

Back story: At this point, the essence of the discussion may already be apparent. However, for better clarity and continuity, it is worth returning to the symbolic “Newton’s Apple,” from which the systematic study of mechanics is often considered to have begun. Yet it must be emphasized that Newton was not the first to contemplate motion and mechanics. Long before him, many great thinkers had laid the foundation of the field. Among the most significant were Aristotle, Archimedes, Galileo, Rene Descartes, and Johannes Kepler. What distinguished Newton, however, was his ability to synthesise these earlier ideas into a single, universal framework—one that could explain both terrestrial and celestial motion with remarkable precision. Till Newton, I suppose, most of us are well aware and conscious. But what happened after Newton? This question does not seem to bother us much—perhaps for two reasons: 1. The idea was so greatly revered that nobody dared to challenge it for more than two centuries. 2. Most of the problems encountered in our broader external environment were effectively tackled by Newton’s laws. It was only in the late 19th century that cracks began to appear in Newtonian mechanics: o Maxwell’s Theory of Electromagnetism hinted that Newton’s framework was not sufficient to fully describe light and electromagnetic phenomena. o Einstein’s Theory of Relativity revealed that Newtonian mechanics failed at very high speeds and in strong gravitational fields. o Quantum Mechanics showed that when we take a closer look at the inner world not from a philosophical standpoint but from the perspective of physics—Newtonian mechanics breaks down at the atomic and subatomic levels. In this essay, we explore how science has progressed from the well-defined realm of the macroscopic world to the intriguing and often uncertain domain of the microscopic—the world of quantum mechanics and examine how quantum principles may be linked to biological systems.

Life: A Journey from Uncertain Chaos to Certain Reality

Introduction

When I was in class 10, I once asked my organic chemistry teacher a question. Ironically, I don’t remember the question itself, but I clearly remember the conclusive statement of his answer. He said, “It’s the non-living biomolecules giving birth to a complete and complex human being.” And with a smile, he added, “And we haven’t yet been able to find how.” This really amazed me. Perhaps, deep down, I was trying to ask: What is life? Or, in a broader sense: How quantum is life? To even approach this question, let’s see how quantum physics connects to quantum biology and ultimately to life itself. “The building blocks of life are cells, governed by molecular biology, which in turn rests on organic chemistry, and ultimately, organic chemistry is governed by the laws of quantum mechanics.” In quantum physics, we often come across terms like quantum tunneling, quantum entanglement, coherence, decoherence, and many more. These concepts have puzzled physicists for decades. Their possible intervention in biology is itself a question mark—one that demands attention. Even today, it is still not clear how it all started and how it will end. In biology, a system is defined using chemical reactions, showing that life is made of the same stuff as everything else. The thought then arises: if we are able to neglect quantum effects in the macroscopic world, why not in the biological world? As humans, we have taken upon ourselves the responsibility of not simply accepting life as it is. We constantly seek a spark—a thrill, a kick in life that pushes us forward. This curiosity, this unwillingness to settle with “not knowing,” is what motivates us. And it is precisely this feeling of not knowing, and the desire to know, that leads us to the astonishing realities of this mysterious universe. This is exactly what Schrodinger did. **Quantum Biology: Amalgamation of surety and skepticism ?** Schrodinger, DNA, and Quantum Tunneling: Erwin Schrodinger did not accept the idea of neglecting quantum effects in the biological world. He argued that the laws of quantum physics must play a role in life. In his book *What is Life?* (1944), he introduced the concept of the aperiodic crystal. Schrodinger reasoned that a simple repeating structure could not store the vast and complex information required for life. Instead, he suggested that the genetic material of living organisms must be a highly ordered yet non-repetitive structure – capable of holding enormous amounts of diverse information. Inspired by such ideas, Watson and Crick went on to discover the double helix structure of DNA. Their discovery was revolutionary, but it left behind a deeper mystery: does quantum physics actively influence DNA itself? Modern research suggests the answer is yes. DNA is not just a stable molecule of heredity; it also exhibits subtle quantum effects. One striking example is quantum tunneling. Classical physics tells us that a particle cannot cross an energy barrier without sufficient energy. Quantum mechanics, however, allows a small probability for the particle to “tunnel” through. In DNA, this occurs when protons tunnel across hydrogen bonds between base pairs. If a proton tunnels to the “wrong side,” it can cause a base to mispair during replication, resulting in a spontaneous mutation. Such mutations are not merely errors; they are also the raw material of evolution, providing the genetic variation on which natural selection acts. In this way, Quantum physics offers a mechanism by which DNA can change naturally, even without external triggers such as radiation or chemicals. Although Schrodinger’s ideas were extremely influential, it

