

Let's start with the simple question: "What is life?". The question is so old, and so persistent, that to even repeat it feels almost embarrassing, as if one were asking again whether fire is hot. Yet embarrassment has never stopped scientists from asking questions. J. B. S. Haldane, in 1947, gave up on any clean answer and confessed: "No one agrees, and I'm not going to try." Schrodinger, two years earlier, wrote an entire book on the subject, not because he knew the answer but because he wanted to test whether the new physics of his time, quantum mechanics, could be relevant for the old mystery of biology. Decades later, Nobel laureate Paul Nurse insisted that life begins with the cell, with its incessant chemical bustle and its ability to reproduce, store information, and evolve. But even Nurse, who has spent a lifetime dissecting cells, ends up circling back to the same unresolved puzzle: how do we move from chemistry to biology? What turns matter into life?

For much of the twentieth century, the answer appeared obvious: the key was DNA, the double helix. In a way, it was too good a metaphor to resist. Here was a molecule that looked like a code, that behaved like a code, that could be sequenced like a book. The genome project promised to deliver nothing less than the "book of life." But here lies a paradox. A book is only a book when someone reads it; otherwise it is just ink on paper. A musical score is only music when an orchestra plays it. The genome is no different. As a molecule, DNA is chemically boring: a long polymer of four bases (A, C, G, T). Left alone in a glass of water, DNA does nothing. Life emerges only when the genome is embedded in a system that can read it, regulate it, translate it, splice it, edit it, and even ignore it. A genome is necessary for life, but it is not life. Life, if anything, is the performance of the genome, not the score itself.

And so the riddle deepens. If the genome is not enough, then where does life come from? The biologist Jacques Monod once remarked that what distinguishes biology is not the molecules it studies—they are the same carbon, hydrogen, oxygen, and nitrogen as in any chemical lab—but the way those molecules are arranged, the way they carry information. Information is perhaps the most underrated concept in biology. When a gene is turned on, the cell is not just producing a chemical, it is making a measurement: is there too much of this protein already? If yes, switch off; if not, keep going. Feedback loops abound. Information is not just encoded in DNA but also in the concentration of metabolites, in the phosphorylation states of proteins, in the folding and unfolding of membranes. The genome itself is less like a library of fixed instructions and more like a jazz score, full of improvisation, full of parts that can be skipped, repeated, or remixed depending on context.

This idea of improvisation is crucial. If one opens a biology textbook, one sees tidy diagrams suggesting a flow of information from DNA to RNA to protein. This linearity is comforting, but it is misleading. In reality, proteins regulate DNA, RNAs fold into complex shapes and regulate proteins, metabolites modify both, and entire tissues feed back into the activity of single genes. Information flows in all directions. Biology is not a hierarchical bureaucracy with DNA at the top, issuing orders down the chain. It is more like a noisy marketplace where thousands of voices compete, interrupt, reinforce, and cancel one another. The cell is not a digital computer running a fixed program but a living improviser, always playing with noise, making decisions in uncertain environments. Even single cells display something like agency: they sense, they evaluate, they choose.

If this sounds abstract, consider development. From a single fertilized cell, the zygote, emerges an entire organism. All the genetic information required to build a human is, in principle, contained in that one cell. Yet that information is latent; it requires a choreography of spatial cues, morphogen gradients, timing, mechanical forces, and stochastic fluctuations to be expressed as form. For example, small changes in the timing or concentration of morphogens can alter limb patterning, producing different numbers of digits. Alan Turing's mathematical insight into reaction-diffusion systems shows how simple chemical interactions can self-organize into complex, reproducible patterns—stripes, spots, fingers—without a detailed instruction manual for every eventuality. This is causal emergence: higher-level patterns arise from lower-level interactions, and those patterns then constrain and guide the lower levels in turn.

