

Quantum biology is the hypothesis that quantum mechanical phenomena influence and meaningfully shape biological effects in living systems. This has been shown to be the case for a number of specific biological effects, and theorized to be the case in more. These results and theories however are largely treated as niche or isolated instances by the larger biological science community. As such, quantum biology considered as a unified field, represents the implicit hypothesis that such cases are more than isolated phenomena: That they represent a common and even universal basis for the properties of all life, so ubiquitous that no study of biology could avoid an understanding of quantum effects.

This essay will undertake to show a path to developing such a unified science. There are three steps in this path: 1. Establishing the basis for an empirical science suitable to biological laboratory methods. The basis of this is the “scale shifting effect”.

2. Establishing a framework in biological theory to guide how and where to look for quantum mechanical effects. There is ultimately only one grand unified theory of life, and that is evolution, so any theoretical framework of quantum biology must place it into a fitness landscape. 3. Identify which research will encourage a unified quantum biology field to coalesce.

1. Scale Shifting Effects: The Key to Unlocking Quantum Biology with Conventional Laboratory Methods

It is tempting to focus upon the unique properties of quantum mechanical processes when considering the possibilities of quantum mechanical aspects of life, and to be sure they are relevant. However, such a focus, on the physics side of the question, misses that living systems are profoundly dissimilar to other material, energetic, and informational systems.

Life is different. Specifically, life has an abundance of what will be termed here “scale shifting effects”. Most of the material world functions in fairly discrete physical scales. For example, the behavior of planets and moons is largely independent of the dynamics that govern the behavior of any individual molecule that composes them. Living systems have a variety of such scales from individual bio-molecules, to macromolecular complexes, to organelles, to cells, to tissues, to organs, to whole organisms, to communities of organisms leading into species, and finally ecosystems.

Scale shifting effects are situations where the fate of a single element at one scale can have outcomes that dominate larger scales. For example, a cancer might start with the chemical mismatch of a single base of DNA to its complementary strand. That one local molecular event involving a scant few atoms can start a cascade that alters the fate of the cell, ultimately giving rise to a tumor, and the death of the complex multicellular organism in which it began. In rare cases, such as the contagious facial tumors of the Tasmanian Devil, it might threaten the survival of an entire species. (<https://doi.org/10.1177/0300985815616444>) If that species were a keystone species, an entire ecosystem’s stability might turn upon a single molecule’s fate.

Scale shifting effects are to be distinguished from aggregate effects. An example of an aggregate effect would be a person’s eye color. That too has its basis at the molecular level, specifically the properties of certain chemical bonds in pigment molecules cause them to absorb certain frequencies of light in the visible range but not other frequencies. The difference is that the eye color of an individual is not the result of any one molecule of pigment, but rather the accumulated contribution of many trillions of iterations of that pigment molecule across the cells of the iris. No individual molecule of pigment, if removed, would visibly alter the eye color of an individual.

The living world is not the only place that we see the scale shifting effect; a few cases in non-living matter also exist (crystallization, and ignition come to mind). However, what is a rare phenomenon for non-living matter is very common in life to the point of dominating living system dynamics. Examples include but are not limited to: carcinogenesis, mutation, infection, signal-transduction, embryo-genesis, and most forms of sensing. Scale shifting effects are pervasive across all scales even if they do not start at individual molecules or cells. Many social dynamics, for example, shift the behavior of just one or a few individuals into the behaviors of whole groups. Similarly, one can scale shift not just in length scales, but in time: memory and learning, whether neurologically mediated, or by some other mechanism, such as the immune system, shift very fleeting events into lasting effects.

For the purposes of this essay, we are most interested in those scale shifting effects that originate at the

very smallest scales involving just a few elementary particles, such as electrons, and that shift from fleeting effects to lasting ones and to physiologically measurable scales. This is because most quantum mechanical states such as entanglement or superposition only exist by default, at temperatures compatible with life, for very small numbers of particles and dozens or hundreds of nanoseconds. But if those fleeting tiny quantum mechanical effects occur within a pre-existing biological process that can shift their scale beyond the tiny and the fleeting, the state of an electron for a mere few hundred nanoseconds might be all life needs.

One might posit bio-molecular structures and systems evolved to stabilize quantum coherence, and indeed if quantum mechanical effects do exist meaningfully in life, it seems inevitable that such structures and mechanisms would eventually evolve if they are at all possible. Enhanced coherence would be a potent tool to harvest from living things, and indeed this is one of the reasons quantum biology is so compelling as a field... as we explore it, we are almost certain to find biomolecular tools that, co-opted for our own uses, will enhance our capacity to further explore it in much the same way that studying molecular genetics led to genetic tools like PCR and CRISPR/Cas9 that made studying molecular genetics easier and more useful. Nonetheless, quantum-coherence-stabilizing biological mechanisms are a separate hypothesis to the base hypothesis that biology has and uses quantum mechanical effects in a way that is meaningful to the biology of the systems they are embedded in. Further, thanks to the prevalence of scale shifting effects in biology, it is also an unnecessary hypothesis for the advancement of the quantum biology field.