took quite some time before another quantum phenomenon in biology was observed. One such breakthrough came with the discovery of quantum coherence in photosynthesis around 2007. While preliminary research had been ongoing earlier, it was after 2007 that studies proliferated, exploring in depth how quantum phenomena might operate in living systems. ? Plants and Quantum coherence: Quantum Coherence is the ability of particles to stay in sync and explore many possibilities at once, leading to highly efficient outcomes. Suppose a man has to reach a particular destination. He has three possible routes. In the classical way, he would try one route at a time to find the best one. Now imagine that the man “splits” into three versions of himself, each taking a different route simultaneously. Once they discover which route is the most efficient, they merge back into a single man who now knows the best path. This is exactly how Quantum coherence takes place during photosynthesis in plants. It allows excitons to travel efficiently through light harvesting complexes to reaction centres, enabling near perfect energy transfer by maintaining wave-like superposition of states and phase relationships for pico seconds. This phenomenon improves the quantum efficiency of the process by providing a quantum path that explores multiple routes simultaneously preventing energy loss and increasing efficiency. ? Animals and the Magnetoreception: This concept is truly fascinating. Haven’t we all wondered how birds manage to migrate from one place to another with such precision? The answer is even more magical than the question itself—thanks to Earth’s magnetic field. We have long known that many animals use the Earth’s magnetic field as a natural compass for navigation. But the real mystery was how they sense it. The exact mechanism is still not fully understood, yet one of the most compelling explanations is the Radical-Pair Mechanism. Birds possess a protein inside their eyes called cryptochrome. When exposed to blue light, cryptochrome becomes excited and triggers an electron transfer, creating a radical pair—two molecules with unpaired electron spins. These electrons can exist in either a singlet state or a triplet state. The radical pair continuously oscillates between these two states, and the rate of interconversion is influenced by the Earth’s magnetic field. This magnetic field changes the balance between the singlet and triplet states, affecting the overall lifetime of radical pair and the resulting Chemical products. The bird’s brain interprets this altered Chemical yield as a signal about the direction of magnetic field, allowing it to navigate. Beyond the well-known cases of photosynthesis, DNA, and magnetoreception, other biological systems also appear to involve quantum effects. These include enzyme catalysis, vision (retinal isomerization), and mitochondrial energy transfer. However, there is still ongoing debate within the scientific community regarding which of these effects are truly quantum in nature and which can be explained through classical mechanisms. Although the roots of Quantum Biology can be traced back a century, it has only been actively researched as a scientific field for the past two decades. We are still in the very early stages of understanding what is happening. We are discovering things, focusing on hints, and are still trying to understand and interpret what is actually happening.

Complexity in Biology: Where Quantum and Classical Worlds Intertwine How Thermodynamics Appeals at the Nanoscale in Biological Systems Biology, at its core, is an energy game – cells survive by capturing, storing, and redistributing tiny amounts of energy with incredible efficiency. Classical thermodynamics explains this well at large scales, but at the molecular level, life operates in a domain where quantum effects can matter. This is where quantum thermodynamics comes in: it combines the laws of thermodynamics with quantum mechanics to study how energy, entropy, and information behave at the quantum scale. Physicists are rebuilding thermodynamics through the lens of quantum mechanics, leading to the powerful idea that energy and information are two sides of the same coin. Currently, we are still at the beginning phase, with much more to uncover. Quantum thermodynamics is not claiming that “biology is already explained”; rather, it provides the mathematical and conceptual tools to ask: How do fragile quantum states survive in warm, wet, noisy environments like cells? What are the thermodynamic costs of maintaining these states? How do energy flow and information processing merge to keep biological systems stable and efficient? So, rather than being purely speculative, quantum thermodynamics is slowly building a framework to test and measure these effects, offering us a path to explain how nature may have learned to harness quantum mechanics for life. Experiments have already been performed that validate the principles of quantum thermodynamics in artificial quantum systems and in model biological systems, such as photosynthetic complexes. One of the best-studied biological systems for exploring quantum thermodynamics is photosynthesis in green sulfur bacteria. In these organisms, a light-harvesting structure called the Fenna-Matthews-Olson (FMO) complex captures sunlight and transfers the energy to where it is needed. Using ultrafast laser pulses, scientists tracked how this energy moves between molecules. Instead of hopping randomly, as classical thermodynamics would predict, the energy showed signs of quantum coherence—moving like a wave and exploring multiple

pathways at once. This wave-like behaviour makes the process remarkably efficient, even in the warm and noisy environment of a living cell. Such experiments suggest that quantum thermodynamics may provide the right framework to understand how living systems manage energy at the molecular scale. However, fully applying quantum thermodynamics inside living cells remains a significant challenge. We are still at the stage of proof-of-principle experiments rather than complete explanations.

