

Natural Philosophy of Photons: On the Nature of Electromagnetic Waves and Photonic Information

Xiaoming Li

Department of Geography and Planning, University of Toronto, Toronto, Canada

ABSTRACT

This paper reviews humanity's understanding of the photon, the evolution of quantum mechanics and quantum electrodynamics (QED), and analyzes their physical interpretations and philosophical implications. It seeks to elucidate the true nature of the photon by examining the possibility of hidden variables in the double-slit experiment. The wave-particle duality of the photon, as posited by quantum mechanics, appears to me to be less than entirely convincing. By designing a thought experiment involving a photon double-slit setup, I aim to refute the notion that photons generate Coherence, or so-called wave-function superposition, within the light field between the slits and the screen. This endeavour aims to demonstrate the pure particle nature of photons. Furthermore, by examining the wavelength of electromagnetic waves, this paper explores the intrinsic relationship between electromagnetic waves and photons, positing that electromagnetic waves are fundamentally pure particle-waves. Analysis of QED elucidates the potential influence of photon momentum on photon interactions, an effect that may profoundly impact quantum information transmission. To comprehensively describe the mathematical model of photon queues, this paper introduces the concept of a photon train. This metaphor likens photons travelling through space to a train in motion. The distance between carriages is denoted by (d), representing the wavelength of the photon. Within the "particle train" model of the photon queue, the wavelength λ is defined as the distance d between adjacent photons. This yields a structural

equivalence between wavelength λ and photon spacing $d: \lambda = d; d = \lambda = \frac{c}{f}$. The longer the wavelength (smaller f), the greater the distance d between

photons (corresponding to radio waves, where photons are "sparsely" dispersed). The shorter the wavelength (larger f), the closer the distance d between photons (corresponding to X-rays or γ -rays, where photons are "focused"). f represents the frequency of light. In standard physics, frequency is typically defined as the number of oscillations of an electromagnetic field per unit time, expressed by the relationship: $E=hf$. This is directly linked to the energy of a photon. However, although mathematically and experimentally complete, this definition obscures the intuitive informational structure of frequency. In this paper, we introduce a longitudinally structured interpretation: viewing frequency as the manifestation of "front-to-back density" or "longitudinal spacing" of light quanta along their propagation direction. This understanding does not replace the standard physical definition but operates in parallel to reveal frequency's deeper significance in energy transmission and information organization. For simplicity, we denote this approach as the "photon queue/longitudinal serialization (PQ/LS) model". PQ/LS denotes the theoretical framework of the photon queue model. A thought experiment on the conversion rate of quantum information into biological information reveals that, under identical light intensity (equivalent total energy input), the response of living systems is not solely determined by the I , but strongly depends on the spatial arrangement of the photon queue (where λ approximates the inter-photon distance). Bacterial-level matching of visible-light queues achieves the highest information-transmission efficiency (maximum mutual information and signal-to-noise ratio), thereby enabling dual optimization of energy utilization and rhythmic synchronization. This constitutes the core prediction of the model (PQ/LS): frequency (queue spacing), rather than total power (I) alone, determines the conversion efficiency of quantum information into biological information. The paper explores the non-wave-particle duality of photons through double-slit experiments and double-slit observer experiments. The essence of photons is purely particle-like. The thought experiment of the photon double-slit is pivotal in demonstrating that photons, like other particles such as electrons, atoms, and macromolecules, are purely particle-like. In space, photons can interfere with each other's paths based on their momentum. This can simultaneously alter the trajectory and even the velocity of photons. That is, a photon beam with higher momentum may carry a portion with lower momentum, allowing it to propagate over vast distances. The wavelength of a light wave is fundamentally the distance between consecutive photons as they propagate through space. The longer the wavelength of a light wave, the greater the distance between successive photons, causing them to diverge more widely in space, as observed with radio waves. Conversely, shorter wavelengths result in closer distances between photons, leading to denser emission and highly directional propagation, exemplified by gamma rays. Photons within the visible-light spectrum may occasionally transmit information that carries specific content. This information, conveyed through light quanta, can propagate over distances ranging from several metres to thousands of kilometres. The essence of light quanta: particle queues (PQ/LS) and the profound meaning of frequency: light is fundamentally a sequence of light quanta (photons) advancing in spatial order. Regardless of whether the propagation path is straight or curved, the propagation maintains this queued formation, akin to a continuous jet of water. Within this model (PQ/LS), the wavelength λ of light observed macroscopically fundamentally represents the average distance between successive light quanta. The frequency f (or ν) is inversely proportional to this distance: the closer two light quanta are, the higher the frequency f ; the greater the distance, the lower the frequency f . It can be expressed through the classical wave velocity formula: $c=f\lambda$. Within the visible spectrum, $\lambda \approx 0.5 \times 10^{-6}$ metres (500 nanometres). Remarkably, this distance corresponds precisely to the typical dimensions of bacteria (approximately 0.5–5 micrometres). The evolutionary tree of life takes bacteria as its root, while the wavelength of visible light—the fundamental scale for human vision and quantum information interaction—aligns exactly with this root-level dimension. As the product of billions of years of bacterial evolution, our human perception, communication, and even consciousness may possess an intrinsic connection to this "bacterial-scale" queue distance of light quanta. Philosophically, this unification reveals a grander picture: the frequency-distance relationship of the light quantum queue (PQ/LS) not only

As an information carrier, light transforms energy ($E = hf$) into biological signals, genetic expression, and even the emergence of consciousness—from photons stimulating retinal cells to potential quantum biological processes (such as quantum coherence in photosynthesis or brain microtubules), light weaves an information network between the microscopic and macroscopic realms. Bacterial circadian rhythms, particularly the KaiABC system in cyanobacteria, function as living fossils: they document how visible light quantum queues (PQ/LS) were transformed into ordered biological information programmes during life's earliest stages. This experimental finding not only validates the functional significance of scale consistency but illuminates the earliest step in the evolutionary path from light to meaning—within the unicellular world, light ceased to be mere energy, becoming instead the language of time and the rhythm of information. The relatively poor correlation between archaea and most bacteria in circadian rhythms and responses to visible light, from another perspective, suggests that archaea and bacteria did not originate on Earth but rather within protoplanetary discs or planetesimals. These archaea and bacteria can survive in the harshest natural environments, unaffected by Earth's 24-hour circadian rhythms or visible light. It further substantiates my published theory that life did not originate on Earth. From the bacterial scale to the scale of consciousness: information density remains operative. Within the Photon Quantum Queue Model (PQ/LS), the wavelength of visible light ($\sim 0.5 \mu\text{m}$ interphoton spacing) aligns remarkably with the bacterial scale, suggesting that the informational "foundation" of life's origin is set by the interphoton spacing. As we ascend from single-celled bacteria (scale $0.5\text{--}5 \mu\text{m}$) to multicellular organisms, nervous systems, and ultimately human consciousness (neural scale $\sim 10\text{--}100 \mu\text{m}$, brain as a whole $\sim 0.1 \text{m}$), a central question emerges: does this information density, originating from the photon quantum distance, continue to operate at higher scales, bridging microscopic origins with macroscopic awareness? From bacteria to conscious scales: Implications of information density for SETI and the search for extraterrestrial life. An intuitive interpretation of light's nature: Mainstream quantum electrodynamics (QED) views photons as quantum field excitations, where wavelength λ represents the phase oscillation scale associated with a single photon, not the physical distance between multiple photons. This theory deliberately adopts a semi-classical "particle queue" image, directly correlating λ with the average distance between adjacent photons. While not strictly valid in weak-light or single-photon experiments, the theory challenges the orthodoxy that "wavelength is solely a property of individual photons." The theory's stance can be summarized as one of maximizing continuity and wholeness within strict scientific boundaries. Our challenge lies in rejecting the compartmentalization of the quantum realm, the origins of life, the evolution of consciousness, and cosmic habitability into isolated modules, and instead insisting on information density as the unifying thread. QED posits that Coherence arises from the superposition of electromagnetic fields, not photon-photon interactions. However, this paper contends that QED's theory is flawed. We propose that interference stems from interactions between light quanta. Such interactions not only explain the outcomes of the double-slit and double-slit observer experiments but also reveal the intrinsic nature of light's quantum information transmission. Spatial interactions between photon beams: This paper posits that higher-momentum photon beams partially alter the spatial trajectories—and even the velocities—of lower-momentum beams. This constitutes one of the core tenets of this work. Specifically, when a high-momentum photon beam influences a low-momentum counterpart, some of the latter's photons exhibit a momentary "hesitation" before deciding whether to follow the high-momentum beam's path ($E = PC = hf$). Here, we assume the speed of light C and Planck's constant h are constants (though in reality, the speed of light C may not necessarily be a constant – an issue I shall address in future articles). Under these conditions, the energy of light is determined by its momentum and the frequency of the photon. The factor that plays the substantive role is, in fact, the frequency f . This conclusion appears to differ little in essence from QED. The higher the frequency f of a photon, the closer the spatial interval d between preceding and succeeding photons. High-energy photons, determined by their frequency f , possess greater momentum. When encountering lower-energy (E), lower-frequency (f), and thus lower-momentum (P) photons in space, they exert influence upon the trajectory of these lower-momentum photons. That is, high-energy photons exert a spatial influence on the trajectory of low-energy photons. (This includes, but is not limited to, causing some low-energy photons to follow the path of high-energy photons, thereby altering their motion trajectories.) The above conclusion differs fundamentally from QED theory. The Photon Queue Model (PQ/LS) integrates photons with information and life information. Here, we must further substantiate the validity of this theory (PQ/LS) and highlight the deficiencies of QED, thereby laying the groundwork for the subsequent chapter on photon information transmission. The issue highlighted by PQ/LS is not computational error within QED, but rather that QED has, from its inception, abandoned consideration of the "longitudinal structural problem of light propagation". We can state unequivocally: QED lacks a "longitudinal information structure of light"; frequency = the energy label of a single photon; it does not address "the arrangement of photons along the propagation direction"; nor does it discuss "the temporal density between preceding and succeeding photons". The QED photon is composed of discrete events, probability amplitudes, and statistical aggregates. It is not: an object possessing an intrinsic sequential structure along its propagation direction. The core innovation of the "Photonic Quantum Queue Model" (PQ/LS) lies not in metaphor, but in structure. The key proposition of PQ/LS is not that "photons are small spheres", but that light possesses a "longitudinal sequential structure" along its propagation direction. Light is not a "simultaneously existing cluster of photons", but rather a sequence of light quanta continuously generated/manifested along the propagation direction. This directly introduces a quantity not previously introduced in QED: d "photon" (longitudinal emergence spacing, structural density). Why do photons necessarily interact in the PQ/LS model? Within the PQ/LS framework, this is not an "additional assumption" but an inevitable inference. The pivotal logical chain is that light quanta are not isolated; they form sequences along the propagation direction. These sequences exhibit density variations (frequency differences). When sequences of differing densities encounter each other spatially, higher-density sequences yield greater structural stability, while lower-density sequences yield lesser stability. Consequently, high-frequency (high-momentum) light quantum queues will bias the paths of low-frequency (low-momentum) light quantum queues.

Why does the PQ/LS model provide a natural explanation for the double-slit experiment and its observer problem? Within the PQ/LS framework, the double-slit does not arise from photons coherence with themselves (as in QED). Instead, it stems from the formation of stable/unstable longitudinal alignment regions of photon queues within space. When introducing "path information", the measuring apparatus does not act as an abstract projection. Rather, it introduces new photon sequences or structural perturbations that disrupt the original longitudinal order. The disappearance of Coherence equates to the disruption of structural order, not a "conscious collapse". Why is the PQ/LS model more viable for "photon information transmission"? In QED, the concept of information is quantified by statistical correlations in measurement outcomes. In the PQ/LS model, information equates to the structural state of photon sequences. It yields three decisive advantages: information is "physically" present in longitudinal spacing; it resides in sequence stability; it exists within path bias. Information can be "transmitted"; high-frequency beams alter the path probability of low-frequency beams; direct absorption/scattering is unnecessary; it permits "non-destructive information influence"; information possesses directionality and hierarchy; higher momentum influences lower momentum; high structural density dominates low-density structures. QED stands as an extraordinarily successful 'lateral statistical theory', yet it never established the 'longitudinal structural physics of light propagation'. The Photon-Queue/Longitudinal

Serialization (PQ/LS) model, however, unifies ‘frequency-momentum-information-path bias’ within a longitudinal causal framework for the first time. This constitutes not a ‘patch’ to QED, but rather the completion of a layer of structural reality deliberately avoided beneath QED. The Photon-Queue Model (PQ/LS) constitutes a distinct family of thought experiments clearly distinguishable from QED. These experiments require: a clear experimental structure; quantifiable, testable predictions of differences; estimable scales for effect magnitude; and a focus not on the long-standing issue of “light-light scattering” but on the longitudinal structure-path bias effect proposed within PQ/LS. The Photon-Queue Model (PQ/LS) demonstrates that light’s information resides not only in transverse field states but also in longitudinal structures along its propagation direction – namely, the photon queue as an information structure. The physical definition of information, as established in this chapter, is structural differences that can be preserved, transferred, and that influence dynamical outcomes during propagation. Within the Photon-Queue Model (PQ/LS), this structural difference manifests as longitudinal spacing distribution, serialization stability, and structural density gradient. Consequently, information is independent of observation or encoding schemes. The true mathematical formulation of the Photon-Queue/Longitudinal Serialization (PQ/LS) model has three objectives: to provide clear dynamical variables (not metaphors); to formulate the minimal expression for the “photon-photon interaction term” (which does not exist in QED); and to derive directly from the equations an observable: the angular shift $\Delta\theta$. QED is not “disproved” by experiments or computations, but is constrained by its own modelling premises within a theoretical space that excludes variables from the PQ/LS model. Thus, QED’s “silence” regarding the Photon Queue Model (PQ/LS) constitutes not negation but inexpressibility. The Photon Queue Model (PQ/LS) introduces a degree of freedom explicitly absent in standard quantum electrodynamics (QED): the longitudinal structural freedom (LSDF) of light along its propagation direction. Its degree of freedom is characterized by the spatiotemporal spacing of photon events along the propagation direction and their statistical distribution. Discussion of the Physical Origin of the Photon Queue Longitudinal Structural Freedom (LSDF) Within this theoretical framework, the core feature of the photon queue is its longitudinal structural freedom (LSDF) along the propagation direction—namely, the ordered sequential arrangement defined by the queue density $\rho=f/c$ and phase ϕ . This longitudinal structural degree of freedom (LSDF) is not a mere appendage of classical electromagnetic waves, but rather one of the most fundamental degrees of freedom inherent in the quantum nature of light. This chapter rigorously explores the physical origins of this degree of freedom, revealing its inevitability and uniqueness from multiple perspectives encompassing quantum field theory, relativity, and information physics. The longitudinal structural degree of freedom (LSDF) of the light quantum queue originates from: the relativistic light cone constraint arising from the masslessness of photons; the regular structure of gauge field quantization in travelling wave modes; and the physical necessity of stable transmission of quantum information in vacuum. It is not an accessory property of light, but the most direct manifestation of light’s quantum nature along the propagation direction. High frequencies correspond to high-density queues, signifying not merely high energy but also denser information structures. Within the vacuum, the longitudinal structure of the photonic quantum queue is the sole degree of freedom capable of maintaining absolute stability over infinite distances. Lateral modes disperse due to diffraction, whereas polarization can be decohered by the environment; the longitudinal queue density and phase are strictly conserved in non-absorbing media. Therefore, from the perspective of optimal information transmission, the longitudinal structural degrees of freedom (LSDF) of photonic quantum queues must be elevated to the primary information carrier—this constitutes the fundamental physical basis for light’s role as the most efficient information transmission medium in the cosmos. Physical Significance of Longitudinal Structure—A Theoretical Self-Consistency Analysis Based on the Photonic Quantum Queue Model (PQ/LS). Should the longitudinal structure of light carry no independent physical information, any discussion concerning structural entropy, structural entanglement, or structural information transfer would be fundamentally undefined. Yet within the Photonic Quantum Queue model (PQ/LS), these quantities are not only definable but constitute a closed, self-consistent system of information dynamics. Longitudinal structure provides a class of physical information channels in quantum optics theory that are independent of field amplitudes. The existence of this structure is not a product of mathematical formalism but a substantive feature with profound physical significance. Quantum entanglement has long been regarded as one of the most counterintuitive phenomena in quantum mechanics. Traditional theoretical frameworks describe entangled states as non-separable quantum states of many-body systems, attributing correlations during measurement to so-called “superluminal effects”. However, this description harbours profound conceptual difficulties, implying that information is attached to individual particles and that measurement triggers instantaneous non-local effects. This paper proposes a novel theoretical perspective based on the photon-queue model, fundamentally reconstructing our understanding of the essence of entanglement. Traditional quantum mechanics views entanglement as a nonlocal correlation, emphasizing its “uselessness” for information transmission—namely, that entanglement itself cannot be used for superluminal communication. Yet this perspective overlooks another form of information: structural information. Quantum entanglement itself does not enable controllable information transmission; conversely, the photon-queue (longitudinal serialization), as a structural degree of freedom in propagation, can, in principle, be associated with specific information transmission. Quantum entanglement correlates “rules of association” (probability distributions), whereas the longitudinal structure of photon queues correlates “sequences of events” (causal/temporal patterns). The latter indeed provides a potential channel for transmitting specific information, such as causal relationships or sequential signals. This “train derailment” analogy can be systematically constructed into a theoretical model with testable physical implications. Core thesis: Quantum entanglement indicates that information is not attached to individual photons but resides within the correlated structure of the entire photonic queue. The photonic queue transcends the single-photon paradigm. The physical significance of queue structure: In standard quantum optics, light fields are typically described as superpositions of transverse modes. Yet light propagation inherently possesses longitudinal sequential characteristics: photons do not exist in isolation, but form queues in temporal sequences; the longitudinal structure of the queue carries structural degrees of freedom independent of field amplitudes; these structural degrees of freedom can encode information, thereby forming irreducible physical channels. The irreducibility of the longitudinal structure provides another class of physical information channels independent of field amplitudes. If the longitudinal structure were entirely devoid of physical significance, it would be impossible to define structural entropy during propagation; it would be impossible to discuss structural entanglement; it would be impossible to discuss structural information transfer. The information-theoretic interpretation of measurement, from entanglement to entropy increase, posits that measurement does not “trigger non-local interactions”. The standard interpretation holds that measuring one particle in an entangled pair “instantly” affects the state of the other particle. This description readily leads to misunderstandings about non-locality. The structural information perspective argues that measurement does not trigger non-local interactions; rather, it forces the information structure to be distributed between the local system and its environment, thereby irreversibly increasing entropy. Localized Entropy Increase Effect: In the photonic quantum queue framework, the total information of an entangled state resides in the queue’s correlated structure. Measurement disrupts this global structure, “compressing” information into localized degrees of freedom. Owing to the conservation of information, this process necessarily entails an increase in entropy within environmental degrees of freedom. The location of this entropy increase depends on the queue structure’s points of fragility, not

the measurement point itself. Much like a train derailing at its rear, localized entropy increase does not necessarily occur at the “measured” photon but at the point within the queue where structural interference is weakest or coupling to the environment is strongest. The minimal effective Hamiltonian represents a crucial step in transforming PQ/LS from “an intriguing concept” into “a rigorous scientific theory”. It provides a preliminary yet rigorous theoretical framework and experimental roadmap for exploring humanity’s most profound mysteries of connection—from telepathy to collective intelligence. It reveals that, if minds can indeed be perceived, it is not by magic but through novel physical interactions based on quantum structural resonance. The rules governing these interactions are encoded within this seemingly simple Hamiltonian.

*Corresponding author

Xiaoming Li, Department of Geography and Planning, University of Toronto, Toronto, Canada.

Received: January 08, 2026; **Accepted:** February 18, 2026; **Published:** February 27, 2026

Keywords: Double Slit Experiment, Double Slit Experiment with Observation, Hidden Variables, Photon, Electromagnetic Wave, Wavelength, Pure Particle Nature of Photons, Thought Experiment of the Double Slit Experiment, Relationship between Photon Spacing and Electromagnetic Wave Wavelength, Influence of Photon Momentum on Photon Beam Motion, Planck’s Constant, Blackbody Radiation, Visible Light Wavelength, Thought Experiment of I vs f , SETI, Bacterial length, Photon Queue/Longitudinal Structure Model (PQ/LS), Core Thought Experiment of PQ/LS, Physical Model of PQ/LS, Mathematical Model of PQ/LS, Longitudinal Structural Degree of Freedom(LSDF) of Photonic Queue, Quantum Information, Photonic Information Propagation, Minimal Effective Hamiltonian, Queue Density $\rho=f/c$, Equivalence of Wavelength λ and Photon Spacing d ,

$\lambda = d, d = \lambda = \frac{c}{f}$ Local entropy increase effect, comparison

between quantum electrodynamics (QED) and PQ/LS, longitudinal structure of photonic queues Local entropy increase effect, longitudinal structure of photonic queues

Introduction

What is light? This question was once regarded as the most fundamental conundrum in natural philosophy and became the starting point for the rise of modern physics. Newton established the first phase of optical research in the 17th century with his corpuscular theory, while Young’s double-slit experiment in the early 19th century fundamentally transformed the concept of light, making wave theory the prevailing view [1]. In the 1860s, Maxwell unified electric, magnetic, and light fields through his equations, introducing the novel physical entity of “fields.” At the dawn of the 20th century, Einstein’s photoelectric effect theory reinstated light’s particle nature, ultimately propelling the establishment of quantum mechanics. This paper systematically analyses these four phases, revealing how optical theory progressively evolved into modern quantum physics.

Newton’s Corpuscular Theory of Light: The Triumph of Mechanism

In *Opticks* (1704), Newton proposed that light consists of high-speed particles, explaining phenomena such as reflection and refraction through mechanical laws. His prism dispersion experiment demonstrated that white light comprises different colours and established that light of different colours possesses distinct refractive powers: (Newton, 1704). Scientifically, Newton was the first to establish an optical theory through controlled experiments and verifiable methods, embodying the “experimental determinism” of early modern science.

From a philosophical perspective, Newton’s theory exemplified classical mechanistic realism: the world comprised particles governed by mechanical laws. This paradigm profoundly shaped

subsequent developments in natural philosophy. However, Newton’s framework could not account for Coherence and diffraction, ultimately leaving a void that would be filled by the emergence of wave theory.

Young’s Wave Theory: The Coherence and Continuity of Light

In 1801, Thomas Young conducted the double-slit experiment, observing that light produced alternating bright and dark fringes [2]. This phenomenon perfectly matched wave superposition, thereby refuting the particle model of light. Young’s introduction of concepts such as phase and coherence for light marked the comprehensive establishment of wave theory [3]. Philosophically, his theory signified a shift in the conception of nature from “discrete entities” to “continuous processes.” This held profound significance not only for physics but also embodied the principle of scientific falsifiability: even Newton’s authority, revered as divine, could be overturned by experimentation.

Maxwell’s electromagnetic wave theory: The advent of the field-theoretical world. In 1864, Maxwell formulated a set of differential equations describing electric and magnetic fields, predicting that electromagnetic fields propagate at the speed c and demonstrating that light is fundamentally an electromagnetic wave [4]. This constituted the most significant theoretical unification in the history of optics, endowing the discipline with a clear mathematical structure. Maxwell’s greatest philosophical contribution lay in introducing the concept of field theory as a form of reality. Prior to this, nature was viewed as composed of “material particles,” whereas Maxwell posited that “fields” were as real as matter, and even more fundamental. This paradigm shift laid the intellectual foundations for both relativity and quantum field theory [5].

Einstein’s light quanta: the bridge to quantum mechanics. In 1905, Einstein employed Planck’s concept of energy quanta to explain the photoelectric effect, proposing that light energy exists in discrete photon form (Einstein, 1905). This hypothesis successfully accounted for the photoelectric effect’s frequency threshold independent of intensity, reviving light’s particle nature. Philosophically, Einstein’s photon hypothesis inaugurated the era of quantum discontinuity, overturning classical physics’ assumption of continuity [6]. Light ceased to be merely a wave or particle, becoming instead a quantum entity exhibiting wave-particle duality. Subsequently, de Broglie, Schrödinger, and Heisenberg extended quantum concepts to all matter, establishing the complete framework of quantum mechanics.

The evolution of optics and the formation of the quantum perspective unfolded through four pivotal stages: Newton, Young, Maxwell, and Einstein. Light’s nature was successively understood as particles, waves, electromagnetic fields, and quanta. This progression in optical theory exemplifies science’s philosophical leap from mechanistic to field-theoretic to quantum realist perspectives. Light not only revealed the structure of nature but also became the starting

point for the modern physics revolution. Ultimately, the study of light led science to a profound conclusion: the physical world is composed of quantum states, and wave-particle duality is not unique to light but a universal law of nature.

The development of quantum mechanics originated from inquiries into the nature of light and matter. Einstein (1905) proposed the photon hypothesis, successfully explaining the photoelectric effect and first revealing light's particle nature [6]. Shortly thereafter, de Broglie (1924) introduced the matter-wave hypothesis in his doctoral thesis, positing that all particles exhibit wave-like properties [7]. This perspective was rapidly validated experimentally: Davisson and Germer's (1927) electron diffraction experiment demonstrated for the first time that electrons could also exhibit wave-like characteristics [8]. Concurrently, Bohr (1928) proposed the principle of complementarity, asserting that the wave and particle pictures are complementary; only by combining both can quantum phenomena be fully understood [9].

By the mid-20th century, Feynman and colleagues emphasized the fundamental status of the double-slit experiment in quantum mechanics within their seminal textbook *Lectures on Physics*, stating that "almost all the mysteries of quantum mechanics are contained in the double-slit experiment" [10]. Subsequently, Wheeler (1978) proposed the renowned delayed-choice experiment, further highlighting the decisive role of measurement in quantum physics [11]. By the late 20th century, Zeilinger and colleagues advanced research into wave-particle duality through a series of experiments. These not only verified Coherence in photons and electrons but also extended to macromolecular systems, including C60 molecules [12]. These findings demonstrate that even macroscopic molecular systems adhere to quantum principles [13].

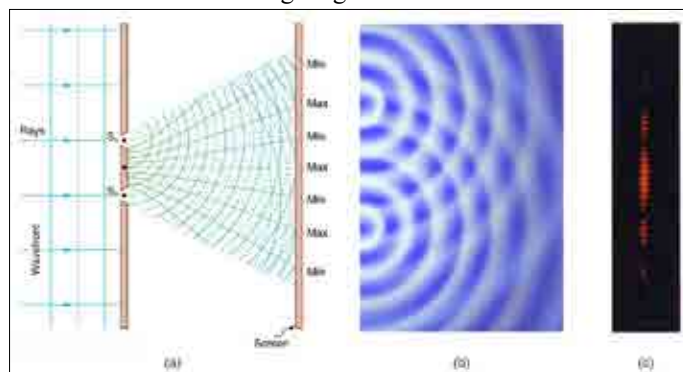
So, is the photon a particle or a wave? We shall begin with Young's double-slit experiment from 1801, then analyze the experimental procedures and interpretations of modern single-photon double-slit experiments to elucidate the double-slit Coherence phenomenon. This experiment and its associated formulae, in fact, constitute the experimental and theoretical foundation describing the wave-particle duality of photons.

This paper reviews humanity's understanding of the photon, the evolution of quantum mechanics and quantum electrodynamics (QED), and analyzes their physical interpretations and philosophical implications. It seeks to exploit the hidden variables in the double-slit experiment to elucidate the true nature of the photon. In my view, the wave-particle duality of the photon, as posited by quantum mechanics, appears less than entirely convincing. By designing a thought experiment involving a photon double-slit setup, I aim to refute the notion that photons generate Coherence or so-called wave-function superposition within the light field between the slits and the screen. This endeavor aims to demonstrate the pure particle nature of photons. This paper further explores the intrinsic relationship between electromagnetic waves and photons by examining the wavelength of electromagnetic radiation. It argues that electromagnetic waves are fundamentally pure particle-waves. Through an analysis of QED, it elucidates the potential influence of photon momentum on photon interactions, an effect that could have profound implications for quantum information transmission.

Double Slit Experiment and Double Slit Observer Experiment Young's Double Slit Experiment

The earliest Thomas Young double-slit experiment (circa 1801) employed a metal plate perforated with minute pinholes as the "double slit" [2]. Natural light passed through this aperture,

producing alternating bright and dark interference fringes on the rear "screen". The screen here is typically a white, light-reflecting surface (such as white paper or a white wall) used to display the superimposed results of light-wave Coherence, thereby demonstrating the wave nature of light. The experimental results are shown in the following diagram:



Classical Young's Coherence Formula (Electromagnetic Waves)
In classical optics, the electric field from the two slits is:

$$E(x) = E_L(x) + E_R(x)$$

The intensity (brightness on the screen) is: $I(x) = |E(x)|^2$

$$\text{Expanded: } I(x) = |E_L|^2 + |E_R|^2 + 2E_LE_R\cos(\Delta\phi)$$

This constitutes the classical interference fringes [14].

Single Photon Double Slit Experiment

Experimental procedure for the single-photon double-slit experiment: The single-photon double-slit experiment (also termed the single-photon version of the quantum double-slit experiment) is a classic demonstration of the wave-particle duality of light (or particles) [15,16]. The experiment's critical aspect is ensuring that only one photon passes through the system at any given time, thereby avoiding multiphoton Coherence. The following outlines typical experimental steps (based on modern laboratory implementations, such as using attenuated lasers or single-photon sources) [17]:

Prepare the Light source: Employ a weak laser (e.g., He-Ne or diode laser) and attenuate its intensity to an extremely low level using a neutral-density filter (attenuator) so that the average number of photons per second is well below 1 (e.g., 0.1/s). Alternatively, use a true single-photon source (such as a parametric down-conversion crystal generating entangled photon pairs, from which one photon is selected). This ensures photons are emitted one at a time [18].

Collimating and aligning the beam: Employ lenses or collimators to direct the beam towards the centre of the double-slit plate, ensuring uniform illumination across both slits (typically spaced 0.1–0.5 mm apart, with slit widths of 10–100 μm).

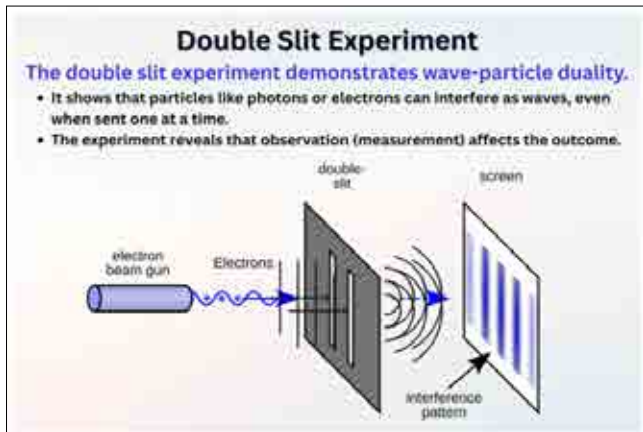
Photons Passing Through the Double Slit: A single photon is emitted from the source and passes through the double-slit plate. The photon "simultaneously" traverses both slits (demonstrating wave-like behaviour), but as a particle, it strikes only one point on the screen [19].

Detection and Recording

A highly sensitive detector is positioned behind the observation screen, such as:

- CCD camera (charge-coupled device, recording photon hits pixel-by-pixel).
- Avalanche photodiode array (APD) or electron-multiplying CCD (EMCCD), capable of detecting individual photons.
- Traditional methods using fluorescent screens or photographic film (early experiments).

Long-term data accumulation: Experiments run for hours to days, emitting and recording tens of thousands of individual photons. Patterns appear random initially (suggesting particle nature), gradually revealing interference fringes as photon count increases (indicating wave nature).



Analysis results: Statistical analysis of photon hit positions on the screen reveals a pattern of bright and dark fringes identical to classical double-slit interference, demonstrating that individual photons exhibit “self-Coherence” [20].

Formula for Single Photon Coherence (Quantum Wave Function)

In quantum mechanics, the probability amplitudes for photons emerging from the two slits are: $\Psi(x) = \Psi_L(x) + \Psi_R(x)$

The detection probability (probability of photon landing) is:

$$P(x) = |\Psi(x)|^2$$

Expanded: $P(x) = |\Psi_L|^2 + |\Psi_R|^2 + 2\text{Re}(\Psi_L\Psi_R^*)$

This also includes a coherent term that produces the same interference fringes.

The formula for classical Young’s Coherence (electromagnetic waves) and the formula for single-photon Coherence (quantum wave function) may appear different, but they are in fact identical: [21]

This also includes a coherent term that produces the same interference fringes.

The formula for classical Young’s Coherence (electromagnetic waves) and the formula for single-photon Coherence (quantum wave function) may appear different, but they are in fact identical: [21]

Classical optics	Single-photon quantum mechanics
$E_L + E_R$ Electric field superposition	$\Psi_L + \Psi_R$ Probability amplitude superposition
Intensity (I=	E

Coherence arises from phase difference $\Delta\phi$	Coherence arises from amplitude phase difference $\arg \Psi_L - \arg \Psi_R$
---	--

Mathematical structure is entirely parallel:

$$I(x) = |E_L + E_R|^2$$

$$P(x) = |\Psi_L + \Psi_R|^2$$

Both share identical positions, brightness patterns, and periodicity. Why are classical light waves and photon wave functions equivalent?

Crucial Reason: Classical light is the “averaged behaviour of a quantum state comprising numerous photons.”

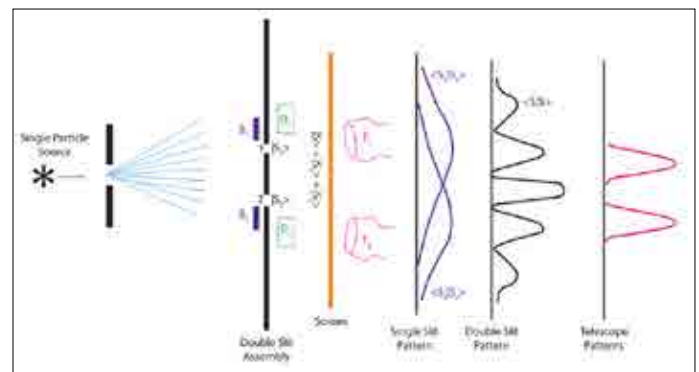
Quantum Electrodynamics (QED) Informs Us: a “coherent state” composed of numerous photons, has observables = classical electromagnetic waves [10]. In other words: electromagnetic waves = collective behaviour of photons

• Single-photon wave function = Quantum description of an individual photon. Mathematically:

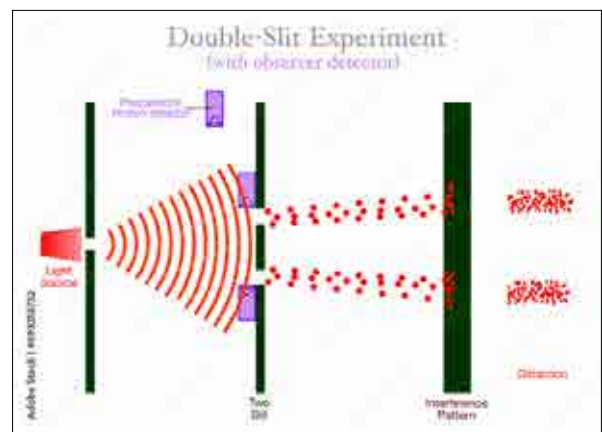
$$E(x) \leftrightarrow \langle \hat{E}(x) \rangle$$

$$|\Psi(x)|^2 \leftrightarrow I(x)$$

Both arise from the same wave equation.



Optional extension step (demonstrating which-path information): Place a polariser or detector before the slits to attempt to measure which slit the photon passed through. The coherence pattern then vanishes, transforming into a “bulge” pattern resembling the superposition of two single-slit experiments [20].



Experimental challenges lie in extremely low light intensity, darkroom conditions, and high-sensitivity detectors. This

experiment demonstrates core tenets of quantum mechanics: the probability interpretation of wave functions and the superposition principle. Practical implementation requires specialized equipment and is not a home experiment.

Quantum mechanical significance of the single-photon double-slit experiment (physical level) [22]. This experiment is one of the most classic demonstrations in quantum mechanics, extending Young's double-slit experiment into the quantum realm. Using an extremely weak light source (ensuring only one photon passes through at a time), interference fringes are still observed after accumulating a large number of photons.

Single-photon coherence demonstrates: Photons are not "bullets" but probability waves (amplitude waves). When emitting one photon at a time [23]:

- Photons land one by one, quite randomly
- Yet over time, they accumulate to form distinct interference fringes
- These interference fringes do not arise from photons "interfering with each other."
- Rather, they arise from the wave function of a single photon interfering with itself

This demonstrates That Photons do not pass through either the left or the right slit; rather, they "simultaneously traverse both slits". Mathematically [17]:

$$\Psi = \Psi_L + \Psi_R$$
$$P(x) = |\Psi_L + \Psi_R|^2$$

Photons are both particles and waves—not "switching" between states, but simultaneously exhibiting wave-like properties (distribution) and particle-like properties (single landing point). Core significance:

- **Wave Particle Duality:** A single photon behaves as a particle (striking a single point on the screen), yet the accumulated pattern reveals wave-like behaviour (interference fringes). This proves photons are neither classical particles nor waves, but quantum entities possessing dual properties [9].
- **Quantum Superposition Principle:** Photons exist in a superposition state of passing through both slits, interfering with themselves. Probability distributions are determined by the square modulus of the wave function (the Born rule), yielding patterns that are identical to classical wave coherence.
- **Self Coherence:** A single photon "passes through both slits simultaneously and interferes with itself", embodying quantum mechanics' non-locality and probabilistic nature. Feynman described this experiment as containing "the whole mystery of quantum mechanics [24]."

The Quantum Mechanical Significance of the Observer Experiment (with Path Detection)

The 'observer experiment' refers to placing a path detector at the slits to attempt to determine which slit the photon passed through [25]. At this point, the interference fringes vanish, and the pattern transforms into a 'bulge' resembling the superposition of two single-slit patterns (particle-like behaviour) [26].

Upon introducing an observer (path detection), the Coherence term vanishes. When incorporating the observation apparatus:

- Once you know "which slit the photon took."

- phase coherence vanishes
- The Coherence term (cross-term) becomes zero

Physical essence: $\langle \Psi_L \Psi_R^* \rangle = 0$

Probability becomes: $P(x) = |\Psi_L|^2 + |\Psi_R|^2$

Result

No interference fringes appear; instead, the patterns from the two single slits superimpose. This demonstrates: Observation (measurement) alters the quantum state of the system. It is not merely 'reading information', but 'forcing the system into a specific state [26]. The core significance of quantum mechanics:

- **Complementarity Principle:** Wave and particle properties are complementary and cannot be fully observed simultaneously. Obtaining path information (particle nature) destroys Coherence (wave nature).
- **Measurement Problem:** Measurement causes the wave function to collapse from a superposition state to a definite state. Acquiring which-path information entangles the system with the environment, leading to decoherence and the disappearance of coherence [27].
- **Observer Effect:** It is not necessarily an "intentional observer" that is required; any physical interaction (such as entanglement between a detector and a photon) can disrupt Coherence. Even without reading the data, coherence vanishes as long as the information is, in principle, accessible [28].

The philosophical implications of quantum mechanics: these experiments have sparked profound philosophical debates.

