

It should be clear that addressing *how quantum is life* presupposes an answer to the equally fraught question, “What is life?”, which many thinkers over the last several millennia have spent time reflecting upon, leading inexorably to Erwin Schrodinger’s essential focus of his Trinity College lectures in Dublin in 1943. This deceptively simple three-word question elicits a slew of others: Where is the dividing line for living organisms, and by which definition should we make the cut? Because life as we know it cannot exist without a suitable host or environment, should objects with the potentiality for life (seeds, viruses, sclerotia, etc.) be considered living? Do more technical distinctions invoking organic chemistry and thermodynamics help matters at all? Can ancient descriptions of the origins of the heavens and the Earth shine light on any of these questions? How, if at all, do quanta from the physical fields shape the structures and functions of living organisms, and their sentient behaviors? While the task before us is great, these perennial questions will propel us from life’s origins in light, to the quantum union of light and biomatter in the evolving cosmos.

In the Beginning

Ancient scripture offers insights to address these questions. The first three verses of the Hebrew Bible reflect a meditation on the nature of Elohim: God is known as creator (*bara*), spirit (*ruach*), and spoken word (*amar*). The Mesopotamian poem is curiously bookended by peculiar forms of nothingness—not “without form, and void” as commonly translated in English for the second verse, but something distinct. In the Hebrew, this *tohu va-vohu* represents a chaotic yet generative sea of fundamental, infinitely rich physical order, which is transformed from the “watery deep” into the “waters” by the brooding, hovering spirit. Thus, in the Hebrew cosmology, the primordial substance of all creation is transformed from a hostile, dynamical vacuum and imbued with the capacity for life-giving order and structure (Greek: *logos*). Per Genesis 1:3, all this occurs in concert with the light that manifests from Elohim’s voice, *bereshit* (“in the beginning”).

In addition to the triplets of *bara* usage, there are other groupings of three: the first three *yom*—unspecified temporal epochs—of separating are mirrored by the second three *yom* of filling by Elohim. There are also phrases that occur in this opening text seven times, a number signifying completion and perfection of a cycle, or in multiples of seven: Most saliently, there are seven non-chronological *yom*; Genesis 1:1 in the Hebrew is composed of seven words, and Genesis 1:2 of 14; the phrase “and saw Elohim” appears seven times; and the word Elohim itself is mentioned 35 times, including the text’s culmination through Genesis 2:3.

Following the repetition of threes and sevens, there are Hebrew phrases that occur each 10 or more times in the poem (allowing for conjugative variation): “to make [*yield, bear, do*]”, “according to its kind”, “and said God”, and “let there be”. Based on this approximate decadal repetition in the Biblical opening, a scientific sketch of life’s defining characteristics is proposed: 1. The capacity to produce (“to make”) 2. Reproductive invariance (“according to its kind”) 3. Wholistic orderly structure and function (“and said God”) 4. Teleological purpose (“let there be”)

Like the organicists, who sought a middle way between mechanism and vitalism to navigate the blockade they believed was stagnating biology, such a definition of life offers new opportunities for understanding the living organism as a whole, and not merely as a reductionist sum of its parts [1].

From *What is Life?* to *Mind and Matter*

The founders of quantum mechanics thought these questions worthy ones to ask, and they reflected on these issues over and over again during their decades-long careers. A decade after Niels Bohr’s essay on “Light and Life”, Erwin Schrodinger delivered his famous lectures at Trinity College Dublin, and in book form *What is Life? The Physical Aspect of the Living Cell* (1944) set off a firestorm of interest in the scientific community, arguing from physical first principles how the fundamental information-carrying molecule of life would be an aperiodic crystal. Schrodinger’s reflections on the thermodynamic constraints governing the size and structure of the genetic molecule supported the search for this foundational cellular codex, a biological Rosetta Stone. Lo and behold, in 1954, Watson and Crick - with the indispensable support of X-ray crystallographic images and ideas from Maurice Wilkins and Rosalind Franklin - codiscovered that aperiodic crystal in the beautiful form of deoxyribonucleic acid (DNA), a doubly helical, winding staircase of informatic complexity encoding the entire web of life on Earth.

