physical systems. Ironically the KvN formalism is the classical analogue to quantum theory - a Hilbert space theory where efficient representations of complex nonlinear dynamics are linearly approximated in Hilbert space [26]. This is the conceptual link necessary to map between physical operation and abstracted purpose. Viewed through this lens, biological systems may be understood as embodied computation in material substrates. I won't pretend it isn't speculative, but buy me a beer and I'll show you my working.

All scientific answers are provisional, because all models are wrong. But some are useful. And algebraic models have proven *most* useful. Given enough dimensions, algebra can represent anything. It does not offer an easy resolution to the mystery of internal experience, but It suggests that sophisticated agents are an emergent property of scale. We are perhaps the ghosts in our own machines. I therefore close on a note of indulgent speculation: with the right frame, and the right scale, there is no phenomenon which cannot be captured in the span of Hilbert space. At any rate that's what I'm telling my wife the next time she insists there is more to life than algebra.