

From its earliest days, quantum theory has gazed toward life. Schrodinger, in quantum theory's first decades, was already asking biological questions. Now we can ask the mirror question: what about life? Was life using quantum theory from its birth?

This essay takes up two entwined tasks. First, it reconstructs the history of quantum biology as a field, with its names and dates. Second, it retells the history of the quantum of biology, asking not merely where quantum effects show up in living matter, but whether life's emergence and evolution have been shaped by "quantum tricks" (e.g. coherence, tunneling, entanglement) from the start. The aim in gathering these histories is to register a frontier: if evolution repeatedly found and stabilized quantum advantages in warm, wet cells, then we should be able to track a trail of hypotheses turning into measurements, and we should be able to design new tests that reveal how organisms delay decoherence, and when and how they exploit it. By registering this story, perhaps it will also inspire more people to enter this still niche and completely fascinating field.

This story begins in Copenhagen. In August 1932 Niels Bohr delivered "*Light and Life*", extending complementarity beyond physics and directly challenging biologists to confront quantum constraints on living processes; Max Delbruck later recalled that Bohr's lecture on August 15, 1932 catalyzed his own migration from physics to biology. Two years later the challenge took molecular form: in 1935 Delbruck, the geneticist Nikolai Timofeev-Ressovsky, and the radiation physicist Karl Zimmer published the "Three-Man Paper" (*Über die Natur der Genmutation und der Genstruktur*), arguing on physical grounds that genes are discrete molecular entities whose mutations could be probed by radiation, a manifesto for what they called "physical biology." These moments established a durable expectation: if heredity is both stable and digital, quantum principles must be somewhere in the basement.

Erwin Schrodinger supplied the era's most famous articulation. His Dublin lectures in February 1943, published as *What Is Life?* in 1944, pressed the discreteness of genetic information as a specifically quantum clue, a bridge between atomic stability and the macromolecular carriers of heredity. Historians and scientists alike have traced how the book inspired the cohort that uncovered DNA's structure; more to the point here, it seeded a question that would echo for decades: beyond the gene's quantum stability, could living systems use quantum dynamics functionally?

The earliest firm biological sightings of a quantum mechanism came from redox biochemistry. In 1966 Don DeVault and Britton Chance reported a temperature dependence in cytochrome kinetics that could not be reconciled with classical over-the-barrier pictures, and in 1967 *Nature* carried "Electron Tunnelling in Cytochromes," bringing tunneling from diodes into metabolism. The idea that electrons sometimes go through rather than over biochemical barriers migrated quickly to protons and C-H bonds; by the 1990s and early 2000s, extensive kinetic isotope studies, culminating in influential reviews by Judith Klinman and colleagues, made a compelling case that hydrogen tunneling contributes to enzyme catalysis, with protein motions gating the donor-acceptor distance for efficient barrier penetration. If enzymes are evolution's speed machines, then tunneling is not an exotic curiosity but a plausible optimization that natural selection could repeatedly rediscover.

Another line began with orientation rather than catalysis. In 1978 Klaus Schulten proposed that birds might sense the Earth's magnetic field via a light-activated radical-pair reaction whose spin dynamics are exquisitely sensitive to weak magnetic fields. The mechanism was sharpened in the late 1990s and early 2000s by Thorsten Ritz and collaborators, who modeled a photoreceptor-based compass and showed that oscillating radio-frequency fields disrupt migratory orientation, as expected for a spin-correlated radical pair. In the following decade, physical-chemistry analyses by C. T. Rodgers and Peter Hore clarified how hyperfine couplings and Zeeman interactions control the signal, while independent evidence converged on cryptochromes in the avian retina as leading candidates for the photoreceptor. Here again, the evolutionary logic is transparent: if spin chemistry can encode a compass with parts already present in the eye, selection has ample opportunity to refine it.

The sensory domain also hosted one of the field's most spirited controversies. Luca Turin revived and modernized the vibrational theory of olfaction in the 1990s, proposing that receptors might detect odorants via inelastic electron tunneling that samples molecular vibrational spectra. Rigorous psychophysical tests by Keller and Vosshall in 2004 failed key predictions, for example that deuterated acetophenone should

smell different from its undeuterated version, and later critiques cataloged further difficulties; defenders and new data have kept the debate alive, but the episode sharpened the standard by which “quantum” claims would be judged in biology. Speculation is not enough; the quantum mechanism must carry quantitative, discriminating predictions that survive contact with experiment.

If tunneling offered the first biochemical foothold and magnetoreception the first spin-chemical case, photosynthesis delivered the coherence surprise. In 2007 Gregory Engel in Graham Fleming’s lab used two-dimensional electronic spectroscopy to observe quantum beating among excitons in the Fenna-Matthews-Olson (FMO) complex at 77 K, direct evidence that electronic excitations explore multiple energy-transfer pathways in a wavelike superposition before settling on a productive route. Subsequent work extended and debated the physiological reach of such coherence, including studies at higher temperatures and in different antenna complexes. The theoretical pivot was equally striking: by 2008 Masoud Mohseni, Patrick Rebentrost, Seth Lloyd, and Alan Aspuru-Guzik formulated environment-assisted quantum transport (ENAQT), showing that moderate dephasing, usually the enemy, can suppress localization and increase transport efficiency in disordered networks like FMO. The cell, on this view, need not eliminate noise; it can shape it. Architecture and vibrational spectra can conspire to preserve just enough coherence for just long enough to matter.