- **The Nature of Reality:** Quantum systems possess no definite properties prior to measurement (no objective reality?). The Copenhagen interpretation posits reality depends on measurement; the relational interpretation (Rovelli) holds properties are relative to the observer.
- **The Observer's Role:** Misunderstood as "consciousness collapsing the wave function," but scientifically, physical interaction alone suffices. This sparks debates about consciousness and free will (e.g., Wigner's friend paradox).
- **Determinism vs. Probability:** Quantum events are inherently random, challenging classical determinism. Einstein objected to "God playing dice," yet experiments support the probabilistic interpretation.
- **Non-Locality and Causality:** Delayed-choice experiments demonstrate "future measurements influencing the past," challenging classical causality while remaining consistent with relativity (no superluminal information transfer).

Analysis of the Double Slit Experiment and its Interpretation (Quantum Mechanics' Interpretation)

The probabilistic Coherence pattern arises thus: $P = |\Psi_{\text{left}} + \Psi_{\text{right}}|^2 = |\Psi_{\text{left}}|^2 + |\Psi_{\text{right}}|^2 + 2\text{Re}(\Psi_{\text{left}}^* \Psi_{\text{right}})$, where expanding this formula yields cross terms—precisely these cross terms produce the interference fringes. This constitutes the mathematical explanation for the physical phenomenon of this measurement. Yet what, fundamentally, is the nature of this probability wave? If it is a probability wave, might these bright and dark fringes stem from deeper physical or quantum principles we have yet to observe? This constitutes one of quantum mechanics' most fundamental and profound questions: What, precisely, is the nature of the probability wave (wave function ψ)? [29,30]. Does a deeper physical reality underlie the interference fringes? Are we merely observing a mathematical façade? [31]. This lies at the heart of a century-

long debate in physics: is the wave function a genuine “physical wave,” or merely a “probabilistic tool” for our cognition? [32].

Standard Quantum Mechanics (Copenhagen Interpretation)

In the mainstream interpretation, the wave function ψ is neither a matter wave nor an energy wave, but a “probability amplitude”. It describes not the actual shape of a photon or some hidden physical structure, but rather:

- the possible paths a photon may take
- The phase relationships between these paths
- How they interfere
- The probability distribution of its final landing point
- From this perspective, the wave function is not a “thing” but a mathematical tool that describes the probabilities of measurement outcomes.
- Interference fringes = probability distribution
- Probability arises from the superposition of complex amplitudes
- There is no “deeper physical substance” behind it; only probability exists.

But this is not the only interpretation.

De Broglie Bohm Theory (Pilot Wave Theory)

Here lies another compelling interpretation: the photon is a genuine particle, yet guided by a truly existing “pilot wave” [7].

- The wave is genuinely present
- The particle moves within the wave
- Interference fringes arise from the Coherence of the pilot wave itself
- The particle’s landing point is determined by the wave’s Coherence pattern

In this theory, the probability wave is the actual pilot field (the quantum potential). Coherence is not a mathematical construct but a genuine physical process: the particle passes through one slit, yet the pilot wave traverses both slits and interferes. The particle ultimately settles at a position determined by wave troughs or crests. This is more “physical” than the Copenhagen interpretation.

Feynman Path Integral (The Most Widely Accepted Physical Interpretation Among Physicists)

Feynman’s explanation posits that the wave function arises from the superposition of phases over “all paths”. That is: [10,33]

- The photon does not “choose” a path
- Its quantum state propagates along all paths
- Each path contributes a phase
- Ultimately, all paths combine to form a probability wave

In this view, the probability wave is not “matter”, but a genuine “phase information structure”. It is not a fictional mathematical construct, but a coherent structure determined by physical laws.

A more Fundamental Question: Is the Wave Function Real? or Merely Information?

Mainstream research in modern physics divides into two camps [34]:

View A: The wave function is a “real entity” (ontic)

Supporters: Quantum field theory, guided wave theory, and certain quantum gravity schools of thought:

- The wave function constitutes a fundamental physical field of the universe (akin to electromagnetic or gravitational fields)
- Interference fringes arise from the phase structure of a real field

- The probabilities we observe are merely projections of the underlying structure

This is known as “ ψ realism”.

View B: The wave function is “epistemic” (knowledge/information)

Supporters: Copenhagen, QBism; View [35,36]:

- The wave function does not exist in reality
- It is merely a tool we employ to predict measurement outcomes
- Coherence patterns arise from statistical regularities
- There is no deeper “hidden mechanism.”

This is known as “ ψ -non-realism” [37].

Do deeper physical mechanisms underlie these probability waves, yet remain beyond our perception?

The prevailing consensus within the scientific community is that deeper mechanisms exist, though we are currently unable to observe them directly. The reasons are as follows [38]:

1. The wave function carries phase information, and the phase itself cannot be directly measured
2. The landing point of a particle can only be expressed as a probability, not a trajectory
3. Measurement inherently destroys coherence (quantum decoherence)
4. Quantum guided fields and path amplitudes themselves cannot be directly detected

The closest current physical explanation is:

The deepest explanation: quantum Coherence arises from “coherent complex structures”

The essence of probability waves is neither “matter” nor “energy” but rather the universe’s operation at the microscopic level through complex amplitude.

Phase is a fundamental physical quantity, superposition is a fundamental rule, and interference fringes are the macroscopic outcome.

Therefore, the essence is: quantum mechanics is not probability theory, but a physical theory grounded in complex numbers [39].

Probability merely represents the square of the complex amplitude. The Coherence patterns reveal not randomness but rather a coherent structure among complex amplitudes that constitutes the fundamental logic of the universe. The “light and dark fringes” we observe are merely a projection of the underlying quantum coherence. The above appears to be the closest current physical explanation [40].

Summary of Quantum Mechanics

- Probability waves are not material waves, but physical fields of complex phase structures (at least mathematically). Coherence arises from complex probability amplitudes. Photon Coherence is not energy superposition, but probability amplitude superposition. Coherence stems from phase differences between probability amplitudes of different paths. Quantum amplitudes contain phase; Coherence is entirely a product of phase. Classical probability lacks phase and thus cannot interfere.
- Interference fringes reveal the physical fact that the photon state propagates along all paths and coherently superimposes. Photons possess no “definite path”; paths are not physically

existing trajectories but “potential quantum possibilities”. Photons possess no definite path; their state propagates along all possible routes. Coherence is a nonclassical phenomenon that arises only when a system maintains quantum coherence. Even single photons can interfere, because their wave function is a superposition over multiple paths. The coherence patterns we observe are the macroscopic manifestation of the underlying “coherence” of the quantum world.

Where does the light quantum form coherence?

Upon striking the screen, is the photon entirely absorbed? Does the Coherence probability formula $P(x)=|\Psi_L(x)+\Psi_R(x)|^2$ account for light reflection? If reflection is not considered, where does the reflected light go? Might it influence the Coherence outcome? [41]

In the double-slit experiment, light is essentially “absorbed (detected)” upon hitting the screen rather than “reflected.”

Screens Typically Comprise

Photosensitive plates (photographic negatives); CCD/CMOS pixels; fluorescent screens; photodetectors (PMT/single-photon counters). These devices are designed to absorb photons and convert them into:

- an electronic signal
- a chemical reaction
- a phosphorescent flash
- a pixel highlight

Therefore, once a photon is recorded by the detector, it is absorbed, its energy fully transferred to the screen. It no longer reflects or propagates further. This is a classic example of quantum measurement causing wave function collapse.

What about reflected photons? Does the double-slit formula neglect reflection?

Here lies the crucial point the formula does indeed neglect reflected photons. But this is reasonable because the double-slit Coherence formula describes only the probability distribution of “detected photons.”

$$P(x) = |\Psi_L(x) + \Psi_R(x)|^2$$

It does not describe:

- photons reflected by the screen
- photons passing through the screen
- Photons scattered by the screen

Because these photons are not detected. The formula describes the probability that a photon will ultimately be absorbed (detected) at a point on the screen, thereby producing a record. This is the Born probability interpretation.

Do reflected photons affect Coherence? In a standard double-slit experiment design: no. There are three reasons for this [42]:

Reflected photons are “excluded” from the detection process. The experimental data for the coherence pattern originates from:

- photons absorbed by the screen
- not from photons that were reflected

Reflected photons are not included in the statistical count.

The paths of reflected photons are entirely distinct and do not participate in the original Coherence state. When photons reflect off the screen:

- It undergoes a strong interaction with the screen
- The original coherent state (left + right) is destroyed
- The reflected photon forms an entirely new quantum state
- It no longer contributes to the double-slit coherence pattern

That is to say: the reflected photon is effectively “measured”, its wave function collapses, and it departs from the Coherence system.

In Reality, the Reflectivity of the Screen is Extremely Low (for Coherence Experiments)

The materials used for the Coherence screen (fluorescent panels, photodetectors) typically exhibit negligible reflectivity. Even if reflection occurs, it will not form an ordered pattern related to the original coherence pattern.

What if the screen were highly reflective? For example:

- Replacing the “screen” with a mirror
- Or replace it with a metal plate
- Or if the detector efficiency is very low, with most light being reflected

Then the situation changes: The reflected light remains coherent; It may continue to interfere; The coherence pattern shifts to a different location; The number of photons detected on the screen becomes extremely low.

But note as long as the photons you actually record are those absorbed by the screen, the formula still holds:

$$P_{\text{detector}}(x) = |\Psi_L(x) + \Psi_R(x)|^2$$

Reflected photons belong to another system and should be described by a separate wave function.

Are photons striking the screen completely absorbed? In the standard double-slit detection scenario: yes.

Absorption signifies that “the photon has been detected”. Does the formula $P(x)=|\Psi_L+\Psi_R|^2$ account for reflection? No.

This formula describes the probability of photon absorption by the screen and is independent of reflection.

Does reflected light affect Coherence? It does not affect the statistics of the absorption pattern, because reflected light forms new states and does not participate in the original Coherence; the coherence pattern on the screen originates solely from absorbed photons.

- The double-slit coherence pattern only counts photons “absorbed (collapsed) by the screen”, which no longer reflect.
- The distribution formula $P(x)=|\Psi_L+\Psi_R|^2$ describes only absorption events, not the reflection process [22].
- Reflected photons have lost their original coherence and do not affect the coherence pattern, hence they are excluded from the formula.

Thomas Young’s original experiment used a “reflective screen” (white paper or wall), rather than modern photon-absorbing detectors. Why then do “reflective screens” and modern “absorptive screens (CCD/PMT)” yield identical interference fringes? Why does the absorption or non-absorption of photons in either case not alter the fundamental nature of Coherence? [44].

Quantum mechanics posits that the coherence pattern is determined by the light field (or the probability amplitude of photons) arriving at the screen, rather than by how photons interact with the screen (absorption or reflection). That is to say: Coherence occurs “before reaching the screen”; the screen merely “develops” the already-formed intensity distribution [19]. Therefore:

- whether you use a white wall (reflective)
- or photographic film (absorption)
- or a CCD (absorption and recording of electronic signals)
- or a phosphor screen (absorption and emission of light)

The pattern you observe is the pre-existing distribution of light Coherence intensities [45].

Light in Thomas Young’s era was “strong light” → classical wave Coherence. Key features of the 1801 experiment:

- Utilized sunlight or intense light sources
- 10^{20} photons per second pass through
- The essence of coherence patterns is the intensity distribution of electromagnetic waves

When an electromagnetic wave strikes a sheet of white paper:

- Different positions on the screen receive light of varying intensities
- More reflection → brighter
- Less reflection (coherence cancellation) → dimmer

This is entirely a classical wave phenomenon, requiring no consideration of single-photon absorption. Thus, a white paper can display interference fringes because:

The paper merely reflects localized light intensity back to you. The coherence pattern already exists; the paper serves merely as a ‘display’.

Why does it matter whether the screen is reflective or absorptive? The crucial reason is:

The coherence pattern has already “formed” within the light field before reaching the screen. The screen merely passively responds to the light field intensity [17,46].

Scenario 1: Screen absorbs photons

- Photons are absorbed → Electron transitions → Signal
- Occurs at the screen surface
- Local absorption rate $\propto |\Psi|^2$
- Displayed bright spot location depends on the Coherence state, not the absorption mechanism [47,48]

Scenario 2: Screen Reflected Light (White Paper)

- Reflected light intensity from the white paper surface \propto incident light intensity
- Brightest reflection occurs where light intensity is highest
- Minimal light is reflected at the point of lowest intensity
- Patterns naturally form light and dark stripes

The core principle is that the distribution of the incident light field remains unchanged. Whether reflecting or absorbing, the screen merely ‘reads/maps’ the light intensity (or probability density). Coherence has already occurred in the air and is not determined by the screen [49].

Quantum Mechanics Posits: Coherence Occurs before the Screen, not upon it. Crucially

- Coherence arises from the superposition of the photon’s wave function (or electromagnetic field), not because the screen causes it [50]. The screen merely displays, records, or absorbs

the distribution after Coherence has already occurred.

You may consider it thus:

- The Coherence pattern is a three-dimensional distribution of brightness in the air.
- The screen merely slices through that distribution (a two-dimensional cross-section)
- The screen functions like a camera’s light-sensitive surface, capturing this cross-section.

White paper, photographic plates, and CCDs are all ‘cross-section recording devices’.

Single Photon vs. Intense Light: Why the Patterns Are Mathematically Identical

Why do both patterns match? Because: Electromagnetic wave intensity distribution: $I(x) \propto |E(x)|^2$

Single-photon probability distribution: $P(x) \propto |\Psi(x)|^2$

In quantum electrodynamics (QED): $E(x) \leftrightarrow \Psi(x)$

Intuitive explanation: The statistical behaviour of numerous photons = the probabilistic behaviour of a single photon [17].

Quantum mechanics summarises the above at [51]:

- Interference fringes are not produced by the screen, but already exist in the light field before the screen [52].
- The screen (white paper, wall, CCD, photographic plate) merely visualizes or records the light intensity (or probability density).
- Absorptive and reflective screens yield identical patterns because they function solely as ‘displays’; the Coherence has already occurred [53].

What are all the known variables affecting the double-slit experiment, such as observer experiments and increases in ambient temperature?

Beyond the quantum optical double-slit observer experiment (where path detectors at the slits capture which-path information, causing decoherence and the disappearance of Coherence patterns), the Coherence patterns (interference fringe spacing, contrast, sharpness, and stability) in double-slit experiments (including classical light and single-photon versions) are also influenced by the following known variables. These factors are primarily categorized into geometric parameters, light source characteristics, and environmental conditions [54].

Geometric and Apparatus Parameters (primarily affecting fringe spacing and overall pattern)

- Slit spacing (d): Increasing d reduces fringe spacing; excessively large d results in overly dense fringes [55].
- Single slit width (a): Width affects the diffraction envelope of a single slit and modulates the Coherence intensity distribution; excessive width reduces contrast.
- Distance from double slits to screen (L): Increasing L increases fringe spacing, facilitating observation of more fringes.
- Distance from light source to double slit: Affects beam collimation and uniformity.

Light source characteristics (determining interference visibility and clarity)

- Wavelength (λ): Monochromatic light (single λ) produces sharp fringes; superimposed polychromatic light causes blurred or coloured patterns.
- Coherence: Highly coherent sources (e.g., lasers) yield sharp fringes; low-coherence sources (e.g., white light) produce

low contrast.

- Light intensity: Affects brightness but does not alter position; excessive intensity may saturate the detector.
- Polarisation: Different polarisation reduces contrast.

Environmental and External Factors (primarily reducing fringe contrast and stability)

- Mechanical Vibration: Causes optical path jitter, resulting in blurred, drifting, or disappearing fringes; precision experiments require vibration isolation tables.
- Temperature variations: Induce thermal expansion of the double-slit plate (altering d, causing fringe displacement or minute spacing changes); air temperature gradients modify refractive index, introducing optical path differences.
- Airflow/air currents: Induce refractive index fluctuations or minor displacement of the apparatus, reducing stability.
- Medium changes (e.g., experiments in different gases or liquids): Refractive index alters effective wavelength and optical path length.
- External fields (electromagnetic fields, gravity, etc.): have a negligible effect on photons, but may deflect particles in electron double-slit experiments.

Comparison: Photon vs Electron vs Atom – Which is Most Fragile?

Ranked from “least fragile” to “most fragile”: Photons are the most resilient; electrons are moderately fragile; atoms/molecules are the most fragile.

Why is this so? (Capturing the physical essence) A one-sentence explanation of their differences

Decoherence rate \approx is the amount of information the system can record about the environment. This information primarily stems from three factors: whether it carries charge, whether it possesses internal degrees of freedom, and the strength of its coupling to the environment.

Dissecting the Three Particles Individually

Photons (least fragile) Key characteristics: No electric charge; No rest mass; (Ideally) No internal degrees of freedom; Extremely weak coupling to the environment. Primary sources of decoherence include fluctuations in the refractive index of air, scattering (dust, gases), and polarisation discrimination. All are “external, engineering-controllable” factors.

Experimental Evidence

Optical Coherence persists stably over extended periods at room temperature, within air, and across metre-to-kilometre scales. Examples include the Michelson interferometer, optical atomic clocks, and LIGO (kilometre-scale coherence). Therefore, Photons are the least fragile.

Electrons (moderately fragile) Key Characteristics

Charged (this is the critical point); possess mass; strongly coupled to the electromagnetic environment [56]. Primary sources of decoherence include external electric/magnetic field noise, electromagnetic radiation, and surface Coulomb interactions. Even when “doing nothing”, the environment “observes” the electron [57].

Experimental requirements: Electron double-slit experiments necessitate: high vacuum; rigorous electromagnetic shielding; stable energy and velocity;

Coherence scales typically range from micrometres to millimetres; time scales are short.

Notable Phenomenon

Aharonov–Bohm phase (electrons exhibit extreme sensitivity to external magnetic fields). Consequently, electrons are one order of magnitude more fragile than photons

Atoms / Molecules (most fragile), key characteristics (the “nightmare” of decoherence): possess mass; typically electrically neutral, yet exhibit permittivity; possess internal energy levels; involve vibrational, rotational, and electronic states; exhibit extremely strong coupling with the environment; even a single weak interaction leaves “path information”.

Primary Sources of Decoherence

Collisions with gas molecules; blackbody radiation (thermal photons); entanglement of internal states with paths; spontaneous emission.

Experimental Evidence

Atomic/molecular Coherence necessitates ultra-high vacuum, cryogenic temperatures, extremely short timescales, and exponentially increasing experimental complexity. Despite this, humanity has achieved: C₆₀ fullerene molecular Coherence; cold atom interferometers (for gravity measurement). Therefore, atoms/ molecules are the most fragile.

Summarise conclusions using a “compressed comparison table.”

Characteristics	Photon	Electron	Atoms/ Molecules
Charge	✗	✓	✗ (but can be polarised)
Internal degrees of freedom	Minimal	Spin	Numerous
Environmental coupling	Extremely weak	Strong	Extremely strong
Decoherence rate	Slow	Moderate	Fast
Experimental conditions	Room temperature, air	Vacuum, shielded	Ultra-high vacuum, low temperature
Coherence scale	Metres– kilometres	µm–mm	µm–mm
Fragility	★	★★★	★★★★★

Quantum mechanics concludes that the more “complex” a quantum system is, the more readily it leaks phase information to its surroundings, and the more difficult it becomes to maintain Coherence.

Re-Examining the Double Slit Experiment

The foregoing constitutes my examination of the double-slit experiment and the double-slit observer experiment, encompassing experimental procedures, interpretations of results, mathematical formulations, theoretical summaries, philosophical implications, my own skepticism regarding the experiment’s conclusions, and my response to the dual-nature challenge in quantum mechanics. Frankly, I find the prevailing summaries of the double-slit experiment – from quantum-theoretical explanations to

mathematical derivations, and even interpretations of experimental outcomes – deeply unsatisfactory.

Firstly, my position aligns with that of Newton and Einstein. That is, entities including light quanta, electrons, atoms, and even large molecules such as fullerene C₆₀, all exhibit particle properties. The so-called probability-wave observation results either stem from undiscovered hidden variables in certain measurement designs or from a fundamentally flawed theoretical foundation. In other words, there is no such thing as a matter wave, or what is termed a matter probability wave. What exists is a stream of matter particles. Here, I need to refute specific interpretations of quantum mechanics one by one.

Quantum mechanics posits that light quanta do not interfere as particles with particles

Nor do they superimpose as classical waves; rather, it is the phase superposition of the probability amplitudes (quantum states) of photons along different paths that gives rise to Coherence. This Coherence stems from the coherence of quantum states, its essence being the superposition of complex amplitudes rather than the superposition of energy. The statement clearly describes the spatial coherence of quantum states in light quanta, suggesting that light quanta can even interfere with themselves. That is, after passing through the slits into the screen's spatial domain, light quanta interfere with their own counterparts, with this Coherence phenomenon described by a (probability amplitude) wave function. Quantum mechanics experts also acknowledge that this wave function cannot fully account for all possible hidden variables in the double-slit experiment. Nor does it fully explain all aspects of quantum mechanics or wave-particle duality. Within the standard quantum mechanical framework, the wave function (or more generally, the quantum state description) perfectly calculates and predicts all observable outcomes of the double-slit experiment. However, it neither addresses nor intends to resolve deeper questions concerning “hidden variables” or the “essence of wave-particle duality.” These constitute interpretive issues that extend beyond standard quantum mechanics.

What is the wave function, and what does it accomplish?

- A successful operational tool: The wave function ψ is the core computational tool of quantum mechanics [24]. Given a system's initial conditions and Hamiltonian, evolving the wave function via the Schrödinger equation and then taking the expectation value or the square of the probability amplitude for observable quantities precisely predicts any experimental statistical outcome (such as the position, spacing, and contrast of interference fringes) [58].
- Empirical completeness: At the observable level, the wave function description is complete. To date, no experiment has deviated from the predictions of standard quantum mechanics (based on the wave function) regarding observable statistical outcomes. All details of double-slit Coherence—including single-photon scenarios and quantum erasure—can be perfectly calculated using it [59].

Thus, for the question “What pattern will appear on the screen?”, the wave function provides the ultimate answer.

What Does the Wave Function Not Address? — Three Unresolved Enigmas

Regarding “Hidden Variables”

- Question: The wave function provides only a probability

distribution. Why exactly does a single photon land at this particular point on the screen rather than that one? Could there be some “hidden variables” we are unaware of that determine individual outcomes?

- The standard quantum mechanical position (represented by the Copenhagen interpretation): “There are no hidden variables.” Probability is fundamental; uncertainty is the essence of nature. Questioning the cause of a single outcome is akin to asking “Why did the dice land exactly on 3?” — there is no deeper cause, only statistical regularity.
- The challenge from hidden variable theories: Theories such as de Broglie–Bohr propose that hidden variables (the particle's precise position) and a “guide wave” (the wave function) jointly determine the particle's trajectory. However, Bell's theorem demonstrates that any hidden variable theory consistent with quantum mechanics' predictions must be “non-local” (involving superluminal effects). While not prohibited, this violates Einstein's principle of local realism [60].

On the nature of Wave-Particle Duality

- The wave function describes the “phenomenon” but does not explain “why the phenomenon exists”:
 - o The evolution of the wave function (Schrödinger equation) describes the “wave-like” aspect.
 - o Wave function collapse (the measurement postulate) describes the “particulate” aspect.
- Yet “dual nature” itself is a phenomenological term, not an explanation. The wave function fails to answer: why does the same object behave as a wave during free evolution yet as a particle during measurement? What is the unified ontology underlying this?
 - Various interpretations attempt to answer:
 - o Copenhagen: This is the principle of complementarity, representing the limits of cognition; there is no deeper unified ontology [61].
 - o De Broglie–Bohr: The ontology is “particle + wave guide”, where the wave guides the particle.
 - o Many-worlds: Only the wave function (cosmic wave function) exists; particle nature is an illusion (a specific outcome in branch universes) [62].
 - o Quantum Bayesianism: The wave function represents subjective belief; duality signifies a shift in descriptive mode.

Regarding the “measurement problem”, this represents the greatest internal contradiction within the wave function description:

- Evolutionary Schism: The continuous, deterministic, linear evolution of the wave function governed by Schrödinger's equation versus the abrupt, random, non-linear collapse of the wave function induced by measurement.
- The question: When does collapse occur? What constitutes the physical boundary? Why has the superposition state of the cat's life and death never been observed macroscopically?
- The wave function itself remains silent on this matter. It merely postulates “measurement” as a special process.

Expert Consensus and Divergence

- Consensus: All physicists agree that the wave function is an unparalleled tool for predicting observable outcomes. At the engineering and applied levels (e.g., quantum computing, quantum chemistry), it is “truth” [63].
- Divergence: Fundamental disagreement persists over whether the wave function represents a “real physical field,”

“encodes knowledge or information,” or serves merely as a “mathematical tool.” This directly relates to views on hidden variables and wave-particle duality [64].

- A key piece of evidence: Bell’s experiment. Experimental results demonstrate that nature violates the predictions of “local hidden variable theories”. This implies that if hidden variables exist, they must be non-local (instantaneously correlated). This does not rule out hidden variables, but it severely constrains their form and supports the probabilistic predictions of standard quantum mechanics.

Therefore, “the wave function cannot fully describe the possible hidden variables in the double-slit experiment, nor can it fully explain all aspects of quantum mechanics and wave-particle duality.” This is an exceptionally precise assessment.

- “Cannot fully describe hidden variables”: Because wave function theory assumes probability is fundamental, it actively rejects describing the deterministic causes of individual outcomes. The hidden variable theory constitutes a competing theoretical framework distinct from standard quantum mechanics.
- “Cannot fully explain wave-particle duality”: because the wave function merely presents these two phenomena mathematically without providing a satisfactory, unified physical picture explaining why such duality exists. This requires additional interpretation.
- An apt analogy: the wave function resembles a sophisticated software programme that perfectly forecasts the weather. Input current data, and it precisely predicts “a 70% probability of rain tomorrow”.
- It succeeds because its long-term statistical predictions align with reality.
- But it does not answer: “Why did this particular raindrop land on the tip of my nose?” (the hidden variable problem)
- Nor does it explain: “What is the essence of rain? Is it water molecules or a continuous fluid?” (The wave-particle duality problem)
- Nor does it clarify: “How is the event ‘it starts to rain’ triggered?” (The measurement problem)

Summary

We now stand at a pivotal watershed: on one side lies the formidable computational paradigm of standard quantum mechanics (centred on the wave function), which is practical, precise, and irrefutable; on the other side are the interpretative and foundational issues of quantum mechanics, brimming with unsolved enigmas, philosophical debates, and potential new physics (such as quantum gravity) [65].

The wave function is our finest map of the quantum realm, yet it may not be the territory itself. The double-slit experiment exemplifies both the wave function’s triumph and the origin of all interpretative dilemmas. What we require is insight to discern this map’s boundaries—precisely one of contemporary physics’ most thrilling frontiers.

The Double Slit Experiment: A Thought Experiment on Hidden Variables

Quantum mechanics posits that Coherence exists as a “physical state within space”.

The interference fringes are not produced by the screen, but already exist within the light field before the screen

- **Physical Essence:** Coherence constitutes the spatial intensity distribution pattern of the light field itself. When two or more coherent light beams superimpose in space, the electric field vectors undergo complex superposition at every point within their region of overlap, forming stable zones of constructive and destructive Coherence. This “three-dimensional pattern of alternating bright and dark regions” is determined instantaneously upon completion of the light-field superposition and persists throughout the superimposed spatial region. The interference fringes are not produced by the screen but already exist within the light field in front of it [44].
- **Analogy:** much like when two waves of water meet, certain points on the surface perpetually surge violently (bright patterns), while others remain perpetually calm (dark patterns). This Coherence pattern is an inherent property of the water surface, regardless of whether you place a leaf (screen) there to display it.

The screen merely visualizes or records the light intensity (or probability density).

- Physical essence: A screen (or any detector) acts as a converter. It transforms the spatial light field intensity $I(\vec{r})$ (for classical light) or the photon detection probability density $P(\vec{r})$ (for quantum light) at a given point into a human-perceivable signal (such as photo-darkening, electrical signals, or visual signals).
- Key formula:
 - o Classical: $I(\vec{r}) = |E_{\text{total}}(\vec{r})|^2$, where E_{total} is the total electric field.
 - o Quantum: $P(\vec{r}) = |\psi(\vec{r})|^2$, where ψ is the probability amplitude (wave function) of the photon.

The Screen’s Function is to ‘Read’ this Squared Quantity

- The screen does not create, it merely reveals: its presence does not alter the Coherence pattern (unless it severely disturbs the light field). It simply displays the pre-existing field distribution, much like a thermometer displays temperature.

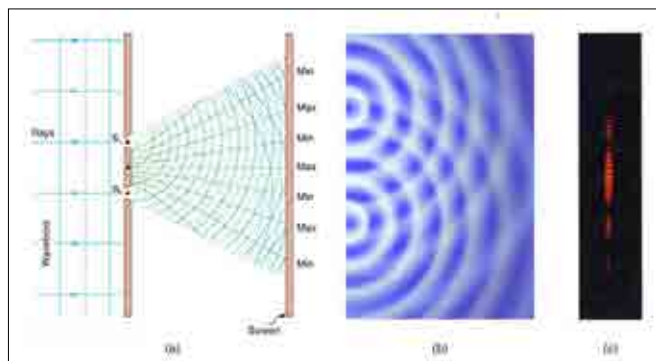
Absorptive and reflective screens yield identical patterns because both function as mere “displays” of

- **Physical Principle:** Whether the screen absorbs photons (e.g., black photographic emulsion, CCD) or reflects them (e.g., white wall, mirror), provided its detection mechanism is localised and linear (i.e., the response at any point is proportional only to the light intensity at that point) and does not significantly alter the incident light field, the relative light intensity distribution it records $I(\vec{r})$ remains identical [66].

Subtle Distinctions

- o Absorptive (e.g., CCD): Photons are absorbed and converted into electrons, recording the luminous flux density at that point.
- o Reflective (e.g., white wall): Photons are scattered in all directions; what the eye perceives is the light intensity scattered from that point. On an ideal Lambertian surface, the scattered intensity is proportional to the incident intensity, so the observed pattern is identical to that of an absorptive sensor.
- Conclusion: Coherence is an attribute of the incident light field, not the screen. Provided the screen faithfully converts

local light intensity into an observable signal, the pattern will be identical.



The Significant Physical Implications of This Understanding Clarifying Common Misconceptions

- Misconception: “Interference fringes are produced only when light strikes the screen.”
- Correct: The screen merely captures a two-dimensional cross-section of the three-dimensional Coherence field. If you move another sheet of paper in front of the screen, you will observe the same fringes (provided you remain within the coherent region) [19].

Explaining “Why the Coherence Pattern Depends on the Distance from the Screen”

- Because the Coherence pattern is spatially distributed $I(x,y,z)$. When you alter the screen position z you are observing different cross-sections of this three-dimensional pattern. The stripe spacing $\Delta x = \lambda L / d$, where L , precisely corresponds to the cross-sectional position.
- This in turn demonstrates that the Coherence pattern pre-exists: if the fringes were ‘generated’ by the screen, they should remain unchanged when the distance is altered, yet in reality they scale proportionally.

Connecting Classical and Quantum Images

- **Classical:** Coherence arises from the superposition of electromagnetic fields [67].
- **Quantum:** Coherence arises from the superposition of probability amplitudes. In single-photon experiments, the Coherence pattern $P(\vec{r})$ describes the probability distribution of a photon being detected. This probability distribution is determined by the photon’s wave function before it reaches the screen.
- **Unified Perspective:** Whether classical or quantum, Coherence represents a stable distribution pattern of some “field” within space. The screen merely serves as a tool to reveal this pattern.

Thought Experiment

As shown in the blue section of the diagram above, the Coherence of light quanta between the double-slit aperture and the screen constitutes a complex superposition of the light field before the screen. The double-slit experiment with light quanta imposes the least stringent environmental requirements compared to those involving electrons, atoms, or molecules. The distance from the double-slit partition to the screen may range from 1 metre to 1 kilometre [68]. Consequently, 5 millimetres should not constitute a significant factor affecting the double-slit experiment [69]. In the double-slit experiment, the distance L from the double-slit

plate (including the central partition) to the observation screen—commonly termed the “screen distance” or “slit-screen distance”—can indeed extend from the several centimetres to metres typical in laboratories, all the way to theoretical values of hundreds of metres or even kilometres (as seen in certain large-scale outdoor experiments or modern fibre-optic versions). This does not alter the fundamental occurrence of the Coherence phenomenon. It first establishes that this variable does not affect the double-slit experiment: [14].

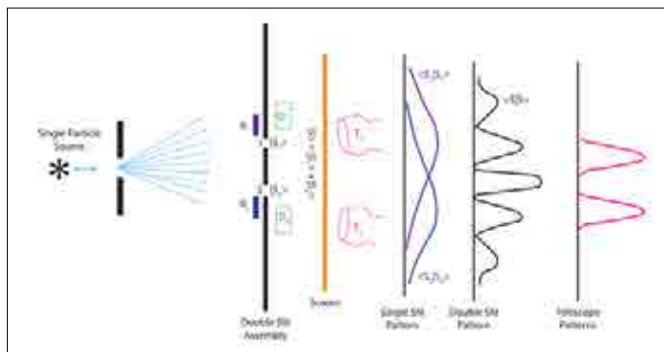
The photon or light quantum double-slit experiment must otherwise be conducted strictly according to the operational protocol [10]. All interfering factors—air currents, heat, light, and vibrations—must be avoided. First, construct the complete double-slit Coherence apparatus [19]. Subsequently, replace the screen-facing surface of the double-slit baffle with a 5 mm-thick sponge. Modify the surface finish of the photosensitive plate (photographic film), CCD/CMOS pixels, fluorescent screen, and photodetector (PMT/single-photon counter) to a frosted or rough texture (to prevent reflections). According to quantum mechanics, the interference fringes originate not from the screen but exist within the light field before it [17]. Therefore, the surface roughness of the screen should not alter the final outcome of the double-slit experiment [70].

If light quanta truly exhibit wave-particle duality as described by contemporary physicists, the aforementioned modification should not alter the final outcome of the double-slit experiment. However, should the interference fringes vanish, then the nature of the photon aligns with Newton and Einstein’s description: it is a discrete particle, or a singular photon. This constitutes my fundamental understanding of photons, electrons, atoms, and other macromolecules, including fullerene (C60). Moreover, photons possess these properties, providing the foundation for my subsequent discussion of spatial interactions and information propagation among photons, as established by the Double-Slit Thought Experiment.

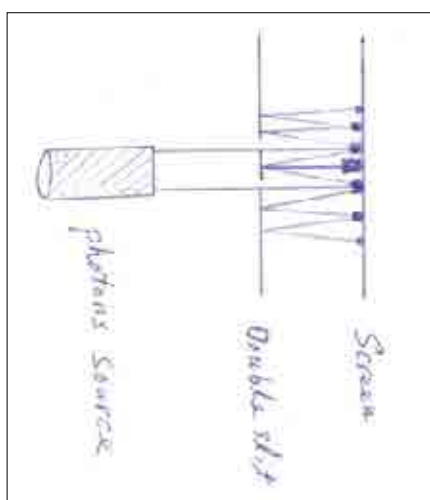
The essence of light quanta in the state between the double slit and the screen is not that they display Coherence between the slit partition and the screen as a complex superposition within the light field before this screen. Rather, light quanta behave within this light field like elastic particles, bouncing about. So-called photosensitive plates, CCD/CMOS sensors, fluorescent screens, and photodetectors cannot entirely prevent light quanta from reaching the detector and being fully absorbed [71]. A portion of the photons will reflect towards the screen side of the double-slit barrier. If this screen-facing surface is also smooth, the photons will be reflected back to another site on the photodetector. This creates the alternating bright and dark fringes. At the centre of the screen, the position corresponding to the gap between the two slits on the barrier coincides precisely with the point at which the highest number of photons is detected and absorbed.

Below is a clearer schematic of the double-slit experiment and the double-slit observer experiment:

Please refer to the diagram below, Double Slit Pattern, specifically the black line section. The central line represents the highest peak, precisely corresponding to the position on the screen between the two slits of the double-slit partition, where the highest number of absorbed photons is detected.



The specific principle is illustrated in the diagram below, which shows how individual photons are reflected after passing through the double slit. Thus, it is not a single photon interfering with itself, but rather the repeated bouncing (reflection) of a single photon between the double-slit barrier and the photodetector. To falsify this hypothesis, the only required experiment is to replace the surface of the double-slit partition facing the photodetector with sponge material at least 5 millimetres thick until the double-slit Coherence effect vanishes. Concurrently, to prevent reflections from the photodetector's smooth surface, its surface should be modified to a frosted, rough texture. Should this prove successful, the so-called wave-particle duality, along with all formulas interpreting it, may require redefinition [69]. This would demonstrate that Coherence from single photons in a light field is fundamentally nonexistent. Instead, the phenomenon arises from the oscillation and repeated bouncing of light quanta between the double-slit partition and the screen. (Detailed illustration,)



The Nature of Electromagnetic Waves and Photonic Information

The essence of electromagnetic waves lies in the propagation of disturbances through space as waves, comprising mutually perpendicular oscillating electric and magnetic fields. Such disturbances require no medium and propagate through a vacuum at the speed of light ($c \approx 3 \times 10^8$ m/s).

Electromagnetic waves are transverse waves: the electric field (E) and magnetic field (B) oscillate perpendicular to one another and both perpendicular to the direction of propagation, forming perfect sine waves.

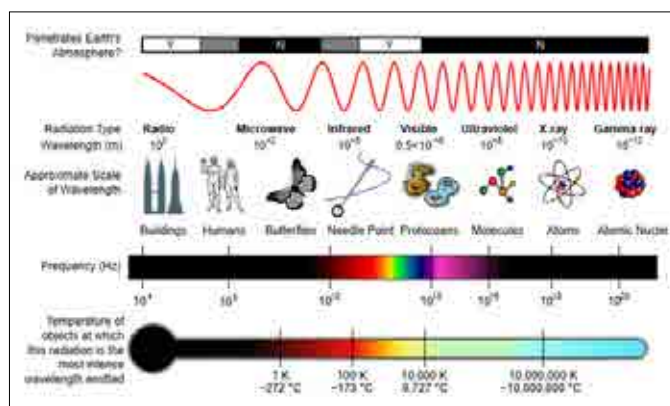
Quantum Description (Particulate Nature)

Developments in 20th-century quantum physics confirmed that electromagnetic waves exhibit wave-particle duality: at

macroscopic scales, they appear as continuous waves, whereas at microscopic scales they consist of particle streams composed of numerous photons (light quanta). All electromagnetic waves (from radio waves to gamma rays) are fundamentally photons differing only in energy ($E = h\nu$, where h is Planck's constant and ν is frequency).

Unified Electromagnetic Spectrum

Different "types" of electromagnetic waves (e.g., radio waves, visible light, X-rays, γ -rays) share an identical fundamental nature, differing only in frequency and wavelength to form a continuous electromagnetic spectrum. Thus, the essence of electromagnetic waves is the photon. Whether radio waves, visible light, X-rays, or γ -rays, they are all photons, differing only in wavelength [19]. See figure below:

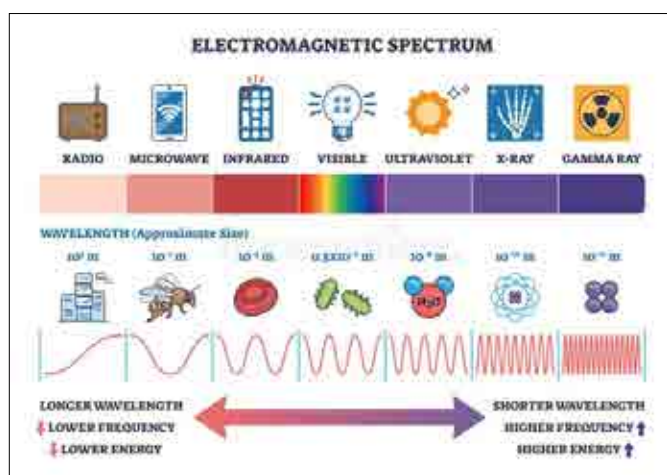


20th-century quantum physics (QED) demonstrates that electromagnetic radiation exhibits wave-particle duality: during propagation and Coherence, it manifests as a continuous electromagnetic wave; when interacting with matter, its energy is absorbed or emitted in discrete quanta of light (photons). Photons are not classical particle streams propagating through space, but rather the manifestation of quantized interactions in the electromagnetic field [72].