Decoherence: Don't fight it, use it! Decoherence is the process by which a quantum system loses its unique quantum properties, such as superposition and entanglement, due to interactions with its environment. This leads to the leakage of information into the surroundings and implies a shift from quantumness to classicalness. Here the question arises: How does the system tackle this? Biological systems manage decoherence not by preventing it but by leveraging it to their advantage in processes like photosynthesis and ion transport. Rather than being a flaw, decoherence enables faster and more efficient quantum coherence and functionality. Let's again take photosynthesis as an example to see how decoherence occurs: In a plant leaf, light energy must travel from where it is absorbed to the reaction center where food production begins. Instead of the energy randomly hopping from one molecule to the next (which would be inefficient and cause significant energy loss as heat), it uses quantum coherence. This works like a particle moving across two parallel bridges, simultaneously exploring all possible paths to the reaction center. The plant's structure is finely tuned to maintain coherence for just a fraction of a second. The moment the energy reaches the target, the system deliberately uses a small amount of environmental interaction (decoherence) to force the energy to land at the destination. In this way, decoherence acts like a brake, ensuring that the energy does not overshoot its target. Is decoherence the reason for classicality? Everything we know so far suggests that the universe is fundamentally quantum, though science never proves things with absolute certainty the way mathematics does. What we can say is that quantum theory has passed every test with astonishing accuracy. One of the main reasons the world appears classical to us is decoherence. In the microscopic world, particles such as electrons can show interference behaving like waves that traverse two paths at once. But in the macroscopic world, objects constantly interact with their surroundings – air molecules, light, vibrations. These interactions scramble delicate quantum effects almost instantly. As a result, larger objects, such as dust particles or everyday items around us, no longer display interference. Decoherence thus explains why we don't observe tables, chairs, or cats existing in strange quantum superpositions. The quantum rules still operate underneath, but they remain hidden because large objects lose their quantum coherence far too quickly. Although decoherence is the fundamental reason behind the classical appearance of the world, it still does not explain why one particular outcome is realized from the many possible outcomes. Decoherence accounts for why quantum superpositions lose their interference and appear as classical mixtures, but the mystery of why we observe a specific result rather than all possibilities or none remains unresolved.

Emergence and Collective Behaviour It is fascinating to consider how classical and quantum interactions at small scales can give rise to complex biological phenomena at higher levels. Life itself is often described as an emergent property of chemistry, while consciousness has been proposed as an emergent property of neural networks. Yet, consciousness remains a deeply subjective experience that is difficult to explain using only classical physics and neuroscience. Some researchers suggest that the brain may exploit quantum effects, since its processes operate in a massively parallel and highly interconnected manner. Features such as superposition, entanglement, and non-locality appear more “quantum-compatible” than purely classical. Still, such ideas remain speculative, with no conclusive evidence so far.

Managing Entropy: How Life Creates Order In living systems, entropy is a measure of disorder or uncertainty. While the natural tendency of the universe is toward chaos, life manages to maintain internal order by constantly taking in energy and releasing waste or heat. For example, our cells use energy from food to carry out essential processes such as metabolism, protein folding, and molecular transport – all while keeping the overall system organised. Entropy is also linked to information: DNA, RNA, and proteins store and process instructions that guide life's functions. By carefully balancing energy use, information management, and heat release, living systems transform potential chaos into structured, complex, and organised behaviour. Living systems are often considered the most complex form of matter, because they are able to maintain order while existing in a constant state of flux. This very complexity becomes a hurdle in fully understanding how such systems work. Life, as we observe it, operates quantum mechanically at the microscopic scale but appears classical at the macroscopic scale. This dual nature may enhance its efficiency and productivity, yet it also leaves us with deeper mysteries to unravel. Quantum effects in living matter have always been present, since quantum mechanics underlies the behaviour of all matter, living or non-living. What seems like an “update” is not

that matter acquired new quantum properties, but rather that evolution found ways to harness and amplify these effects for biological advantage. Complexity in biology primarily arises from classical processes: chemistry, self-organisation, feedback loops, evolution, and information storage in DNA. These mechanisms alone can generate staggering complexity without directly invoking quantum phenomena. Quantum effects, where demonstrated (such as in photosynthesis, avian navigation, or enzyme reactions), seem to provide efficiency advantages – faster energy transfer, more sensitive detection, or better tunnelling through energy barriers. Thus, while quantum mechanics is foundational (all matter is quantum), the emergence of biological complexity is largely the result of evolutionary and classical mechanisms. Quantum features may act as hidden helpers, optimising certain processes rather than driving complexity outright.