In Schrodinger's chapter on Order, Disorder and Entropy, he quoted Spinoza's *Ethics* (1677): "Neither can the body determine the mind to think, nor the mind determine the body to motion or rest or anything else." And yet, for a living organism to avoid decay and death, it must somehow activate its will to produce, eat, or otherwise sustain itself against the dangers of increasing entropy. Schrodinger framed the open living system expelling positive entropy to its environment as feeding on "negative entropy" - a curious, admittedly awkward turn of phrase that maintained the allure of something non-physical, like entelechy or the *elan vital*. But Schrodinger made his argument quantitative by rewriting Boltzmann's famous equation as $(\text{negative entropy}) = -(\text{entropy}) = k_B \log(1 / \text{microstates})$, where k_B is Boltzmann's constant. He acknowledged the doubt and opposition his remarks on negative entropy had elicited from physicist colleagues, which he knew preferred the more technical discussion of free energy. He went on to describe the astonishing gift given to an organism: drinking a concentrated "stream of order" from its suitable environment to escape the decay into atomic chaos.

Invoking the "all-penetrating mind" or superintelligence once conceived by Laplace, to which every causal connection lay immediately open without statistical limit, Schrodinger envisioned the chromosome fibers as a codescript that this superintelligence could read and foretell, from mere structure, whether a given set of genetic instructions would develop the cell into this or that creature. Schrodinger's aim in *What is Life?* was to describe the information encoded in biomolecular matter for life's successful function and reproduction. This approach sometimes contrasted with that of Max Planck, his predecessor in Berlin, another "quantum giant" synonymous with the fundamental constant $h = 4.136 \times 10^{-15}$ electron-volt (eV) per hertz describing a characteristic quantum scale. Again invoking the Laplacian superintelligence, Planck wrote in *The New Science* (1959) about the false dichotomy between strict determinism and freedom of the will:

- What then does it mean if we say that the human will is causally determined? It can only have one meaning, which is that every single act of the will, with all its motives, can be foreseen and predicted, naturally only by somebody who knows the human being in question, with all his spiritual and physical characteristics, and who sees directly and clearly through his conscious and subconscious life. But this would mean that such a person would be endowed with absolutely clear-seeing spiritual powers of vision; in other words, he would be endowed with divine vision.

For Planck, the "inadmissible logical disjunction" reflected observational perspective, between the view of a resource-limited human and that of a supreme superintelligence.

Schrodinger was not to be outdone. His follow-up to *What is Life?*, co-printed as *Mind and Matter* in 1967 (from his Turner Lectures delivered at Cambridge in 1956), also explored the physical basis of consciousness. He was conflicted about the removal of the subjective consciousness from the objective world-picture envisioned by Newtonian science, and in *Mind and Matter* he quoted and affirmed Carl G. Jung's view: "All science (*Wissenschaft*) however is a function of the soul, in which all knowledge is rooted. The soul is the greatest of all cosmic miracles..." Schrodinger was sympathetic, venturing to say that "a rapid withdrawal from the position held for over 2,000 years is dangerous." He acknowledged that the subjective's expulsion from science would signify at best a Pyrrhic victory [2].

A coherent theory of life would seek laws by which mind shapes matter, and matter shapes mind. A wealth of data has been collected on the former: how conscious states correlated to brain states and neural correlates influence a range of biomolecular, signaling, and regulatory markers. Far beyond where Schrodinger could have predicted at the time, we now know that even traumas and habits can be passed on to our children epigenetically, a vision reminiscent of old-school Lamarckism. Eugene Wigner's 1961 article "Remarks on the mind-body question" reinstated the role of the conscious mind in collapsing the quantum wavefunction, thereby shaping that observer's register or picture of the material object being measured. For matter shaping mind, however, Schrodinger found the localization of the conscious mind inside the body as only symbolic, a practical heuristic, remarking on the "supremely interesting bustle...of cells of very specialized build in an arrangement that is unsurveyably intricate but quite obviously serves a very far-reaching and highly consummate mutual communication and collaboration...[with] maybe other changes as yet undiscovered." As I will describe, new science about these unsurveyably intricate, quantum architectures of life suggests how they give rise to what we call the mind.