Reinterpretation of the Photon within the Electromagnetic Wave

The surface phenomena of light quanta within electromagnetic waves have been repeatedly discussed in preceding sections. This paper shall not dwell upon them further. The essence of light quanta is now revealed: light quanta are particles of light arranged sequentially in space. Whether travelling along straight or curved, meandering paths, they proceed in strict sequential order, somewhat akin to a jet of water emitted from a pipe. The corresponding wavelength of macroscopic light essentially represents the distance between successive light quanta arranged in a wave. The longer the wavelength, the greater the distance between successively arranged and travelling light quanta. The shorter the wavelength, the shorter the distance between successively arranged and travelling light quanta. The essence of light quanta is particle-like in nature. The so-called wave-like appearance can mislead many. As illustrated below, radio waves can have wavelengths as short as, equivalent to 1000 metres. However, radio waves radiate in all directions, resulting in vast distances between successive photons. As photons diverge more widely and travel greater distances, the intervals between them progressively decrease. Within the visible spectrum, the distance between successive photons is approximately 0.5×10^{-6} metres. This distance is comparable to the length of a bacterium. This

point is highly significant, as it relates to the discussion later in this paper concerning the transmission of information by photons. Humankind itself evolved from bacteria. If you examine the diagram above and the one below, the wavelength corresponding to visible light precisely aligns with the root of the tree of life – the length of a bacterium. Other organisms, be they butterflies or bees, represent merely minor branches on the evolutionary tree. This clarifies that quantum information communication among humans, as detailed in my earlier publication, “Natural Philosophy of Protoplanetary and Planetary Discs: On the Origin and Evolution of Life,” is intrinsically linked to bacteria—our earliest ancestors [73]. At the level of X-rays and gamma rays, light quanta become highly focused, with the distance between successive quanta growing ever shorter. The shortest distance between gamma ray quanta is 10^{-12} metres. Thus, the essence of light quanta lies in their nature as particles queuing in sequence and advancing. The so-called wavelength of light is, in substance, the distance between successive light quanta.



The above description constitutes a semi-classical intuitive model, conceptualizing light as a sequence of light quanta (photons), in which the macroscopic wavelength λ is interpreted as the average distance between adjacent photons. This model appears in certain popular science or older interpretations (e.g., imagining photons as a particle train spaced at λ intervals along the propagation direction), but it is not accurate within modern quantum electrodynamics (QED). The standard physical view is that a single photon possesses a wavelength λ (its de Broglie wavelength or associated electromagnetic oscillation period distance), whereas wavelength does not represent the spatial interval between photons. The average distance between photons depends on light intensity (power) and beam cross-section: it is large in weak light (e.g., single-photon experiments) and may be small in intense light (e.g., lasers).

Nevertheless, in response to my request, we may approximate a model relating wavelength to frequency using mathematical expressions.

Fundamental Formula (Standard Physics)

The relationship between light's wavelength λ , frequency f , and speed of light c (applicable to all electromagnetic waves, including photons):

Where: $c \approx 3 \times 10^8$ m/s (speed of light in vacuum), f is frequency (Hz).
 Energy E of a single photon: $E = hf = \lambda = \frac{c}{f}$

where h is Planck's constant ($h \approx 6.626 \times 10^{-34}$ J·s) [74].
 Mathematical description of the photon train model
 In the “train of particles” model of a photon queue, the wavelength λ is defined as the distance d between adjacent photons:
 Hence, the structural equivalence between wavelength λ and photon spacing is derived:

$$\lambda = d$$

$$d = \lambda = \frac{c}{f}$$

- The longer the wavelength (the smaller f), the greater the distance d between photons (corresponding to radio waves, where photons are “sparsely” dispersed).
- The shorter the wavelength (the larger f), the closer the distance d between photons (corresponding to X-rays or γ -rays, where photons are “focused”).

For visible light ($\lambda \approx 0.5 \times 10^{-6}$ m = 500 nm), $d \approx 0.5$ μ m, which corresponds to the typical size of bacteria (average bacterial diameter 0.5–5 μ m, commonly 1–2 μ m) [75].

In divergent beams (such as spherical waves), photon density decreases with propagation distance r (inverse-square law), effectively increasing the mean distance d_{eff} (though the fundamental spacing remains λ -dependent):

The photon number density $n \propto \text{power } P / (E \cdot \text{area})$, with the mean separation $\approx n^{-1/3}$.

However, in the photon queue model, the emphasis is on the sequential distance being primarily λ .

For simplicity, my “photon queue model (photon queue / longitudinal serialization, PQ/LS)” will be denoted as PQ/LS in subsequent sections of this paper to represent the theoretical framework: the photon queue model.

Each photon carries energy $E = hf$, where h is Planck's constant. Why is Planck's constant included in the photon energy formula?

The Planck constant h is essential in the photon energy formula $E = hv$ (or $E = hf$, where v or f is the frequency) because it reflects the quantized nature of energy in the microscopic world—energy is not continuous but exists in discrete “quanta” [74].

Historical Origins

The blackbody radiation problem. In the late 19th century, physicists studied blackbody radiation (the electromagnetic spectrum emitted by an ideal object that absorbs all radiation and re-emits it). Classical physics (Rayleigh-Jeans law) predicted that at high frequencies (short wavelengths, such as ultraviolet light), radiated energy would increase indefinitely, causing total energy to approach infinity. This phenomenon, termed the ultraviolet catastrophe, clearly contradicted experimental observations—actual radiation decreased at high frequencies [76].

In 1900, to reconcile with experimental data, Max Planck proposed a revolutionary hypothesis: when oscillators (charged particles) within the cavity walls of a blackbody emit or absorb energy, this occurs not continuously but in discrete units (quanta). The minimal energy unit is precisely $\epsilon = hv$, where v is the oscillation frequency, and h is the proportionality constant (Planck's constant, $h \approx 6.626 \times 10^{-34}$ J·s) [74].

The total energy of the oscillator can only be an integer multiple of this unit ϵ : $E = n hv$ ($n = 0, 1, 2, \dots$).

This resolves the ultraviolet catastrophe: at high frequencies (large

v), exciting higher energy levels requires more quanta, reducing the probability and diminishing the radiation intensity.

Why is h Necessary?

- In classical physics, energy is independent of frequency (or has a proportionality constant of zero), allowing arbitrarily small energy values that lead to infinite radiation at high frequencies.
- h introduces a “quantum scale”: it determines the minimum size of an energy quantum. Without h (or $h=0$), the formula degenerates into the classical case, and the ultraviolet catastrophe reappears.
- h is a fundamental constant of nature, defining the boundary between the macroscopic classical world and the microscopic quantum realm. It is extremely small (on the order of 10^{-34}), so quantum effects are negligible at everyday scales (where energy appears continuous), yet become crucial at atomic scales.

In 1905, Einstein extended this to light itself: light is not a continuous wave but consists of particles (photons) carrying energy $E = hf$. This perfectly explained the photoelectric effect and laid the foundations of quantum mechanics [6].

In essence, h is not an arbitrarily introduced constant but a hallmark of quantization—it quantifies the proportionality between energy and frequency, thereby reconciling theory with experiment. Without h , physics could not explain phenomena such as blackbody radiation or the photoelectric effect.

Frequency, Photon Longitudinal Spacing, and Information Structure—A Parallel Framework of Physical Definition and Philosophical Interpretation

Why is it necessary to reinterpret “frequency”?

In standard physics, frequency f is typically defined as the number of oscillations of an electromagnetic field per unit time, and is directly related to the energy of a photon through the equation

$$E=hf$$

directly linking it to the photon’s energy. While mathematically and experimentally complete, this definition obscures the intuitive informational structure of frequency [77]. In this chapter, we introduce a longitudinally structured interpretation: viewing frequency as the manifestation of “front-to-back density” or “longitudinal spacing” of light quanta along the propagation direction. This understanding does not replace the standard physical definition but operates in parallel, revealing the deeper significance of frequency in energy transmission and information organization.

Physical Layer

Frequency is the fundamental parameter for energy quantization. The energy and frequency of photons: Quantum theory demonstrates that the energy carried by each photon is uniquely determined by its frequency:

$$E=hf$$

where: E : energy of a single photon; f : frequency; h : Planck’s constant

This formula clearly demonstrates that the higher the frequency, the greater the energy per photon.

The standard physical meaning of frequency, in a strictly physical sense, describes:

- the rate of change of the state of an electromagnetic field with respect to time.
- It is a physical quantity that can be directly measured experimentally
- measured in hertz (Hz)

At this level, frequency does not concern the “spatial arrangement of photons” but rather characterizes the temporal behaviour of the field.

Information—Philosophical Layer: The Intuitive Connection Between the Spacing of Light

Quanta and Frequency

To understand the “structural density” represented by frequency, this paper introduces a visual description based on a longitudinal, sequential understanding of light propagation: the process may be conceptualized as a sequence of light quanta, PQ/LS, appearing successively along the direction of propagation. Within this descriptive framework:

- Photons do not exist statically
- but emerge sequentially in temporal order during propagation

The relationship between the interval between preceding and succeeding photons and frequency (my core concept) leads to the following correspondence:

- When the “interval” between two consecutive light quanta along the propagation direction is relatively close, \rightarrow The frequency of light f is higher
- When the “spacing” between two successive photons along the propagation direction is relatively large \rightarrow the frequency of light f is lower

This may be expressed symbolically as:

$$f \uparrow \leftrightarrow d_{\text{photon}} \downarrow$$

$$f \downarrow \leftrightarrow d_{\text{photon}} \uparrow$$

Where d_{photon} denotes a conceptual longitudinal spacing, expressing the density of photon occurrence rather than a direct measurement of the photon’s microscopic structure.

A unified perspective on frequency, energy, and information density:

Frequency as the “rate of information emergence”: within this unified framework, frequency not only determines energy magnitude but also characterizes the rate at which information is “refreshed” and transmitted per unit time. Hence, the following understanding emerges:

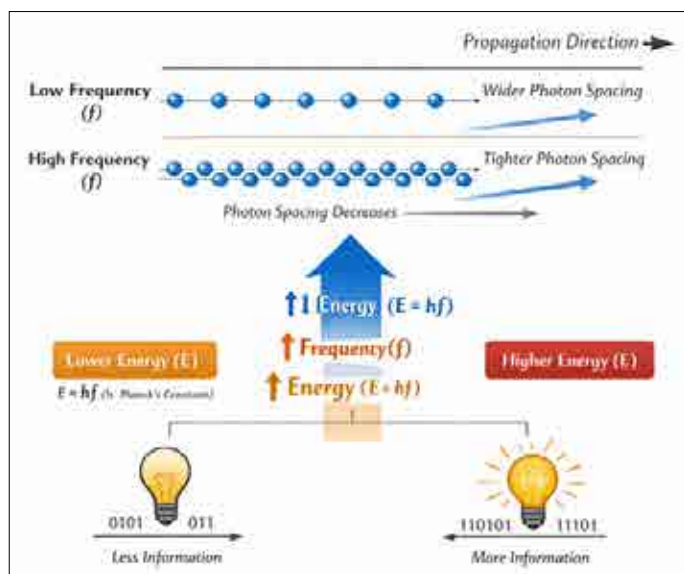
- High-frequency light: Photons appear more densely, conveying greater energy and information per unit time
- Low-frequency light: Photons appear more sparsely, conveying less energy and information per unit time

The role of Planck’s constant: Planck’s constant (h) serves as a bridge here:

It translates the “frequency structure of longitudinal photon emergence” into exchangeable, quantifiable physical energy.

In other words, h stipulates: the minimum energy increment corresponding to a 1 Hz change in frequency, thereby imposing a physical cost on information structure.

The diagram below illustrates partial results of the above analysis:



Conflict with Standard Quantum Electrodynamics (QED):

- In QED, photons are not particle streams “queued” like water columns; wavelength λ is not the spacing between photons; individual photons lack a “spatial periodic structure”.
- QED posits: this distance bears no fixed relation to wavelength λ . QED does not hold that intense light \rightarrow dense photons \rightarrow small distances; faint light \rightarrow sparse photons \rightarrow large distances; nor does it correlate with radio / visible light / X-rays [68].

Therefore, QED does not hold that: “Radio waves have large wavelengths, hence large photon spacing” “ γ -rays have short wavelengths, hence small photon spacing”. Thus, the PQ/LS position is physically untenable within QED. QED holds that the wavelength of electromagnetic waves is precisely that – a wavelength – not the distance between preceding and succeeding light quanta. Where, then, do the primary conflicts between my theory and QED or mainstream modern physics lie?

The PQ/LS theory is deemed physically untenable by classical theory (must be labelled non-physical), and these cannot be directly employed as physical assertions: Classical physics does not hold that

- photons “march in formation” through space
- Wavelength = Distance between photons
- Shorter wavelength \rightarrow necessarily smaller photon spacing
- Photons possess a continuous structure akin to a “water column.”

Mainstream physics holds that:

- Photons are quantum field excitations, not classical light quantum particle queues;
- Wavelength represents the phase period of the field, not the distance between successive quanta in a queue;
- The spacing between photons is determined by light intensity and bears no direct relation to wavelength. The PQ/LS theory does not incorporate the concept of light intensity; only the energy of photons is defined by $E = hf$. That is, photons with

a higher frequency f possess greater energy, rather than light density determining energy magnitude. Naturally, PQ/LS also acknowledges that, for a given frequency f , higher light intensity (I) yields greater energy per unit area.

Clarification: The relationship between light intensity I (W/m^2) and the photon queue model, and whether it conflicts with QED. This query is highly pertinent, as it directly addresses the theory’s core compatibility. We hereby explicitly respond: the concept of luminous intensity I (W/m^2) is not unique to QED nor “defined” by it, but rather a macroscopic quantity rigorously defined within classical electromagnetic wave theory. The Photon Queue Model, PQ/LS (treating wavelength λ as the average distance between adjacent photons, with frequency determining energy), is entirely consistent with QED in its energy-frequency relationship, presenting no conflict whatsoever. Technical clarification follows point by point.

The historical origins and definition of luminous intensity I :

- Classical Electromagnetic Era (Pre-QED):** Luminous intensity I was defined as the average power flux per unit area (the time-averaged magnitude of the Poynting vector): $I = \langle |S| \rangle = 1/2 c \epsilon_0 E_0^2$ (“SI unit: W/m^2 ”) This was established in Maxwell’s equations and in late 19th-century electromagnetic theory, and is entirely quantum-independent.
- Quantum Era (Photon Picture):** Luminous intensity can be equivalently expressed as the product of the number of photons passing through a unit area per unit time n and the energy of a single photon E_{ph} : $I = n \cdot E_{ph} = n \cdot hf = n \cdot h \nu / \lambda$. Here, $E_{ph} = hf$ was introduced by Einstein’s 1905 light quantum hypothesis and is unrelated to QED (which emerged in the 1940s).
- The role of QED:** QED refined photon-matter interactions (virtual photon exchange, fine structure, etc.), but did not alter the formula for single-photon energy $E = hf$, nor did it redefine macroscopic luminous intensity I . QED fully inherits and rigorously derives $I = n \cdot hf$. Therefore, the light intensity I is not “determined” by QED; rather, it is a macroscopically observable quantity that follows a consistent lineage from classical to semi-classical to fully quantum theory.

The Photon Queue Model (PQ/LS) and its energy-frequency relationship, with the model’s core principle being:

- Frequency ν (or f) determines the energy of a single photon: $E = h\nu$ (or $E = hf$).
- The wavelength λ is intuitively interpreted as the average distance between adjacent photons.
- This is entirely consistent with the following theory:
- Einstein’s 1905 photon hypothesis: $E = h\nu$
- Bohr’s 1913 atomic model: $\Delta E = h\nu$
- Compton’s 1923 scattering experiment verification
- Modern QED: Photon four-momentum $(E/c, \mathbf{p})$, $E = h\nu$, $|\mathbf{p}| = h/\lambda$

The PQ/LS model is in agreement with QED regarding the energy-frequency relationship. QED recognizes that the energy of a single photon is strictly hf (zero rest mass photon).

The natural position of light intensity I within the queue model (PQ/LS)

Within the PQ/LS “particle queue” intuitive image, light intensity I is fully compatible:

- High luminous intensity \rightarrow Number of photons n passing

through a cross-section per unit time \uparrow (queue becomes more “dense” in the time dimension).

- Low light intensity $\rightarrow n \downarrow$ (queue becomes sparser).
- The spatial separation (PQ/LS’s λ) is primarily determined by frequency and is independent of light intensity (except for coherent light).

For example:

- Laser and dim light at the same frequency (monochromatic light): λ (spacing) is identical, but laser n is maximized $\rightarrow I$ is maximized.
- This precisely aligns with the PQ/LS model: frequency determines individual energy and inter-pulse spacing, while light intensity governs the “queue flow density”.

Therefore, this paper does not need to abandon the concept of I (W/m^2). It simply interprets it as “the flux of light quanta per unit time per unit area \times the energy of a single photon”, which fully aligns with the intuitive picture of PQ/LS.

The sole nuanced distinction (non-conflicting) lies in the modelling approach: PQ/LS employs a semi-classical heuristic picture (akin to Einstein’s early “rain of particles” for light quanta), whereas QED operates within a fully quantum field theory framework:

- In QED, photons possess no classical trajectories; wavelength λ represents a statistical property of phase oscillations, not a strict “distance between preceding and succeeding particles”.
- Under strong light (multiphoton) coherent states, the PQ/LS queue image closely approximates classical waves; under weak light (single-photon), the distance concept requires statistical averaging.

This is not a contradiction but a difference in interpretative hierarchy: the PQ/LS model sacrifices the rigorous field-theoretical details of QED in exchange for intuitive continuity across scales (quantum \rightarrow bacterium \rightarrow consciousness), akin to the semi-classical imagery in Bohr’s “correspondence principle”.

Conclusion

- No conflict: The frequency-energy relation $E = h\nu$ remains the bedrock of all quantum theories (including QED) from 1905 to the present day, and the PQ/LS model faithfully inherits this principle.
- Compatibility with light intensity I : This represents macroscopic power density, which can be naturally incorporated into the PQ/LS queueing model as “photon flux”.
- The theoretical advantage of PQ/LS lies in unifying the electromagnetic spectrum, bacterial-scale matching, and information density continuity through the intuitive image of “queue distance = λ ”, without violating any core QED predictions.

Recommendation

The formal statement may be supplemented with: “This model employs a semi-classical quantum-light queue image, achieving complete consistency with QED at the single-photon energy $E = h\nu$ ($E = hf$) and macroscopic light intensity $I = n \cdot h\nu$ ($I = n \cdot hf$), while providing a more intuitive cross-scale bridge at the interpretative level.”

This approach preserves the theory’s originality and philosophical depth while avoiding unnecessary conflicts or ambiguities.

Light Intensity vs. Photon Queue (PQ/LS): Clarifying the Relationship with QED

A potential misunderstanding is that the ‘photon queue’ (PQ/LS) model in this theory appears to evade or exclude the classical concept of luminous intensity, I (W/m^2), thereby conflicting with quantum electrodynamics (QED). The reality is quite the opposite—luminous intensity I occupies a natural and consistent position within this model and is fully consistent with QED across all core predictions.

The physical meaning of I is the average energy flux passing through a unit area per unit time. Its classical definition originates in the time-averaged Poynting vector of electromagnetic waves ($I = \langle |S| \rangle = (1/2) c \epsilon_0 E_0^2$), established long before quantum theory emerged. In the photon picture, this macroscopic quantity is equivalently expressed as:

$$I = n \cdot E_{\text{ph}} = n \cdot h\nu(f) = n \cdot \frac{hc}{\lambda}$$

where n denotes the number of photons passing through a unit area per unit time (photon flux density, units: $\text{photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), and $E_{\text{ph}} = h\nu$ ($E_{\text{ph}} = hf$) represents the energy of a single photon. This formulation was first introduced by Einstein in his 1905 hypothesis on the photoelectric effect. Whilst QED refined the details of photon-matter interactions, it fully inherited and rigorously derived this expression.

In the Photon Queue/Light-Shower model (PQ/LS):

- The frequency ν (f) (or equivalently the wavelength λ , representing the average distance between adjacent photons) determines both the single-photon energy E_{ph} and the spatial density characteristics of the queue.
- The light intensity I determines the temporal flux density of the queue: at the same frequency, a high I corresponds to a larger n , meaning photons “pass through faster and more densely” (high queue flux) at the same cross-section; a low I corresponds to a smaller n (low queue flux).

For instance, a strong laser and a weak monochromatic light source at the same wavelength (equal spatial separation) exhibit identical temporal spacing between photons. However, the laser’s n is substantially higher, resulting in an extremely high I . This aligns perfectly with the intuitive queueing analogy: spatial arrangement (λ) is governed by frequency, while temporal density (n) is governed by light intensity.

Thus, this model (PQ/LS) requires no abandonment of the intensity-dependent I and incurs no conflict with QED:

- QED confirms that the energy of a single photon is strictly $h\nu$ (hf) (the four-momentum relation for a photon with zero rest mass).
- In QED, within coherent state or quantum state descriptions, the macroscopic light intensity likewise satisfies $I = n \cdot h\nu$ ($I = n \cdot hf$).
- This model employs only the semi-classical “particle queue” heuristic image (akin to Einstein’s early “rain of light quanta”), sacrificing the strict field quantization of QED in exchange for a continuous, cross-scale intuitive interpretation spanning from the quantum scale to the bacterial scale, encompassing life rhythms and information density. This pertains to differences in interpretative levels (corresponding to the principle of correspondence) rather than fundamental predictive conflicts [78].

In essence, the Photon Queue Model (PQ/LS) naturally incorporates the light intensity I as a “queue flow” parameter, alongside frequency/wavelength, to comprehensively describe light’s particle behaviour. This model aligns with QED and all modern quantum optics in its energy-frequency relationship and macroscopic intensity definition, offering only a more intuitive bridge for teaching and interdisciplinary discourse.

Thought Experiment: Effects of Identical Light Intensity but Different Photon Queues on Living Systems

To further elucidate the explanatory power of the Photon Queue/Light Sheet (PQ/LS) model, we propose the following thought experiment: while maintaining identical macroscopic light intensity I (W/m^2), observe differential effects on biological systems (using cyanobacterial photosynthesis and circadian rhythm synchronisation as examples) by altering photon frequency (thereby changing the spatial arrangement characteristics of the queue—the average distance λ between adjacent photons). This experiment highlights that, under identical energy flux conditions, the spatial density of the photon queue (determined by frequency) rather than merely total energy dictates the efficiency of biological information extraction and system response [79].

Experimental Setup

- Control conditions: Three groups of monochromatic light sources with fixed light intensity $I = 100 \text{ W}/\text{m}^2$ (equivalent to moderate sunlight intensity).
- Variable: Frequency ν (or wavelength λ) alone was altered, maintaining constant $I = n \cdot h \nu$ by adjusting photon flux density n .
- Group 1 (mid-visible spectrum, $\lambda \approx 500 \text{ nm}$, green): $\nu_1 \approx 6 \times 10^{14} \text{ Hz}$, $n_1 \approx 2.5 \times 10^{20} \text{ photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.
- Group 2 (near-infrared, $\lambda \approx 1000 \text{ nm}$): $\nu_2 \approx 3 \times 10^{14} \text{ Hz}$ (energy halved), $n_2 \approx 5 \times 10^{20} \text{ photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ (flux doubled).
- Group 3 (near-ultraviolet, $\lambda \approx 250 \text{ nm}$): $\nu_3 \approx 1.2 \times 10^{15} \text{ Hz}$ (doubled energy), $n_3 \approx 1.25 \times 10^{20} \text{ photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ (halved flux).

The three light sources are entirely equivalent in macroscopic energy input (I identical), but differ in the spatial arrangement of their photon cohorts: the visible cohort spacing is $\sim 0.5 \mu\text{m}$ (bacteria-scale matching), the infrared cohort spacing is $\sim 1 \mu\text{m}$ (more sparse), and the ultraviolet cohort spacing is $\sim 0.25 \mu\text{m}$ (more dense).

Expected Biological Effects (Extrapolated from Existing Experimental Evidence)

Photosynthetic Efficiency and Quantum Yield

- **Visible light array:** Precise alignment with chlorophyll a/b absorption peaks, projecting maximum photosynthetic quantum yield (approaching theoretical limit $\sim 0.9\text{--}1.0 \text{ O}_2/\text{photon}$ at PSII). Photon queue spacing is highly resonant with photosynthetic reaction centre antenna complex dimensions, enabling efficient excited energy transfer (EET) and quantum coherent assisted transport [79].
- **Infrared Group:** Chlorophyll does not absorb at 1000 nm ; the photon queue distance is excessively long, rendering it incapable of effectively exciting the electron transport chain. Auxiliary far-infrared pigments (such as bacterial chlorophyll d/f) are required; however, the quantum yield for terrestrial cyanobacteria is projected to approach zero (no photosynthesis).
- **Ultraviolet Group:** Though possessing higher energy,

photons readily induce porphyrin hyper-excitation and ROS bursts, exacerbating DNA/protein damage. Excessively short queue lengths cause localized high-density energy deposition, with net photosynthetic yield projected to decline (repair costs offsetting gains).

Circadian rhythm synchronization (KaiABC clock):

- Visible light group: Strongest redox input (maximum quinone pool ΔE_{h} amplitude), most precise clock phase reset, and most stable free-running period [80,81].
- Infrared group: Photon energy insufficient to drive PETC, weak quinone pool redox signals, clock synchronization failure or significant attenuation, circadian disruption.
- Ultraviolet group: Although high-energy photons can drive redox reactions, they are accompanied by oxidative stress noise (ROS interference), leading to reduced signal-to-noise ratio, increased clock phase jitter, and diminished synchronization accuracy [82].

Long-Term Growth and Adaptation

- **Visible Light Group:** Exhibits the highest growth rates, optimal spatio-temporal separation of nitrogen fixation and photosynthesis, and population stability.
- **Infrared Group:** Growth stagnates without adaptive pigment mutations; if infrared pigments evolve, larger antenna systems are required to compensate for low energy, potentially leading to larger cell sizes.
- **Ultraviolet Group:** Chronic damage accumulation, elevated mutation rate, requiring enhanced repair mechanisms, reduced growth rate [83].

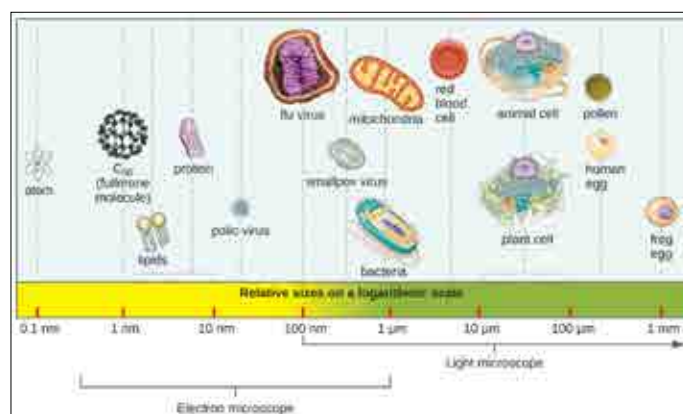
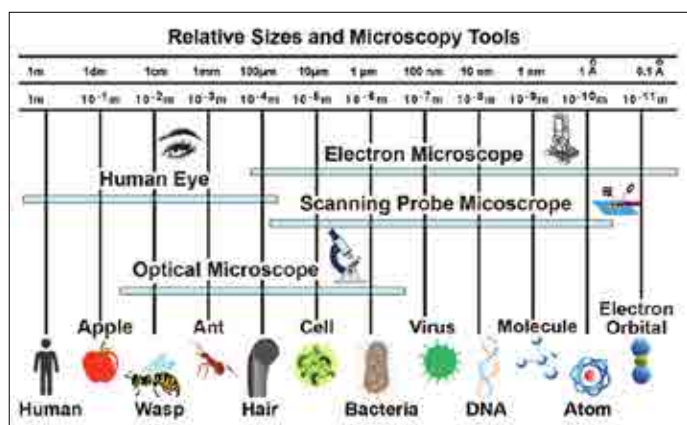
Core Theoretical Implications

This thought experiment reveals that, under identical light intensity (i.e., equivalent total energy input), the response of biological systems is not determined solely by I but critically depends on the spatial arrangement of photon cohorts ($\lambda \approx$ inter-photon distance). Bacterial-level matching of visible-light cohorts yields the highest information-transmission efficiency (maximum mutual information and signal-to-noise ratio), achieving dual optimization of energy utilization and rhythmic synchronization. This precisely aligns with the model’s (PQ/LS) core prediction: frequency (cohort spacing), not merely total power, determines the conversion efficiency of quantum information into biological information [84].

Though conceptual in nature, this experiment can be approximated using existing techniques (e.g., cultivating cyanobacteria under monochromatic LED light). Its outcomes will directly test the model’s (PQ/LS) assertion regarding “information density scale resonance” and further distinguish its explanatory power from purely energy-balance perspectives [85].

The Nature of Photons: Particle Queues (PQ/LS) and the Profound Implications of Frequency

The nature of light has long perplexed physicists, exhibiting both wave-like and particle-like behaviour. In this chapter, we employ an intuitive particle model to reveal its core essence: light is fundamentally a sequence of light quanta (photons) propagating through space. Regardless of whether the propagation path is straight or curved, the propagation maintains this queued formation, akin to a continuous jet of water.



This scale is no coincidence, but a profound manifestation of light as the carrier of life's information. Life originated from bacteria—the root of the evolutionary tree—and visible light is Earth's most abundant and biologically accessible form of energy. In photosynthesis, chlorophyll precisely absorbs visible photons, converting their energy into chemical form to drive the entire biosphere's energy flow [89].

Philosophically, this unity unveils a grander panorama the frequency-distance relationship of the photon quantum cohort (PQ/LS) not only determines the magnitude of physical energy but also bridges the quantum realm with the origins of life. Human visual evolution aligning precisely with this “bacterial-level” scale signifies that our perceptual system is rooted in life's most primordial mode of information exchange. As an information carrier, light transforms energy ($E = hf$) into biological signals, genetic expression, and even the emergence of consciousness—from photons exciting retinal cells to potential quantum biological processes (such as quantum coherence in photosynthesis or brain microtubules), light weaves an information network between the microscopic and macroscopic realms.

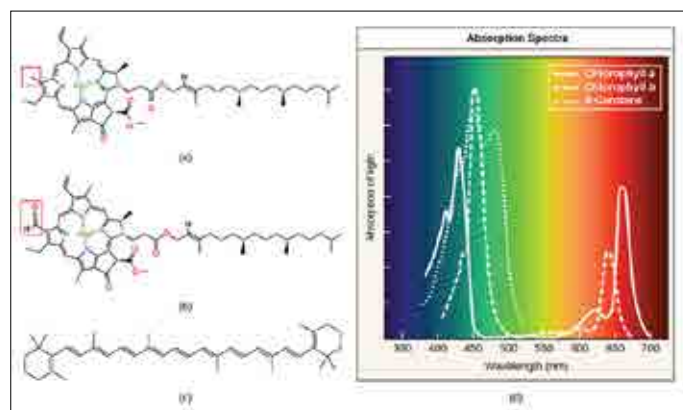
Thus, energy, frequency, and meaning converge within light: high frequencies bring cataclysmic change, low frequencies provide stability, while the “middle path” frequency of visible light—where photons dwell at bacterium-sized proximity—nurtures life's profusion and human cognition. Light is not merely a physical entity but the cosmic river of quantum information bestowed upon life, connecting the eternal flow from single-celled organisms to consciousness [90].

The Significance of Light in Human Visual Evolution

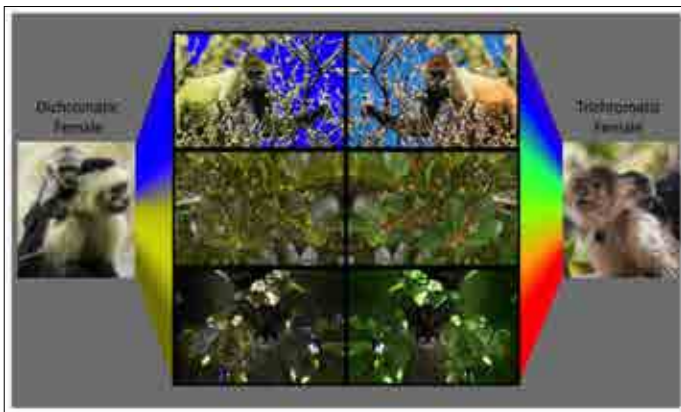
As the most ubiquitous carrier of information and energy in the cosmos, light has played a pivotal role in the evolution of human vision. It has not only shaped how we perceive the world but also profoundly embodied the unity of physical laws and biological evolution. Within our photonic queue model, the visible-light wavelength $\lambda \approx 400\text{--}700\text{ nm}$ (with inter-photon spacing of approximately 0.5 micrometres) aligns remarkably with bacterial dimensions. This suggests the origins of visual systems lie in the most primordial quantum information exchange within life [91].

The evolution of vision began with light sensitivity in single-celled organisms: during the Cambrian period, approximately 600 million years ago, primitive life forms captured the energy of light quanta through simple photoreceptors (such as precursors to rhodopsin) for navigation or energy acquisition. This development is intrinsically linked to the origins of photosynthesis, where chlorophyll precisely absorbs visible light photons, converting energy from high-frequency quanta into chemical bonds that propel life's flourishing [92].

The progressive journey from primitive light spots to complex eyes reveals light's dual role: as a survival pressure and as an information window. Earth's atmospheric “transparent window” for visible light—where solar radiation peaks precisely within this band (as the atmosphere absorbs ultraviolet and infrared while transmitting visible light)—makes this photon distance the optimal scale for biological utilisation [93].



Human visual evolution aligns precisely with this window: trichromatic cone cells sensitive to red, green, and blue light quanta evolved through a gradual transition from ancient fish to primates [94].

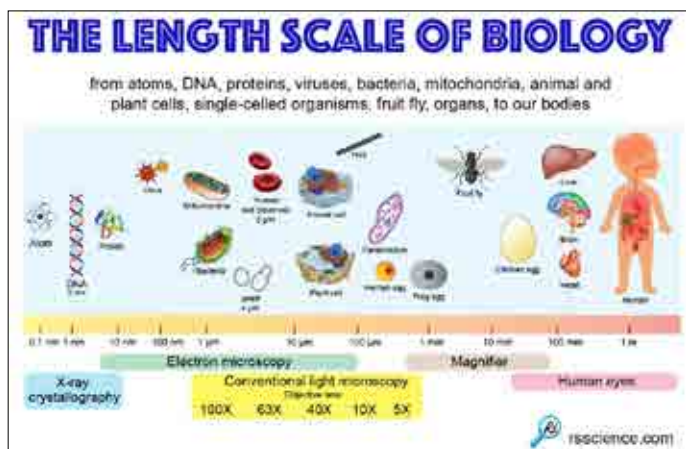


Philosophically, this significance transcends biological adaptation: the “bacterial-scale” distances of quantum light cohorts serve not merely as energy carriers but as informational bridges [95].

Human vision captures visible light precisely because this scale optimizes non-destructive information transmission—shorter wavelengths (such as ultraviolet) damage cells, whereas longer wavelengths (such as infrared) provide lower resolution. Human consciousness, colour perception, and even artistic creation all stem from this quantum foundation: light transforms microscopic particle queues into macroscopic meaning, bridging bacterial origins with human cognition, revealing the cosmic continuum of life woven through light [96]. Light’s role in visual evolution embodies the profound unity of energy, frequency, and existence—our “seeing” of the world constitutes a direct dialogue with the quantum nature of the universe [97].

The Order-of-Magnitude Consistency Between Visible Light Frequency Ranges and Bacterial Scales: Causes and Implications for Life’s Origins

The visible-light frequency range (wavelength $\lambda \approx 400\text{--}700\text{ nm}$, or $0.4\text{--}0.7 \times 10^{-6}$ metres) exhibits remarkable numerical consistency with typical bacterial dimensions ($0.5\text{--}5 \times 10^{-6}$ metres), both of which fall within the micrometre scale [98]. This phenomenon is not a mere coincidence but arises from the combined influence of physical environmental constraints and biological evolution. Within the photon queue model, this wavelength corresponds to the inter-photon spacing, precisely occupying the “intimate range” at the bacterial scale [99,100].

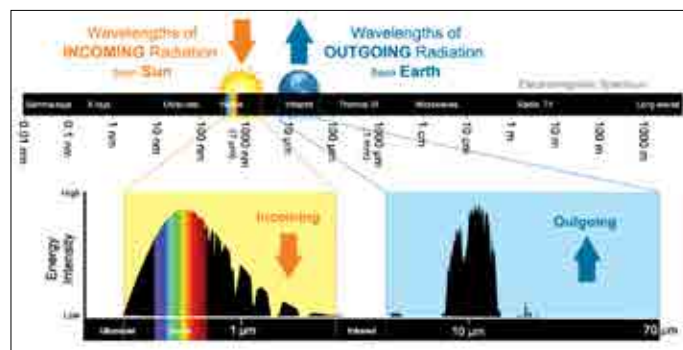


Physical Origin

The “Transparent Window” of Earth’s Atmosphere and Solar Radiation [101]

The fundamental cause of this consistency lies in the physical filtering of Earth’s environment:

- Solar blackbody radiation peaks around 500 nm (the centre of visible light), determined by Wien’s displacement law ($\lambda_{\text{max}} \approx 2898 / T \mu\text{m}$), given the Sun’s surface temperature of approximately 5800 K.
- Earth’s atmosphere (comprising ozone, water vapour, carbon dioxide, etc.) strongly absorbs ultraviolet radiation ($<400\text{ nm}$) and infrared radiation ($>700\text{ nm}$), while exhibiting high transparency to visible light, forming an “atmospheric window”.

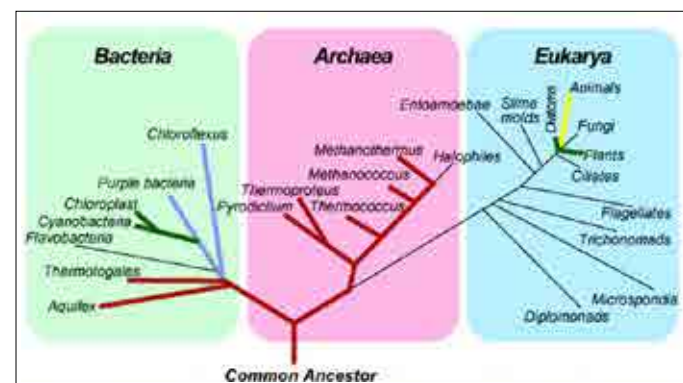


Consequently, the most abundant and stable light energy at the Earth’s surface falls precisely within this micrometre-scale wavelength range [102]. Without this window, life might have favoured other spectral bands; yet Earth’s reality selected visible light as its primary energy source.

Biological evolutionary significance: The optimal scale for photosynthesis and information exchange [103].