The 2012 Nobel Prize in Physiology or Medicine rewarded a discovery that felt almost like a magic trick. Shinya Yamanaka showed that introducing just a handful of transcription factors, such as Oct4, Sox2, Klf4, and c-Myc, can reprogram an adult skin cell back into a pluripotent state, producing what are now called induced pluripotent stem cells (iPSCs). This is far more than a technical trick. It reveals that the genome

encodes immense potentialities, which are unlocked or silenced depending on regulatory context. From iPSCs, scientists can generate organoids: miniature, self-organizing tissues that recapitulate key features of organs such as the brain, heart, kidney, and even embryo-like structures known as embryoids. Brain organoids develop layered neural architecture and spontaneous electrical activity; cardiac organoids contract rhythmically; embryoid bodies recapitulate early embryogenesis. The orchestration of development, then, is as much about the dynamic interplay of regulatory networks and cellular interactions as it is about the linear sequence of bases in DNA.

This is why genes cannot be said to “make decisions.” A gene is a biochemical locus that responds to the cell’s milieu; it does not possess agency. Decision-making in organisms is emergent and distributed. At the level of the brain, decision-making acquires a qualitatively different flavor: the brain integrates sensory input, memory, and internal state to make context-sensitive choices. No genome could possibly encode the full repertoire of contingencies a nervous system must handle; instead, genomes build architectures capable of learning, improvising, and inventing new behavioral responses. In this sense the genome provides the scaffolding; development, experience, and neural computation provide the improvisation.

This “messiness” from biology has always irritated scientists, and so, historically, we tended to simplify. We studied the parts that our tools could measure and ignored the rest. X-ray crystallography gave us breathtaking images of proteins, but only the ordered ones that could form crystals. For decades, we believed most proteins were neat little machines with rigid shapes. Only later did we realize that nearly half of them are “disordered,” flopping around in flexible ways essential for regulation. The error was not in the biology but in our tools. We could not see disorder, so we assumed it did not exist. As the Nobel Prize-winning biologist Sydney Brenner once put it: “Progress in science depends on new techniques, new discoveries, and new ideas, probably in that order.”

In cancer research, the same blindness repeated. For years, researchers obsessed over sequencing tumors, convinced that hidden inside the genome lay the master “cancer genes.” As cancer biologist Michael Yaffe put it in 2013: “Like data junkies we continued to look to genome sequencing when the really clinically useful information lay someplace else.” Perhaps quantum biology, too, suffers the same fate. Maybe it has always been there, quietly shaping processes in living cells, but our instruments were tuned to the wrong frequencies.

What does it mean to say biology might be quantum? The safe answer, the answer every physicist gives, is that of course all matter is described by quantum mechanics. Without it, atoms would not exist, chemical bonds would not form, and molecules would not be stable. However, that is not the interesting part. The real question is whether life uses specifically quantum features, such as coherence, entanglement, tunneling, and spin, in ways that make a functional difference. Does biology exploit the quantum world in order to be more efficient, more adaptive?

Consider photosynthesis. Plants and bacteria capture sunlight and convert it into chemical energy with nearly perfect efficiency. For decades, we thought of this as a matter of classical energy transfer: photons excite electrons, electrons hop from pigment to pigment, eventually reaching the reaction center. But spectroscopic experiments over the last fifteen years suggest something stranger: the excitations spread through pigment molecules in a wavelike superposition, exploring multiple pathways at once, guided by long-lived quantum coherence. Even more surprising, the noisy environment of the cell does not destroy this coherence; it seems to sustain it, helping the excitation avoid traps and reach its target. This is counterintuitive. In quantum computers, noise is the enemy; in photosynthesis, noise is a collaborator.

Or take birds. Migratory species navigate across continents, sensing Earth’s magnetic field as reliably as a compass. Classical explanations failed. The most compelling theory today is the radical pair mechanism: light excites electrons in certain proteins, creating entangled pairs spin states whose reaction probabilities depend on the orientation of the magnetic field relative to the molecule. The orientation of the bird relative to the Earth subtly alters the chemical reactions, providing directional information to be interpreted by the nervous system. If this is true, it means that entanglement—one of the strangest quantum phenomena—persists long enough inside a bird’s eye to inform behavior across thousands of kilometers.