The Genesis of Quantum Biology

As the Second World War raged on, many were awakening to the impact that thermodynamics and quantum mechanics would have on almost all areas of science. In a duo of articles in *Science* and *Nature* in 1941, before Schrodinger's Trinity College Dublin lectures, the Hungarian biochemist Albert Szent-Gyorgyi may have bested the quantum physicist, pointing out "that the knowledge of common energy levels will start a new period in biochemistry, taking this science into the realm of quantum mechanics." Outdoing himself in the same year as Schrodinger's Turner lectures, Szent-Gyorgyi wrote, again in *Science*, "that biological phenomena, such as muscular contraction, cannot be described in terms of classical chemistry but belong to the domain of quantum mechanics, to 'quantum biology'."

In addition to the DNA double helix, the year 1954 brought other new discoveries into the purview of science's domain. The American physicist Robert Dicke became interested in collective light-matter interactions after studying the quantum mechanical Doppler effect. In 1954, Dicke calculated the effect that a collection of quantum emitters in a gas cloud, coherently excited with even a single photon, could have on its spontaneous emission rate. He called this enhancement superradiance, and the field of quantum optics was born. Ensuing efforts would lead to the theoretical inclusion of more field modes with increasingly complex forms of quantized matter. Experimentalists have since realized tests of these models in a variety of settings, giving birth to the field of "polaritonic chemistry," where quantized, hybrid states of light and matter can control the fate of chemical reactions.

The theoretical physicist Richard Feynman once described the almost magical way that trees grow literally "out of thin air", sequestering the bulk of their carbon in the form of glucose from atmospheric carbon dioxide during photosynthesis. When we burn the wood of a tree's trunk in the presence of oxygen, Feynman noted, we undo the photosynthetic process, liberating carbon back into the atmosphere and recapitulating the sun's initial energetic contribution in the form of fire, with the benefit of its light and heat in due proportion to the carbon dioxide released. A similar reversal occurs during aerobic respiration, when organisms break down nutrients like glucose (with oxygen as an electron acceptor) to produce ATP, carbon dioxide, and other byproducts.

With the advent of and widespread commercial access to photomultiplier tubes for single-photon detection, many groups of scientists began to explore light emissions from living organisms in these metabolic furnaces, the "light of life" that Bohr had not envisioned. In a series of experiments in the late 1980s and early 1990s, Terence Quickenden and coworkers used photomultiplier tubes to detect just tens of photons per second per square centimeter of liquid culture surface from yeast species, across the ultraviolet and visible bands. They noticed a marked increase in these ultraweak metabolic photon emissions (MPEs) in the ultraviolet range during the exponential growth phase of the cellular cycle, where dividing cells are actively undergoing mitosis. Anaerobic respiration halted all luminescent signatures from the growing yeast cells. Taken together with findings in the last two years confirming similar emissions in plant roots and human mitochondria, these results suggest that eukaryotic aerobic metabolism - the chemical inverse of photosynthetic carbon fixation - is a rich source of ultraweak MPEs from electronically excited free radicals generated in the digestion and breakdown of food.

The Language of Life's Order

The alphabet of amino acids that comprise the language of life did not emerge overnight. This carbon-based dialect is life's own manifestation of the *logos*, the whispers of God, whose atomic letters were originally formed in stellar nucleosynthesis. At the cosmological Hubble scale, this stardust exhibits faint matter tracks from these whispers, the large-scale structure emanating from the low-entropy state of the big bang.

Recent astrophysical observations have amplified discussion of these cosmic origins. In the interstellar medium and in circumstellar clouds lie vast sheets of so-called astronomical polycyclic aromatic hydrocarbons (PAHs), which are essentially flakes and clusters of fused benzene and other aromatic rings. Large PAH aggregates are fragmented into smaller PAHs under exposure to ultraviolet photons, with further PAH degradation and cosmochemistry resulting in the formation of the amino acid tryptophan. There has been lively debate in the last two years over the claim that tryptophan has been spectrally identified in the

interstellar medium. Such a discovery would provide strong support for the exogenous origin of meteoritic amino acids and the seeding of prebiotic conditions for life on Earth.