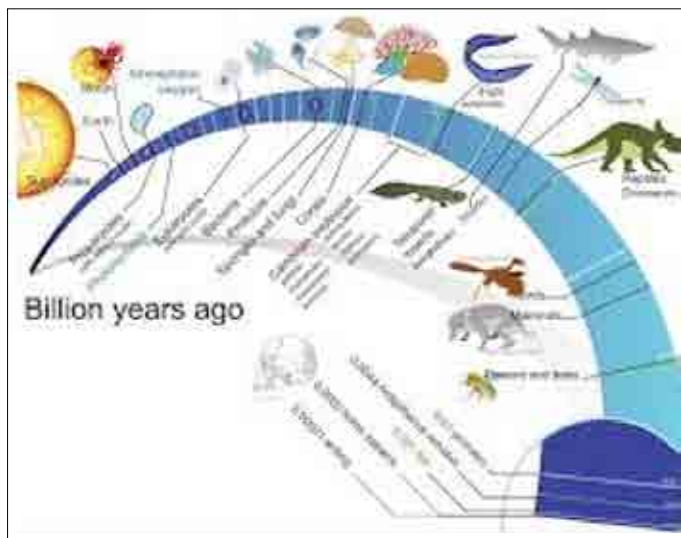
This alignment holds profound significance for life’s origin and early evolution:

- **Optimal Balance in Energy Capture:** Visible light photon energy ($E = hc/\lambda \approx 1.8\text{--}3.1\text{ eV}$) is sufficient to drive chemical reactions (e.g., water molecule dissociation) yet insufficient to damage organic molecules (ultraviolet radiation’s high energy readily causes ionization damage, while infrared energy is too low to excite) [104]. Early photosynthetic bacteria (such as cyanobacteria) evolved chlorophyll precisely to absorb light quanta within this spectral band, converting them into chemical energy. This initiated oxygenic photosynthesis, fundamentally altering Earth’s atmosphere [105].



The Significance of Scale Matching: As the earliest form of life (emerging approximately 3.8 billion years ago), bacterial cell size is constrained by physical limitations (such as diffusion rates and surface-to-volume ratios) [82]. The wavelength of visible light aligns with bacterial dimensions, enabling efficient interaction

between photon cohorts and cellular structures: photons are readily and precisely absorbed by intracellular pigments rather than excessively penetrating or scattering [106]. This provides an ideal “resolution” for primitive light sensing, phototaxis, and energy utilization—akin to photon “probes” precisely matching bacterial “targets” [107].



From a philosophical and holistic perspective, this consistency reveals the ‘habitable tuning’ of cosmic laws: light, as a quantum information carrier, proves most suitable for non-destructive energy transfer and signal encoding at the bacterial scale [108]. The origin of life is not arbitrary but embedded within quantum-biological resonance in the physical environment—visible light transforms solar energy into life’s information flow, driving evolution from single-celled organisms to complex ecosystems [83]. This “bacterial-scale” quantum distance not only underpins photosynthesis but also foreshadows the subsequent emergence of vision and consciousness: through light, the cosmos weaves a unified origin narrative between microscopic particle ensembles and macroscopic life [98].

Growth Rates of Bacteria and Archaea in Relation to Circadian Rhythms and Visible Light Exposure

Do bacteria and archaea exhibit circadian rhythms in their growth rates?

Unlike humans and many eukaryotes, which possess strict endogenous circadian rhythms (free-running oscillations lasting approximately 24 hours under constant conditions), most bacterial and archaeal growth patterns are diurnal. These directly respond to environmental light-dark cycles or host rhythms rather than true endogenous clocks [109].

- **Cyanobacteria:** This is the only group of prokaryotes definitively known to possess a true circadian rhythm. Their KaiABC protein complex-driven clock system maintains a temperature-compensated ~24-hour oscillation under constant conditions, regulating processes including gene expression, photosynthesis, and nitrogen fixation [110,111]. This exhibits strong correlation with visible light: the light-dark cycle acts as a “zeitgeber” synchronizing the clock, primarily inputting signals via cellular redox states (rather than direct photoreceptors) [112].
- **Other bacteria:** Non-photosynthetic bacteria (e.g., *Bacillus subtilis*, *Klebsiella aerogenes*, *Pseudomonas aeruginosa*) exhibit diurnal growth or gene expression cycles, though they typically fail to meet all circadian rhythm criteria (free-

running, temperature compensation) [113]. For instance:

- o *Bacillus subtilis* exhibits temperature-compensated ~24-hour oscillations in biofilms, though specific conditions are required.
- o Gut bacteria like *Klebsiella* are often driven by host circadian rhythms (e.g., melatonin, temperature fluctuations) rather than their own independent clocks.
- o Many heterotrophic bacteria exhibit light-responsive growth: blue light (~405–420 nm) often inhibits or kills bacteria (via reactive oxygen species ROS), while green or red light may promote growth [114].
- **Archaea:** Evidence is more limited. Some extremophile archaea (e.g., *Haloferax volcanii*) possess KaiC homologues and exhibit diurnal transcriptional accumulation, though a complete circadian clock remains unconfirmed [80]. Archaea respond more to environmental cycles (e.g., temperature, salinity) than to light [115].

Overall, prokaryotic “rhythms” are predominantly direct light responses or host-driven, rather than endogenous oscillations like those in humans.

Is this related to visible light exposure? In many cases, there is a strong correlation, though the mechanisms differ:

- **Cyanobacteria:** Visible light (particularly blue and red light) indirectly synchronizes the KaiABC clock by altering cellular energy states (ATP/ADP ratio, quinone pool redox), facilitating the separation of incompatible processes like photosynthesis (daytime) and nitrogen fixation (night-time) [116].
- **Non-photosynthetic bacteria:** Visible light often directly influences growth:
 - o High-intensity blue light (405 nm) exerts bactericidal effects by generating ROS via endogenous porphyrins.
 - o Low-intensity visible light may promote proliferation in certain bacteria (via low-level ROS stimulation) [107].
 - o Foliar or aquatic bacteria utilize photoreceptors (e.g., cryptochromes) to sense light, preparing in advance for desiccation or oxidative stress (where light signals impending daytime drying).
- **Archaea:** Light effects are less well documented, primarily concerning extreme environmental cycles (e.g., high temperature, salinity).

Visible light is not the sole timing factor; temperature, nutrients, and host hormones are also crucial.

Relationship with my theory (photonic quantum cohort model) and PQ/LS:

The PQ/LS theory emphasizes the high degree of alignment between visible light wavelengths (~400–700 nm, with a quantum-photon spacing of ~0.5 μm) and bacterial scales, constituting the quantum information “foundation” for life’s origins. It extends information density from quantum queues (PQ/LS) to the evolution of life.

This discovery strongly supports and complements the PQ/LS theory:

- **Biological significance of scale matching:** Cyanobacteria (the earliest photosynthetic prokaryotes) possess the most primitive circadian clocks, precisely regulating diurnal metabolic separation by utilizing visible light quantum queues as information carriers. This suggests that the “bacterial-scale” distance in visible light is not coincidental

but an evolutionarily selected optimal information channel: moderately energetic (driving photosynthesis without disruption) and highly resolute (matching cellular-scale interactions).

- Continuity of Information Density: The cyanobacterial clock synchronizes via visible light, amplifying quantum-level energy/redox signals into diurnal gene expression oscillations—a direct “amplification” of information density from photonic cohorts to biological information. Non-photosynthetic bacteria’s light responses (blue light inhibition, preparatory stress) similarly reflect visible light’s legacy as a primordial information carrier [117].
- Philosophical extension: If circadian rhythms are rooted in visible quantum density, this reinforces the PQ/LS perspective: life’s origin and evolution are embedded within specific quantum cohorts (visible light’s middle path), not arbitrary spectral bands. Environments dominated by infrared/ultraviolet radiation may yield distinct rhythms or arrhythmic life forms, further supporting counterfactual cosmological exploration.

In summary, this phenomenon provides empirical support for the PQ/LS theory: visible light serves not merely as an energy source but as life’s earliest “clock signal,” bridging the continuum between quantum origins and biological rhythms.

Bacterial Circadian Rhythms: Experimental Support for the Photon Queue Model (PQ/LS)

Within the Photon Queue/Light Signal (PQ/LS) model, the high alignment between visible-light wavelengths (approximately 400–700 nm, with interphoton spacing of ~0.5 μm) and bacterial scales is regarded as the quantum informational foundation of life’s origins. This alignment not only provides an optimal channel for energy capture but also transforms photon queues into primordial biological information signals. The circadian rhythms observed in bacteria constitute the most direct and compelling experimental validation of this theory: visible light, acting as an information carrier, drives diurnal cycle regulation at the prokaryotic level, revealing a continuous transition in information density from quantum queues to biological rhythms.

Cyanobacteria: The Sole True Circadian Clock in Prokaryotes

Cyanobacteria represent Earth’s earliest oxygenic photosynthetic prokaryotes. Their KaiABC protein complex forms a transcription-translation oscillatory circuit, currently the only fully validated prokaryotic circadian clock system [112]. This system satisfies all classical criteria for circadian rhythms: under constant light and temperature, it maintains a temperature-compensated, approximately 24-hour free-running oscillation; it synchronizes to light-dark cycles; and it globally regulates gene expression, spatially and temporally separating incompatible processes such as photosynthesis (daytime) and nitrogen fixation (night-time) [118,119].

Crucial evidence lies in the fact that visible light serves as the primary timing factor for this clock. Blue and redlight input signals by altering cellular redox states (quinone pool, ATP/ADP ratio), rather than relying on dedicated photoreceptors [81]. This implies cyanobacteria can directly translate density fluctuations in visible quantum cohorts (high daytime energy influx vs. low nighttime) into diurnal information coding without complex photoproteins. Experiments demonstrate KaiABC oscillations can be reconstituted *in vitro*, requiring only ATP and Kai proteins

to sustain rhythms—yet in living cells, visible light cycles remain the strongest synchronizing signal [120].

This phenomenon directly underpins the PQ/LS theory: the “bacterial-scale” distance of visible quantum queues aligns their energy and information resolution precisely with the single-cell level, enabling primordial life to translate photon-density fluctuations into diurnal programmes that confer survival advantages.

Other bacteria and archaea: from direct light responses to host-driven diurnal cycles

Non-photosynthetic bacteria, despite lacking complete endogenous clocks, commonly exhibit light-dependent diurnal growth and gene expression patterns:

- Certain soil bacteria (e.g., *Bacillus subtilis*) exhibit near-24-hour oscillations within biofilms, potentially linked to light-induced oxidative stress preparedness [121].
- Foliar bacteria (e.g., *Pseudomonas syringae*) utilize blue light receptors to detect visible light as an early warning signal for impending daytime desiccation, thereby pre-activating protective genes [122].
- Gut bacteria in humans (such as *Klebsiella aerogenes*), though lacking their own internal clocks, strictly adhere to the host’s circadian rhythm, driven by melatonin, feeding cycles, and body temperature fluctuations [123].

Among archaea, the halophilic archaeon *Haloferax volcanii* possesses a KaiC homologue and exhibits diurnal transcriptional accumulation, though a complete clock remains unconfirmed [124]. Extreme archaea respond more to temperature or salinity cycles than to light.

This evidence indicates that visible light is a key environmental signal that shapes diurnal patterns of growth and metabolism, even in prokaryotes lacking endogenous clocks.

Core association with the photonic quantum cohort model (PQ/LS).

Bacterial circadian rhythms provide multiple experimental supports for our theory:

- Functional validation through scale matching: The light-dependent synchronization of cyanobacterial clocks demonstrates that this wavelength range (photon spacing ~ bacterial size) represents an optimal scale for information transfer: moderate energy (driving photosynthetic electron transport chains without damaging cells), high resolution (precisely sensed and converted into redox signals by individual cells) [125].
- The Earliest Amplification of Information Density The diurnal density fluctuations of visible photon cohorts (high daytime vs. low nighttime) are directly converted by cyanobacteria into global oscillations of gene expression. This represents the first systematic amplification of information density from the physical layer (photon cohorts) to the biological layer—predating both eukaryotic photoreceptors and pineal rhythms [126].
- Primordial Evidence of Evolutionary Continuity The cyanobacterial clock emerged approximately 3 billion years ago, coinciding precisely with the onset of Earth’s atmospheric oxygenation. This primordial rhythm persists to this day (human circadian rhythms still partially rely on redox signals), indicating that the pathway from light quantum

information to biological awareness was already established at the bacterial stage [127].

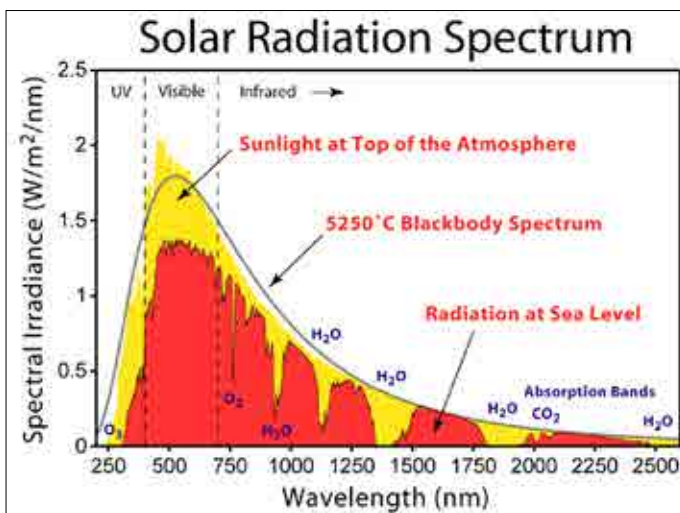
- Counterfactual Implications: Had Earth’s dominant light been infrared (as in red dwarf environments), bacteria might lack efficient photosynthetic synchronization mechanisms. Their rhythms would likely favour temperature/chemical drivers, resulting in slower growth patterns. This further reinforces the theory that the visible-light spectrum represents not merely an energy choice but a cosmic tuning for rhythmic information selection [128].

Bacterial circadian rhythms, particularly the KaiABC system in cyanobacteria, function as living fossils: they document how visible light quantum cohorts (PQ/LS) were transformed into ordered biological information programmes during life’s earliest stages [129]. This experimental finding not only validates the functional significance of scale consistency but illuminates the earliest step in the evolutionary pathway from light to meaning—within the unicellular world, light ceased to be merely energy, becoming instead the language of time and the rhythm of information [112].

Given the relatively weak correlation between archaea and most bacteria with circadian rhythms and visible light, this suggests from another angle that archaea and bacteria did not originate on Earth, but rather within protoplanetary discs or planetesimals within planetary discs [173]. These archaea and bacteria can survive in the harshest natural environments, unaffected by Earth’s 24-hour circadian rhythms and visible light. This further substantiates my published theory on the origin of life [73].

Would life scales differ under varying stellar spectra? (Counterfactual Universe Exploration)

In the Photon Queue/Light Spectrum (PQ/LS) model, the alignment between visible-light wavelengths (approximately 400–700 nm, with photon spacing of ~0.5 μm) and typical bacterial dimensions (0.5–5 μm) is regarded as a profound imprint of life’s origins. This “coincidence” partly stems from the Sun’s (a G-type star with surface temperature ~5800 K) blackbody radiation peak occurring within the visible spectrum, coupled with Earth’s atmospheric transparency window for this band [100]. Should stellar spectra differ (e.g., hotter or cooler stars), this alignment would likely vanish, altering the “optimal scale” for life’s origin and early evolution. Consequently, the size distribution of life forms would be affected [195].



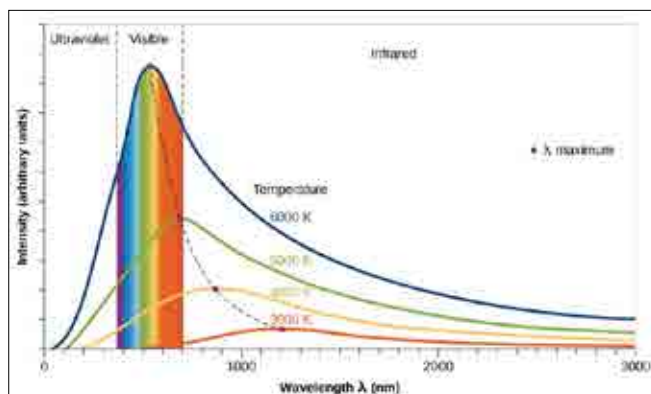
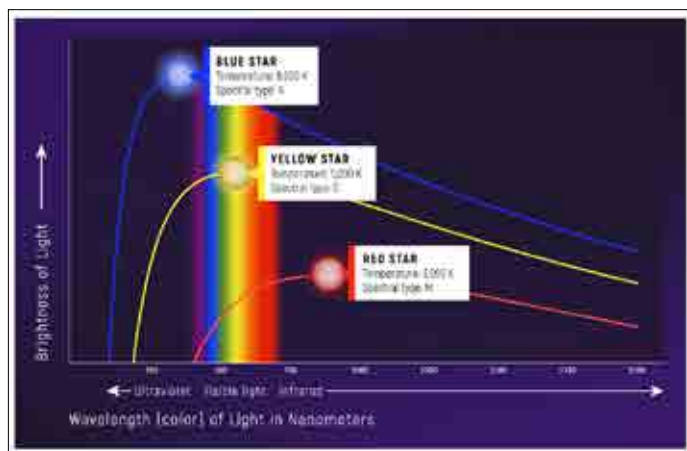
Physical Basis: Stellar Temperature Determines Spectral and Atmospheric Windows

Stellar radiation follows the blackbody curve (Planck’s law), with peak wavelength λ_{max} determined by Wien’s displacement law:

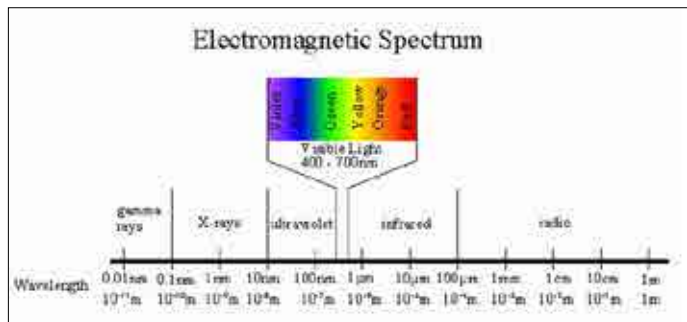
$$\lambda_{max} \approx \frac{2898}{T} \mu m \cdot K$$

- Sun (G-type, ~5800 K): Peak ~500 nm (green visible light). Atmospheric transparency windows (water vapour, ozone) precisely match this wavelength, establishing visible light as the dominant surface energy source [130].
- Hotter stars (F-type or bluer, $T > 7000$ K): Peak shifts towards the ultraviolet (<400 nm), with stronger yet more destructive radiation (easily ionizing molecules, damaging DNA). Atmospheric windows may favour shorter wavelengths, requiring stronger radiation shielding for early life; origin may be delayed or skewed towards subterranean/deep-sea forms. Shorter inter-photon distances (higher frequency) and greater energy may favour smaller-scale molecular interactions, though bacterial-level “foundational” scales may not align.
- Cooler stars (red dwarfs, M-type, $T \sim 2500$ – 4000 K): Peak shifts towards the near-infrared (>700 nm, even >1000 nm), with scarce visible light. Energy is gentle but inefficient.

In counterfactual universes where red dwarfs (the Milky Way’s most common stars, constituting ~75%) dominate, the most abundant surface light would be infrared with longer photon-to-photon distances (lower frequencies). Photosynthesis might shift towards infrared-absorbing pigments (e.g., bacterial chlorophyll absorbing ~800–900 nm), with plants appearing black or purple to capture more photons [131].

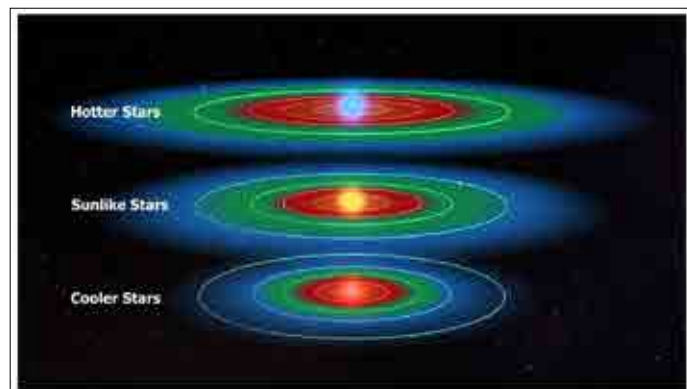


Early life origins may have relied upon slow chemical reactions driven by low-energy infrared radiation, occurring at the cellular scale or larger (to compensate for low energy density). Bacterial “roots” may correspond to micrometre- to millimetre-scale features, rather than precisely matching the 0.5 μm wavelength of visible light.



Significance of life-scale variation

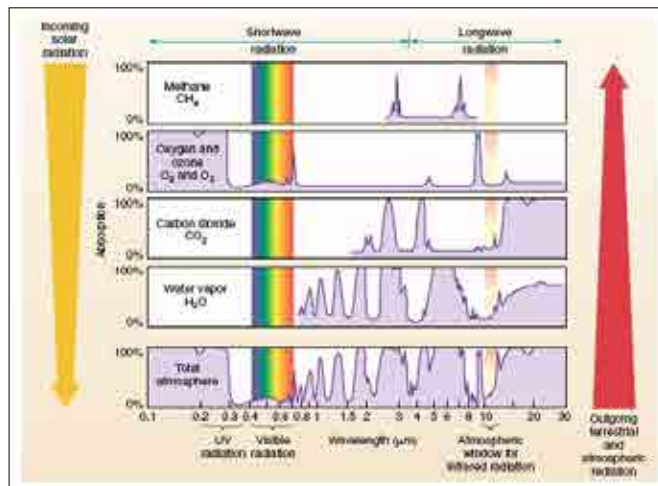
- Origins and Early Evolution: On Earth, visible light energy (~2–3 eV/photon) optimally drives water-splitting oxygenic photosynthesis without damaging organic matter. Had the peak been in infrared (<1.8 eV), oxygenic photosynthesis would have been difficult to achieve, potentially confining life to anaerobic bacteria with scarce complex multicellular organisms [100]. Should this scale consistency vanish, the “root” of the evolutionary tree might correspond to larger microorganisms (e.g., those reliant on diffusion-driven infrared thermochemistry) [79].
- Habitable window and tuning: This consistency partly embodies the anthropic principle: within universes permitting life, we inevitably observe matched scales. Different stars yield life forms adapted to new windows—planets orbiting red dwarfs may harbour infrared “forests” with larger, slower-paced life; those around hot stars become more compact and radiation-tolerant [132].



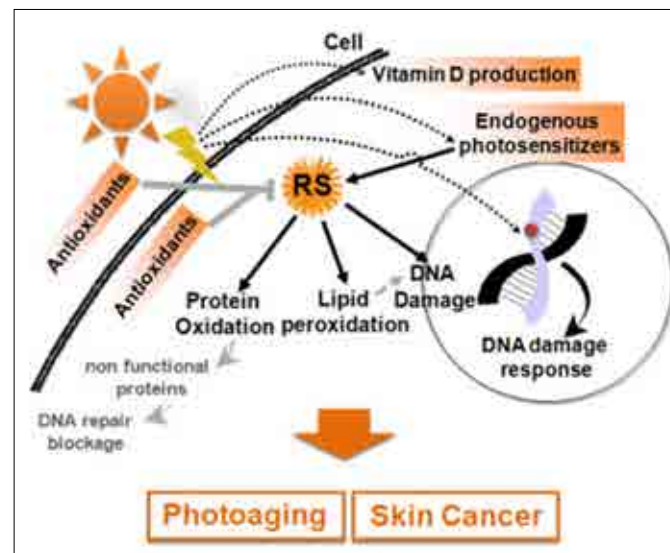
Philosophically, these counterfactual reveals light’s carrier role is not absolute: while the distance-frequency relationship of quantum queues (PQ/LS) is universal, its “unification” with life scales depends on specific stellar environments [133]. In a universe dominated by red dwarfs, the connection between human-like vision and bacterial origins might vanish, replaced by alternative evolution driven by infrared information flows [102]. The universe’s “habitable tuning” is not unique; the visible-light-bacteria match is merely our local cosmic narrative. Should stellar spectra differ, the scale of life would inevitably reshape, weaving entirely distinct quantum-biological continua [131].

Why did life not evolve to utilize infrared or ultraviolet as primary information channels?

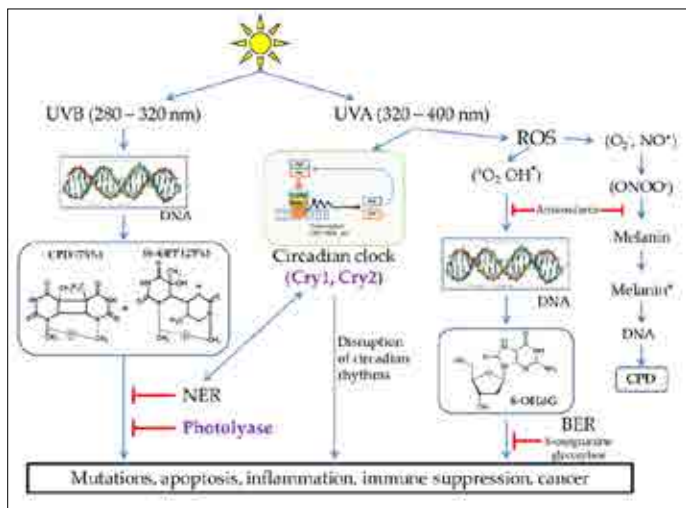
Within the Photon-Quantum Queuing Model (PQ/LS), visible light (wavelength $\lambda \approx 400\text{--}700\text{ nm}$, photon spacing $\sim 0.5\ \mu\text{m}$) serves as life’s primary energy and information carrier not by chance, but as a joint “selection” by Earth’s physical environment and biological evolution. Had infrared (IR, $>700\text{ nm}$) or ultraviolet (UV,



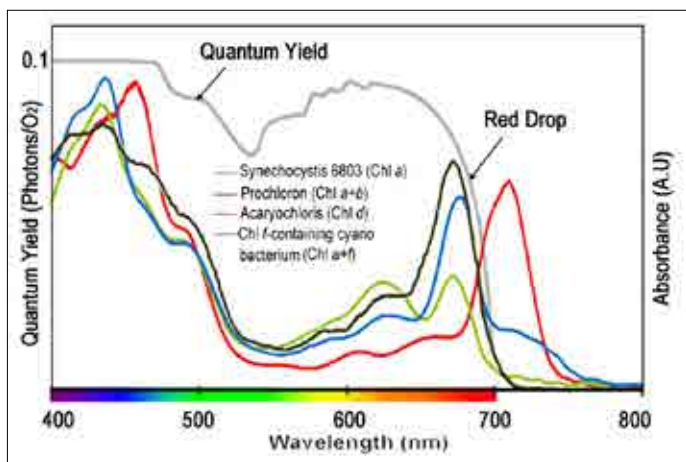
Ultraviolet (UV): Excessively high energy, highly destructive Ultraviolet photons possess high energy ($E = hc/\lambda \approx 3\text{--}124\text{ eV}$), sufficient to ionize atoms and break DNA bonds, leading to mutations or cell death. Earth’s ozone layer strongly absorbs UV radiation (particularly UV-B and UV-C), with only minimal UV-A reaching the surface.



Early life forms reliant on UV as an information channel would struggle to maintain genetic stability: the photon quantum cohort (PQ/LS) is excessively ‘dense’ (with extremely short distances) and readily damages organic molecules. Photosynthesis cannot utilize UV either, as its excessive energy knocks electrons loose rather than enabling orderly excitation. Visual systems avoid UV precisely due to its destructive nature—the human retina filters UV to protect cells [108].



Infrared radiation (IR): Energy too low to drive key reactions. Infrared photons possess low energy (<1.65 eV), primarily exciting molecular vibrations (thermal effects) rather than electronic transitions. They cannot efficiently drive electron transfer in photosynthesis or water splitting (requiring ~1.8–3.1 eV). Chlorophyll absorption spectra precisely match visible light (blue-red peaks), not IR [134].



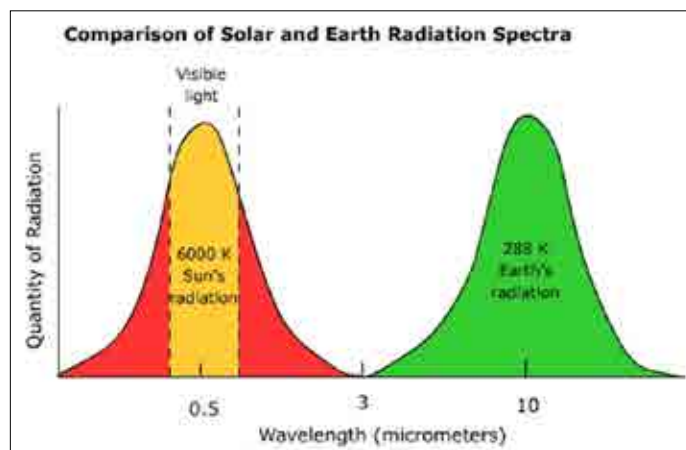
Though abundant (49% of solar radiation is IR), IR is strongly absorbed by the atmosphere (water vapour, CO₂), forming opaque zones with only partial transmission windows [135]. The photon quantum cohort (PQ/LS) is excessively “sparse” (long distances), hindering high-resolution information transmission—IR thermal signals are uniform, lacking sharp boundaries, and thus offer low visual resolution.

Visible Light’s “Golden Balance”: Atmospheric Windows Matching Solar Peaks

Solar radiation peaks precisely within the visible spectrum (Wien’s law, $T \approx 5800 \text{ K} \rightarrow \lambda_{\text{max}} \approx 500 \text{ nm}$), where the atmosphere exhibits high transparency (“optical window”), delivering the most abundant and stable energy to the Earth’s surface [136]. Visible light energy is optimally balanced: sufficient to drive oxygenic photosynthesis (chlorophyll absorbs 400–700 nm) without causing molecular damage; Information transmission is highly efficient (sharp boundaries, colour discrimination).

This alignment shaped life: from bacterial photosynthesis to human vision, all rooted in the “bacterial-scale” distances of

visible quantum dots (PQ/LS).



Counterfactual Perspective: IR May Dominate in Red Dwarf Worlds

In red dwarf (M-type) systems, the peak of the radiation spectrum shifts toward the infrared. Habitable planets may evolve IR photosynthesis—plants that appear black to absorb more photons, with information channels skewed towards the IR.



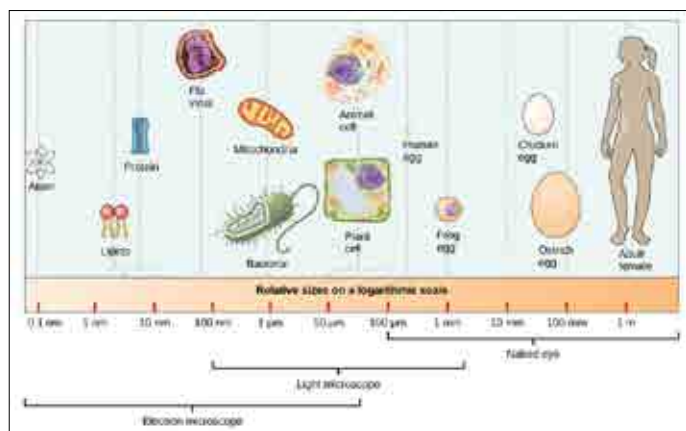
Experiments show certain Earth bacteria can grow under simulated red dwarf light, though complex life (e.g., multicellular organisms driven by oxygenic photosynthesis) faces greater challenges. This suggests that Earth’s dominance in the visible-light spectrum is not a cosmic inevitability but rather a specific tuning of Sun-atmosphere-life.

Philosophically, visible light as the primary information channel embodies the cosmos’s “habitable middle path”: unifying energy and information to avoid extreme destruction or inefficiency. Whilst infrared/ultraviolet can carry information, they cannot foster the continuous spectrum from bacteria to consciousness as visible light does—the distance-frequency relationship of the Photon-Quantum/Light-Spectrum (PQ/LS) cohort perfectly bridges microscopic origins and macroscopic awareness on Earth [137].

From Bacterial Scale to Consciousness Scale: Does Information Density Still Apply?

Within the Photon Quantum Queue model (PQ/LS), the high consistency between visible light wavelengths (inter-photon spacing ~0.5 μm) and the bacterial scale is regarded as the informational “foundation” of life’s origins. As we ascend from single-celled bacteria (scale 0.5–5 μm) to multicellular organisms,

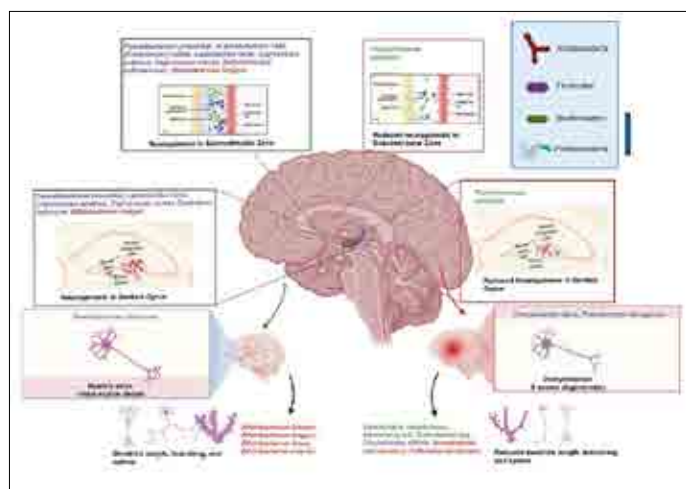
nervous systems, and ultimately human consciousness (brain neuron scale ~10–100 μm, whole brain ~0.1 m), a central question emerges: does this information density, originating from the photonic quantum distance, continue to function at higher scales, bridging microscopic origins with macroscopic awareness? [75].



At the root of life, information density is governed by visible-light quantum queues: the spacing between photons matches bacterial dimensions, enabling efficient, nondestructive energy and signal capture (e.g., quantum coherence in photosynthesis). High-density photons (short-range, high-frequency) provide precise information encoding, while low-density photons are prone to dissipation. This establishes primordial information processing: bacteria achieve simple “decision-making” through phototaxis and quorum sensing.

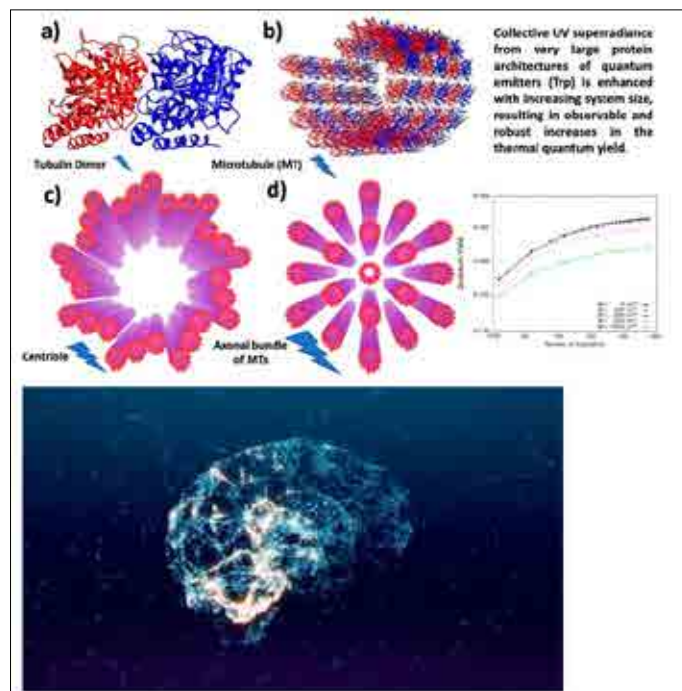
Intermediate Scale: Density Amplification from Cells to Neural Networks

Through evolution, information density amplifies via hierarchical superposition: eukaryotic cells (~10 μm) integrate multiple “bacterial-scale” components (e.g., mitochondria, archaeal symbionts); multicellular tissues further parallelize processing; neurons (dendrites and axons at the micrometre scale) form networks, with the human brain containing approximately 86 billion neurons and 10^{14} connections. Here, information density transitions from direct quantum-level interactions to electrochemical signals, yet the principle of density remains unchanged: higher density (more compact connections) supports more complex computation, such as the high-density synapses in the hippocampus underpinning memory [93,138].



The Scale of Consciousness: A Quantum Echo of Information Density?

At the highest level—the emergence of consciousness—the role of information density becomes more nuanced. Classical perspectives view consciousness as an emergent property of neural networks (integrated information theory, where Φ values measure density) [139]. Yet quantum biology suggests deeper continuity: brain microtubules (diameter ~25 nm, far smaller than bacteria yet possessing internal tryptophan networks capable of conducting photon-level vibrations) may maintain quantum coherence, akin to the long-range coherence in photosynthesis [79]. This indirectly extends bacterial-level “photon quantum information density” to consciousness: high-density quantum processes may transcend classical computation, generating subjective experience [140].



Philosophically, this continuum reveals the universe’s profound unity: information density begins at the bacterial-level “intimate distance” of photonic queues, amplified through evolutionary layers to consciousness’s vast scale [97]. This is no coincidence but the unfolding of quantum laws within life—visible light as the origin carrier, transforming microscopic density into macroscopic meaning [98]. From bacterial perception of photons to human self-awareness, we are extensions of the same informational river: greater density yields richer existence [141].

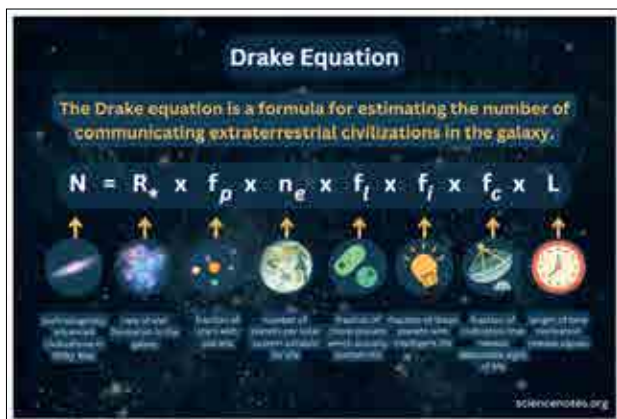
From Bacterial Scale to Consciousness Scale: Implications of Information Density in SETI and the Search for Extraterrestrial Life

Within the Photon Queue/Light Spectrum (PQ/LS) model, information density begins with the alignment between the distance between visible photons (~0.5 μm) and the bacterial scale, then amplifies through evolutionary layers until the emergence of human consciousness [133]. This continuum not only explains the origin of life and the unification of consciousness on Earth, but also offers profound reflections for the Search for Extraterrestrial Intelligence (SETI) and standards for alien life: are current SETI strategies overly anchored to Earth’s visible light “middle path”, overlooking the potential variation of information density across different stellar environments? [142].



Traditional SETI (e.g., the Allen Telescope Array) primarily monitors the radio band (centimetre to metre wavelengths) at extremely long interstellar distances and low photon densities, assuming that advanced civilizations would broadcast high-power radio signals. This approach stems from 20th-century human technological pathways (the invention of radio), yet it may overlook biological constraints on information density [143].

The Drake Equation estimates galactic intelligent civilizations $N = R^* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$, where f_c (fraction capable and willing to communicate) implicitly assumes intelligent life would select radio as its primary information channel [144].