Examples accumulate. Weak magnetic fields, barely perceptible in classical terms, appear to influence

certain biochemical reactions. Life evolved under Earth’s magnetic presence; perhaps it learned to exploit it. Tissues emit ultraweak photons (also known as biophotons) that are orders of magnitude weaker than thermal emission expected from a blackbody at physiological temperature. Blackbody radiation is broad-spectrum thermal glow that depends only on temperature, following Planck’s law. Biophoton emission is different: its intensity is tiny, its spectrum can show discrete features, and its temporal patterns sometimes correlate with metabolic states, cell division, or stress. The source is often biochemical: reactive oxygen species, lipid peroxidation, and certain oxidative reactions can release photons. Some groups have reported that tissues “glow” differently during development or when under stress, and a controversial hypothesis suggests these emissions could serve as a form of intra- or intercellular signaling—an optical whisper too faint for our eyes but legible by sensitive detectors. If these emissions exhibit coherence or structured correlations, then they would demand a quantum-mechanical treatment rather than a simple thermal one. The idea that cells might use light—faint, structured, and perhaps quantum in character—as an additional layer of information is provocative, and remains to be rigorously tested.

Even more provocative is the phenomenon of chiral-induced spin selectivity (CISS). Electrons traveling through chiral molecules (which lack mirror symmetry), such as DNA seems to favor the transport of electrons with a particular spin orientation. This is not supposed to happen at room temperature, in wet biological environments, and yet it does. Charge transport in bacterial nanowires shows the same effect. Nature seems to be filtering spins as if it were running a primitive form of spintronics. Spin is a quantum degree of freedom; if biology routinely exploits spin preferences, then electron transport in metabolism or cellular respiration might carry not only charge but spin information, with potential functional consequences. Vibrational dynamics—phonons—also deserve attention. Molecular recognition is usually cast as a lock-and-key or induced-fit process, but there is growing appreciation that vibrational resonances affect binding kinetics and selectivity. Specific phonon modes can open or close reaction channels, tune transition-state energies, and mediate energy redistribution across complexes. If vibrational modes are coherent or display resonant coupling across macromolecular assemblies, then quantum vibrational effects could influence enzymatic catalysis, receptor activation, and even viral docking.

What unites these phenomena is not just chemistry and physics, but information. Cells are machines for managing uncertainty. They measure concentrations, adjust outputs, and maintain stability in a chaotic environment. In doing so, they embody the principles of information theory, a concept introduced by Claude Shannon but reinterpreted in biological terms. DNA makes sense only as a storage medium in a system that can copy, read, and transmit information across generations. Without that, it is nothing more than a polymer. But perhaps information theory itself is not enough. If life is exploiting coherence and entanglement, then we may need quantum information theory to describe it fully. A qubit, unlike a bit, can be both 0 and 1, entangled with others across space and time. If biology operates at this level, even partially, then the very language of life may be quantum.

There is a reciprocal possibility. We are used to thinking of physics as the foundation, biology as the application. But biology may teach us about physics. One of the deepest questions in science is the boundary between quantum and classical. Why do quantum effects dominate at the scale of electrons but vanish at our day-to-day life scales? If coherence and entanglement can persist in the warm, wet chaos of a cell, then perhaps the boundary is not where we thought. Life may be performing quantum experiments continuously, showing us how fragile states survive in environments where, by rights, they should collapse. Biology could become a laboratory not only for medicine but for quantum mechanics itself.

Evolution is the crucible in which these possibilities are forged. Natural selection has no foresight; it conserves what works. If a quantum trick offers an edge—slightly faster energy transfer, subtly better sensitivity to magnetic fields, a vibrational filter that improves specificity—selection can preserve and refine it. Over evolutionary timescales, what began as subtle physical biases can be amplified into macromolecular architectures that look, to our eyes, as if designed for quantum tasks. Life, by iterative tinkering, can arrive at functional solutions that exploit the quantum realm.