Being the most strongly fluorescent amino acid, tryptophan can conveniently be described as a molecular quantum emitter, absorbing and emitting in the ultraviolet spectrum. Tryptophan’s absorbing $1L_b$ state relaxes to its emitting $1L_a$ state on the timescale of femtoseconds, while tryptophan fluorescence occurs on the nanosecond timescale. Thus, on its much longer fluorescence timescale, tryptophan can be treated effectively as a two-level system (a qubit).

Superradiant Life, with Single Photons

From Robert Dicke’s pioneering work, we know that coherently sharing even a single photon across a collection of quantum emitters increases the spontaneous emission rate from the single-emitter decay rate up to a factor proportional to the number of emitters. Single-photon superradiance is thus a distinctively quantum effect, capable of increasing both the coupling of such collectives of emitters to the electromagnetic field, and the computational capacity of matter organized in the unique symmetrical architectures of life. Intriguingly, theoretical physicist Philip Kurian and coworkers have predicted and experimentally confirmed that helical networks of tryptophan—ubiquitous in many naturally occurring protein fibers and filaments—demonstrate observed fluorescence quantum yield enhancements due to single-photon superradiance, even at thermal equilibrium in aqueous solution.

How can such protein architectures of molecular qubits exhibit resilience to thermal disorder in the presence of a decohering environment? The physics is remarkable, but well-known. Such helical networks of tryptophan in protein fibers and filaments, excited coherently by just a single photon, can generate superradiant collective states in the lowest-energy portion of their spectra, which weights these states more strongly in the thermal Gibbs ensemble, each proportionally to $\exp(-E_j/k_B T)$. Thus, clear signatures of superradiant enhancement for micron-scale protein fibers at room temperature have been observed in their thermal quantum yields of fluorescence, relative to the monomers in the same solution. And this quantum yield enhancement is not a result of reducing the nonradiative decay rate, which actually increases from bare tryptophan in solution to tryptophan in the solvated protein.

These results provide strong evidentiary support that certain molecular qubits in the protein architectures of carbon-based life—exploited collectively, in the presence of uncontrolled thermalized degrees of freedom—can be used for logical operations and information processing, above the thermal noise floor. Harkening back to the organicism of Jordan and Bohr, such collective quantum optical physics in the single-photon limit may be the mechanism by which an “irreversible act of amplification” brings fuzzy quantum reality into sharper focus, in a manner conspicuously different from inanimate matter.

Present even in aneural organisms, these protein fibers thus maintain the requisite organization, in principle, to support quantum information processing. The single-photon limit is a regime of physics consistent with the in vivo physiological environment of aerobic life producing ultraweak MPEs. Moreover, in the brain, large stabilized bundles of these cytoskeletal fibers form the signaling superhighways of neurons. As the brain consumes a significant fraction of the vertebrate energy budget, generation of MPEs becomes the driving light and powerhouse for a quantum fiber optic network, which will be shown to exceed by many orders of magnitude the greatest expectations of classical neuroscience and its estimates for biological computational capacity.

Computing at the Speed of Life, with Quantum Advantage

In 1998, Margolus and Levitin proved that physical systems have a minimum time required to evolve between two orthogonal states. Because many protein polymers comprise enormous networks of molecular qubits, they are therefore subject to similar quantum speed limits on their computational capacity. These protein polymers, which are ubiquitous across all eukaryotic and even some bacterial species, exhibit Dicke superradiance in the single-photon limit. Based on calculations of the state lifetimes and ultrafast transient absorption measurements on ensembles of single fibers, the upper bound for this type of superradiant computation in these protein fiber bundles is $\sim 10^{13}$ operations per second, more than a billion times faster than the computational capacity expected of a single Hodgkin-Huxley neuron ($\sim 10^3$ operations per second)

spiking according to conventional ionic action potentials. As these superradiant states are stimulated by ultraviolet photons (~ 4.4 eV) [3], the Margolus-Levitin bound gives $2/\hbar \sim 10^{15}$ operations per second, indicating that these protein fiber bundles are operating within two orders of magnitude of this limit. These information-processing enhancements can support error correction rates far beyond existing state-of-the-art qubit architectures [4], with reasonable energy throughputs for dissipation consistent with Landauer’s bound and reflecting Schrodinger’s “negative entropy” as expulsion of positive entropy from the living system to its environment in the form of heat. Intriguingly, in 1981, before Margolus and Levitin’s proof, Bekenstein established an upper bound of 10^{15} operations per second on the speed of an ideal digital computer.