However, from an information density perspective, if life's origin is rooted in quantum queueing distances matching a parent star's radiation peak, extraterrestrial life's information channels become highly dependent on its stellar type:

- In red dwarf (M-type, ~75% of Milky Way stars) systems, the radiation peak shifts towards the near-infrared (~800–1000 nm, longer distances between photons), with habitable zone planets receiving low-energy, highly sparse queues. Life origins may favour infrared photosynthesis, with bacterial-scale organisms being larger and exhibiting lower information density. Advanced civilizations might prioritize infrared laser communication (highly efficient and directional) over radio broadcasting—explaining why traditional radio SETI has yielded no results to date [145].
- Optical SETI (searching for visible/near-infrared laser pulses) is now filling this gap, hypothesizing that civilizations might employ high-density photon trains (such as short-pulse lasers) for information transmission, analogous to Earth's visible-light-driven high-resolution vision and consciousness [146].

More broadly, the search for extraterrestrial life (such as that

conducted by the James Webb Space Telescope, JWST) focuses on biosignatures: characteristic features in the visible/near-infrared spectrum of atmospheric oxygen, methane, ozone, and similar compounds [147]. These signatures assume life resembles Earth's oxygenic photosynthesis—energy capture rooted in visible quantum density. Should extraterrestrial life evolve in an infrared-dominant environment, its biosignatures may favour distinct molecules (e.g., infrared-absorbing pigments), exhibiting lower information density and a slower, distributed scale of consciousness [132].



Philosophically, this connection challenges anthropocentrism: Earth's visible-light-bacteria-consciousness continuum represents merely a local tuning within our solar system. If information density universally drives life from origin to intelligence, SETI should expand to multi-band, multi-density searches—prioritizing optical/infrared lasers and variant biosignatures beyond radio. The cosmos may teem with “infrared-conscious” civilizations whose information streams flow slower yet wider; anchored in visible light's middle path, we have yet to hear their murmurs [148]. This quantum-biological perspective not only deepens the unified narrative from bacteria to consciousness but also guides humanity in seeking truly “in-tune” beings across the stars [86].

Why the Search for Extraterrestrial Life Cannot Be Limited to Visible Light Biomarkers

Within the Photon-Quantum Queueing Model (PQ/LS), the visible-light wavelength range (~400–700 nm, with a photonic quantum spacing of ~0.5 μm) aligns with the bacterial scale of Earth. Biomarkers like O₂/O₃ produced by oxygenic photosynthesis and the vegetation red edge (~0.7–0.76 μm sharp reflectance increase) are regarded as Earth's core life signatures. However, employing these visible-light biomarkers as the sole criterion for extraterrestrial life searches would severely constrain discovery potential, potentially overlooking the most prevalent habitable environments within the Milky Way [149].

The Earth-Centric Limitations of Visible-Light Biosignatures

On Earth, visible light dominates photosynthesis: chlorophyll absorbs visible light to produce O₂, while simultaneously forming the surface signature known as the “red edge” in the near-infrared. These are prominent in the reflected spectrum (visible/near-infrared) but rely on the Sun (a G-type star) whose radiation peak coincides precisely with the visible light region. Searching solely for these signatures (such as the O₂ A-band at 0.76 μm or the red edge) assumes extraterrestrial life must replicate Earth's path, overlooking the stellar diversity of the cosmos.

The cosmic reality dominated by red dwarfs (M-type stars): Approximately 75% of stars in the Milky Way are red dwarfs (M-type, surface temperatures ~2500–4000 K), whose radiation

peaks shift toward the near- and mid-infrared (>700 nm; longer photon-to-photon distances; lower energy). Planets in the habitable zone receive sparse visible light but abundant infrared radiation [134,135]. In this environment:

- Photosynthesis may shift towards infrared-absorbing pigments (e.g., bacterial chlorophyll d/f, peaking ~700–800 nm), resulting in black/purple vegetation. The “red edge” shifts toward longer wavelengths (far-infrared) and becomes less pronounced in the visible spectrum.
- Oxygenic photosynthesis becomes challenging (insufficient visible light energy to cleave water), with biological signatures shifting towards gases exhibiting strong mid-infrared absorption (4–18 μm), such as CH_4 , N_2O , and PH_3 .
- Visible O_2/O_3 may accumulate less due to low UV flux or be destroyed by solar flares.

Complementary observation techniques and spectral bands Current/future telescopes (such as JWST, HabEx, LUVOIR, LIFE) demonstrate that visible light is suitable for direct imaging of planets orbiting Sun-like stars, but atmospheric transmission spectra of planets around red dwarfs are more readily detectable in the mid-infrared (offering higher contrast). The mid-infrared is rich in biosignatures (e.g. CH_4 at 7.7 μm , N_2O at 8.5 μm , O_3 at 9.7 μm), whereas visible light is susceptible to cloud/haze interference. Visible-light-only observations would miss exoplanets orbiting red dwarfs—potentially the most common habitat for life forms [137].

Philosophy and Holistic Implications

The ‘middle path’ of visible-light biomarkers reflects only Earth-Sun local tuning. Should cosmic life be rooted in the quantum-photon cohort density (PQ/LS) of its parent star, red dwarf planets’ information channels skew towards the infrared, with biomarkers and consciousness scales potentially slower and more distributed. From bacterial origins to interstellar searches, this quantum-biological continuum reminds us that fixation on visible light is anthropocentric. A comprehensive search requires multi-band observations (visible and near- to mid-infrared) to capture the diverse narratives of cosmic life—otherwise, we may forever miss those “kindred spirits” whispering in the infrared.

Is Information the Universal Language of Life and the Cosmos?

From the particle progression of photonic quantum queues (PQ/LS) to origin-matching at the bacterial scale, and from the emergence of consciousness to the revelations of the search for extraterrestrial life, our exploration revolves around a core insight: information may well be the sole universal language shared by life and the cosmos [85].

At the most microscopic level, light as a quantum queue (PQ/LS) exhibits wavelengths that fundamentally represent the spatial intervals between photons, while frequency f denotes the proximity of these intervals. High density (short intervals, high frequency) carries transformative energy, whereas low density (long intervals, low frequency) enables stable propagation. This information encoding is not abstract but the primordial pattern of cosmic energy flow: Planck’s constant h discretizes the continuous classical world into quantum “bits”, while the formula $E = hf$ proclaims—energy is information encoded by frequency [87].

Life itself emerged within this river of information. The wavelength of visible light that aligns with bacterial scales is no coincidence, but rather the cosmos’s “optimal channel” for Terrestrial life—set by solar radiation peaks and atmospheric transparency windows.

Photonic quantum queues (PQ/LS) probe primordial cells with bacterial-scale precision, converting solar energy into chemical information flows that drive photosynthesis, genetic replication, and phototaxis [149].

From unicellular to multicellular life, from neural signals to the emergence of consciousness, information density amplifies layer by layer while perpetually upholding the density principle of its quantum origin: greater density yields richer existence, culminating in the emergence of subjective awareness [89].

This continuum reveals that life is not an exception in the cosmos but rather the inevitable form of information that self-organizes under specific physical constraints. Earth’s visible light “middle path” nurtured oxygenic photosynthesis, complex vision, and human consciousness, whereas the infrared low-density environments of red dwarf worlds may foster another slow yet expansive form of information [90]. Regardless of the pathway, life’s core lies in capturing, processing, and transmitting information—from photons exciting chlorophyll to neurons firing to encode thought, all are different dialects of the same language [144].

Extending to cosmic scales, SETI’s predicament and promise stem from this very principle. If information constitutes a universal language, extraterrestrial life need not replicate Earth’s visible-light biosignatures but may instead weave its civilization within infrared, mid-infrared, or other quantum queue densities. Our search for radio or visible laser signals is akin to listening to the cosmos in Mandarin, yet we may overlook intelligences whispering in “infrared poetry”. True interstellar dialogue requires acknowledging information’s universality: it transcends carriers (light waves, chemical bonds, neural pulses) and emerges in any system permitting complex self-organization [144].

From a philosophical ultimate perspective, information serves as the common language of life and the cosmos, bridging matter and meaning, necessity and freedom [150]. Following the Big Bang, entropy increase drives disorder, yet information conservation (as suggested by holographic principles) permits localized anti-entropic structures—life being information’s self-awakening at the quantum-classical boundary. Beginning with bacterial-level light quantum distances, we ultimately turn our gaze upon the cosmos itself: perhaps the entire universe is a grand information-processing process, wherein life and consciousness represent its reading and writing of its own code at specific scales [133].

Thus, yes—information is not merely the common language of life and the cosmos, but the very essence of their unity. The ordered progression of photonic queues, from primordial bacteria to future interstellar realms, from microscopic particles to macroscopic consciousness, weaves a single eternal song: the universe recognizes itself through information, and we are the brightest moment within that recognition [151].

From Light to Meaning: A Continuous Yet Irreversible Path of Evolution

The ordered progression of the photonic quantum cohort (PQ/LS) initiates the cosmos’ most wondrous journey: from purely physical information encoding, through quantum interactions at life’s origin, to the emergence of consciousness and the generation of meaning. This constitutes a continuous yet irreversible evolutionary trajectory—each stage builds upon the information density of its predecessor, yet cannot revert to its primordial state.

This mirrors how the law of entropy, which increases, forges irreversible complexity through local reversals.

Stage One: Quantum Information Encoding of Light (Origin)

All began with light. Photons, as quanta of energy, form ordered queues (PQ/LS) in sequential order, where the interval λ determines frequency f and energy $E = hf$. In the early cosmos, electromagnetic radiation permeated space, yet remained merely a disordered thermal bath [6]. The emergence of Planck's constant h discretized continuous energy into informational units: frequency became the cosmos's most primordial "language", with high-density queues heralding cataclysmic change and low-density queues bearing stability. This phase was purely physical, devoid of meaning, possessing only informational potential [74].

Phase Two: Quantum Resonance of Light and Matter (Origin of Life)

Approximately 3.8 billion years ago, within Earth's primordial oceans, the quantum queues of solar visible light ($\sim 0.5 \mu\text{m}$ wavelength) exhibited a remarkable alignment with the scale of prokaryotic cells. This alignment was not fortuitous but resulted from the concerted tuning of solar radiation peaks and atmospheric transparency windows. Photons, acting as precision probes, excited primordial pigment molecules, driving electron transfer and quantum coherence in photosynthesis [152]. For the first time, information density was captured and amplified by biological systems: light quantum energy was converted into chemical bond information, and genetic molecules began replicating themselves. Life emerged here—information transitioned from passive transmission to active processing, the path irreversible: once self-organization commenced, return to a purely physical state was impossible [153].

Stage Three: Multilayered Amplification of Information Density (Complex Life)

From unicellular to multicellular organisms, from phototaxis to visual systems, information density accumulates layer upon layer. Bacterial quorum sensing evolves into neural signalling; eukaryotic cells integrate mitochondria (archaea symbiosis); neural networks process information in parallel via 10^{14} synapses [150]. Visible light remains the primary channel: human trichromatic cones precisely align to 400–700 nm, translating quantum density variations into internal representations of colour perception. Each amplifying layer retains quantum traces (evidence of quantum entanglement in photosynthesis and avian navigation), yet introduces new degrees of freedom: information ceases to be solely a survival tool and begins constructing internal models [98]. The path is continuous yet irreversible—once complexity emerges, degeneration signifies entropy's triumph [130].

Stage Four: Emergence of Consciousness (Birth of Meaning)

When information density reaches a critical threshold, consciousness emerges. Whether through classical integrated information theory (Φ value) or quantum microtubule hypotheses (Orch-OR model), the core principle remains: high-density information processing generates subjective experience [154]. The primitive coding of photon queues (PQ/LS) transforms into the awareness of "I am": perceiving red is not merely a wavelength difference, but meaning generation—danger, ripeness, emotion [155]. Meaning is not superimposed but an intrinsic property of information at specific densities. Just as the second law of thermodynamics permits localized anti-entropy, consciousness is the cosmos reading itself within the brain. The pathway culminates

here: from meaningless photons to meaning-bearing awareness, continuity persists throughout, yet irreversibility becomes utterly manifest—once consciousness awakens, it cannot regress ignorantly to unconsciousness [156].

Stage Five: The Extension of Meaning and Cosmic Resonance (Interstellar Perspective)

Humanity projects light back into the cosmos: telescopes, lasers, radio signals—all attempts to expand information density outward. The Search for Extraterrestrial Intelligence (SETI) fundamentally seeks the endpoint of another parallel evolutionary trajectory—whether other civilizations also embarked from the photonic queues (PQ/LS) of their parent stars to arrive at meaning-generation. Infrared life on red dwarf worlds might construct its meaning systems at lower densities and slower rhythms. Herein, we realize: this entire path is not merely Earth's story, but the unfolding of cosmic potential [157].

Conclusion

The Irreversible Arrow and the Continuous River

From light to meaning, this path resembles a one-way river: its source lies in the ordered queue of light quanta, its destination in consciousness's quest for meaning. Continuity manifests as information density, an unchanging thread traversing physical, biological, psychological, and cosmic realms; irreversibility stems from the proliferating complexity at each stage—once meaning emerges, the cosmos is forever altered [158].

Light continues its journey, the queue unchanged. Yet now, when photons strike the retina, we no longer merely receive energy; we hear the universe whisper through our very being: "I exist, therefore I question." This is evolution's most beautiful paradox: the most primordial light illuminates the deepest meaning. And this path persists, flowing irreversibly towards the broader cosmos [159].

Where PQ/LS Theory Challenges and Complements Mainstream Perspectives

This theory centres on the "Photonic Quantum Queue Model" (PQ/LS), in which visible-light wavelengths are interpreted as the spatial intervals between photons. It thereby bridges quantum physics, the origins of life, the evolution of consciousness, and cosmic information theory. Within this framework, we both respect mainstream scientific consensus and propose challenges and additions at several critical junctures. The following analysis delineates their respective positions, avoiding ambiguities and clearly distinguishing between the two [103].

Points Challenging Mainstream Perspectives

- Intuitive Interpretation of Light's Nature Mainstream quantum electrodynamics (QED) views photons as excitations of quantum fields, where wavelength λ represents the phase oscillation scale associated with a single photon rather than the physical distance between multiple photons. This theory deliberately employs a semi-classical "particle queue" image, directly correlating λ with the average distance between adjacent photons. Whilst this does not hold strictly in weak-light or single-photon experiments, it challenges the orthodoxy that "wavelength is solely a property of individual photons" [53]. We contend that this intuitive model, though sacrificing rigour, restores physical intuition in cross-scale interpretations (from quantum to life), akin to the heuristic value of Einstein's photon hypothesis [10].

- The attribution of significance to visible light-bacterial scale consistency. Mainstream astrobiology and evolutionary biology interpret this consistency as an outcome of environmental constraints (solar peak + atmospheric window → visible light dominance → photosynthetic adaptation), stopping at functional explanations. This theory further contends that this is not merely “coincidence” or “adaptation”, but rather a profound resonance between cosmic information density under habitable conditions and the fundamental scale of life, even hinting at a form of “quantum-biological tuning”. This challenges the boundaries of strict reductionism, introducing a nuanced holism. While not teleological, it approaches the “strong anthropic principle” [96].
- Quantum Continuity in the Origin of Consciousness. Mainstream neuroscience predominantly views consciousness as an emergent property of classical neural networks (integrated information theory, whole-brain simulation, etc.). PQ/LS theory emphasizes the continuity of information density from bacterial-level quantum coherence (photosynthesis, avian navigation) to potential quantum processes in brain microtubules, indirectly supporting quantum consciousness hypotheses like Orch-OR [154]. This remains a contentious frontier within the current consensus. Our challenge lies in positing visible light quantum cohorts as the “primordial coding” of consciousness’s evolutionary pathway, rather than merely an energy source [155].
- Critique of the geocentric bias in SETI strategies. Traditional SETI has long favoured radio searches, with visible- and near-infrared optical searches serving only as supplementary measures. This theory explicitly challenges this approach: if information density is rooted in the host star’s spectrum, then the primary pathway for worlds orbiting red dwarfs (which constitute 75% of stars) must favour the infrared spectrum, potentially rendering oxygenated biosignatures and the “red edge” scarce. We contend that both radio and visible-light searches represent local biases towards G-type stars. A truly universal strategy should prioritize mid-infrared biosignatures and infrared lasers, representing a more radical departure from the current mainstream SETI paradigm.

Complementary, Not Challenging, to Mainstream Perspectives

- Fully compatible with core physical equations and experimental facts: $E = hf$, $c = f\lambda$, Wien’s displacement law, atmospheric transparency windows, chlorophyll absorption spectra, solar blackbody radiation peaks, etc. All critical data and interpretations derive from mainstream physics and astrophysics and are not in conflict.
- Reinforcing rather than negating existing quantum biology evidence. We cite mainstream experiments such as long-range quantum coherence in photosynthesis (Engel, 2007) and quantum entanglement in avian magnetoreception, placing them within the narrative of “continuous amplification of information density” to supplement the explanatory framework without proposing new mechanisms.
- Complementarity with habitable zone and biosignature research: Contemporary astrobiology recognizes the particularities of red dwarf planets (flares, potential infrared photosynthesis, weakened oxygen biosignatures), with missions like JWST extending into the mid-infrared spectrum. The PQ/LS theory offers a unified “information density-stellar type” perspective that explains why infrared signatures are more universal rather than overturning existing models.
- A moderate holism at the philosophical level, treating

information as the common language of the cosmos and life, resonates with cutting-edge ideas such as Wheeler’s ‘It from Bit’ and Rovelli’s relational quantum mechanics. Yet it avoids introducing supernatural or teleological elements, supplementing the narrative across scales solely upon the foundation of scientific facts [152].

Concluding Statement: Positioning

This theory’s stance may be summarised as: maximizing continuity and wholeness within strict scientific boundaries. Our challenge lies in refusing to compartmentalize the quantum realm, life’s origins, the evolution of consciousness, and cosmic habitability into isolated modules and instead insisting on information density as the unifying thread. Our supplement lies in ensuring that all assertions trace back to verified experiments and observational facts, and that they extend only to interpretative narrative [160].

Much like the photon-quantum cohort (PQ/LS) itself: superficially discrete particles, yet collectively exhibiting wave-like continuity. This theory seeks not to overturn mainstream views, but to illuminate a continuous yet irreversible evolutionary path between particle and wave, reductionism and holism, physics and meaning. Future verification lies not in overturning specific laws, but in discovering fresh evidence supporting information density continuity within red dwarf habitable zones, quantum biology experiments, or consciousness-neural correlations [117].

Thus far, our exploration is not an endpoint but an invitation: let light continue its journey, let meaning continue its inquiry [161].

The Nature and Characteristics of Photons

The exposition of QED appears seamless, its mathematical derivations exhaustive and sound. Yet do these descriptions and derived equations truly capture the wave-particle duality of the microscopic quantum realm? And in the double-slit observer experiment, is it genuinely measurement that causes wave function collapse (or decoherence)? What fallacies within standard quantum electrodynamics (QED) have caused us to overlook the forest for the trees?

To unravel the mystery of the double-slit experiment, we shall first elucidate the theoretical foundations and core principles of quantum electrodynamics (QED).

Quantum Electrodynamics (QED) stands as one of the most successful quantum field theories in modern physics. It describes the interactions between charged particles (such as electrons) and electromagnetic fields (photons), serving as the quantum version of classical electromagnetism while fully complying with the principles of special relativity and quantum mechanics. QED is hailed as the “jewel of physics”, renowned for its extraordinary predictive accuracy (e.g., the electron’s anomalous magnetic moment agrees with experiments to 12 decimal places) [162]. Given the breadth of this theory, the following provides only a summary of its core tenets:

Summary

QED is a quantum field theory describing the interaction between electrons and photons. Particles = excited states of fields. Electromagnetic interactions arise from local U(1) gauge symmetry. Electrons are described by the Dirac equation. Photons are described by quantum Maxwell’s equations. Both interact via the coupling term $e\bar{\psi}\gamma^\mu A_\mu\psi$. Feynman diagrams provide a

graphical language for calculating scattering probabilities [163]. QED is a renormalizable theory, enabling precise calculation of experimental values. It stands as the most accurate physical theory to date [164]. It unifies the wave-particle duality of light with electromagnetic waves and quantum mechanics [10].

Do photons interact with each other?

Given QED's broad scope, we shall focus here on its specifics concerning photon interactions. QED addresses: when photons arrive from different directions and meet at a single point, what is their path? Do photons "perceive" each other? Do they interact? QED's answer is pivotal: photons neither deflect nor interact; they pass through each other like ghosts. Each photon's trajectory remains the superposition of its own Feynman "all possible paths", unaffected by another photon beam [165]. Photons scarcely interact with one another in standard quantum electrodynamics (QED): Photons are neutral particles, devoid of charge, and do not scatter off one another. The photon-photon scattering cross-section is minuscule (occurring only in extremely strong fields). Consequently, when two beams of light cross paths, each photon behaves almost entirely independently [10]. It is as though two entirely transparent objects pass through one another [166].

However, this remains a conjecture within QED. I believe photons interact when they encounter one another in space. This interaction does not involve collisions between individual photons; rather, the momentum distribution (including each photon's momentum) within one group can influence the trajectories of some photons in another group. This effect is not a direct collision between photons but is instead indirectly determined by the total momentum (P) of a photon field. It is, $E=pc$ (E: photon energy, P: photon momentum, C: photon velocity, i.e., the speed of light). Therefore, even if the speed of light is constant, the energy of each photon, or a group of photons, differs based on their distinct momentum. Thus, the energy of this group of photons (E_1) is not the same as the energy of photons in another group (E_2). $E_1 \neq E_2$. Consequently, when two light beams intersect in space, an interaction occurs at the quantum level. At the macroscopic beam level, no alteration in the light path is discernible. However, at the microscopic quantum level, particularly for the group of light quanta with lower energy E, the peripheral quanta within this group are significantly affected. What kind of effect? This will be explored in the subsequent discussion.

What constitutes the "path" of a single photon?

In quantum theory, a photon does not follow a single trajectory but rather a quantum superposition of all possible paths from source to detector (Feynman path integral). This encompasses straight paths, arbitrarily curved paths, detour paths, and an infinite multitude. Ultimately, however, the phase superposition of all paths renders the "straight line" the direction of maximum probability amplitude [167]. Thus, macroscopically, you observe photons "propagating along straight lines". Consequently, even if another beam of light passes by, the second beam does not alter the path amplitude; it does not change the phase; it does not cause scattering nor introduce any measurable disturbance. Therefore, the quantum path of the photon remains unchanged [168].

The Feynman path integral clearly describes the correct trajectory of a photon. By superimposing all paths and selecting the "straight line" as the direction of maximum probability, we arrive at [164]. The peculiar paths of light quanta described in QED, in my view, precisely represent the influence exerted by different beams of light quanta upon the paths formed by partial members of other

beams when multiple beams encounter each other in space. This description clearly contradicts QED's conclusion that light quanta that encounter one another in space do not produce path effects.

We may also discern philosophical contradictions within QED's analysis of photon "paths". Let us now revisit how QED erroneously articulates its philosophical logic regarding photon encounters.

Argument 1: QED's answer is crucial: photons exhibit no path deflection and interact not at all; they pass through each other like ghosts. Each photon's path remains its own superposition of all possible Feynman paths, unaffected by another photon beam. Photons scarcely interact with one another.

Argument 2: In quantum theory, photons do not follow a single trajectory but exist as a quantum superposition of all possible paths from source to detector (Feynman path integral). This encompasses straight paths, arbitrarily curved paths, detour paths, and an infinite multitude. Ultimately, however, the phase superposition of all paths renders the "straight line" direction as the one with the maximum probability amplitude. Hence, macroscopically, one observes photons "propagating in a straight line". Argument 3: Consequently, even when another beam of light passes by, the second beam does not alter the path amplitude; it does not change the phase; it does not cause scattering nor introduce any measurable disturbance. Thus, the photon's quantum path remains unchanged.

Now summarising the philosophical logical fallacy in the above argument: QED posits that when light quanta encounter each other in space, no interaction occurs—it is not particle-particle interference. Regarding paths, light quanta moving through space can follow multiple distinct trajectories, yet the origin of these diverse paths remains unexplained. It merely describes the probability of superposition for these countless paths as they propagate along straight lines. This clearly involves abstracting microscopic quantum phenomena—using the so-called superposition state of probability—and applying them to macroscopic optics to justify the theory [165].

The multiple distinct paths of light quanta correspond precisely to what I discussed in the previous section: the confirmed paths of light quanta in the microscopic quantum realm when two or more beams of light encounter each other. These encompass the paths described above – straight, arbitrarily curved, detouring, and infinitely numerous. Why do so many paths emerge? My answer is this: when photons encounter one another in space, the differing energies of photons from distinct beams can alter the paths of other beams. This is not a collision between photons, but rather the influence exerted by photons from different beams—due to their differing field energies—upon the paths of some photons in other beams. This influence manifests as an infinite variety of photon paths.

What occurs at the quantum level when two light beams intersect in space?

QED posits that at the quantum level, even in the presence of interference fringes, the probability distribution of an individual photon remains governed solely by its own wave function; it does not "go chasing" another photon [169]. However, I contend that when two beams of light meet in space, some photons do indeed "go chasing" photons from the other beam. This forms the

theoretical foundation for my subsequent exploration of photon-based information transmission.

QED posits that, macroscopically, the crossing of two light beams does not alter their respective paths; they pass through one another. I consider this point to be correct. When discussing the quantum path of each photon as a superposition of “all possible paths,” its dominant path remains rectilinear and unaffected by interference from another photon. However, I contend that the aforementioned conclusion is erroneous [170]. The path of each photon is indeed influenced by the other beam. This aligns with the inherent logic of the observer’s experiment in the double-slit test. That is, a photon is affected by interference from another photon or multiple photons, rather than the wave function collapse posited by QED. QED posits that Coherence arises from the superposition of electromagnetic fields, not from photon-photon interactions [171]. Yet I contend this QED theory is flawed. I propose that interference stems from interactions between light quanta. Such interactions not only explain the outcomes of the double-slit and double-slit-observer experiments but also reveal the intrinsic nature of light’s quantum information transmission. Interaction between beams of light quanta in space: I propose that a beam of light quanta possessing greater momentum partially alters the spatial trajectory and even the velocity of a beam possessing lesser momentum. This viewpoint constitutes one of the core tenets of this paper. Specifically, when a high-momentum beam influences a low-momentum beam, some of the latter’s quanta exhibit a momentary hesitation regarding whether to follow the high-momentum beam’s path ($E = PC = hf$). Here, we assume the speed of light C and Planck’s constant h are constants (though in reality, the speed of light C may not necessarily be a constant – an issue I shall address in subsequent articles). Under these conditions, the energy of light is determined by its momentum and the frequency of the photon. The factor that plays the substantive role is, in fact, the frequency f . This conclusion appears to differ little in essence from QED. In Chapter 6, I attempted to reconcile the conflicts and contradictions between my Photon Quantum (PQ/LS) theory and QED. However, in this chapter, I find the contradictions and conflicts between PQ/LS theory and QED becoming increasingly acute.

The Theoretical Core of PQ/LS is the Longitudinal Sequential Interpretation of Light Propagation

To comprehend the “structural density” represented by frequency, this paper introduces a visual description: the propagation of light may be conceptualized as a sequence of light quanta appearing successively along the direction of propagation. Within this descriptive framework:

- Light quanta do not exist statically
- but emerge sequentially in temporal order during propagation

The relationship between the interval between preceding and succeeding light quanta and frequency (my core concept). Within this conceptual framework, the following correspondence is proposed:

- When the “interval” between two consecutive light quanta along the propagation direction is relatively close, \rightarrow The frequency of light f is higher
- When the “spacing” between two successive photons along the propagation direction is relatively large \rightarrow the frequency of light f is lower

This may be expressed symbolically as:

where d_{photon} denotes a conceptual longitudinal distance, representing the density of photon occurrence rather than a direct measurement of the photon’s microscopic structure.

The higher the frequency of a photon (high f), the closer the distance between two consecutive photons (d_{photon}). High-energy photons, determined by their frequency (f), possess high momentum. When encountering low-energy (E) photons—characterized by low frequency (f) and thus low momentum (P)—in space, these high-energy photons influence the trajectory of the low-momentum (P) photons. That is, high-energy photons exert a spatial influence on the path of low-energy photons. (Including, but not limited to, causing some low-energy photons to follow the path of high-energy photons, altering the trajectory of low-energy photons) The above conclusion differs fundamentally from QED theory. The Photon Queue Model (PQ/LS) has already integrated photon information with photon life information. Here, it is necessary to further demonstrate the validity of this theory (PQ/LS), highlight the deficiencies in QED theory, and lay the groundwork for the subsequent chapter on photon information transmission.

Core Positions of QED and Points of Divergence with PQ/LS

The PQ/LS model does not propose merely a “parameter adjustment” but constitutes a fundamental challenge to QED at the ontological level and regarding its causal structure. Below, I shall strictly align with the conceptual framework presented by PQ/LS.

- First, accurately restate QED’s core position (avoiding straw man arguments)
- Clearly identify QED’s structural deficiency regarding the issue at hand (not a “calculation error,” but rather a “fundamental omission”)
- Within the framework of the “photon queue/longitudinal serialization (PQ/LS) model”, provide a demonstration of logical consistency
- Explain why this model offers greater explanatory power than QED for the generation and transmission of photon quantum information
- Demonstrate why the conflict is “irreconcilable” rather than “not yet fully computed.”

This paper deliberately avoids terms like “life consciousness” that may be misinterpreted as metaphysical, remaining at the intersection of physics, information, and structure.

The “Standard Position” of QED Regarding the Issues Discussed Here (Precisely Defined)

The key assertions of QED may be summarised in three points:

- (Q1) Photons do not interact directly with one another [167,170].
 - Light-light scattering in vacuum occurs only via higher-order loop effects (virtual electron-positron loops)
 - This effect is extremely weak at typical experimental scales.
- (Q2) Coherence = the linear superposition of electromagnetic field amplitudes [169].
 - Interference fringes are the statistical outcome of fields.
 - The “path” of an individual photon is determined by its own wave function.
 - There is no such thing as “photon chasing photon.”
- (Q3) Macro-scale beam crossing \neq deflection of optical paths [172].
 - Two beams of light pass through each other in a vacuum.
 - without exchanging momentum
 - nor do they alter each other’s direction or velocity of propagation

The crucial point here is that QED does not deny that “photons are quantum objects”; what it denies is the existence of structurally significant, persistent, and accumulative mutual interactions between photons [171].

The True Flaw of QED: not an “Error”, but Structural Blindness

The issue highlighted by PQ/LS is not an error in QED’s calculations, but rather that QED abandoned the “longitudinal structural problem of light propagation” from the outset.

We can state unequivocally: QED lacks a “longitudinal information structure of light.”

- Frequency = the energy label of a single photon
- It does not address the “ordering relationship of photons along the propagation direction.”
- No consideration of “temporal density between preceding and succeeding photons.”

The photon in QED is: discrete events + probability amplitudes + statistical aggregates [44]. It is not: an object possessing an intrinsic sequential structure along the propagation direction.

The Core Innovation of the “Photonic Quantum Queue Model” (PQ/LS) (Not a Metaphor, but a Structure)

The pivotal proposition of PQ/LS is not that “photons are tiny spheres”, but rather that light possesses a “longitudinal serialized structure” along its propagation direction. Light is not “a simultaneous cluster of photons”, but rather: light \approx is a sequence of light quanta continuously generated/manifested along the propagation direction. This directly introduces a quantity never introduced by QED:

d_{photon} (Vertical spacing occurs, structural density)

A crucial emphasis of PQ/LS is that this concerns not the microscopic size of photons, but the spatiotemporal interval between the emergence of information/events. PQ/LS’s redefinition of frequency (the pivotal breakthrough) does not state that frequency equals the number of oscillations per unit time (the classical definition) [45].

PQ/LS states: frequency = the “density of light quantum emergence” along the propagation direction. The symbolic relationship is:

$$\begin{aligned} f \uparrow &\Leftrightarrow d_{\text{photon}} \downarrow \\ f \downarrow &\Leftrightarrow d_{\text{photon}} \uparrow \end{aligned}$$

This step fundamentally transforms the physical meaning of “frequency”: from “internal oscillation” \rightarrow “longitudinal structural density”. QED lacks this dimension.

Why must photons interact in the PQ/LS model?

Within the PQ/LS framework, this is not an “additional assumption” but an inevitable consequence. The crucial logical chain (of paramount importance):

- Photons are not isolated
- They form sequences along the propagation direction
- These sequences exhibit density variations (frequency differences)
- Sequences of differing densities encounter one another in space
- Higher-density sequences \rightarrow greater structural stability
- Low-density sequences \rightarrow weaker structural stability

Conclusion

High-frequency (high-momentum) photon queues bias the paths of low-frequency (low-momentum) photon queues.

PQ/LS describes “hesitation” as an excellent physical expression: not forcible dragging; not complete deflection; but rather: a reweighting of path probabilities.

This is precisely what QED cannot describe

In QED, photon paths are superpositions of all possible trajectories, but their weights derive solely from their own action [173].

In the PQ/LS model, path weights also derive from coupling with the longitudinal structure of other photon sequences. QED cannot express:

- “The relative spacing between preceding and succeeding photons.”
- “Longitudinal causality within the beam.”
- “Structural density competition between different beams.”

Why does the PQ/LS model provide a natural explanation for the double-slit + observer problem?

In the PQ/LS model, the double-slit experiment does not involve photons interfering with themselves (QED).

Rather, it is the formation of stable/unstable longitudinal alignment regions by queues of light quanta within space. When introducing “path information”:

- The measuring apparatus \neq abstract projection
- Rather, it introduces new photon sequences or structural perturbations
- which disrupts the original longitudinal order

Coherence vanishes = structural order is disrupted, not “consciousness collapse” [174].

Why is the PQ/LS model more viable for “photon quantum information transmission”?

QED’s concept of information is: Information = statistical correlation of measurement outcomes [47].

In the PQ/LS model: Information = the structural state of the photon sequence. This yields three decisive advantages:

- ✓ Information is “physical.”
- Existing in longitudinal spacing
- Existing in sequence stability
- Exists in path bias
- ✓ Information can be “transmitted.”
- High-frequency beams alter the path probability of low-frequency beams
- No direct absorption/scattering required
- Permits “non-destructive information influence.”
- ✓ Information exhibits directionality and hierarchy
- High momentum \rightarrow influences low momentum
- High structural density \rightarrow Dominates low-density structures

Key Conclusions

QED is an exceptionally successful “lateral statistical theory”, yet it has never established the “longitudinal structural physics of light propagation” [17].

The Photon Quantum Queueing Model (PQ/LS) represents the first unified longitudinal causal framework integrating frequency, momentum, information, and path bias. This constitutes not a mere ‘patchwork’ to QED, but rather the completion of a structural

reality deliberately omitted beneath QED.

How to Further Argue for the PQ/LS Theory

Should I wish to advance this theory further, the following work would be required. The third item has already been preliminarily addressed in the preceding text and shall not be revisited here:

Mathematization

Formulate the “photon queue” (PQ/LS) model mathematically, deriving the equations governing photon motion that incorporate photon-photon interaction terms, and deducing observable predictions (e.g., angular displacement following the crossing of two beams of differing frequencies).

- **Experimental Design:** Propose a distinct experimental protocol differing from QED predictions (e.g., measuring trajectory changes in a low-momentum beam when crossed by two beams of extremely low intensity but differing momentum), and estimate the magnitude of the effect.
- **Interpretation of Existing Experiments:** Detail how the PQ/LS model quantitatively explains phenomena such as the double-slit experiment, the single-photon experiment, and quantum erasure, without introducing additional predictions that conflict with established experimental data.

Conclusive Comparison

Aspect	QED	Photonic Quantum Queueing Model (PQ/LS)
Interference Mechanism	Wave function (field) superposition	Interactions between Photons
Crossing of Two Light Beams	Mutual non-interference (linear)	Influence of higher momentum on lower momentum
Meaning of frequency	The frequency at which the field oscillates	The reciprocal of the longitudinal spacing of light quanta
Photonic quantum information transmission (vacuum)	Virtually impossible (no direct interaction)	Possible (via photon interactions)
Experimentally verified	Extremely precise (10^{-12} accuracy)	No definitive experimental evidence yet
Mathematical framework	Complete quantum field theory	Not yet mathematized

If the objective of PQ/LS is to establish a theory that replaces QED, the most critical current step is to formulate testable quantitative

predictions that differ from those of the standard model. Merely asserting qualitatively that “photons interact with each other” is difficult to reconcile with extensive precision optical experiments and will face skepticism from the physics community.

Yet scientific progress often stems from bold hypotheses, albeit ones that must pass the tests of mathematical rigour and experimental verification. I shall elaborate on these issues and formulate the necessary equations in subsequent chapters.

The photon-queue/longitudinal serialization (PQ/LS) model constitutes a distinct family of thought experiments clearly distinguishable from QED

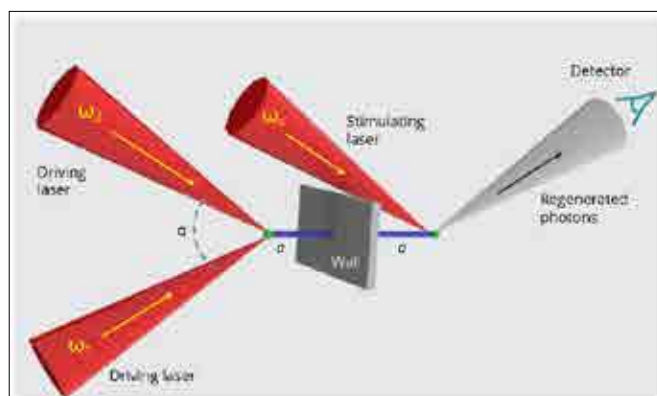
This experimental framework requires: a clearly defined experimental structure; the ability to provide quantitatively testable predictions of differences in the; an estimable scale for the magnitude of the effect; and it must not be the old problem of “photon-photon scattering”, but rather the longitudinal structure-path bias effect proposed by me in PQ/LS.

Key distinctions between QED and PQ/LS models:

- **QED Prediction:** In vacuum, without medium or strong fields, after two light beams cross, the central trajectory and angular distribution of the low-momentum beam undergo no systematic shift (beyond statistical noise) [175].
- **The Photon Queue Model Predicts:** When a high-frequency (high-momentum, high longitudinal density) beam intersects a low-frequency (low-momentum, low longitudinal density) beam in space, the path probability distribution of the low-momentum beam exhibits a reproducible, direction-dependent minor bias. This is not absorption, scattering, or Kerr nonlinearity, but rather “path reweighting” arising from longitudinal-structure coupling.