Finally, thanks to the many ‘omics’ data types that can be sampled experimentally using established molecular biology techniques, a scale shifting effect need not shift a quantum mechanical phenomenon all the way into macroscopically visible phenotypes for it to be observed. The collective bandwidth of transcriptomics, metabolomics, proteomics, and genomics (typically read out through various sequencing platforms and mass spectrometry) represents a massive capacity to turn any living organism into a sophisticated and highly sensitive detector for any physiologically relevant response, and wholly without the need for complex bespoke instrumentation.

2. The Rumor Mill of Biomarkers: The Evolutionary Fitness Advantage of Quantum Sensing.

As Dobzhansky contended, “Nothing in biology makes sense except in the light of evolution.” (<https://doi.org/10.2307/4444260>) But nothing in evolution makes sense except in the context of selection and fitness. If we are to build a field of quantum biology, central to that effort must be the question: Why does life use quantum processes? What is the quantum fitness advantage prompted that evolutionary trajectory?

To consider that, we have to go back to the pervasive aspect of the scale shifting effects in life. They are not just a convenient way to perceive a quantum biological effect, but also speak to a fundamental aspect of life’s most basic nature. Letting the very small or fleeting affect the very large or enduring suggests that life’s essential processes should be considered as intrinsically about sensing and amplifying weak signals to the advantage of the organism. We tend to think of an organism’s properties as static: This is *B. anthracis*; it produces deadly spores. Or, that is *E. coli*; it can double in number every 30 minutes. Etc. But the prevalence of scale shifting effects amplifying weak signals in life suggests a far more contingent and reactive nature to living things constantly balanced on a knife’s edge, of cells poised to jump at the slightest rumor of an environmental change. Detecting such a signal, even a fraction of a second earlier, when it is still encoded by the presence of a scant few molecules diffusing across the cell’s outer membrane, might be the difference between survival and extinction.

This is entirely in keeping with evidence that we have from several directions: Micro-organisms, when confronted in culture with other organisms (competitors, co-pathogens, or host cells, it doesn’t matter), up-regulate dozens or hundreds of genes that are normally quiescent when the organism is grown alone in pure culture. Further, the suite of up-regulated genes is unique to the organism that is in confrontation; *E. coli* will up-regulate different genes when confronted with yeast than when confronted with *B. subtilis*. (<https://doi.org/10.1038/s41598-018-26738-1>, <https://doi.org/10.1038/ismej.2010.196>)

Similarly, the Epstein lab at Northeastern has solved the culture problem (that most micro-organisms do not grow on even the richest media in the lab). They did this by determining that it was not that the micro-organisms *couldn’t* grow in the lab, but rather that they *wouldn’t* grow in the lab. Most micro-organisms are waiting for the presence of specific environmental signals that they are evolved to gate growth upon.

(<https://doi.org/10.1126/science.1070633>) Cell division is a resource intensive and slow procedure, that if embarked upon or completed in unfavorable conditions, may lead to the death of one or both daughter cells. It makes sense that most micro-organisms would not, like *E. coli*, attempt to grow unconditionally but rather husband their resources for an optimal time in which conditions are not just acceptable now, but likely to remain so for long enough to complete cell division. And it turns out that, almost universally, the signals that micro-organisms look for come from other living things. Taken together with the confrontation experiments, microbiology and micro-ecology are revealed as a complex rumor mill of biomarkers. Indeed significant signal processing may be performed by the ensemble of many organisms far beyond the capabilities of any one.

It is in this circumstance of biomarker rumors that we can discern an evolutionary fitness advantage in quantum mechanical effects for biological systems: sensing. Famously, migratory birds are known for being sensitive to the Earth's magnetic field. (<https://doi.org/10.1038/s41586-021-03618-9>, [https://doi.org/10.1016/S0006-3495\(00\)76629-X](https://doi.org/10.1016/S0006-3495(00)76629-X)) The basis for this sensitivity is the "radical pair" mechanism which involves a pair of excited electrons in a flavoprotein called 'cryptochrome 4', which are in a superposition between a singlet state (opposed spins) and triplet state (correlated but not opposed spins). The degree to which that superposition is dominated by either the singlet or triplet state is sensitive to external magnetic fields if they are in the same approximate intensity as the hyperfine magnetic fields generated predominantly by the nuclear spins of the atoms surrounding the two electrons (one on the flavin of the cryptochrome and one on a nearby tryptophan).