Certainly, as textbooks explain, these architectonic tendencies arise in part from the atomistic structure of proteins that are insoluble in water yet possess special sidechains which have a high affinity for water. However, the interaction of life with a classical light field or its quanta is also essential to the generation of this long-range symmetry and order. It underscores how the architectures of life are inextricably tied to the quantum realm, from their “initial conditions” and polymeric structure to the exploitation of their quantum optical networks in the single-photon limit. There is, rather poignantly, a stream of order flowing from light into life, vastly enhancing the information-processing capacity of “pumped” active matter, far beyond the classical bit rates and logic of DNA or inanimate systems. This represents a photonic logic, the quantized field merging and unifying coherently with matter in superposed oneness, holding profound clues for the immaterial’s union with the flesh.

Novel Experimental Approaches

The confirmed observation of superradiance—a collective quantum optical effect—from solvated protein fibers in vitro at room temperature motivates the search for other systems exhibiting this phenomenon. Indeed, biology supports a vast suite of protein architectures containing networks of quantum emitters and boasting helical, spherical, chiral, palindromic, or other symmetry. In particular, other cytoskeletal filaments and pathological fibrils would be obvious choices to verify whether single-photon superradiance is observed from their tryptophan networks in the form of enhanced thermal quantum yields of fluorescence with increasing length. Such measurements should be made at 280 nm (tryptophan’s peak absorption, subtracting contributions from other aromatics and cysteine) and also at 295 nm (where no other amino acid but tryptophan absorbs), taking care to correct for Rayleigh scattering from the micron-scale filaments and fibrils so as not to overestimate their absorption factors. As the quantum yield (QY) of fluorescence is the ratio of the radiative decay rate and the sum of the radiative and non-radiative decay rates, clear QY measurements for each protein monomer in the same solution as the polymer should be performed, to confirm whether any observed QY enhancement is specifically due to the radiative enhancement from the superradiant architecture and not from mere reduction in non-radiative channels due to protein conformational changes. Furthermore, new protocols are being developed to control the polymerization length, rate, and bundling architecture for more precise observations of superradiant enhancements to the QY, with increasing numbers of quantum emitters and packing density on the scale of the excitation volume. Other bioarchitectures with visible light-absorbing chromophores including photosynthetic light-harvesting complexes may exhibit single-photon superradiance over much greater length scales.

Quantum Life: Anti-Materialist Key to Mind and Consciousness?

As the arguments and evidence presented above attest, biology—particularly the physiology of the brain—is fundamentally and non-trivially quantum. So what role does quantum physics play, if at all, in understanding consciousness? [5] Certainly the quantum information processing modalities instantiated in the “wetware” architectures of life are distinct from contemporary quantum computing implementations, which are stringently isolated from their environments to control decoherence, but such biomolecular qubit networks—engineered to generate robust signals in warm, wet, and wiggly contexts, above thermal noise—reveal new horizons for the computational capacities of living systems. Problem-solving abilities of even single-celled organisms can point to shadows of a primitive mind, interconnected and whole, computing as part of a grand, cosmic simulation—the mysterious, vastly unknown, open universe.

Can the enhanced rate of carbon-based life’s quantum information-processing possibly be the same as consciousness? Absolutely not. Learning from Schrodinger, we should take care not to flatten consciousness

to mere information processing in the physical world. But in the wrestling with these questions, we have found a renewed appreciation for the journey of light in superradiant life: the imbuing of the personal in the cosmos, a revitalization of the subjective soul in science, and an awareness of our limits as physical agents, on the road from slime to sublime.