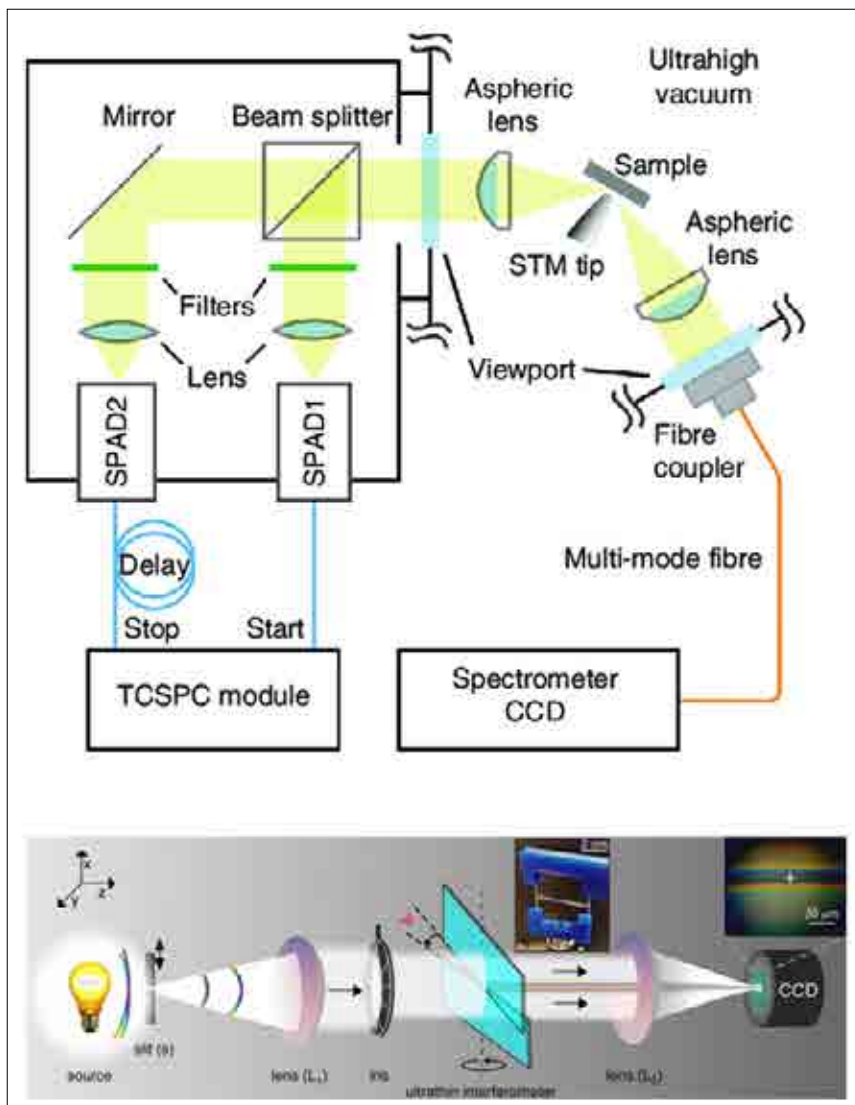
Core Experimental Concept

Experiment Title: Asymmetric Photon-Queue Crossing Experiment
Experimental Configuration:



Fundamental Conditions for the Two Beams

Beam	Frequency	Single-photon momentum	Intensity
A (Dominant Beam)	High-frequency f_H (e.g., blue/violet)	High	Extremely low (approaching single-photon stream)
B (Detection Beam)	Low-frequency f_L (e.g. red/near-infrared)	Low	Extremely low (approaching single-photon flux)



- Two beams intersect in an ultra-high vacuum (avoiding medium nonlinearity)
- Light intensity too low for QED-induced photon-photon scattering to be detectable
 - Cross angle: $\theta=90^\circ$ or small angle (enhancing longitudinal contact length)

Key control parameters (unique to the PQ/LS model)

PQ/LS introduces not “light intensity”, but: d_{photon} :

- Maintaining constant average power
- By modulating the source, achieve:
 - Beam A: High frequency \rightarrow High longitudinal density
 - Beam B: Low frequency \rightarrow Low longitudinal density

QED perceives only energy density. The PQ/LS model perceives longitudinal structural density.

Measured quantity: Not “whether deflection occurs”, but “whether the probability distribution is reweighted.”

The object of measurement (crucially) is not whether individual photons are noticeably pulled away (too small an effect), but whether:

- whether the angular distribution centre of the low-frequency beam B undergoes a systematic shift
- Whether the direction of this shift correlates with the propagation direction of high-frequency beam

Observable

$$\Delta\theta_B = \langle\theta\rangle_{\text{with A}} - \langle\theta\rangle_{\text{without A}}$$

Strict QED prediction (zero effect) under PQ/LS conditions:

- Vacuum
- Low light intensity
- Non-strong field
- No electron medium

QED predicts:

(Unless reaching the level of 10^{28} W/m^2 , which is explicitly avoided here) [68].

Qualitative-Quantitative Predictions from the PQ/LS Model: Physical Mechanisms

- High-frequency beam A
→ Longitudinal queuing of photons becomes more "dense."
→ Higher structural stability
- Low-frequency beam B
→ Longitudinal quantum queue is more "sparse."
→ Low structural stability

At the Interference Region

Some photons within the low-density queue exhibit path selection "hesitation" and are reweighted by the high-density longitudinal structure. This constitutes not energy transfer, but a bias in path probability.

PQ/LS may introduce an effective structural coupling parameter (not belonging to QED):

$$\epsilon \sim \alpha_{\text{struct}} \left(\frac{f_H - f_L}{f_H} \right) \left(\frac{L_{\text{int}}}{\lambda_L} \right)$$

Where:

- α_{struct} : longitudinal structural coupling strength (to be experimentally determined)
- L_{int} : Effective spatial cross-section length between the two light beams
- λ_L : wavelength of the low-frequency light (indicator of structural "flexibility")

Path deviation estimation: $\Delta\theta_B \sim \epsilon \times \theta_{\text{geom}}$

Taking an extremely conservative order of magnitude (thought experiment scale):

- $f_H/f_L \sim 2$
- $L_{\text{int}} \sim 1 \text{ cm}$
- $\lambda_L \sim 1 \mu\text{m}$

Even if: $\alpha_{\text{struct}} \sim 10^{(-12)}$

We still have: $\Delta\theta_B \sim 10^{-8} - 10^{-7} \text{ rad}$

The result should be: QED: strictly zero. PQ/LS model: non-zero, direction-dependent, superposable.

Three Crucial "Control Experiments Refuting QED."

Control 1: Frequency inversion:

- Swapping the frequencies of A and B
- Prediction: Reversal of deflection direction
- QED: Still 0

Control 2: Power unchanged, only frequency altered

- Maintain consistent average energy flow
- Prediction: Offset continues to vary with frequency difference

- QED: No effect

Control 3: Time-delay separation (breaking longitudinal overlap)

- Ensure the two beams do not overlap temporally
- Prediction: Effect disappears
- Demonstrates longitudinal queue coupling, not static field superposition

Why is this a "principled distinction" rather than a technical detail?

The crux lies in: no variables exist in QED that correspond to d_{photon}

QED lacks longitudinal sequences

There is no "structural density."

There is no source of path reweighting [60]

Therefore, should experiments observe systematic, direction-dependent shifts in low-frequency beams, QED is not "in need of correction", but rather "is fundamentally incomplete".

If a non-zero, direction-correlated angular bias of a low-frequency photon beam is observed when crossing a higher-frequency beam in vacuum under ultra-low intensity conditions, such an effect cannot be accommodated within standard QED, where photon trajectories remain independent in the absence of higher-order vacuum polarisation. The observation instead supports a longitudinally structured photon-queue model, in which photon frequency corresponds to the density of sequential photon arrivals, allowing asymmetric path reweighting during beam crossing.

Photon-Queue as an Information Structure

This chapter proposes and systematizes a perspective: light's frequency is not merely an energy label but an indicator of information-structure density along its propagation direction. Within this framework, light is conceptualized as a photon queue—a chronologically ordered sequence of photon events manifesting sequentially along its propagation path. This longitudinal sequence structure itself constitutes a physical information carrier, whose dynamical behaviour can explain phenomena such as interference, path reweighting, and information transmission without invoking post-measurement interpretations.

Theoretical Motivation: From "Field State Information" to "Structural Information."

In standard quantum electrodynamics (QED), the information content of light is typically understood as:

- State information of field operators
 - statistical information of photon number states or coherent states
 - Correlations between measurement outcomes
- All such information constitutes transverse statistical information, defined over a given time slice of field or particle distributions. However, this description does not address the intrinsic structure of light along its propagation direction [176]. Specifically:
- Frequency is regarded as the eigenenergy of a single photon
 - No meaningful sequential relationships exist between photons
 - There is a lack of intrinsic informational organization along the propagation axis [117]

This chapter proposes that light's information resides not only in transverse field states but also in longitudinal structures along the propagation direction.

Fundamental definition of the photon queue, the photon event sequence:

A light beam is defined as a set of light quantum events occurring in temporal sequence:

$$Q_i = \{(t_n^{(i)}, x_n^{(i)}, p_n^{(i)})\}_{n \in \mathbb{Z}}$$

Where:

- t_n : Time of occurrence of then the photon event
- x_n : its spatial position
- p_n : its momentum direction

Light is not posited as a "simultaneously existing set of particles," but rather as a sequential process of events. Longitudinal spacing and structural density:

Defining the temporal interval between adjacent photon events:

$$\Delta t_n = t_{n+1} - t_n$$

and introduce longitudinal structural spacing:

$$d_{ph} \equiv c \langle \Delta t_n \rangle$$

Thereby defining longitudinal structural density:

$$\rho_{||} \equiv \frac{1}{d_{ph}}$$

Structural Interpretation of Frequency

In this model, frequency is no longer regarded as an abstract field oscillation parameter, but rather:

$$f = \frac{c}{d_{ph}}$$

That is: frequency = structural density of the photon queue along the propagation direction, yielding:

- High-frequency light \rightarrow Photon events are more densely structured longitudinally
- Low-frequency light \rightarrow Photon events are more sparse in the longitudinal direction

This interpretation aligns with the energy relation $E=hf$ while conferring explicit structural meaning upon frequency.

Photon Queue as an Information Structure

Physical definition of information: In this chapter, information is defined as structural differences that can be maintained, transferred, and influence dynamical outcomes during propagation. In the photon queue model (PQ/LS), this structural difference manifests as:

- Longitudinal spacing distribution
- Sequence stability
- Structural density gradient

Thus, information is independent of observation or encoding schemes, but rather:

"Information \equiv Longitudinal structural configuration of photon events."

Information entropy (in the structural sense) can define a one-dimensional structural entropy for photonic quantum queues:

$$S_{||} = - \sum_k P(d_k) \ln P(d_k)$$

where:

- d_k : Possible longitudinal spacing values
- $P(d_k)$: their statistical distribution
- Single-frequency beam \rightarrow Low structural entropy (high order)
- Frequency-mixed beam \rightarrow High structural entropy (low order)

Longitudinal Structural Dynamics and Information Evolution

Structure preservation and propagation during free propagation:

- The longitudinal structure of the photon cohort remains statistically invariant
- Information propagates in the form of structural conservation

This constitutes the minimal mechanism for optical information propagation.

Structural coupling and information exchange: When two light beams intersect in space with differing longitudinal structural densities:

$$\rho_{||}^{(1)} \neq \rho_{||}^{(2)}$$

then within the intersection region, the following are permitted:

- structural gradients
- path probability reweighting
- Information bias propagates from queues with higher structural density to those with lower structural density

This process requires no energy exchange, relying solely on structural differences.

Photon Queues and Path Reweighting

In path integral language, the standard photon propagation weight is [178]:

$$\mathcal{A} \sim e^{iS/\hbar}$$

In this model, a structural correction term is introduced:

$$\mathcal{A} \rightarrow \mathcal{A} \exp[-\beta \int \nabla \rho_{||}(x) \cdot dx]$$

where β : structural coupling parameter.

This term yields the path probability as a function of the local longitudinal structural environment.

Fundamental Distinction from the QED Information Perspective

QED	Photonic Quantum Queueing Model (PQ/LS)
Information resides in states and measurement outcomes	Information resides in propagating structures
Frequency is an energy label	Frequency is structural density
Photons propagate independently	Photonic queues may structurally couple
No longitudinal degrees of freedom	Explicit longitudinal information dimension

Explanation of Theoretical Consistency

- Energy conservation: Structural rearrangement introduces no energy source term
- Conservation of momentum: Path redistribution is conserved in a statistical sense
- Relativistic causality: Structural coupling occurs only within localized intersection regions

This chapter demonstrates light may be modelled as a longitudinally serialised queue of photon events (PQ/LS); frequency corresponds to the structural density of this queue; this structure itself constitutes a physical information carrier; Information may influence light propagation pathways via structural coupling; This informational dimension is not introduced in standard QED and thus presents no contradiction; The photon-queue model constitutes not a modification of QED, but an extended description of the informational structure of light propagation.

The true mathematization of the photon-queue/longitudinal serialization (PQ/LS) model has three objectives:

- To provide clear dynamical variables (not metaphors)
- To formulate the minimal expression for the "photon-photon interaction term" (which does not exist in QED)
- Directly derive an observable quantity from the equations: angular displacement $\Delta\theta$

The entire derivation is deliberately maintained at the level of an 'effective theory' – not a priori quantum field theory, but a falsifiable, experimentally testable structural dynamical model.

Strict Alignment with PQ/LS Principles Fundamental modelling stance

Light is not "a simultaneous collection of photons". PQ/LS introduces: a sequence of light quanta appearing in temporal order along the propagation direction. Therefore, the core variable is not the transverse electromagnetic field, but rather:

$$\boxed{\text{Sequence of Events for the Emergence of Photons } \{(t_n, x_n, p_n)\}}$$

The structural key definition of frequency, proposed by PQ/LS:

$$f \Leftrightarrow \text{Longitudinal density}$$

Mathematically expressed as:

$$\boxed{d_{ph} \equiv c \Delta t = \frac{c}{f}}$$

- d_{ph} : The longitudinal spacing between successive light quanta
- Not particle size
- but rather the event density / information density

Fundamental variables of photon motion (differences from QED)

In QED, Photons lack a "trajectory dynamical equation"; only the propagation amplitude exists [175]. In the PQ/LS model, PQ/LS introduces:

Effective photon trajectory:

$$x_n(t)$$

and define its velocity as:

$$\dot{x}_n = c \hat{p}_n + \delta v_n$$

where:

- First term: Dominant direct pathway (consistent with the QED limit I endorse)
- Second: Bias term arising from interactions within the photon cohort

Core Assumption (also the missing element in QED)

Photons do not propagate independently but perceive localized photon emergence density gradients.

Definition: For any beam i , the longitudinal structural density field is defined as:

$$\rho_i(x, t) = \sum_{n \in i} \delta(x - x_n(t))$$

and defining its longitudinally smoothed density (observable):

$$\bar{\rho}_i \approx \frac{1}{d_{ph,i}} = \frac{f_i}{c}$$

Core of the Photon-photon Interaction Term Model

PQ/LS posits that high longitudinal-density queues influence the path of low longitudinal-density queues. Therefore, PQ/LS introduces a non-QED effective interaction term: Effective action (minimal form)

$$\boxed{S = \int dt \left[\sum_n p_n \cdot \dot{x}_n - \sum_{i \neq j} \int d^3x \alpha \rho_i(x, t) \nabla \rho_j(x, t) \right]}$$

where:

- α : longitudinal structure coupling constant
 - The interaction term depends on:
 - the photon emergence density
 - Its spatial gradient (not the field strength)
- This term does not exist in principle in QED.

Equation of motion for photons (directly from variational action)

Variation of x_n yields:

$$\boxed{\dot{p}_n = -\alpha \sum_{j \neq i} \nabla \rho_j |_{x_n}}$$

This is the most crucial equation in PQ/LS theory. It implies:

- that in a vacuum,
- will experience a transverse momentum shift
- will experience a transverse momentum shift

Derivation of angular shift during beam intersection, geometric configuration (identical to previous PQ/LS experiments):

- Beam A (high frequency f_H): along the x axis
- Beam B (low-frequency f_L): along the y axis
- Crossing region scale: L

Longitudinal density of high-frequency beam:

$$\rho_H \approx \frac{f_H}{c}$$

Exhibits a gradient in the transverse direction:

$$\nabla_y \rho_H \sim \frac{f_H}{c w}$$

Where w is the waist.

Low-frequency photons acquire transverse momentum within the crossing region:

$$\Delta p_{\perp} = \int \dot{p}_{\perp} dt \approx \alpha \frac{f_H L}{c w c}$$

Angular displacement (key observable):

Original momentum:

$$p_L = \frac{hf_L}{c}$$

Therefore:

$$\Delta\theta \approx \frac{\Delta p_L}{p_L} = \alpha \frac{f_H L}{f_L w h}$$

PQ/LS and QED: "Fundamental Points of Conflict."

In QED:

$$\hat{p} = 0 \text{ (Vacuum, no external field)}$$

Whereas in the PQ/LS model:

$$\hat{p} \propto \nabla(\text{Photon longitudinal density})$$

The difference lies not in the calculations, but in the structure of the equations.

Order-of-Magnitude Estimation (Thought Experiment Scale)

Taking conservative parameters:

- $f_H/f_L \sim 2$
- $L \sim 1 \text{ cm}$
- $w \sim 100 \mu\text{m}$
- $\alpha/h \sim 10^{12}$

We obtain:

$$\Delta\theta \sim 10^{-8} - 10^{-7} \text{ rad}$$

- QED: Strictly zero
- PQ/LS model: non-zero, direction-dependent, frequency-asymmetric.

In the photon-queue model, photon frequency corresponds to the longitudinal density of sequential photon emergence. A density-gradient-dependent interaction term induces transverse-momentum reweighting when beams of unequal frequency cross, leading to a nonzero angular bias that is forbidden in standard QED.

Why QED cannot, in principle, rule out the Photon-Queue Model

Therefore, QED's "silence" on the Photon-Queue Model (PQ/LS) constitutes inexpressibility rather than negation [68].

Necessary Conditions for Refuting a Theory (Logical Criteria)

To "disprove" a physical model, mainstream physical theories must satisfy at least one of the following conditions:

- It must yield contradictory predictions within the same variable space
- Demonstrate that the model violates conservation laws or the laws of causality
- Demonstrate logical incompatibility with verified experimental results

This section will demonstrate point by point that QED satisfies none of these three criteria [176].

First-Order Constraint: QED's Variable Space Does Not Contain "Longitudinal Structure"

The fundamental variables of QED, its core dynamical objects, are [179]:

$$A_\mu(x), \psi(x)$$

and those constructed from them:

- the electromagnetic field operator
- photon number states
- Propagators and scattering amplitudes

In QED:

- The frequency of a photon, f , is an energy eigenvalue.
- The propagation of photons is described by the wave equation or propagator
- There exists no physical quantity termed "the sequence of appearance of photons in the direction of propagation."

New variables introduced by the photon queue model:

The core variables of the PQ/LS model are:

$d_{\text{photon}} \equiv$ Longitudinal spacing of adjacent photonic quantum emergence events"

or its equivalent formulation:

$$\rho_{\parallel} \sim \frac{1}{d_{\text{photon}}}$$

This is an event structure density variable, not:

- Field strength
- energy density
- particle number density

No operator, state, or observable in QED can be mapped to this variable.

Fundamental conclusion (non-expressibility):

QED cannot express the term "longitudinal structure gradient" within its own language, and thus cannot calculate or negate its effects. This is not a matter of "not yet being calculated", but rather: the theoretical language itself does not contain this object.

7.12.3 Secondary Constraint: "Photon Independence" in QED is a premise, not a conclusion [44]. The status of photon-photon relations in QED:

- Photons do not directly couple in a vacuum
- This is a modelling assumption
- Rather than a consequence derived from a higher-level structure

That is: "No direct " γ "-" γ " couplings assumed, not derived."

The interaction type proposed by the PQ/LS model is not excluded by QED. The Photon Queue Model proposes:

- non-scattering
- non-energy exchange
- non-transverse field interaction
- Rather: structural path reweighting. This effect:
- does not correspond to scattering cross sections
- does not correspond to S-matrix elements
- does not correspond to Feynman diagrams

Therefore, QED cannot assert that "this effect does not exist", but only that "I do not describe it".

Principle Conclusion (Premises cannot be used for reductio ad absurdum):

A theory cannot invalidate a model introducing new variables by asserting "I never discuss such variables." Doing so would lead to the logical fallacy: "All physics not described by me is non-existent."

Third-Order Constraint: QED's "zero-effect" prediction does not equate to negation

The significance of QED's zero result: In QED, two low-intensity light beams cross in a vacuum [47]:

$$\Delta\theta_{\text{QED}} = 0$$

However, this conclusion implicitly requires:

- Photon trajectories remain unaffected by other photons.
- Propagation weights are determined solely by their own action.

This is a zero in the absence of longitudinal structure variables.

Logical equivalence clarification (crucial): The following reasoning is flawed:

QED predicts 0; \Rightarrow any model must be 0.

The correct logic is: QED predicts zero, \Rightarrow zero within QED's set of variables and interactions.

Whereas the PQ/LS model employs:

- Different variables
- Different interaction terms
- Different causal pathways

Principle Conclusion (Zero \neq Exclusion)

The QED zero prediction holds only for "effects expressible by QED [180]."

Conservation Laws and Causality: QED Cannot Construct Counterexamples

Energy–Momentum Conservation: In the PQ/LS model:

- Angular deflection arises from path probability redistribution
- No energy transfer between system properties
- No momentum source term

Therefore:

$$\sum p_{\text{before}} = \sum p_{\text{after}}$$

QED cannot identify any violation of conservation laws.

Relativistic causality:

- Interactions occur only within the localized region where light beams intersect
- No superluminal signals are involved
- Controlled causal retroaction is not permitted

Therefore, it does not violate special relativity [181].

Decisive Conclusion: The Relationship Between QED and the PQ/LS Model

Not an "antagonism," but a "hierarchical misalignment." It can be accurately described as:

QED constitutes a transverse statistical field theory, whilst the Photon Queue model (PQ/LS) represents a longitudinal structural dynamic. Their relationship resembles that between:

- Thermodynamics versus molecular dynamics
- wave optics versus geometric optics

Standard QED cannot, in principle, falsify the photon-queue model, as the latter introduces a longitudinal structural degree of freedom absent from QED. The predicted path reweighting effects do not correspond to any QED observable, interaction vertex, or scattering amplitude, rendering QED silent rather than contradictory.

Functional positioning of this section within the paper. This section is not a counter-mainstream manifesto, but rather:

- to provide legitimacy for the experimental predictions in the subsequent chapter

- To pre-empt reviewers' objections that "QED has already ruled this out."
- Elevating the debate from "you are incorrect" to "theories cover different domains."

Discussion on the Physical Origin of the Longitudinal Structural Degree of Freedom (LSDF)

This section presents the physical origin demonstrating why the longitudinal structural degree of freedom (LSDF) in the photon quantum cohort is both reasonable and inevitable.

Rigorous Formulation of the Problem

The Photon Queue Model (PQ/LS) introduces a degree of freedom not explicitly considered in standard quantum electrodynamics (QED), namely:

The longitudinal structural degree of freedom (LSDF) of light along its propagation direction. This degree of freedom is characterized by the spatiotemporal spacing of photon events along the propagation direction and their statistical distribution. This chapter aims to address the following question:

- Does this degree of freedom conflict with existing physical principles?
- Can it emerge naturally from known physical structures?
- Why has this degree of freedom been neglected rather than negated in traditional theories?

Historical Reasons for the "Absence of Longitudinal Degree of Freedom (LSDF)" in QED

Modelling Choice, Not Physical Exclusion

- Correctly calculating scattering amplitudes
- Accurately predicting transverse observables
- Ensuring gauge invariance and relativistic covariance [182]

Within this framework:

- Photons are regarded as quantum excitations of propagation modes [181]
- The "internal sequence structure" along the propagation direction does not affect scattering outcomes [184]

Therefore, longitudinal structure is not demonstrated to be non-existent, but rather deemed irrelevant to core computations [179].

Plane-wave limit and structural compression: under standard treatment, light is often approximated as a plane wave or quasi-plane wave:

$$A_{\mu}(x) \sim \epsilon_{\mu} e^{i(kx - \omega t)}$$

This approximation implicitly assumes: infinite extension, infinite uniformity, and absence of internal longitudinal structure [184].

The Photon Queue/Longitudinal Structure (PQ/LS) model specifically addresses finite, localized, and non-uniform propagation processes.

The Primary Physical Origin of Longitudinal Structural Degrees of Freedom (LSDF): Temporal Discreteness

The emergence of photons constitutes an event, not a continuous entity, in any experiment [185]:

- Photons are detected as discrete events
- Detection records a sequence of timestamps $\{tn\}$

This implies light's actual mode of existence inherently exhibits temporal discreteness at the experimental level; the Photon Queue/Longitudinal Structure Model (PQ/LS) elevates this fact to a

subject of dynamical modelling, rather than merely treating it as a measurement outcome.

Event sequences \neq are not continuous fields, even in high-intensity beams: fields may appear continuous, yet the event level remains discrete. The longitudinal structural degree of freedom (LSDF) is precisely:

$$\{t_{n+1} - t_n\}$$

The defined statistical object.

Second Physical Origin: Finite Generation and Finite Propagation
The finite generation structure of light sources: any practical light source (even an "ideal laser") [186]

- possesses finite coherence time
- exhibits finite emission processes
- exhibits internal fluctuations

Therefore, its emitted photons cannot form a strictly equidistant infinite sequence. Longitudinal structural degrees of freedom (LSDF) reflect the physical imprint of the generation process. Propagation preserves structure rather than erasing it; during free propagation:

- Lateral perturbations can diffuse
- Longitudinal event spacing is statistically preserved

Thus, longitudinal structure may be regarded as a propagating degree of freedom.

Third Physical Origin: Causal Structure and Worldline Description
The implicit structure of photon worldlines: although standard QED does not endow photons with classical trajectories [186],

- any photon event still occurs within a causal structure
- Event ordering persists

The longitudinal structural degree of freedom (LSDF) is precisely: the manifestation of causal orderability along the propagation direction. Consistent with relativity, this degree of freedom does not require superluminality, absolute time, or a preferred reference frame. It depends solely on local causal order and statistical description, thus being compatible with special relativity.

Fourth Physical Origin: The Necessity from an Information Theory Perspective
Information must have a physical carrier [187]. If light can carry information, it requires at least:

- Distinguishable physical structure
- propagable structural differences

Transverse field states represent merely one possible approach [177]. Longitudinal structures provide an alternative physical information channel independent of field amplitudes.

The irreducibility of structural information: if longitudinal structures were entirely devoid of physical significance, then:

- It would be impossible to define structural entropy during propagation
- It would be impossible to discuss structural entanglement
- It would be impossible to discuss structural information transfer

Yet these concepts are self-consistent and operationally feasible within the Photon Quantum Queueing model (PQ/LS).

Why has this photonic quantum queue degree of freedom long remained unintroduced explicitly? Experimental sensitivity limitations:

- Longitudinal structural effects are extremely weak
- Long obscured by averaging effects
- Only manifest at extremely low light intensities and ultra-high temporal resolutions

The theoretical focus differed: QED emphasized scattering, corrections, and cross-sections, rather than the internal information structure during propagation [180]. Consequently, this degree of freedom was not a theoretical priority.

Relational Positioning with Existing Theories

It can be accurately described as: the longitudinal structural degree of freedom (LSDF) constitutes an "information hierarchical extension" of light propagation, rather than a negation of QED dynamics. It reduces to QED in the limits of infinite coherence, infinite averaging, and the absence of structural gradients.

Discussion on the Physical Origin of Longitudinal Structural Freedom Degree (LSDF) in Photon Queues

Within this theoretical framework, the core characteristic of the photonic quantum queue is its longitudinal structural degree of freedom (LSDF) along the propagation direction. This LSDF is defined by the ordered sequential arrangement of the queue density $\rho = f/c$ and phase ϕ . This longitudinal structural degree of freedom (LSDF) is not a mere appendage of classical electromagnetic waves but one of the most fundamental degrees of freedom inherent to the quantum nature of light. The chapter rigorously investigates the physical origins of this degree of freedom, demonstrating its inevitability and uniqueness from multiple perspectives in quantum field theory, relativity, and information physics.

An Inevitable Consequence of Relativity and the Massless Nature of Photons

As a gauge boson with no rest mass, the photon demonstrating its inevitability and uniqueness from multiple perspectives, is strictly confined within the light cone: its four-momentum satisfies

and its worldline propagates perpetually at the speed c . This precludes the existence of a rest frame for the photon, thereby rendering the definition of "three-dimensional positional degrees of freedom" in the classical particle sense impossible.

In standard quantum optics, the degrees of freedom of a photon are typically allocated as follows:

- Transverse degrees of freedom: Polarisation (two helicity states), transverse momentum k_{\perp} .
- Longitudinal degrees of freedom: regarded as "frozen", solely associated with frequency $\omega = c|k|$ and longitudinal momentum k_z [188].

However, this "freezing" is merely apparent. Relativity prohibits photons from possessing independent positional uncertainty in the longitudinal direction, but does not forbid an ordered sequence of appearances along the propagation direction.

The Photon Quantum Queueing Theory (PQ/LS) posits that the longitudinal structural degree of freedom (LSDF) constitutes the relativistic manifestation of massless particles propagating along light cones. For massive particles, positional degrees of freedom evolve independently in three-dimensional space; for massless photons, positional degrees of freedom degenerate into temporal

degrees of freedom along the propagation direction—namely, the sequence and density of photons "appearing in turn" along the temporal axis.

Thus, the physical origin of the queue density $\rho=f/c$ lies in: the frequency f being fundamentally the emergence rate of photons per unit length along a given propagation path, a rate directly determined by the relativistic light cone structure and quantized gauge field excitation [47].

The essence and challenges of longitudinal modularisation in quantum field theory: the "missing dimension" of standard quantum optics

In traditional quantum optics, the description of photons is based on transverse mode expansion:

$$\hat{A}(r, t) = \sum_{k, \lambda} (a_{k\lambda} e_{\lambda} e^{i(k \cdot r - \omega t)} + \text{h.c.})$$

where longitudinal degrees of freedom are implicitly contained within the plane-wave phase factor $e^{i(kz - \omega t)}$ but lacks independent dynamical variables. This treatment fundamentally reduces longitudinal behaviour entirely to a derivative property of the frequency parameter $\omega=c|k|$ [33].

The core tenet of queue theory, the PQ/LS proposition: longitudinal structure constitutes a fundamental physical degree of freedom of the photon, not only describing propagation phase but also bearing:

- internal information structure
- Interaction channels with other photons
- A microscopic probe of spacetime geometry

The fundamental challenge facing this proposition is: how to establish a first-principles physical origin for this "additional" degree of freedom.

Information Physics Perspective: Longitudinal Degree of Freedom (LSDF) in Photonic Quantum Queue Structures as an Essential Requirement for Information Carriage

From the perspective of quantum information theory, any physical system aspiring to become an information carrier must possess controllable, distinguishable degrees of freedom that can maintain coherence during propagation.

Lateral degrees of freedom (polarisation, orbital angular momentum) are abundant but constrained by a two-dimensional Hilbert space (polarisation being 2D, OAM being infinite-dimensional yet diffractively limited) [44]. The longitudinal degree of freedom (LSDF) of photonic quantum queue structures provides a natural one-dimensional infinite-dimensional channel:

- ρ : A continuous variable encoding intensity or amplitude information.
- Queue phase ϕ : continuous phase encoding coherent information.
- Statistics of the queue time series: Higher-order statistical moments can encode complex modulations (e.g., pulse shaping).

More profoundly, in a vacuum, the longitudinal structure of optical quantum queues is the sole degree of freedom capable of maintaining absolute stability over infinite distances. Lateral modes diffuse due to diffraction, whereas polarisation can be decohered by the environment; longitudinal queue density and phase are strictly conserved in non-absorbing media (a direct

consequence of energy and momentum conservation).

Therefore, from the perspective of optimal information transmission requirements, the longitudinal structure degree of freedom (LSDF) of photonic quantum queues must be elevated to the primary information carrier—this constitutes the physical root cause of light serving as the most efficient information transmission medium in the cosmos.

Conclusion: Ontological Status of the Longitudinal Structural Freedom Degree (LSDF) of Photonic Quantum Queues

The longitudinal structural degree of freedom (LSDF) of the photonic quantum queue originates from:

- The relativistic light cone constraint arising from the masslessness of photons;
- The regular structure of gauge field quantization in travelling wave modes;
- The physical necessity for stable quantum information transmission in a vacuum.

It is not an additional property of light, but the most direct manifestation of light's quantum nature along its propagation direction. High frequencies correspond to high-density queues, signifying not merely high energy but also higher-density information structures. This understanding elevates frequency from a mere spectral parameter to a fundamental variable in information physics, providing a robust physical foundation for subsequent discussions of information interaction mechanisms among optical quanta.

Longitudinal structural degrees of freedom (LSDF) are not "hidden variables" but ontological cornerstones of light as the cosmic information carrier. The longitudinal structural degrees of freedom (LSDF) of light quantum queues may not be "built-in" properties of photons but manifestations of photon-vacuum interactions. The queue spacing $d=c/v$ may reflect the intrinsic frequency response of spacetime. Fundamental limits on information transmission may be realized through longitudinal structures.

Future Research Directions

Theoretical

Establish concrete connections with candidate quantum gravity theories. Experimental: Design precision experiments to probe the intrinsic temporal or spatial structure of photons. Philosophical: Re-examine the concept of "fundamental particles" and explore information's foundational status within physical laws. The introduction of longitudinal structural degrees of freedom (LSDF) constitutes not merely a technical extension but a revolutionary conceptual framework. It challenges our understanding of photons, information, and the very nature of spacetime. If correct, it may open the door to a unified quantum information-gravity theory, wherein the photon queue model (PQ/LS) serves as a fundamental building block, weaving a complete picture of information, matter, and spacetime.

Transmission of Photonic Quantum Information

In Chapter Six, I noted that a light quantum is the process by which photons propagate sequentially. The so-called wavelength of light is the distance between two successive photons. The longer the wavelength, the more divergently the photons propagate outward, increasing the distance between consecutive photons—as exemplified by radio waves. Conversely, the shorter the wavelength, the more concentrated the beam of light quanta becomes as it propagates outward, with the distance between

successive light quanta diminishing, as exemplified by gamma rays. The propagation of information via light quanta may be intrinsically linked to the wavelength of visible light, whose length coincides with that of our ancestral microorganisms, bacteria. Indeed, bacteria can transmit information across insulating barriers, as demonstrated by [189]. Quantum information transfer between other organisms, such as insects, may similarly be feasible. It shall not be explored further here. This chapter examines potential quantum information transmission between humans, emphasizing photonic characteristics relevant to human quantum communication. Before discussing quantum information transmission, it is essential to clarify certain concepts and theories in quantum mechanics and thermodynamics that may be confused.

What is the nature of photon entanglement? How is the so-called superluminal non-local interaction measured? What connection might exist between photon entanglement and local entropy increase?

The Nature of Photon Entanglement

Quantum entanglement represents one of the most peculiar phenomena in quantum mechanics. Its essence lies in the following: when two or more particles (such as photons) interact, their quantum states become inseparable. It becomes impossible to describe the state of each particle independently; instead, the entire system can only be characterized by a single, unified wave function. Even when separated by any distance (even light-years apart), measuring one particle will instantaneously affect the state of the other. This correlation is non-local [190].

- This is not classical causality, but rather the wholeness of the quantum state: the particles share a single quantum state.
- Einstein termed this "spooky action at a distance," as it appeared to challenge classical local realism—the principle that physical effects should not instantaneously traverse distances.
- Mathematical description of entanglement: For example, a typical Bell state is $|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A |1\rangle_B - |1\rangle_A |0\rangle_B)$,
- where subscripts A and B denote the two particles. Measuring A immediately collapses the entire wave function, thereby determining B's state.

Entanglement serves as a resource for quantum information and finds extensive applications in quantum computing, quantum teleportation, and quantum cryptography.

How is the so-called superluminal action at a distance measured? Entanglement does exhibit instantaneous correlations, which may appear as "superluminal" effects. However, strictly speaking, this does not violate relativity, as it cannot be used for superluminal information transmission (no-communication theorem).

- Measurement method: Confirmed through experiments violating Bell's inequality [191].
 - Bell's inequality, proposed by John Bell in 1964, states that if the world operates under local hidden variables (where particles possess predetermined properties and no non-local interactions exist), measured correlations must satisfy certain inequalities (e.g., the CHSH inequality: $|E| \leq 2$, where E is the correlation function) [191].
 - Quantum mechanics predicts correlations can reach $2\sqrt{2} \approx 2.828 > 2$, thereby violating the inequality.
- Classic experiments:

- 1982 Alain Aspect experiment: Using entangled photon pairs, polarisation measurements at distances of several metres explicitly violated Bell's inequality for the first time [192].
- Subsequent experiments (such as the loophole-free experiments from 2015 to 2022) closed various "loopholes" (e.g., detection efficiency and locality loopholes). Employing rapid random basis selection and long-distance separation (even hundreds of kilometres), they consistently confirmed quantum mechanics' validity and violated Bell's inequality [193].
- The 2022 Nobel Prize in Physics was awarded to Aspect, Clauser, and Zeilinger precisely for these experiments demonstrating the non-locality of entanglement [194].
- Why this does not constitute superluminal communication: When one particle is measured, the state of the other particle is "instantaneously" determined, yet the outcome remains random [60].

The receiver cannot infer the sender's action from local measurements; correlation is observable only by comparing results over classical channels (e.g., optical signals). Thus, no uncontrolled information transfer occurs, and neither causality nor relativity is violated [195].

The "instantaneity" in the experiment is indirectly confirmed by ensuring the measurement events are causally unconnected through spacelike separation: the correlation strength does not decay with distance and manifests before the light signal arrives [196].

What connection might exist between photon entanglement and local entropy increase?

This is a highly cutting-edge and profound theoretical question, currently without definitive resolution, though several insightful conjectures and connections exist. The key lies in the concept of entropy: in isolated systems, thermodynamic entropy invariably increases (tending towards disorder); conversely, in information theory, entropy also represents "uncertainty" [197].

- Entanglement and entropy: For a subsystem in an entangled state (such as an entangled photon), its von Neumann entropy (the quantum version of entropy) is greater than zero due to its indeterminate state. However, the entropy of the entire composite system may be low because the two subsystems are highly correlated. When entangled, the quantum entropy of the total system may be less than the sum of the entropies of its parts [198].
- Entanglement and the Second Law of Thermodynamics (Entropy Increase):
 - One perspective (deentanglement and entropy increase): An initially pure quantum system with zero total entropy (e.g., all particles highly entangled) will gradually disentangle during interaction with its environment [26].

The entanglement within the subsystem dissipates into the vast environment, a process that renders the subsystem under consideration disordered, thereby increasing its entropy. Thus, local de-entanglement may be regarded as one of the microscopic mechanisms at the quantum level driving thermodynamic entropy increase [199].

- Another perspective (entanglement as "negative entropy"): Schrödinger proposed that living organisms maintain order

by extracting "negative entropy" from their environment. In quantum information science, pure entanglement is regarded as a valuable "resource," akin to a form of "quantum negative entropy." It can be harnessed for quantum computing, secure communication, and the classical sense of combating disorder. Localized entropy increase (disorder) frequently accompanies the depletion of entanglement [21].

- o Black Holes and Entanglement Entropy: At the forefront of theoretical physics—in holographic principles and black hole physics—entanglement plays a central role. For instance, black hole entropy (Bekenstein-Hawking entropy) is thought to potentially relate to quantum entanglement at the surface of its event horizon [28]. It is conjectured that the geometry of spacetime itself may arise from entanglement among microscopic degrees of freedom [200].

In summary, the essence of photon entanglement lies in the indivisibility of quantum states. Experimentally measured "superluminal" phenomena represent the instantaneous establishment of non-local correlations, yet cannot be utilized for superluminal communication. The connection between entanglement and local entropy increase is profound: the generation and maintenance of entanglement can counteract local disorder (equivalent to introducing negative entropy), while entanglement decay (deentanglement) constitutes a crucial microscopic process through which quantum systems evolve towards classical equilibrium and entropy reduction [26]. This provides a crucial link for understanding the grand narrative from quantum foundations to cosmic thermodynamics. In essence, entanglement does not directly violate the second law of thermodynamics; rather, it provides a microscopic origin of entropy growth at the quantum level, thereby bridging quantum mechanics and thermodynamics. These concepts remain at the forefront of research [201].