The problem is measurement. We do not yet have the tools to directly see these processes. Imagine trying to prove the existence of DNA before the invention of X-ray crystallography, or the existence of a cell before the invention of a microscope. Similarly, quantum biology awaits its instruments. But this is changing:

optical spin microscopes could combine magnetic resonance with optics, perturbing proteins with weak magnetic fields and watching their reactions in real time. Electrophysiology spin microscopes could test, for example, whether spin chemistry influences ion channels. Scanning tunneling microscopes enhanced with spin sensitivity could probe how electrons move through chiral biomolecules, revealing whether DNA is indeed filtering spins. These are not science fiction. Prototypes and early experiments already exist in labs. If successful, they would not only confirm quantum biology but also open new doors: medical therapies activated by weak magnetic fields, non-invasive control of neuronal activity, bio-inspired spintronics, and so on.

A striking development in this direction is the discovery that certain fluorescent proteins, such as enhanced yellow fluorescent protein (EYFP), can act as genetically encodable spin qubits. Originally evolved and engineered as optical tags for visualizing cells, these proteins unexpectedly harbor triplet states that can be coherently controlled and optically read out. In other words, biology has already provided us with a qubit, hidden inside one of our most common laboratory tools. This opens an entirely new path for quantum biology: instead of relying on artificial probes like diamond NV centers, we can now embed quantum sensors directly into the living system itself, targeted to whichever protein, organelle, or tissue we wish to study. With such tools, one could imagine monitoring spin-dependent reactions during development, mapping magnetic-field sensitivities in organoids, or even testing whether ultra-weak photon emissions from tissues correlate with coherent spin dynamics. The irony could not be richer: while we search for quantum effects in biology, it may turn out that biology has been quietly building the instruments for us all along.

If such experiments/tools confirm a functional role for quantum effects, the implications will be profound and twofold. Suppose we learn that weak magnetic fields can influence disease progression by altering spin-dependent chemistry. Then medicine might gain a new tool, one that works remotely, non-invasively, and personally, tuned to each patient's biology. Practically, they would suggest novel therapeutic modalities: weak, targeted magnetic fields that tune spin-dependent chemistry; non-genetic modulators of ion-channel function; bio-inspired spintronic devices that exploit molecular chirality. Conceptually, they would invert the classical hierarchy in science: biology would no longer be merely an application of physics but a source of experimental insight into quantum phenomena. The classical problem of decoherence—how and why quantum possibilities collapse into particular outcomes—has been studied predominantly in cold, isolated systems. If living systems routinely stabilize and exploit coherence in warm, wet, noisy milieus, then the dream of quantum technology—computers, sensors, communication—might advance by following biology's blueprint.

This realization forces us to reframe the central paradox. The genome is a score; the cell is the orchestra; development, reprogramming, and the brain are the rehearsal, the improvisation, and the conductor. Quantum phenomena, where they occur, are part of the instrumentation—sometimes subtle, sometimes decisive, and always integrated into the multilayered dynamics of living systems. Life does not need to be quantum everywhere to profit from quantum effects in crucial contexts. In the small number of places where coherence, spin, or tunneling materially alter a biochemical pathway, evolution will amplify and entrench those solutions.

We began with a question: how quantum is life? Perhaps the honest answer is: just enough. Not everything in biology is quantum. Most of it is chemistry, thermodynamics, evolution. But in key places—where efficiency matters, where sensitivity confers survival, where adaptability is priceless—life appears to dip into the quantum toolbox. And perhaps that is what makes it life. Not a rigid program, not a deterministic machine, but a system willing to exploit every available advantage, classical or quantum, to persist and flourish.

There is a final irony. Schrodinger asked “What is life?” partly in the hope that quantum mechanics might illuminate biology. Nearly a century on, we stand at the threshold of a reciprocal insight: biology may illuminate quantum mechanics. The living cell, imperfect and messy as it is, might be the best available technology for preserving and exploiting quantum features in hostile environments. Through blind trial and persistent selection, life has built architectures that stabilize, manipulate, and exploit quantum phenomena for function. Recognizing this does not poeticize biology; it reframes how we investigate it. If we are to understand life fully, and to build technologies that harness similar robustness, we must listen to the faint photons, track the whisper of spins, and read the vibrational signatures that living systems have been

using long before we knew how to look. If we want quantum technologies that work outside the pristine refrigerators of physics labs—sensors, networks, even computing elements that survive room temperature and messy surroundings—then evolution’s long experiment may be the blueprint we have been waiting for.