By the early 2000s, quantum biology had become a community with an agenda. NASA Ames hosted a “Quantum Aspects of Life” workshop in October 2003, chaired by Paul Davies, and a year later a public debate in Gran Canaria under the title “Quantum Effects in Biology: Trivial or Not?” pitted enthusiasts against skeptics, with the proceedings and essays collected in the 2008 volume *Quantum Aspects of Life*. In retrospect, those events marked a disciplinary coming-of-age: claims about tunneling, coherence, and magnetoreception were no longer curiosities but programmatic, targets for spectroscopy, isotope substitution, mutagenesis, and spin-sensitive experiments.

What, then, of evolution? Two distinctive attempts to connect quantum dynamics to life’s search strategies illustrate both the promise and the limits of the idea. On the algorithmic side, Apoorva Patel argued that canonical molecular numbers, four bases and roughly twenty amino acids, could be understood as optima of Grover-style quantum search in molecular recognition, even speculating that enzymes might maintain coherence long enough to realize such queries. The thesis remains controversial, but it sharpened a testable intuition: where recognition bottlenecks dominate, selection might favor mechanisms that emulate quantum speed-ups. On the thermodynamic side, Jeremy England derived lower bounds on the heat dissipated by driven self-replicators, reframing growth and heredity as non-equilibrium processes that pay in entropy. Although England’s bound is classical, it invites a synthesis with quantum resource theories in those biological settings, especially light-driven ones, where coherence and vibronic coupling are integral to function. Evolution, in this picture, is less a metaphorical quantum computer than a patient engineer, stabilizing physical tricks whenever the fitness ledger balances in their favor.

The brain has long been the cautionary counterpoint. Roger Penrose’s 1989 and 1994 books, and the Penrose-Hameroff Orch-OR model in the mid-1990s, proposed microtubule-based quantum processing for consciousness, but Max Tegmark’s 1999-2000 calculations of decoherence times in neural tissue, around 10^{-13} to 10^{-20} seconds, many orders shorter than neural dynamics, argued that the relevant degrees of freedom are effectively classical on cognitive timescales. Whether one takes Tegmark’s parameters as definitive or merely a high bar to clear, the upshot for the field has been salutary: claims about quantum roles in biology must carry explicit timescales, couplings, and noise models sufficient to survive an accountant’s audit.

Across these episodes a pattern emerges. First, the quantum shows up where fast, selective, or ultra-weak processes are at a premium: tunneling in catalysis, spin correlations in magnetosensation, coherence in exciton transport. Second, organisms rarely need macroscopic superpositions; the relevant resources are local and short-lived but structured, protected by geometry, by protein scaffolds, or even by the right amount of noise. Third, the evidentiary bar has risen: it is not enough to gesture at mystery. One must show that a quantum mechanism changes an efficiency curve, a rate law, or a sensory threshold in ways a classical surrogate cannot.

This, finally, is what I mean by the quantum of biology: the minimal budget of quantum resources a living system must generate, protect, or exploit to gain a fitness advantage, within its native noise. That budget

can be measured. In pigment-protein complexes, mutating residues that set site-energy correlations should shorten coherence lifetimes and reduce transfer yields as ENAQT models predict. In cryptochrome-based magnetoreception, field-tuned pulse EPR on engineered radical pairs should map hyperfine couplings to orientation sensitivity and disrupt it with specific radio-frequency fields. In tunneling-dominated enzymes, heavy-atom or site-specific deuteration should move kinetic isotope effects along curves that only quantum models fit. None of these proposals require mystical extensions of physics; all of them extend the field's most successful habit, quantify first, philosophize later.

Seen from 1932, the trajectory would have pleased Bohr: complementarity did not dissolve biology into physics, it taught biologists where physics matters. Seen from 1944, it honors Schrodinger's wager that quantum rules matter for life, but in a way he could not have foreseen: not only in the stability of the gene, but in the choreography of electrons and spins under continual environmental agitation. And seen from evolution's long view, it suggests a simple, conservative maxim: wherever a quantum mechanism improves function under real cellular noise, and the architecture exists to stabilize it, life has had billions of years to find it. The task now is curatorial and experimental at once: to continue assembling the record of how speculation became measurement, and to register, with dates and numbers, the places where biology learned to speak quantum.

Here, I wanted to show why retelling and curating the record matters. Collecting names, dates, mechanisms, and tests is not antiquarianism; it is how a field teaches itself what to try next. But I also want to turn back to the present and the near future. Quantum biology still lives in a niche that should be widened. So share it. Join seminars and conferences. Read books and papers. Teach and debate it in your labs and classrooms. Perhaps the next Delbruck will catch a spark in one of your talks. As a brief anecdote, the recent School of Quantum Biology in Paraty, Brazil, gathered an unusually interdisciplinary crowd, and the intensity of the exchange was the point: new ideas travel fastest when people from different languages of science sit at the same table.

Competitions like this one, hosted by FQxI and the Paradox Science Institute, are not only calls for essays; they are instruments for shaping the next decade of work. By recording what has been tried, by proposing clear measurements for what comes next, and by inviting new voices into the conversation, they help convert curiosity into protocols and protocols into results. That is a future worth writing toward: a community that remembers its history, sets falsifiable goals, and grows wide enough that the next great idea can come from anywhere.