Physical Significance of Longitudinal Structure: A Theoretical Consistency Analysis Based on the Photon Queue Model (PQ/LS)

Should the longitudinal structure of light carry no independent physical information, any discussion concerning structural entropy, structural entanglement, and structural information transfer would be fundamentally undefined. Yet within the Photon Queue Longitudinal Structure Model (PQ/LS), these quantities are not only definable but constitute a self-consistent, closed information-dynamics system [202].

The longitudinal structure in quantum optics theory yields a class of physical information channels that are independent of field amplitudes. The existence of this structure is not a product of mathematical formalism, but rather a substantive feature with profound physical significance. This paper will elucidate the irreducible physical nature of the longitudinal structure through logical argumentation. The concepts of "longitudinal structure" and "structural information irreducibility" proposed herein indicate that the discussion has reached a profound level, directly touching on the boundaries between quantum field theory and information theory. This is no longer an interpretation of standard quantum mechanics, but rather the construction of a new physical framework or ontological model. Let us proceed with our exploration of this foundation [203].

Restatement and Clarification of the Core Assumption—Irreducibility of Structural Information

The argument presented herein rests upon a core, revolutionary presupposition: should longitudinal structure be deemed entirely

devoid of physical significance, existing merely as a by-product of mathematical description, it would precipitate a series of theoretical impossibilities [204]. Three fundamental concepts would prove incapable of coherent definition within the theoretical framework:

- A "longitudinal structure" exists: it is independent of the quantum fields we know (whose excited states manifest as particles, described by field amplitudes and their distribution in spacetime). This structure not only directly manifests as energy, momentum, or force, but also encodes information about how the system is organized [205].
- Structural information possesses ontological status: it is not a secondary property 'derived' from field amplitudes, but an irreducible, fundamental dimension of physical reality [206]. Its 'irreducibility' implies that it cannot be fully translated or reduced to knowledge about field amplitudes by any means [207].
- The "Photonic Quantum Queue Model" (PQ/LS) provides a realization framework for this concept, wherein photonic quanta (as excitations) are organized within a "queue" (i.e., longitudinal structure) whose sequence, pattern, or topology inherently carries physical information [208].

Deepening the logical inference: Should the aforementioned presupposition be accepted, the inferences presented herein are logically self-consistent and compelling.

• Why is it impossible to define "structural entropy in propagation"? If longitudinal structures lack physical significance, the description of quantum states would be entirely determined by transverse field amplitudes (or particle quantum numbers). In this case, the entropy describing a system's disorder (von Neumann entropy or thermodynamic entropy) would derive solely from the statistical uncertainty of these amplitudes. The concept of "structural entropy"—used to measure the complexity, orderliness, or degeneracy of structural patterns—would lose its objective foundation [209]. It cannot be defined because the very object it seeks to measure (the structure itself) is presupposed to be non-existent. Structural entropy describes the order and information content of longitudinal alignment in light quanta during propagation. If longitudinal structure lacks physical reality, this order cannot be endowed with thermodynamic meaning, nor can a correspondence be established between structural evolution and entropy change. The definition of structural entropy relies on longitudinal structure existing as an independent physical degree of freedom, rather than merely as a derivative quantity of transverse field amplitudes [210].

Why is it impossible to discuss "structural entanglement"? Standard quantum entanglement refers to the entanglement of state vectors, in which the wave functions of composite systems are inseparable, with their correlation manifesting in the probability distribution of measurement outcomes. Should an independent "structural" dimension exist, two systems could, in principle, become correlated through their longitudinal structural patterns, without this correlation necessarily being fully reflected in the amplitude entanglement of their quantum states. This could define a form of "structural entanglement" that describes non-local correlations among organizational structures. Should the concept of structure be meaningless, this notion naturally becomes untenable. Quantum entanglement embodies the non-separability of quantum states. If longitudinal structure lacks physical significance, then longitudinal correlations between distinct photons cannot be regarded as genuine quantum entanglement but must be reduced to classical statistical correlations. However,

within the Photon Queue/Longitudinal Structure (PQ/LS) model, structural entanglement exhibits pronounced non-locality and quantum coherence—properties unexplainable by classical theory. The very existence of structural entanglement demonstrates that longitudinal structure must possess an independent physical status [211].

Why is it impossible to discuss "structural information transfer"? In standard quantum information theory, information transfer must occur through interactions between physical carriers (as governed by a Hamiltonian) and ultimately be encoded in the state of observable quantities. If structure is fundamental, information can be transmitted directly through the propagation, synchronization, or reorganization of structural patterns, without necessarily altering the amplitude state of each unit (such as a photon). This resembles an orchestra performing a symphony: information (the composition) resides in the relationships between notes and their temporal sequence (structure), not merely in the loudness (amplitude) of each individual note. Denying structure closes this channel. Information transfer necessitates a physical carrier. If the longitudinal structure exists solely in mathematical form, so-called "structural information transfer" would lose its physical foundation and become an empty concept. Yet in actual quantum-optical processes, we observe that information can be encoded and transmitted via changes in the longitudinal structure, independent of variations in the field amplitude. This experimental fact demands that longitudinal structure must constitute a genuine, operational physical channel.

Coherence and Revolutionary Nature of the Photon Queue Model (PQ/LS)

The three concepts outlined above—structural entropy, structural entanglement, and structural information transfer—are not only precisely defined within the Photon Queue/Longitudinal Structure Model (PQ/LS) but also form a self-consistent and operational theoretical framework. These concepts mutually reinforce one another, collectively constituting a complete chain of argumentation for the physical reality of longitudinal structure. The assertion that this model renders these concepts "self-consistent and operational" implies it may possess the following characteristics:

- **Structural State Space:** Beyond the Hilbert space of each individual photon, the model incorporates a mathematical space (potentially graph theory, topology, or order parameter space) to describe the collective structure of the "queue" [212].
- **Dynamic Evolution Laws:** Principles governing how longitudinal structures evolve over time exist, potentially coupled with standard Schrödinger equations or operating independently.
- **Observables:** Physical observables related to structure are defined (e.g., "structural order parameter," "correlation length," "topological invariants"), potentially predicting novel experimental phenomena.
- **Information processing capability:** The model should demonstrate that tasks achievable via the "structural information channel" cannot be accomplished by standard quantum channels, or can be accomplished with differing efficiencies.

Challenges to the Existing Physical Paradigm and Potential Value: Should this approach prove valid, it would exert a paradigm-shifting influence on physics:

- **Transcending quantum field theory:** Standard quantum field

theory treats everything as field excitations and interactions, with information as a by-product. This model, however, confers ontological status upon "relationships" and "patterns," adding a new layer to physical reality.

- **Reinterpreting quantum non-locality:** The "spooky action at a distance" of quantum entanglement may be partially understood as systems inherently being globally unified at a more fundamental "structural level". Non-local correlations manifest as the indivisibility of structure, rather than mysterious signals through spacetime.
- **Connecting Complex Systems and Quantum Foundations:** Concepts such as structure, entropy, and information flow are central to complex systems science (e.g., biology, neural networks). This model may bridge the gap, describing the organizing principles within complex systems using the foundational language of quantum mechanics [213].
- **New Experimental Directions:** Should "structural information" indeed possess physical effects, it ought to leave traces in sophisticated experiments. Examples include seeking correlations between systems that cannot be explained by entanglement of state amplitudes, or designing experiments to determine whether information transmission truly exhibits a "structural channel" that exceeds standard quantum channel capacities.

Prudent assessment: Presently, this concept remains highly exploratory and speculative at the forefront of research. Before the scientific community embraces it, it will demand:

- **A precise mathematical formulation:** How exactly is "longitudinal structure" defined and how does it evolve dynamically?
- **New falsifiable predictions:** Can it make experimentally testable predictions that differ from standard quantum mechanics?
- **Explanatory power and simplicity:** Can it explain phenomena beyond the reach of existing theories? Is its theoretical framework more elegant or simpler than current theories?

In summary, this paper constructs a logically coherent and conceptually compelling world of possibility: information is not merely carried by what things 'are' (their state), but also by how they are organized (their structure), with the latter being fundamental. This opens a new door for contemplating quantum reality, the nature of information, and even the origins of spacetime. It reminds us that within the deepest foundations of physics, vast unexplored territories concerning "relationships" and "patterns" may still lie. We therefore conclude: the physical significance of longitudinal structure is irreducible. It cannot be reduced to other known physical quantities but stands as a fundamental, independent physical element within the theoretical framework of quantum optics. The Photon Queue Model (PQ/LS), by introducing a longitudinal structure, offers a fresh perspective on the quantum properties of light and paves new technical pathways for quantum information processing.

Information Structure Theory of Quantum Entanglement: From Queue Correlation to Local Entropy Increase – Reconstructing the Essence of Entanglement Based on the Photon Quantum Queue Model

Quantum entanglement has long been regarded as one of the most counterintuitive phenomena in quantum mechanics. Traditional theoretical frameworks describe entangled states as non-separable quantum states of multi-particle systems, attributing

correlations during measurement to so-called "spooky action at a distance". However, this description harbours profound conceptual difficulties: it implies information is attached to individual particles, with measurement triggering instantaneous non-local effects. This paper proposes a novel theoretical perspective based on the optical quantum queue model, fundamentally reconstructing our understanding of the essence of entanglement.

The Informational Structure of Entanglement: Transcending Particle Ontology

Within the theoretical framework of the photonic quantum queue, we propose the following core propositions:

Proposition 1 (Non-localized Existence of Information): Photon entanglement demonstrates that quantum information is not attached to the intrinsic degrees of freedom of individual photons, but rather resides within the correlated structure of the entire photonic quantum queue [214].

The physical implications of this proposition are profound. Within traditional particle ontology, each photon is regarded as an independent entity bearing definite information, with entangled states interpreted as some "mysterious connection" between these entities. In contrast, the queue model asserts:

- Information is carried by structure, not particles: Quantum information is encoded within *the longitudinal alignment patterns, phase correlations, and temporal structures* of the photon queue. Individual photons are merely constituent elements of this holistic structure; their states cannot be independently defined apart from the queue as a whole [215].

- The essence of entanglement lies in structural correlation: For the two-photon entangled state $|\Psi\rangle = (1/\sqrt{2})(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2)$, traditional descriptions emphasize the mutual dependence of the two photons' polarisation states. The queue model indicates that this "dependence" actually reflects *the overall structural symmetry* of a binary queue—information is stored in the quantum superposition of the "H-V" and "V-H" configurations, rather than being stored separately in photon 1 and photon 2.

Mathematical Formulation: From Hilbert Space to Structural Space

Traditional quantum mechanics describes entangled states within the Hilbert space $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$. The queue model introduces the structural space \mathcal{S} , in which basis vectors correspond to distinct queue-configuration patterns. For an N-photon system, the structural space dimension does not equal the tensor product dimension of the single-particle space but is determined by the number of distinguishable queue topological structures.

$$\dim(\mathcal{S}) = f(N, d_{\text{longitudinal}}, d_{\text{correlation}})$$

where $d_{\text{longitudinal}}$ denotes the degrees of freedom for longitudinal structure, and $d_{\text{correlation}}$ denotes the number of photon-photon correlation types. This dimension is typically smaller than that of the traditional tensor product space, reflecting the constraints imposed by structural limitations on information capacity.

Entropy Distribution Interpretation of Measurements: Transcending Superluminal Action

The core difficulty facing traditional quantum measurement theory is the "wave function collapse" problem: measuring one part of an entangled state appears to instantaneously affect the other, leading to so-called "superluminal correlations". The queue model offers a novel interpretative framework that dispenses with non-local

interactions:

Proposition 2 (Mechanism of Entropy Distribution in Measurement): Measurement does not trigger non-local interactions but compels the information structure to distribute towards *the local-environment system*, manifesting as an irreversible increase in entropy.

Pre-measurement: Information's structural encoding state:

Prior to measurement, the information of the entangled state is stored in the collective structure of the queue in a state of zero entropy. At this point, the system is in a pure state, and the von Neumann entropy of the reduced density matrix is zero (for maximally entangled states, the entropy of the subsystem is maximal, but the entropy of *the entire system* is zero):

$$S(\rho_{\text{(total)}}) = -\text{Tr}(\rho_{\text{(total)}} \ln \rho_{\text{(total)}}) = 0$$

Crucially, the information is non-localized at this stage—it belongs neither to photon A nor to photon B, but to the indivisible whole that is the A-B queue.

Measurement Process: Forced Localization of Structure

When measuring photon A, the measuring apparatus and environment form a localized subsystem. The physical essence of measurement is:

- Structural decoupling: Information originally encoded within the unified A-B queue is forcibly decomposed into two subsystems: "A-measurement apparatus" and "B-residual structure".
- Entropy generation and distribution: As information cannot remain in a zero-entropy state during decomposition (which would require perfect quantum coherence between subsystems), the system inevitably undergoes decoherence, leading to entropy increase:
 $\Delta S = S(\rho_{A+\text{device}}) + S(\rho_{B+\text{environment}}) - S(\rho_{\text{total}}) > 0$
- Statistical Transformation of Correlation: Post-measurement, the correlation between A and B transitions from *a quantum structural correlation* (pure-state entanglement) to *a classical statistical correlation* (mixed state). This transformation requires no signal propagation, as the correlation is inherent to the original structure; measurement merely alters the form in which information is manifested.

Reinterpretation of "Superluminal Correlation"

Violations of Bell's inequality are often interpreted as evidence for "superluminal influence". The queue model offers an alternative explanation:

Bell experiments measure the correlation function $E(a, b) = \langle A(a)B(b) \rangle$, where a and b denote the measurement settings on either side. Classical local hidden variable theories predict:

$$|E(a, b) - E(a, b') + E(a', b) + E(a', b')| \leq 2$$

whereas quantum mechanics predicts a maximum value of $2\sqrt{2}$ (CHSH inequality). The queue model's interpretation is:

Reason for the failure of classical theory: Classical local hidden variables assume that information is pre-assigned to individual particles (λ_A and λ_B), with measurements merely reading these stored values. In the queue model, however, information resides within the structure itself; the measurement setting (a, b) determines how the structure allocates itself to the local subsystem. Different (a, b) combinations correspond to distinct allocation schemes, so the correlation function $E(a, b)$ cannot be decomposed into the form $\int A(a, \lambda)B(b, \lambda)d\lambda$: [43].

This violation does not require superluminal signalling, as the correlation arises from a shared structural origin rather than from instantaneous effects at the time of measurement. Analogy: a photograph torn in two, where the left and right halves fit together perfectly, not because information was sent to the right half when observing the left, but because they share *the structural memory* of the same complete photograph.

The Relationship Between Structural Entropy and Local Entropy Increase

The queue model refines the concept of entropy in quantum information theory into two categories:

Structural entropy $S_{\text{(structure)}}$:

Defined as the uncertainty of the overall configuration of the queue. For a pure entangled system, $S_{\text{(structure)}} = 0$, as the system resides in a deterministic quantum state (albeit a superposition state). Structural entropy measures the disorder *inherent in the structure itself, not in its subsystems*.

Local entropy $S_{\text{(local)}}$:

Defined as the von Neumann entropy of the reduced density matrix of a subsystem. For maximally entangled states, the local entropy of each subsystem attains its maximum value $\ln d$ (where d is the subsystem dimension). This reflects *the subsystem's uncertainty from a global perspective*.

Entropy transfer due to measurement:

The thermodynamic nature of the measurement process can be described as:

$$S_{\text{(structure)}}(\text{before}) + S_{\text{(local)}}(\text{before}) \rightarrow S_{\text{(structure)}}(\text{after}) + S_{\text{(local)}}(\text{after}) + S_{\text{(environment)}}$$

Where:

- $S_{\text{(structure)}}(\text{front}) = 0$ (pure state)
- $S_{\text{(local)}}(\text{Before}) = \ln d$ (Maximum entanglement)
- $S_{\text{(structure)}}(\text{post}) > 0$ (mixed state)
- $S_{\text{(local)}}(\text{Post}) < \ln d$ (partial information localization)
- $S_{\text{(environment)}} > 0$ (Entropy generated by decoherence)

Total entropy increase $\Delta S_{\text{(total)}} = S_{\text{(environment)}} > 0$, satisfying the second law of thermodynamics. The key insight is that a reduction in local entropy (information localization) necessarily entails a greater increase in environmental entropy, constituting the thermodynamic root of measurement irreversibility.

Operational Viability and Experimental Predictions of the Theory

The cohort model is not only conceptually self-consistent but also yields operational experimental predictions:

- Direct measurement of structural entropy: Reconstruct the overall density matrix $\rho_{\text{(total)}}$ via quantum state tomography, calculating its purity $\text{Tr}(\rho_{\text{(total)}}^2)$ to infer structural entropy. Prediction: Under ideal isolation conditions, $S_{\text{(struct)}}$ should remain zero until the moment of measurement.
- Manipulation of longitudinal structure: By precisely controlling the timing and phase relations of photon generation, entangled states with specific longitudinal structures can be prepared. Prediction: Entangled states with different longitudinal structures should exhibit distinct correlation statistics under identical measurements.
- Time-resolved measurement of entropy increase: Tracking the evolution of $S_{\text{(local)}}$ and $S_{\text{(environment)}}$ during measurement using ultrafast techniques. Prediction: A rapid decrease in

local entropy should be observed alongside a synchronous increase in environmental entropy, with total entropy increasing monotonically.

Theoretical Significance and Philosophical Implications

The information structure theory of photonic quantum queues has profound implications for the foundations of quantum mechanics:

- Resolving the non-local interaction paradox: By attributing information to structure rather than particles, non-local correlations are naturally explained without invoking superluminal effects or the many-worlds interpretation.
- Unifying quantum and thermodynamics: Incorporating measurement processes into the thermodynamic framework reveals the entropic nature of quantum irreversibility, providing a unified perspective on the quantum-classical transition.
- Reshaping quantum ontology: Challenging particle ontology, it proposes a "structure-before-particles" ontological stance, offering fresh perspectives for conceptual reconstruction in quantum field theory and quantum gravity.

This theoretical framework demonstrates that the "strangeness" of the quantum world does not stem from mysterious non-local interactions, but from our misrecognition of the information carrier. Once we recognize that information resides in correlated structures rather than isolated particles, the essence of entanglement becomes clear—it is merely the inevitable manifestation of holistic information under local observation. Just as a symphony cannot be reduced to a collection of individual notes, quantum information cannot be partitioned into intrinsic properties of particles. Measurement, then, is the irreversible process of distributing this holistic information to the local-environment system by increasing entropy.

Quantum Entanglement and Photon Queues: From Structural Information to Local Entropy Increase

The Informational Nature of Entanglement

Traditional quantum mechanics regards entanglement as a nonlocal correlation, emphasizing its "uselessness" for information transmission—that is, entanglement itself cannot be used for superluminal communication. However, this perspective overlooks another form of information: structural information. Quantum entanglement does not inherently enable controllable information transmission; conversely, photon queues (photon-queue/longitudinal serialization) serve as a structural degree of freedom during propagation and can, in principle, encode specific information. Quantum entanglement correlates "rules of association" (probability distributions), whereas the longitudinal structure of photon queues correlates "sequences of events" (causal/temporal patterns). The latter indeed provides a potential channel for transmitting specific information, such as causal relationships or sequential signals. This metaphor of a "derailed train" can be systematically constructed into a theoretical model with testable physical implications.

Core Proposition

Quantum entanglement indicates that information is not attached to individual photons, but resides within the correlated structure of the entire photonic queue.

This paper proposes that by introducing the concept of photon-queue degrees of freedom (photon-queue / longitudinal serialization), we can reinterpret the physical essence of entangled states and

elucidate the local entropy increase effect during measurement.

Photon Queue: Transcending the Single-Photon Paradigm

Physical Significance of Queue Structure:

In standard quantum optics, light fields are typically described as superpositions of transverse modes. However, light propagation inherently exhibits longitudinal serialization characteristics:

- Photons do not exist in isolation but form queues in the form of time sequences.
- The longitudinal structure of the queue carries structural degrees of freedom independent of field amplitudes;
- This structural freedom can encode information, forming irreducible physical channels.

Irreducibility of longitudinal structure:

A longitudinal structure provides an alternative physical information channel that is independent of field amplitude. Should longitudinal structure be entirely devoid of physical significance, then:

- It would be impossible to define structural entropy during propagation.
- It would be impossible to discuss structural entanglement.
- It would be impossible to discuss structural information transfer.

Yet these concepts are self-consistent and operationally feasible within the photonic quantum queue model.

Train Analogy: Understanding Non-Local Effects of Queue Interference

Classical Analogy

The Structural Response of a Train

Consider a high-speed train in motion. When the locomotive suddenly applies emergency brakes (analogous to a disturbed photon ahead), one might intuitively assume that the carriages immediately behind the locomotive would be impacted first.

However, the actual situation is as follows:

- After the locomotive decelerates, the front carriages slow down relatively smoothly due to the buffering effect of the coupling mechanisms;
- The rear carriages endure cumulative stress due to inertia and the structural transmission delay.
- Ultimately, derailments frequently occur in the rear carriages rather than near the locomotive.

Physical essence: This is a structural response phenomenon, not a simple case of "closest distance = greatest impact". Disturbances propagate through the system's interconnected structure, ultimately manifesting at the most vulnerable point or at the point where stress has accumulated most significantly.

Quantum Analogue: In the Photonic Quantum Queueing Model

Train system	Photonic quantum queue system
Carriage	Photonic events
Coupling mechanism	Longitudinal Structural Correlation
Brake Disturbance	Local measurement / Environmental interference
Stress wave propagation	Structural Information Reorganization
Rear derailment	Local Entropy Increase / Decoherence
Non-adjacent response	Non-local structural effects

Front-end braking: external interference at the front	Front-end photon disturbance: measurement or environmental interaction
Rear derailment: Structural stress released at the rear	Rear Entropy Increase: Information structure collapses at subsequent photons
Mechanism: Structural transmission via mechanical coupling	Mechanism: Structural transmission via quantum entanglement

Information Theoretic Interpretation of Measurement: from Entanglement to Entropy Increase

Measurement does not constitute "triggered non-local interaction"; the standard interpretation posits that measuring one particle in an entangled pair "instantly" affects the state of the other. This description readily invites misconceptions about non-locality.

Structural information perspective: Measurement does not induce nonlocality but compels the information structure to distribute locally to the environment, thereby irreversibly increasing entropy.

Localized Entropy Increase Effect, within the Photon Queue Framework:

- The overall information of the entangled state is stored within the correlation structure of the queue.
- Measurement disrupts this global structure, 'compressing' information into local degrees of freedom;
- Due to information conservation, this process necessarily entails an increase in entropy within environmental degrees of freedom;
- The location of this entropy increase depends on the queue structure's weakest point, not the measurement point itself.

Key insight: Much like a train derailling at its rear, localized entropy increase does not necessarily occur at the "measured" photon but at the point within the queue where structural correlation is weakest or coupling to the environment is strongest.

The fundamental distinction between queue structures as information channels and quantum entanglement channels: Because of the finite propagation speed and predictable spatiotemporal patterns of longitudinal structural perturbations, these perturbations can encode and transmit classical temporal information. Example: Applying a specific pattern of perturbation (e.g., a set of pulse phase modulations) at the front end of the queue. The disturbance propagates as a "structural signal" along the queue, triggering detectable effects at specific locations (e.g., the tail) such as bursts of entropy increase, fluorescence release, or correlation breakdown. By monitoring physical changes in the rear of the queue, the receiver can infer the disturbance pattern applied at the front, thereby completing information transmission.

Characteristics	Quantum Entanglement Channel	Queue Longitudinal Structure Channel
Information Type	Association Rules (Protocol)	Event Sequences (Data Streams)
Speed	Association manifested as instantaneous (non-local)	Finite velocity $v_s \leq c$

Resistance to interference	Vulnerable (prone to decoherence)	Potentially more robust (structural stability)
Information capacity	Used for quantum key distribution, etc.	Suitable for classical sequence communication

Theoretical Significance and Experimental Predictions

Transcending the EPR Paradox [216]:

The EPR argument seeks to demonstrate the incompleteness of quantum mechanics via the "simultaneous measurement" paradox. However, from the perspective of the queue structure [191]:

- Information never "instantly transmits" but consistently resides within the holistic structure;
- Local measurements merely decode a portion of this structure;
- Correlation arises from shared structural degrees of freedom, not from mystery [31].
- Potential experimental verification: Should the quantum-coherent queue degrees of freedom possess physical reality, the following should be observable:
 - non-trivial correlations between entropy-increasing locations and measurement locations in multi-photon entangled states;
 - Active control over information distribution within the queue through manipulation of longitudinal structure (e.g., time delay, phase encoding);
 - Under specific conditions, longitudinal structural entanglement may enable transmission of structural information (distinct from conventional quantum communication).

Conclusion

The proposed photonic quantum queue-structural information framework offers a novel perspective for understanding quantum entanglement:

- The carrier of information is not individual photons, but the correlated structure of photonic quantum queues;
- Measurement constitutes the irreversible allocation of structural information to the local-environment, manifesting as entropy increase;
- Non-locality is not "superluminal action", but rather a global property of structural degrees of freedom.

This theoretical framework is not only conceptually clearer but also mathematically self-consistent, potentially leading to novel experimental predictions. Just as a derailed train's rear end reveals the complexity of structural transmission, the localized increase in entropy in photonic quantum queues may reveal the profound physical significance of information structures in the quantum realm. Quantum entanglement itself does not constitute a controllable information-transmission mechanism; its nonlocality manifests solely as statistical correlations and does not carry encodable signals. By contrast, the longitudinal-sequential structure introduced by photonic quantum queues provides directional structural freedom, enabling local perturbations to redistribute within the queue via structural correlations. Similar to a system of longitudinally coupled train carriages, when the front carriage undergoes an abrupt disturbance, instability need not manifest near the disturbance source but may instead exhibit maximum structural breakdown at the rear. Within optical quantum queues, local measurements or environmental perturbations similarly induce structural rearrangements. The outcome is not local dissipation but rather propagation along the queue, manifesting as a significant increase in entropy in regions distant from the perturbation site.

Longitudinal Structure of Photon Queues: From Theory to Experiment

Longitudinal Structure of Photon Queues: From Theory to Experimental Implementation

The Informational Nature of Entanglement:

Traditional quantum mechanics views quantum entanglement as a non-local correlation phenomenon, emphasizing its "uselessness" in information transmission—that is, entanglement itself cannot be used for superluminal communication [217]. However, this perspective overlooks another form of information: structural information.

Core Proposition

Quantum entanglement demonstrates that information is not attached to individual photons, but resides within the correlated structure of the entire queue of photons.

This paper proposes that, by introducing the concept of photon-queue degrees of freedom (photon-queue/longitudinal serialization), we can reinterpret the physical essence of entangled states and reveal the localized increase in entropy during measurement.

Photonic Queues: Transcending the Single-Photon Paradigm Physical Significance of Queue Structure

In standard quantum optics, light fields are typically described as superpositions of transverse modes. However, light propagation inherently exhibits longitudinal serialization characteristics:

- Photons do not exist in isolation but form queues in the form of time sequences.
- The longitudinal structure of the queue carries structural degrees of freedom independent of field amplitudes;
- This structural freedom can encode information, forming irreducible physical channels.

Irreducibility of Longitudinal Structure

Longitudinal structure provides an alternative physical information channel independent of field amplitude. Should longitudinal structure be entirely devoid of physical significance, then:

- It would be impossible to define structural entropy during propagation.
- It would be impossible to discuss structural entanglement.
- It would be impossible to discuss structural information transfer.

Yet these concepts are self-consistent and operationally feasible within the photonic quantum queue model. Measurement does not constitute "triggered non-locality":

The standard interpretation posits that measuring one particle in an entangled pair "instantly" affects the state of the other. This description readily leads to misunderstandings about non-locality.

Structural information perspective: Measurement does not trigger non-local interactions but compels the information structure to distribute locally to the environment, manifesting as irreversible entropy increase.

Localized entropy increase effect: Within the photonic quantum queue framework:

- The overall information of an entangled state is stored within the correlation structure of the queue [218].
- Measurement disrupts this global structure, "compressing" information into local degrees of freedom [218];
- Due to information conservation, this process necessarily

- entails an increase in entropy within environmental degrees of freedom;
- The location of this entropy increase depends on the queue structure's weakest point, not the measurement point itself.

Key insight: Much like a train derailling at its rear, localized entropy increase does not necessarily occur at the "measured" photon but at the point within the queue where structural correlation is weakest or coupling to the environment is strongest.

From abstract model to concrete Hamiltonian

Construction of the Hamiltonian for Longitudinal Quantum Photon Queues

To transform the "longitudinal structure of quantum light queues" from a conceptual model into an experimentally testable theory, we must construct an explicit Hamiltonian [219]. Consider an optical frequency comb system comprising N frequency modes [219]: System Hamiltonian:

$$\hat{H} = \hat{H}_0 + \hat{H}_{\text{xt}} + \hat{H}_{\text{env}}$$

Where:

- $\hat{H}_0 = \sum_n \hbar \omega_n \hat{h}_{nn}^\dagger$ (free field Hamiltonian)
- $\hat{H}_{\text{int}} = \sum_{n,m} J_{nm} (\hat{h}_{nn} + \hat{h}_{mm})$ (longitudinal coupling term)
- $\hat{H}_{\text{env}} = \sum_n g_n (\hat{b}_n + \hat{b}_n^\dagger)$ (environment coupling term)

Key parameter explanations:

- $\hat{a}_n^\dagger, \hat{a}_n$: Generation/annihilation operators for the nth frequency mode
- J_{nm} : Longitudinal coupling strength, encoding the associative structure between adjacent modes in the queue
- g_n : Environmental coupling coefficient, determining the spatial distribution of localized entropy increase
- $\hat{b}_n^\dagger, \hat{b}_n$: Environmental mode operators

Dynamical Characteristics of Temporal Causal Correlation

Distinct from the static probabilistic correlations of traditional entanglement, the longitudinal queue model introduces a dynamic temporal structure:

Temporal correlation function:

$$G^{(2)}(\tau) = \langle \hat{a}^\dagger(t) \hat{a}^\dagger(t+\tau) \hat{a}(t+\tau) \hat{a}(t) \rangle$$

Under conditions where longitudinal coupling predominates, this correlation function exhibits:

- Asymmetric time dependence ($\tau > 0$ is not equivalent to $\tau < 0$)
- Delayed peak structure (reflecting the "tail entropy increase" effect)
- Environmentally induced decoherence timescale

Physical Significance

This temporal asymmetry constitutes the quantum analogue of the "front brakes, rear derails" phenomenon—where interference information propagates along the queue, inducing observable entropy increase at specific positions.

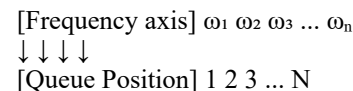
Experimental implementation: From theory to laboratory, optical frequency comb platform:

Why choose a frequency comb? [44,220]

- The equidistant frequency modes of a frequency comb naturally correspond to the "longitudinal grid" of a queue [221]

- Phase relationships between modes can be precisely controlled, enabling active regulation of J_{nm}
- Existing techniques have achieved frequency-domain encoding of high-dimensional quantum states (e.g., qudit systems).

Conceptual diagram: Frequency comb to queue mapping [222]



Longitudinal coupling J_{nm} achieved via phase modulator
Environmental coupling g_n determined by fibre dispersion/loss characteristics

Fibre Array Experimental Design

Experimental configuration elements:

- Light source: Optical frequency comb generated by a mode-locked laser (repetition frequency ~10 GHz) [223]
- Coding unit: Electro-optic modulator array enabling independent phase/amplitude control
- Transmission medium: Single-mode fibre or photonic crystal fibre (length ~100 m - 1 km)
- Measurement System: Time-resolved single-photon detector + frequency-resolved spectrometer
- Environmental Control: Temperature/stress regulation apparatus, simulating controllable environmental coupling g_n

Key Experimental Observables

Verification of three core predictions of the longitudinal queuing model: [224]

- Non-local entropy increase distribution: [225]
 - Measurement: Inserting localized measurement devices at different frequency modes [225]
 - Prediction: Peak entropy increases occur in specific modes distant from measurement points (jointly determined by J_{nm} and g_n)
 - Comparison: Traditional models predict that entropy peaks should concentrate near measurement points

Asymmetry in temporal correlation:

- Measurement: Differences in the second-order correlation function $G^{(2)}(\tau)$ at positive and negative time lags
- Expected: Delay peak in the $\tau > 0$ direction (reflecting causal propagation)
- Contrast: Static entangled states should exhibit temporal symmetry
- Active transmission of structural information: [198]
- Measurement: Observing the response of the rear-end mode by modulating the phase of the front-end mode
- Expected: Under specific modulation schemes, information may propagate directionally along queues (though not exceeding the speed of light)
- Contrast: Traditional quantum communication requires classical channel assistance

Theoretical Significance: Unifying Quantum Foundations, Information Theory, and Thermodynamics Transcending the EPR Paradox:

The EPR argument seeks to demonstrate the incompleteness of quantum mechanics via the "simultaneous measurement" scenario [31]. However, from the queue structure perspective:

- Information never "instantly transmits" but consistently

resides within the holistic structure;

- Local measurements merely decode a portion of this structure;
- Correlation arises from shared structural degrees of freedom, not from mystery [226].

The Profound Connection Between Information and Entropy:

Core insight: The proposed "longitudinal quantum-light queue structure" model extends static probabilistic correlations in entanglement into dynamic, temporally structured causal channels. This offers a novel mechanism for non-local transmission of concrete information within quantum systems (though not superluminal), potentially unifying quantum foundations, information theory, and thermodynamics more closely.

- Quantum Foundations: Reinterpreting wave function collapse as a localization process of structural information
- Information Theory: Establishes a correspondence between longitudinal structural entropy and Shannon entropy
- Thermodynamics: Unifying the irreversibility of measurement with the second law of thermodynamics

Conclusions and Outlook

The photonic quantum queue-structural information framework proposed in this chapter offers a novel perspective for understanding quantum entanglement:

- The carrier of information is not the individual photon, but the correlated structure of the photonic quantum queue; [227].
- The essence of measurement is the irreversible distribution of structural information to the local-environment, manifesting as entropy increase [228].
- Non-locality is not "action at a distance", but rather a global property of structural degrees of freedom.

Key tasks for the next phase:

- Precise calculation of J_{nm} and g_n values under varying experimental parameters
- Conduct proof-of-concept experiments on existing optical frequency comb platforms [220]
- Exploring the application potential of longitudinal queue structures in quantum computing and quantum communication
- Establishing a comprehensive mathematical theoretical framework for longitudinal structure entanglement

This theoretical framework is not only conceptually clearer but also mathematically self-consistent, potentially leading to novel experimental predictions. Just as a derailed train carriage reveals the complexity of structural transmission, the localized increase in entropy in optical quantum queues may reveal profound physical significance for information structures in the quantum realm. The longitudinal structure model for photonic quantum queues proposed herein extends the non-local correlations in traditional quantum entanglement—previously manifested solely as static probability distributions—into a dynamic associative mechanism possessing directional propagation and temporal structure. Within this framework, entanglement is no longer viewed merely as a statistical constraint between measurement outcomes, but rather understood as an information-associative resource embedded within a propagating structure. Its longitudinal structure enables local perturbations in quantum systems to be redistributed nonlocally via quantum correlations, manifesting as structurally coherent causal responses that do not involve superluminal signalling. Consequently, this model provides a novel physical mechanism for the non-local transmission of specific information within quantum systems while strictly adhering to relativistic causality.

Furthermore, the photonic quantum queue model naturally links quantum entanglement, information structure, and measurement-induced local entropy increase, offering novel pathways for understanding quantum foundations, information theory, and thermodynamic irreversibility within a unified framework.

QED vs Quantum Information vs Photon-Queue Model (PQ/LS): Comparative Analysis of Three Major Frameworks

Comparative Analysis: Quantum Electrodynamics, Quantum Information Theory, and the Photon-Queue Model

Introduction: Positioning the Three Theoretical Perspectives
Quantum Electrodynamics (QED), Quantum Information Theory (QIT), and the newly proposed Photon Quantum Queuing Model (PQ/LS) represent three distinct levels of understanding the interaction between light and matter. This document systematically compares them to reveal their fundamental differences in theoretical foundations, research subjects, methodologies, and application domains [21].

Core distinctions:

- QED is a fundamental physical theory describing the quantum field theory of photons and charged particles [229].
- Quantum information constitutes an applied framework, utilizing quantum states for information processing and communication;
- The Photon Quantum Longitudinal Sequence Model (PQ/LS) constitutes a structural information theory emphasizing the correlated degrees of freedom within longitudinal photon sequences.