Exploring Entropy, Complexity, and Quantum Dynamics in Biological Systems In living systems, complexity, quantum dynamics, and entropy are closely interconnected. Complexity arises when many components interact to produce organised behaviour. Quantum effects, such as superposition and entanglement, can make the transfer of energy and information more efficient at the microscopic level. Entropy measures disorder, and living organisms keep it in check by exchanging energy and matter with their surroundings. Together, these factors shape how life maintains order and performs intricate functions: quantum dynamics enhance efficiency, entropy sets fundamental limits, and complexity emerges from the interplay of many parts. Scientists can measure different aspects of living systems to better understand how life works. Quantum features like superposition and entanglement can be studied by observing how molecules share energy or information in non-classical ways. Complexity is measured by examining how many parts of a system interact such as networks of proteins or neurones and how organised or interconnected these interactions are. Entropy, representing disorder or uncertainty, can be assessed by tracking energy flow, heat release, or the information stored in DNA and proteins. Together, these measurements reveal how living systems maintain order, process information, and use energy efficiently, even amidst constant change.

From Essence to Reality The practical applications of quantum physics are expanding rapidly. Beyond computing, quantum technologies are providing powerful new tools for biology. These tools enable researchers to quantify fundamental properties such as entropy, complexity, and quantum dynamics in living systems, offering a deeper understanding of life at its most basic level.

Tools for Quantification

- Multi-scale Entropy (MSE):** A key methodology that analyses biological signals across different time scales. Unlike traditional entropy measures, which can give misleading results, MSE accounts for the fact that biological systems operate at multiple spatial and temporal scales. It is widely used to analyse signals such as heart rate variability and electroencephalograms (EEGs), consistently revealing a loss of complexity in aging and disease.
- Transfer Entropy (TE):** Based on information theory, TE quantifies the directed flow of information between different parts of a system. It is especially valuable in neuroscience, where it helps researchers understand how distinct brain regions influence one another.
- Complexity Spaces:** An emerging approach that visualises and quantifies complexity across multiple dimensions. It is used in evolutionary studies to measure morphological complexity in organisms, based on factors such as the number of parts and their degree of differentiation.
- Quantum Metrology:** A field that exploits quantum properties to achieve unprecedented precision in measurements. For example, quantum sensors can detect extremely weak magnetic fields, which may play a role in biological phenomena such as avian navigation.
- Advanced Spectroscopic Techniques:** New methods such as entangled twophoton absorption (ETPA) spectroscopy are being used to probe the electronic states of biological molecules. These approaches allow researchers to study energy transfer with greater resolution and sensitivity than classical methods.
- Computational Modelling and Simulation:** Advances in computational chemistry and open quantum systems theory enable simulations of complex biological interactions at the quantum level. These models help explain how quantum effects such as electron tunnelling and proton tunnelling contribute to processes like enzyme catalysis and DNA mutation.

Is Life Inseparable from Quantum Mechanics? We don't yet have a complete answer. What we do know is that quantum effects clearly play a role in some biological processes—such as photosynthesis, enzyme activity, bird navigation, and possibly even in the brain. But how widely and fundamentally they impact life as a whole remains uncertain. Research is ongoing, and while evidence suggests that quantum mechanics is important in certain functions, we have not yet reached a final conclusion about whether life itself depends on it. Science always allows room for refinement. It is the one discipline with which I most deeply resonate, for it mirrors the human journey itself oscillating from hope to despair and back to hope again, a cycle that is at once exhausting and yet profoundly reassuring. This very rhythm gives me the courage to persist, to attempt an experiment even when failure seems inevitable. The paradox is striking: experiments exist to be tested, and often to fail, yet it is through such failures that progress

emerges. Science has taught me that the outcome is not always the ultimate goal; rather, the pursuit itself can be beautiful. And when we reflect on where we stand today tracing the path from Newton's falling apple to Schrodinger's enigmatic cat—we recognise that the journey of science has been shaped as much by failures as by triumphs. If we continue to push forward with research despite the hurdles we face, whether in terms of finances, the absence of a unified theory, or even reluctance to move ahead the field remains truly promising. How magical it feels to imagine that one day we may come to know what consciousness really is, how living systems function the way they do, why efficiency seems to be their guiding principle, and ultimately, what life itself truly is. Quantum mechanics and life appear to share a complex relationship. We may not yet have a definitive answer about how they interact, but the hints are growing. One example is quantum computing and quantum sensors. These technologies, governed by the principles of quantum mechanics, are advancing rapidly and reshaping our world. What was once thought impossible is now a reality. This leads to an intriguing question: What will happen when quantum principles are fully integrated into life itself?