Relying upon no large-scale structures such as the lens of an eye, or the drum of an ear, there is nothing about the radical pair mechanism that can't be employed by microbial single celled life. Further, every microbial organism is replete with flavoproteins, much like cryptochrome 4, and these proteins are the basis of some of the most basic and fundamental biological processes shared by all living things... central carbon metabolism, reactive oxygen species management, electron transport chains, and such. What if some, or maybe all, of these flavoproteins exhibit magneto-sensitive properties too?

If that is a plausible mechanism by which *E. coli* might be using a quantum mechanical phenomenon, why would it be doing so? The birds sense magnetic fields to migrate, an essential part of their life cycle after all. The answer comes back to our understanding of microbial life being balanced on a knife's edge between highly tailored genetically programmed responses to environmental signals. Sensing the magnetic field represents a profoundly different information space than sensing chemicals, because an intracellular molecule that has not actually come into contact with the surface of a cell might as well be on Mars for all that it can relay information to that cell. Conversely, the magnetic field samples information from a large surrounding volume that shapes the field lines passing through the cell. This is information from far beyond the surface of that cell. Even if the field derived information is noisy and only marginally relevant, it represents a completely independent and different source of environmental sampling, which can provide contextualizing information for all of the chemical rumors informing the cell's genetic program.

3. Which Research Can and Can't Coalesce the Field of Quantum Biology

From this conceptual basis of how microbiology and micro-ecology work, a vision of a quantum biological scientific field begins to come into focus that flips the traditional quantum mechanical methodology. Instead of cooling samples to almost absolute zero to create conditions in which quantum phenomena are stable enough to interact with in a highly bespoke and expensive apparatus, the prevalence of biological scale shifting effects reveals that biological systems represent an ideal place to look for quantum mechanical effects because they natively contain many evolved signal amplification responses that gate large-scale easily and cheaply measured biological phenomena. Further, the instruments and software to sample such responses in very high resolution already exist and are developed to a high degree.

But like all emerging fields, there is a danger that it will stumble down blind alleys and enticing but impossible, or at least very hard, problems. Therefore, it is worth pointing out two such blind allies that the emerging field of Quantum Biology should not focus upon even though many in the nascent field seem determined to do so:

The first enticing blind alley that quantum biology should avoid is being overly concerned with humans or animals. Concordantly, the study of large scale tissues such as the brain and late evolution traits such as

intelligence are bottomless resource sinks for continuous but never conclusive effort. Rather, a focus upon microbial model systems and traits that are encoded by genes that have evolutionary origins at the very dawn of life on Earth will advance the field much more rapidly. This is the case for three very different reasons.

First, it makes sense evolutionarily: We have every reason to believe that the laws of physics have not changed in the vicinity of Earth over the 3.5 billion years that life has existed here. So, the opportunity and evolutionary advantage for quantum mechanical phenomena to be leveraged by life is not something that would be expected to emerge only with multicellular animals in the Ediacaran Period a mere 635 million years ago. To a researcher entering the field of quantum biology, I would suggest studying no trait younger than oxygenic photosynthesis, believed to be around 2.7 billion years ago, although there is some doubt about that date. (<https://doi.org/10.1038/nature07381>) (Photosynthesis efficiency, like magnetosensing, also represents a promising direction for quantum biology research because it meets all of the same requirements: microbial, scale shifting evolutionary fitness rationale, easy read-outs, easy probing, fast experiments).

Second, focusing on microbes makes sense practically: complex traits are, well... complex! This is what makes probing higher reasoning, social structures, long term development, senescence and longevity, so experimentally difficult. Even simply defining what these phenomena are and are not can often be fraught. The consequence is that the study of such phenomena requires very large effect sizes and/or large Ns to achieve unambiguous reproducible results. That's a heavy requirement for an emerging field in its infancy. To a researcher entering the field of quantum biology, I would suggest avoiding traits connected to scientific fields that have been heavily impacted by the crisis in reproducibility. (<https://doi.org/10.7554/eLife.78518>, <https://doi.org/10.1016/j.bpsc.2022.12.006>, <https://doi.org/10.3389/fpsyg.2017.00862>) It's hard enough getting convincing evidence of classical phenomena in such fields.

Third, a microbial focus makes sense pragmatically: Experiments on human or animal tissue require blood-based media, which is expensive, and experiments on whole humans or animals require lengthy ethics review and compliance, which are also expensive because time really is money. (It might be tempting to counter that on the pragmatic side, there is more funding available for human studies that might yield medical application, but that contention is wholly countered by the much greater competition for that much greater funding, and competition from established labs with established techniques at that). Conversely, microbes are cheap, easy, and perhaps revealing a multi-cellular-centrism; nobody cares if they are subjected to pain and suffering and then sacrificed at the end of the experiment! But most importantly, microbial studies are fast allowing for rapid iteration of experimental design and hypothesis testing.

The second enticing blind alley that the emerging quantum biology field must avoid is the investigation of quantum phenomena that cannot be probed and modulated easily. For example, entanglement and quantum computing like effects would be very hard to establish unambiguously in a living biological system. They are in fact hard to establish even in purpose-built quantum computers designed with no other purpose than to establish that they exist. (<https://doi.org/10.1103/PhysRevA.70.052328>, https://www.businessinsider.com/amazon-exec-casts-doubt-microsoft-quantum-claims-2025-3?utm_source=chatgpt.com) These phenomena likely do exist meaningfully in biological systems, but until they possess easy and unambiguous ways to probe their quantum biological natures experimentally, they represent not a source of field-legitimizing results, but rather a source of field-destabilizing controversy.

Conversely, superposition of electron states in the radical pair mechanism can very easily be probed via magnetic fields. Similarly, tunneling of hydrogen, a major component of the activity of most biological proton pumps, can be probed by enzyme kinetics and by the tunneling mechanism's discrimination between protium and deuterium, since deuterium, being twice as massive, has a shorter de Broglie wavelength and a lower tunneling probability. (<https://doi.org/10.1016/j.bbabi.2007.09.009>)

Despite the danger of certain blind allies, which rather than land-mines to be avoided indefinitely merely represent areas of study that should be de-prioritized until the field is more mature, the thesis of this essay is actually quite optimistic for the future of the science of quantum biology.

The takeaway message here is that quantum biology enjoys a target-rich field of under-studied phenomena

that are easily, cheaply, and quickly accessible to experimental interrogation with the convenient probes and with conventional readouts: There are many dozens of microbial model organisms that collectively express thousands of characterized gene products that are prospects to possess quantum biological properties such as, but by no means limited to, flavoproteins. This is true even if we restrict the list of targets to those that could likely be probed with magnetic fields. Further, magnetic fields possess many degrees of freedom (intensity, orientation, static vs. oscillating, frequency if oscillating, etc.), with large dynamic ranges making them subtle probes that can allow for sophisticated probing such as dose-response curves. And each of these molecular target and probe combinations can be subjected to high resolution multi-omics data gathering and analysis, which is already adapted for economically processing many samples in parallel. The potential to decode the quantum-omics space is staggering because many more degrees of freedom of data informing the solutions can be applied, than the problem has degrees of complexity to solve for. It is a near certainty, therefore, that such problems will be solved for at least some molecular targets. Each “solution” in this magneto-sensing case would be a bio-molecule that senses magnetic fields with defined parameters (intensity, frequency, etc.) and leads to consequential downstream biological effects (altered metabolism, growth rate, gene expression, etc.).

With every such solved bio-molecule, the potential for bioinformatically predicting the solution for more bio-molecules improves. This is in keeping with the sort of virtuous cycle that has informed other biotechnologies. For example, restriction enzymes which cut DNA at specific sequences are an important tool in most bioengineering. Restriction enzymes that were characterized early needed to have the sequences they recognized and cut at determined experimentally. But with enough experimental data to inform bioinformatic models, the recognition and cut sites of novel restriction enzymes could be predicted just from their sequences. In quantum biology, we will want to be able to similarly predict which magnetic field properties will be able to maximally alter the radical pair magneto-sensing mechanism of a sequenced enzyme based on the empirical characterization of similar enzymes. One effect of achieving this will be the ability to render quantum biology relevant to more and more of the mainstream biological research being performed in other fields as a direct consequence of being able to annotate the genes those other fields are already concerned with as to quantum properties that had been hitherto unsuspected.

But these empirical solutions informing predicted ones would not be mere academic curiosities to specialists in other fields. Magneto-sensitivity of living things represents a way to manipulate and direct their behavior in a highly tuned way because the organisms that possess such mechanisms, including, likely, our own bodies, are already quantum devices in effect.

Imagine: in the not too distant future, a patient with a multi-antibiotic-resistant infection. Her doctor has the infecting organism sequenced and then prescribes an oscillating magnetic field tuned to a targeted flavoprotein in just that one infecting bacterium, but no other, tricking the problematic organism’s replication regulating mechanisms to falsely detect unfavorable conditions, causing it to pause its growth and allowing time for her immune system to clear the infection. Layered on top of the tuned oscillating magnetic field that is functioning as an antibiotic, different frequencies that alter the oxidative stress based inflammation response of the patient’s body are prescribed to reduce fever and pain. Such a scenario is only the tip of the iceberg of what a science of quantum biology could provide us! What’s more, such applications are the final step in mainstreaming the science of quantum biology. Nothing speaks to the legitimacy and reality of a phenomenon like the ability to use it in practical, money making, and life saving products.