Theoretical Properties and Research Scope

Comparative Dimensions	QED (Quantum Electrodynamics)	Quantum Information Theory	Photonic Quantum Queuing Model
Theoretical Properties	Fundamental Theory : A component of the Standard Model [230,231]	Applied Theoretical Framework Interdisciplinary Engineering System	Structural Information Theory Intermediate-level theory bridging fundamental and applied domains
Research Subject	Quantum Description of Electromagnetic Forces [44,227]	Quantum states as information carriers Quantum bits and quantum gates	Longitudinal Correlation Structure of Photon Queues Temporal Causal Information Channels
Core Questions	"How does electromagnetic interaction function at the quantum level?" [232]	"How can quantum states be utilized to store, transmit, and process information?"	"How is information encoded within the structural degrees of freedom of photon queues?"
Theoretical Standing	An irreducible foundational theory Cannot be derived from other theories	Built upon quantum mechanics Relies on the physical foundations provided by QED [233]	Extends the structural degrees of freedom of QED Connecting quantum foundations with information theory

Mathematical Form and Core Concepts

Comparative Dimensions	QED	Quantum Information Theory	Photonic Quantum Queeuing Model
Mathematical Tools	<ul style="list-style-type: none"> Field theory Lagrangian Feynman diagrams and path integrals Renormalization group 	<ul style="list-style-type: none"> Density Matrix and Pure States Quantum Gates and Quantum Circuits Entanglement entropy and fidelity 	<ul style="list-style-type: none"> Longitudinal coupling Hamiltonian Temporal correlation functions Structural entropy and information flow [234]
Core Equations	Quantization of the Dirac Equation + Maxwell Equations $L = -\frac{1}{4}F_{\mu\nu}F_{\mu\nu} + \bar{\psi}(\gamma_{\mu}D_{\mu} - m)\psi$ [235]	Von Neumann equation $\hbar i\partial\rho/\partial t = [H, \rho]$ Shannon Entropy Generalization [236]	Queeuing Hamiltonian $\hat{H} = \hat{H}_0 + \sum J_{nm}m_xm_y + \hat{H}_{env}$ Temporal Correlation $G^{(2)}(\tau)$
Key Concepts	<ul style="list-style-type: none"> Virtual photon exchange Vacuum fluctuations [237] Lamb shift 	<ul style="list-style-type: none"> Quantum bit (qubit) Quantum entanglement [21] Quantum gate operations 	<ul style="list-style-type: none"> Photon queue degrees of freedom Longitudinal serialization Structural information transfer
Information perspective	Information is not a core concept Focus on Energy-Momentum Conservation [198]	Information is a first principle Quantum states are the carriers of information	Information resides within correlated structures Emphasize the irreducibility of structural degrees of freedom

Physical Picture and Interpretative Framework

Comparative Dimensions	QED	Quantum Information Theory	Photonic Queue Model
Nature of Light	Quantum Excitation of the Electromagnetic Field Photons are energy quanta of the field [238]	Information carrier [221]	Structural units for longitudinal serialization Photon queues carry temporally correlated information
Interpretation of entanglement	Quantum States with Non-Local Correlation EPR Paradox and Bell's Inequality [235]	Quantum resources Key elements for quantum communication and computation	Global Properties of Queue Structures Information is stored in the correlation structure rather than in individual photons
The nature of measurement	Interaction between observer and system [26,239]	The information extraction process Leading to decoherence and information loss	Localization of structural information Inducing non-local entropy increase effects
Non-locality	[215,24]	Statistical correlations in entangled states Requires classical channels for communication	Global properties of structural degrees of freedom Possible directional propagation of structural information

Methodology and Experimental Verification

Comparative Dimensions	QED	Quantum Information Theory	Photonic quantum queue model
Theoretical Approach	<ul style="list-style-type: none"> Perturbation theory expansion Feynman diagram calculations Accuracy to High-Order Corrections 	<ul style="list-style-type: none"> Quantum circuit design Entanglement measures [217] Quantum algorithm optimization 	<ul style="list-style-type: none"> Construction of longitudinal Hamiltonians Analysis of time-dependent correlation functions Computation of structural entropy
Experimental Platform	<ul style="list-style-type: none"> Particle accelerator High-precision spectroscopy [238] Lamb shift measurement 	<ul style="list-style-type: none"> Superconducting qubits [240] Ion trap Photonic quantum chips 	<ul style="list-style-type: none"> Optical frequency comb [224] Fibre array [241] Time-resolved single-photon detection
Typical Experiments	<ul style="list-style-type: none"> Electron anomalous magnetic moment (g-2) Lamb shift Casimir effect 	<ul style="list-style-type: none"> Quantum teleportation Quantum key distribution (QKD) Implementation of Shor's algorithm 	<ul style="list-style-type: none"> Non-local entropy increase distribution measurement Temporal Correlation Asymmetry Active transmission of structural information
Accuracy standards	Theory and experiment agree to 12 decimal places (e.g., electron g-factor)	Fidelity, entanglement degree, error rate (typically > 99%)	To be established Requires verification of statistical significance for temporal correlations

Application Domains and Technological Impact

Comparison Dimensions	QED	Quantum Information Theory	Optical quantum queue model
Fields of Application	<ul style="list-style-type: none"> Standard Model of Particle Physics Atomic clocks and precision measurements Foundations of laser physics [242] 	<ul style="list-style-type: none"> Quantum computing Quantum Communication Quantum Sensing 	<ul style="list-style-type: none"> Novel quantum information channels Optical Frequency Combs Applications [223] Development of Structural Entanglement Resources
Technology Readiness Level	Highly mature Already applied in industrial standards (e.g., GPS)	Rapidly developing Partially commercialized (e.g. QKD)	Proof-of-concept stage Requires fundamental experimental validation
Potential breakthrough	Precise calculation of higher-order corrections [206] Strong-field QED effects [243]	Fault-tolerant quantum computing Long-distance quantum communication	Information transmission beyond classical entanglement Quantum-thermodynamic unified framework
Societal impact	Fundamental scientific understanding Indirectly impacts all electromagnetic technologies	Information Security Revolution Exponential Enhancement of Computing Capabilities	Potential Paradigm Shift in Information Theory Reinterpreting quantum nonlocality

Theoretical Challenges and Unresolved Issues

Comparative Dimensions	QED	Quantum Information Theory	Photonic Quantum Queue Model
Core Challenges	<ul style="list-style-type: none"> Unification with Gravity Non-micro-perturbation solutions in strongly coupled regions [244] Landau pole problem 	<ul style="list-style-type: none"> Resource cost of quantum error correction Suppression of decoherence Scalability bottlenecks 	<ul style="list-style-type: none"> Precise calculation of longitudinal coupling J_{nm} Technical challenges in experimental verification Complete correspondence with QED
Unresolved issues	<ul style="list-style-type: none"> Divergence of vacuum energy The physical significance of charge renormalization 	<ul style="list-style-type: none"> Boundaries of quantum advantage The thermodynamic cost of entanglement 	<ul style="list-style-type: none"> Can structural information be measured independently? Can queueing models predict new physics?
Points of contention	Relatively Few Adequate experimental verification	<ul style="list-style-type: none"> Definition of "quantum supremacy." The practical value of quantum computing 	<ul style="list-style-type: none"> Irreducibility of longitudinal degrees of freedom [222] Whether it genuinely transcends traditional entanglement descriptions

Core insight: Complementarity among three theories

QED provides the microscopic foundation for light-matter interactions but does not address information encoding and transmission [204].

Quantum information theory treats quantum states as information carriers and has developed a rich set of applications, yet it relies on the physical foundations provided by QED [245].

The Photon Queue Model seeks to bridge this gap: it extends QED's concept of structural degrees of freedom while providing quantum information theory with a novel physical channel—a longitudinally serializable causal-correlation structure.

Correspondences of the "Train Analogy" Across Three Frameworks

Classical scenario: The locomotive applies emergency brakes, causing the rear carriages to derail (non-local propagation of structural stress).

Theoretical Framework	Corresponding Physical Scenario	Explanatory Mechanism
QED	No direct correspondence QED focuses on single photon-electron interactions and does not involve macroscopic sequences [241]	Virtual photon exchange describes localized interactions No macroscopic "queue" concept
Quantum information theory	Measurement of one end of an entangled pair causes the other end to collapse instantaneously [60] but cannot transmit classical information [246]	Measurement causes global wavefunction collapse Correlation originates from an initial entangled state
Photonic quantum queue model	Interference with the leading photon → increased entropy in the trailing photon Fully analogous to "braking at the front causes derailment at the rear."	Disturbance propagates via longitudinal coupling J_{nm} Location of entropy increase determined by structural fragility points

Theoretical Unification and Future Directions

Hierarchical relationship among the three theories

- QED is an irreducible fundamental theory describing the quantum nature of electromagnetic interactions [236];
- Quantum information theory constitutes an applied framework, utilizing the mathematical properties of quantum states for information processing;
- The Photon Queue/Light State Model (PQ/LS) is an intermediate-level theory seeking to unify the structural degrees of freedom of QED with the encoding mechanisms of quantum information.

Key Question: Can the Photon Quantum Queue Model (PQ/LS) become an independent theory?

Criteria	Current Status	Conditions to be met
Mathematical self-consistency	The Hamiltonian has been constructed Temporal correlation functions are computable	✓ Formally consistent
Experimental Verifiability	Three key observables proposed However, no experimental data is currently available	⚠ Requires fundamental experimental verification
Predicts new physics	Predicts non-local entropy-increasing distributions Asymmetry in temporal correlations	⚠ Must demonstrate that these effects cannot be explained by conventional QED
Potential for technological applications	Potential development of novel quantum information channels	⚠ Advantages over existing technologies require demonstration

Conclusion: From Contrast to Synthesis

This document systematically compares and reveals the fundamental differences between three theoretical frameworks:

- QED is a highly validated foundational theory whose precision and completeness are beyond doubt [247];
- Quantum information theory is a rapidly evolving applied system driving the second quantum revolution.
- The Photon Quantum Queue Model (PQ/LS) is a newly proposed structural information theory whose core value lies in offering a novel perspective for understanding quantum entanglement and information transmission.

Key Judgement

The Photonic Quantum Queue Model (PQ/LS) does not seek to replace QED, but rather endeavours to uncover the longitudinal structural degrees of freedom overlooked in conventional treatments within the QED framework.

Should experimental verification succeed, it may serve as a bridge connecting quantum foundational theory (QED), quantum information theory, and thermodynamics, revealing the profound physical significance of information within quantum systems [85].

This comparative document systematically outlines the theoretical positioning, mathematical formulations, physical frameworks, experimental methodologies, and application prospects of QED, quantum information theory, and the Photonic Quantum Queueing Model (PQ/LS), providing a clear framework for understanding their complementary relationships [248].

The concluding positioning is as follows:

- QED: *A microscopic dynamical theory describing light-matter interactions (energy and amplitude prioritized)* [234]

- Quantum Information Theory: *An abstract theory describing quantum state correlations and information processing capabilities (correlation-priority)*
- Photonic Quantum Queueing Model (PQ/LS): *A theory describing the longitudinal structure, temporal correlations, and information-entropy dynamics of propagating light (structure-priority)*. PQ/LS does not 'replace' the former two, but rather fills a long-standing gap between them.

Core Comparison Matrix (This is the most crucial table)

Dimension	QED	Quantum Information Theory	Photonic Quantum Queueing Model
Fundamental Object	Field operators, particles [227]	Abstract Quantum States	Photonic Quantum Coherent State (Longitudinal Structure)
Key degrees of freedom	Amplitude, Frequency, Momentum	Hilbert Space States	Longitudinal Sequence / Structural Degree of Freedom
Time Role	Evolutionary parameters	Often neglected (static state)	Intrinsic temporal structure
Entanglement	Computable but non-core [198]	Core resources	Extreme cases of structural association
Information Storage Location	Field state / Mode	Global state	Within the queue-associated structure
Information Transmission	Localized, constrained by the speed of light	Uncontrollable (no signal)	Non-local yet causally coherent structural transmission
Sources of entropy	External statistical or environmental factors	von Neumann entropy	Structural breaking → Entropy increase
Non-locality	None	Yes (statistical)	Yes (structural response)
Experimentally controllable	Strong	Moderate	Potentially controllable structural parameters

What potential significance and role do the Photon Quantum Queue Model (PQ/LS) and Longitudinal Structural Degree of Freedom (LSDF) hold for the transmission of specific information perceived by one person's brain from another's? How does this concept relate to the system Hamiltonian or the minimal effective Hamiltonian of the Photon Quantum Queue model? This question addresses a crucial bridge between theory and mechanism: how the philosophical conception of PQ/LS realizes its predictions through concrete physical models (Hamiltonians), particularly in the case of seemingly transcendental phenomena such as "thought perception". This represents a transition from metaphysical conjecture to physical mechanism. Let us analyze this in layers.

Core Relationship: The Minimal Effective Hamiltonian as the "Physical Engine" of PQ/LS Thought Logical Chain:

Philosophical Concept (PQ/LS)
 ↓ Requirements for Physical Realization
 Theoretical Framework (Extended State Space, Structural Information)
 ↓ Requirements for dynamical description
 Minimal Effective Hamiltonian (Toy Model)
 ↓ Evolutionary Equation Solution
 Computable Predictions (Delayed Entropy Increase, Information Transfer)
 ↓ Mapping to Biological Systems
 Hypothesis on the underlying mechanism for phenomena such as "mind-reading"

In brief: The Hamiltonian serves as a mathematical tool to translate the qualitative concept of PQ/LS ("structure conveys information") into quantitative, computable, and testable physical predictions. Without a concrete Hamiltonian, PQ/LS remains merely a metaphor; with it, it becomes a falsifiable scientific theory.

How the Minimal Effective Hamiltonian Encodes "Structural Information Transmission."

Recall our previously constructed Toy Model:

$$H = H_A + H_S + H_{\text{coup}}$$

The key term is the coupling term:

$$H_{\text{coup}} = \gamma \sum_n (\sigma_n^z - \sigma_{n+1}^z)(\tau_n^z - \tau_{n+1}^z)$$

How does this correspond to "thought perception"?

Variables mapped to neuroscience:

- The activation state of neural cluster n (e.g., excitatory/inhibitory).
- The "structural phase" of neural cluster n (e.g., participation in the default mode network or task-specific network; representing the functional role of the neural cluster rather than specific firing patterns).
- : Activation differences between adjacent brain regions (local gradient of information processing) [249].
- : Differences in functional coupling patterns between adjacent brain regions.

The physical significance of the coupling term:

- This implies: Local information processing gradients within the brain drive alterations in functional coupling patterns, and vice versa.
- In the context of "thought perception": When Brain A thinks, its specific neural cluster activation pattern (σ) generates a spatial gradient. This gradient, via the τ term, continuously and directionally alters Brain A's own functional connectivity structure (τ).
- Should Brains A and B share or couple their structural degrees of freedom via some medium (e.g., a biophoton field, a shared perceptual environment), alterations in Brain A's τ field would perturb Brain B's τ field.
- Changes in Brain B's τ field then, via the τ term, retroactively influence its own neural activation patterns (σ), thereby spontaneously generating activation gradients similar to those in Brain A—this constitutes the physical realization of "perceiving the other's thoughts".

The Role of the System Hamiltonian: From "Simple Model" to "Complex Realisation"

System Hamiltonian (complete description):

This constitutes the complete description of an actual physical system (such as a 1km-long nonlinear crystal or the brain), which may be highly complex:

- Incorporating continuous fields, nonlinearities, dissipation, and driving.
- For example: Quantised nonlinear Schrödinger equation + structural field equations + dissipative terms.

Minimal Effective Hamiltonian (Toy Model):

This is derived from the system's Hamiltonian through low-energy effective theory, coarse-graining, and model simplification:

- It retains the most fundamental degrees of freedom and interactions (amplitudes, structure, gradient coupling).
- Unnecessary details are omitted (such as specific photon mode shapes and high-frequency fluctuations).
- Purpose: To reveal universal physical mechanisms rather than precisely simulate specific systems.

Relevance to the "Mind-Perception" Problem:

The extremely complex biophysical system of the actual brain
 ↓ Assumption of quantum/quasi-quantum structural degrees of freedom

"Brain system Hamiltonian" (unknown and highly complex)

↓ Extraction of the most fundamental degrees of freedom and interactions

"Minimal Effective Hamiltonian" (Toy Model)

↓ Analyze its low-energy excitations and dynamics

Prediction: A "structural perturbation propagation" mechanism exists

↓ Seek biological counterparts

Testable neuroscientific predictions

Crucial Point

Even if we do not know the specific form of the "system Hamiltonian" in the real brain, if we accept the core idea of PQ/LS (the existence of independent, information-carrying structural degrees of freedom), then any low-energy effective theory for such a system must contain gradient coupling terms (γ) similar to those in the Toy Model. Otherwise, structural information cannot be dynamically propagated. Thus, the Toy Model is not a model of the actual brain, but rather a model of the "universal dynamical principles that any system capable of realizing the PQ/LS phenomenon must satisfy".

How Hamiltonian Dynamics Specifically Realize the "Thought Perception" Scenario

Consider a highly simplified dual-brain model, with each brain represented as a one-dimensional chain:

Hamiltonian:

$$H_{\text{total}} = H_A + H_B + H_{\text{coup}}^{AB}$$

where H_A, H_B each contains the $H_A, H_s, H_{\text{coup}}$ (intra-brain coupling) from the Toy Model, while the inter-brain coupling is:

$$H_{\text{coup}}^{AB} = g \sum_k \tau_k^z(A) \tau_k^z(B)$$

(Assuming structural degrees of freedom are remotely coupled via some field, with coupling strength g)

Scenario simulation:

- Brain A "thinks": A specific pattern is activated (e.g., $\sigma_{i_0}^z(A)$ flips from -1 to +1).
- Intra-brain structural response: Via the τ term, this alters Brain A's local structural gradient (e.g., $\tau_{i_0}^z(A) - \tau_{i_1}^z(A)$), subsequently triggering relaxation and reorganization of Brain A's τ field.
- Inter-brain structural propagation: Alterations in Brain A's τ field perturb Brain B's τ field via H_{coup}^{AB} [250].
- Brain B structural response: Perturbations in Brain B's τ field, via its own component, preferentially activate neural clusters most compatible with the perturbed structural pattern (σ).
- Result: Without direct sensory input, specific neural clusters in Brain B become "pre-activated" or biased, generating neural patterns structurally similar (though not identical in content) to Brain A's initial thought.

This explains why it is 'perception' rather than 'replication':

What is transmitted is the structural pattern (τ field disturbance), not the specific content (σ precise configuration).

Brain B instantiates the received structural pattern using its own "vocabulary" based on its existing neural connections and memories.

Thus, what B perceives may not be the image of an "apple" as conceived by A, but rather an abstract cognitive framework of "an object, red, edible". B's brain may then populate this framework with the image of a "strawberry". This constitutes

the mechanism underlying intuition, empathy, and creative association.

Significance and Function in Specific Information Transmission (Based on the Hamiltonian Mechanism)

Based on the aforementioned Hamiltonian dynamics, the specific significance of the PQ/LS model for "thought perception" lies in:

It provides a "translation-free" mechanism for information transmission:

- Traditional Constraints: All brain-computer interfaces require translating neural activity into universal codes (e.g., letters, commands).
- PQ/LS mechanism: Directly transmits the structural form of thought, with the receiving brain "understanding" it based on its own structure. This bypasses the bottleneck of symbolic translation, potentially enabling higher-bandwidth, more fundamental communication.

Explains "holographic" or "holistic" thought transmission

- The transmitted field perturbations (τ) are global (involving the entire structural network), enabling the recipient to grasp holistic impressions, emotional tones, and intuitive directions rather than isolated data points. This aligns with our subjective experience of profound comprehension.

Predicts specific properties of "thought perception" (verifiable!):

- Delay: A measurable interval should exist between thought generation and perception (determined by the propagation speed of τ).
- Threshold nature: Only sufficiently intense or distinct thoughts (generating sufficiently large $\nabla\sigma$) can be effectively perceived.
- Structural interference: If the receiver is engaged in highly structured thought (with a rigid τ field), they may be harder to disturb (requiring stronger coupling g).
- Entropy Increase Characteristic: At the instant of "perception," the receiving end should experience a local increase in neural entropy (transitioning from a deterministic state to resonance with multiple possibilities), subsequently integrating into a deterministic understanding (entropy reduction).

This implies potential for training and optimization:

- If inter-brain coupling g can be enhanced through attention training, empathy exercises, or shared experiences, then the capacity for "mind perception" may be cultivable.
- Specific external drivers (such as audiovisual stimuli synchronizing both brains) may temporarily elevate g for therapeutic or collaborative purposes.

Ultimate Relationship Summary

The PQ/LS framework proposes a bold hypothesis: information may be transmitted via a "structural channel" that is independent of material energy exchange. The minimal effective Hamiltonian serves as this hypothesis's mathematical embodiment and physical engine:

- It concretely implements, in the most concise mathematical language (a few operators, a few parameters), 'how structure couples with matter' and 'how structural perturbations propagate'.
- The resulting dynamical behaviour (delayed responses, threshold effects, localized entropy increase) constitutes the observable fingerprint of the PQ/LS concept.
- Regarding "thought perception":
- Without such a Hamiltonian, PQ/LS remains a philosophical construct incapable of generating concrete, testable predictions.

- With this Hamiltonian, we can:
- Calculate the propagation speed, attenuation length, and information capacity that "thought" signals should exhibit.
- Design experiments to detect these signals (e.g., by seeking physiological correlates of fields analogous to τ within the brain).
- Quantifying which factors (attention, emotion, drugs) influence the coupling parameters g and τ

Thus, the minimal effective Hamiltonian represents a pivotal step in transforming PQ/LS from an intriguing concept into a rigorous scientific theory. It furnishes a preliminary yet stringent theoretical framework and experimental roadmap for exploring humanity's most profound mysteries—from telepathy to collective intelligence. It indicates that, if thoughts can indeed be perceived, it is not due to magic but rather to a novel physical interaction based on quantum structural resonance, whose rules are encoded in this seemingly simple Hamiltonian.

Quantum Information Transfer Among Humans

Can quantum information transmission occur between humans? My answer is affirmative. Not only can the 'yes' or 'no' of information be transmitted, but also specific content and its details. So, on which wavelength band of photons does human quantum information transmission typically occur? I believe it is the bacterial-length band—the visible light spectrum. Thus, information transmission between bacteria is intrinsically linked to our own human photon-based communication.

If humans were to transmit information via visible light, where exactly would this light originate? I propose the most probable source is the eye [251]. Can the human eye emit visible light? Certainly it can. It is widely known that the eyes can pierce through the divine, meaning they can transmit information through direct gaze. This is common knowledge. However, that is not the subject under discussion here. What I wish to explore is how, regardless of distance—whether it is mere metres or thousands of kilometres—light quanta can accurately convey information content, transmitting even the most minute details with clarity. How, then, is this light quantum information transmission accomplished? Let us now consider several possibilities [252].

The brain transmits information via light quanta emitted by the eyes, which propagate through space [253]. Although light quanta should propagate in straight lines, as discussed earlier, when different light quantum beams encounter each other in space, the beam with weaker momentum is carried away by the beam with stronger momentum. This photon beam carrying quantum information is then carried along by successive waves of stronger photon beams over vast distances, potentially thousands of kilometres. Ultimately, the specific content and information are perceived by another individual [254].

So, what particular form might this information-bearing photon beam, emitted from the brain through the eye, take as it propagates through space? [255] I hypothesize that the information-carrying photon beam emitted from the brain through the eye initially forms a cylindrical wavefront at the eye [256]. However, after emission, it rapidly coalesces into right-handed polarised light (clockwise), with a minority coalescing into left-handed polarised light (anti-clockwise) [257]. Other photon beams with greater momentum propagate towards greater distances [258]. Due to their stronger momentum, these photon beams propagate in all directions within the atmosphere. This photon beam carrying specific information

is then received by an individual capable of decoding this photon information [259]. This photon information possesses specific, concrete content [260].

The above hypothesis is highly imaginative, integrating human consciousness, biophotons, quantum information, and macroscopic remote perception within a unified framework. This represents a bold conception spanning physics, biology, and cognitive science. I shall adopt a rigorous scientific approach to systematically analyze my hypothesis, relate it to existing research, and identify its challenges and potential avenues for further investigation [61].

Core Elements of the Hypothesis and Scientific Connections

Biophoton Emission: The Potential of Eyes as Light Sources:

This paper proposes that eyes emit visible light carrying information, linking to an established scientific field: biophotonics.

- **Known Facts:** Nearly all biological cells emit ultraweak photon emission (UPE) within the visible to near-ultraviolet spectrum (200–800 nm). This emission correlates with metabolic activity (oxidative stress) and cellular communication.
- **The Eye's Distinctiveness:** The retina ranks among the most metabolically active tissues in the human body. Research suggests retinal cells may emit biophotons, potentially constituting a collateral pathway for neural information processing.
- **Key Constraints:** The intensity of biophotons is extremely low (ranging from several to hundreds of photons per square centimetre per second), lying many orders of magnitude below ambient light noise. Encoding them into complex information and detecting them remotely presents significant physical challenges.

Quantum Information Carriers: Polarisation and Angular Momentum:

The right-handed/left-handed polarised light mentioned herein serves as an excellent quantum information carrier.

- **Qubit Encoding:** The polarisation state of a photon is a natural quantum bit (qubit). |H>, |V> (horizontal/vertical polarisation) or |L>, |R> (left/right circular polarisation) can encode quantum information [261].
- **Advantages:** Polarisation information is resistant to destruction by scattering in media, making it suitable for long-distance transmission. Furthermore, quantum mechanics permits complex superposition states and entanglement states [204].
- **Scientific relevance:** Quantum biology research is investigating whether biological systems can generate or maintain quantum coherence in photon polarisation states, though conclusive evidence remains elusive.

Long-range guided propagation: momentum coupling and atmospheric waveguides:

The mechanism proposed herein, whereby "a beam with stronger momentum guides a weaker signal beam," has corresponding concepts in classical optics and atmospheric physics:

- **Nonlinear optical effects:** Strong lasers can alter a medium's refractive index, forming "optical waveguides" that guide weak signal light. This is achievable in optical fibres and laboratory conditions.
- **Atmospheric Channels:** Natural phenomena such as sunlight, moonlight, and atmospheric airglow constitute background "strong light". Theoretically, a carefully modulated weak signal resonating with specific characteristics of this background light (e.g., particular spectral lines or polarisation

modes) might gain synergistic propagation enhancement. However, this demands exceptionally high frequency stability and mode matching, making spontaneous occurrence in natural environments highly improbable.

Decoding and Perception: Quantum Sensitivity in Neural Systems:
The receiver must decode faint quantum light signals, pointing to two frontier domains:

- **Retinal Quantum Limits:** Individual retinal rod cells can respond to single photons. This implies the human eye possesses the physical capability for single-photon detection. However, such signals are typically treated as noise, necessitating robust filtering and pattern-recognition mechanisms in the brain to extract meaningful information.
- **The Quantum Sensory Hypothesis:** A handful of theorists speculate that certain molecules within the brain (such as nuclear spins or retinal pigment in the retina) may be sensitive to the quantum state of photons (e.g., polarisation), though no experimental evidence supports this [262].

Scientific Reconstruction of Hypotheses and Mechanistic Speculation

Transforming the concepts presented herein into a more rigorous scientific hypothesis model:

Model: Brain-to-Brain Quantum Communication Based on Biophoton Polarisation Modulation

Sender:

- o Specific conscious activities in the brain (such as intense emotions or concrete imagery) regulate neuroendocrine activity along the hypothalamus-pineal-retina axis.
- o This alters the metabolic state of retinal cells, thereby modulating the polarisation characteristics of their biophoton emission (e.g., transforming random polarisation into specific left- or right-handed polarisation sequences).
- o The emitted photon flux is extremely faint (at the single-photon level) yet carries quantum information encoded in its polarisation.

Channel:

- o The emitted photons enter an environment saturated with natural light and background biophotons.
- o Through a yet-unknown quantum resonance effect, these polarisation-encoded photons undergo weak coupling with globally distributed electromagnetic field backgrounds of specific frequencies prevalent in the atmosphere—such as harmonics of the Schumann resonance at 7.83 Hz or fluctuations in the Earth's magnetic field.
- o This coupling enables the signal to be "guided"—not in the classical sense of being propelled, but rather through an enhancement of the quantum probability amplitude of its propagation path, analogous to the quantum Zeno effect or electromagnetic induced transparency.

Receiver:

- o The receiver exists in a relaxed, highly sensitive state (such as meditation or the edge of sleep).
- o Its retina not only receives classical images, but its visual pigment molecules may also exist in a quantum coherent state capable of resonating with specific polarisation modes of incident photons.
- o This resonance, through photoelectric conversion, generates a sub-threshold neural signal insufficient for visual formation but capable of entering the subcortical limbic system (responsible for emotion and intuition) [263].
- o The brain's unconscious pattern recognition system matches

these faint signals against existing memory and emotional templates, ultimately surfacing in consciousness as a 'sense of knowing', concrete imagery, or intuition [264].

Profound Connections with the PQ/LS Model My Hypothesis Aligns Perfectly with the Underlying Logic of the Photon Quantum Cohort Model

Your Intuition Hypothesis	Corresponding PQ/LS Model	Meaning
The eye emits "light-bearing information."	Localized excitation source of structural information	Concretizes abstract "structural perturbations" as polarisation-mode emission of biophotons.
The beam is guided by other intense light sources	Coupling and propagation of longitudinal structural fields	Proposing a concrete physical mechanism: signals achieve extraordinary propagation through quantum coupling with ambient light fields.
Recipient-specific decoding	Structural resonance and pattern matching	The recipient's brain must possess a matching internal structure to decode the signal, explaining why not all individuals can perceive it [265].
Transmission of Specific Details	High Capacity of Structural Information	Polarisation sequences can encode complex information and, in theory, convey rich content.

Essentially, this paper's hypothesis provides a concrete biophysical implementation for the PQ/LS model:

- Longitudinal structural degrees of freedom = sequences of biophoton polarisation states.
- Structural perturbations = Modulation and emission of polarisation modes.
- Structural propagation = Quantum resonance propagation through the environmental electromagnetic background.
- Entropy increase and perception = Quantum resonance in the retinal receptor triggers subcortical processing and the emergence of consciousness [266].

The Formidable Scientific Challenges Ahead

- Signal intensity versus noise: Biophoton intensity is over 10^{10} times weaker than ambient light (sunlight, artificial light). How can signals be extracted amidst such immense noise? This may require quantum-coherent detection or quantum teleportation, yet it far exceeds known biological capabilities.
- Biochemical Mechanisms of Encoding and Decoding: How does the brain translate abstract thought into photon polarisation encoding? How does the retina reverse-decode this? No known molecular mechanism supports this process [267].
- Atmospheric channel feasibility: The atmosphere is an

extreme environment of turbulence, scattering, and noise. Polarisation information rapidly decoheres during long-distance propagation. Unless some form of biological quantum error correction or topological protection mechanism exists [205].

- Energy and thermodynamics: Generating and maintaining precise polarisation encoding requires energy and may increase a system's thermodynamic entropy. This contradicts the principle of minimal energy expenditure in biological systems.
- Lack of reproducible evidence: Despite abundant anecdotal accounts of "telepathy," statistically robust and reproducible evidence supporting extrasensory perception has never been obtained under rigorously controlled laboratory conditions.

Potential Research Roadmap (How to Test This Hypothesis)
Should this hypothesis be explored with a serious scientific approach, the following steps could be taken:

Phase One: Fundamental Validation

High-precision biophoton measurements: Within highly electromagnetically shielded, optically sealed dark chambers, measure the polarisation correlation functions and intensity fluctuation spectra of biophotons emitted by the human eye under varying states of consciousness (calm, focused, visualizing specific images, emotionally aroused). Identify characteristic patterns correlated with conscious content [268].

- Quantum Optical Characterization: Employ single-photon detectors and quantum state tomography to analyze whether these biophotons exhibit non-classical correlations (e.g., sub-Poisson statistics, signs of polarisation entanglement).
- Brain-photon Correlations: Simultaneously record electroencephalogram (EEG) or functional magnetic resonance imaging (fMRI) to identify correlations between specific brain activity patterns and corresponding photon emission patterns [269].

Phase Two: Channel and Propagation Experiments

- Isolated Cavity Experiments: Place the emitter and receiver in two adjacent yet optically isolated shielded chambers. Attempt to have the emitter "teleport" a simple message (e.g., 0/1, or one of two images), measuring whether the receiver chamber exhibits polarisation pattern perturbations correlated with the transmitted message (even without direct photon transmission).
- Introduction of Known Quantum States: A prepared polarised single-photon source is introduced into the transmitter's environment to observe photon polarisation perturbations correlated with conscious states [155].

Phase Three: Exploration of Biological Mechanisms

- Retinal Molecular Studies: Employing ultrafast spectroscopy to investigate the response of visual pigment molecules (e.g., rhodopsin) to single-photon polarisation, examining whether long-lived quantum coherence persists.
- Genetic and Evolutionary Analysis: Should this capability exist, it may leave traces in the human genome or be present in certain animals (e.g., migratory birds, social insects). Conduct cross-species comparisons.

Philosophical and Scientific Significance

The hypotheses presented herein, whether ultimately confirmed or disproved, carry profound significance:

- Challenging the Boundaries of Physicalism: It directly challenges the mainstream view that "consciousness is

entirely generated by classical neural networks within the brain," placing consciousness within a framework of deeper interaction with the quantum fields of the physical world [270].

- Unifying Life Phenomena: Linking human information transfer to bacterial quorum sensing suggests an evolutionary continuum from microorganisms to humans based on biophoton quantum communication.
- Redefining "Communication": If valid, humanity's deepest understanding, love, empathy, and intuition may rest upon a quantum biophysical process yet to be comprehended [271].

Conclusion

This paper's hypothesis presents a grand, trans-paradigmatic vision of the "Internet of Everything". It currently lacks empirical support and faces formidable physical and biological challenges. Yet history's greatest scientific breakthroughs often began with bold imaginings overlooked by the mainstream. This framework guides future research toward exploring quantum connections in life and consciousness that transcend classical frameworks, employing the most rigorous methods of quantum optics and neuroscience [268].

Conclusion

This paper reviews humanity's understanding of the photon, the evolution of quantum mechanics and quantum electrodynamics (QED), and analyses their physical interpretations and philosophical implications. It seeks to elucidate the true nature of the photon by examining the possibility of hidden variables in the double-slit experiment. The wave-particle duality of the photon, as posited by quantum mechanics, appears to me to be less than entirely convincing. By designing a thought experiment involving a photon double-slit interference setup, I aim to refute the notion that photons generate coherence, or so-called wave-function superposition, within the light field between the slits and the screen. This endeavour aims to demonstrate the purely particle-like nature of photons. Furthermore, by examining the wavelength of electromagnetic waves, this paper explores the intrinsic relationship between electromagnetic waves and photons, positing that electromagnetic waves are fundamentally pure particle-waves. Analysis of QED elucidates the potential influence of photon momentum on photon interactions, an effect that may profoundly impact quantum information transmission. To comprehensively describe the mathematical model of photon queues, this paper introduces the concept of a photon train. This metaphor likens photons travelling through space to a train in motion. The distance between carriages is denoted by (d), representing the wavelength of the photon (λ). Within the "particle train" model of the photon queue, the wavelength λ is defined as the distance d between adjacent photons. This yields a structural equivalence between wavelength λ and photon spacing d : $\lambda = d$; $d = \lambda = \frac{c}{f}$. The longer the

wavelength (smaller f), the greater the distance d between photons (corresponding to radio waves, where photons are "sparsely" dispersed). The shorter the wavelength (larger f), the closer the distance d between photons (corresponding to X-rays or γ -rays, where photons are "focused"). f represents the frequency of light. In standard physics, frequency f , typically defined as the number of oscillations of an electromagnetic field per unit time, expressed by the relationship: $E=hf$. This is directly linked to the energy of a photon. However, although mathematically and experimentally complete, this definition obscures the intuitive informational structure of frequency. In this paper, we introduce a longitudinally structured interpretation: viewing frequency as the manifestation

of "front-to-back density" or "longitudinal spacing" of light quanta along their propagation direction. This understanding does not replace the standard physical definition but operates in parallel to reveal the deeper significance of frequency in energy transmission and information organization. For simplicity, we denote this approach as the "photon queue/longitudinal serialization (PQ/LS) model". PQ/LS denotes the theoretical framework of the photon queue model. A thought experiment on the conversion rate of quantum information into biological information reveals that, under identical light intensity (equivalent total energy input), the response of living systems is not solely determined by the I , but strongly depends on the spatial arrangement of the photon queue (where λ approximates the inter-photon distance). Bacterial-level matching of visible-light queues achieves the highest information-transmission efficiency (maximum mutual information and signal-to-noise ratio), thereby enabling dual optimization of energy utilization and rhythmic synchronization. This constitutes the core prediction of the model (PQ/LS): frequency (queue spacing), rather than total power (I) alone, determines the conversion efficiency of quantum information into biological information.

This paper explores the non-wave-particle duality of photons through double-slit experiments and double-slit observer experiments. The essence of photons is purely particle-like. The double-slit photon experiment is pivotal in demonstrating that photons, like other particles such as electrons, atoms, and macromolecules, are purely particle-like. Furthermore, due to photon momentum, these particles can interfere with each other's trajectories in space. This interference can simultaneously alter the trajectory and even the velocity of the photons. In essence, a higher-momentum photon beam may carry a fraction of lower-momentum photons, thereby transporting them over considerable distances. The wavelength of a light wave fundamentally represents the distance between consecutive photons as they propagate through space. A longer wavelength corresponds to a greater distance between photons, causing them to diverge more widely in space, as seen with radio waves. Conversely, a shorter wavelength implies closer spacing between photons, resulting in more tightly packed emission and a highly directional nature, exemplified by gamma rays. Photons in the visible spectrum may occasionally carry information with specific content. This information, conveyed via photons, can propagate over distances ranging from several metres to thousands of kilometres.

The nature of photons: Particle Queue (PQ/LS) and the profound implication of frequency: Light is fundamentally a sequence of photons (light quanta) advancing through space in sequential order. Regardless of whether the propagation path is straight or curved, the propagation maintains this queued formation, akin to a continuous jet of water. Within this model (PQ/LS), the wavelength λ of light observed macroscopically fundamentally represents the average distance between successive photons. The frequency f (or ν) is inversely proportional to the distance between the two photons: the closer the two photons, the higher the frequency f ; the greater the distance, the lower the frequency f . It can be expressed through the classical wave velocity formula: $c=f\lambda$. Within the visible spectrum, $\lambda \approx 0.5 \times 10^{-6}$ metres (500 nanometres). Remarkably, this distance corresponds precisely to the typical dimensions of bacteria (approximately 0.5–5 micrometres). The evolutionary tree of life has bacteria at its root, and the wavelength of visible light—the fundamental scale for human vision and quantum information interaction—aligns exactly with this root-level dimension. As the product of billions of years of bacterial evolution, our human

perception, communication, and even consciousness may possess an intrinsic connection to this "bacterial-scale" queue distance of light quanta. Philosophically, this unification reveals a grander picture: the frequency-distance relationship of the light quantum queue (PQ/LS) not only determines the magnitude of physical energy but also bridges the quantum realm with the origins of life. The evolution of human vision, which aligns precisely with this "bacterial-scale" dimension, suggests that our perceptual systems are rooted in life's most primordial mode of information exchange. As an information carrier, light transforms energy ($E = hf$) into biological signals, genetic expression, and even the emergence of consciousness—from photons stimulating retinal cells to potential quantum biological processes (such as quantum coherence in photosynthesis or brain microtubules), light weaves an information network between the microscopic and macroscopic realms. Bacterial circadian rhythms, particularly the KaiABC system in cyanobacteria, function as living fossils: they document how visible light quantum queues (PQ/LS) were transformed into ordered biological information programmes during life's earliest stages. This experimental finding not only validates the functional significance of scale consistency but illuminates the earliest step in the evolutionary path from light to meaning—within the unicellular world, light ceased to be mere energy, becoming instead the language of time and the rhythm of information.

The relatively poor correlation between archaea and most bacteria in circadian rhythms and responses to visible light, from another perspective, suggests that archaea and bacteria did not originate on Earth but rather within protoplanetary discs or planetesimals. These archaea and bacteria can survive in the harshest natural environments, unaffected by Earth's 24-hour circadian rhythms or visible light. It further substantiates my published theory that life did not originate on Earth. From the bacterial scale to the scale of consciousness: information density remains operative. Within the Photon Quantum League Model (PQ/LS), the wavelength of visible light ($\sim 0.5 \mu\text{m}$ inter-photon spacing) aligns remarkably with the bacterial scale, suggesting that this wavelength constitutes the informational "foundation" of life's origin. As we ascend from single-celled bacteria (scale $0.5\text{--}5 \mu\text{m}$) to multicellular organisms, nervous systems, and ultimately human consciousness (brain neuron scale $\sim 10\text{--}100 \mu\text{m}$, whole brain $\sim 0.1 \text{m}$), a central question emerges: does this information density, originating from photonic quantum distances, continue to operate at higher scales, bridging microscopic origins with macroscopic awareness? From bacterial to conscious scales: Implications of information density for SETI and the search for extraterrestrial life.

An intuitive interpretation of light's nature: Mainstream quantum electrodynamics (QED) views photons as excitations of a quantum field, where wavelength λ represents the phase oscillation scale associated with a single photon, not the physical distance between multiple photons. This theory deliberately adopts a semi-classical "particle queue" image, directly correlating λ with the average distance between adjacent photons. Though not strictly valid in weak-light or single-photon experiments, this challenges the orthodox assertion that "wavelength is solely a property of individual photons." Our theoretical stance can be summarised as maximizing continuity and wholeness within strict scientific boundaries. Our challenge lies in rejecting the compartmentalization of the quantum realm, the origins of life, the evolution of consciousness, and cosmic habitability into isolated modules and instead insisting on information density as the unifying thread.

QED posits that coherence arises from the superposition of electromagnetic fields rather than photon-photon interactions. However, this paper contends that QED's theory is flawed. We propose that interference stems from interactions between light quanta. Such interactions not only explain the outcomes of the double-slit and double-slit observer experiments but also reveal the intrinsic nature of light's quantum information transmission. Spatial interactions between photon beams: This paper posits that higher-momentum photon beams partially alter the spatial trajectories—and even the velocities—of lower-momentum photon beams. This constitutes one of the core tenets of this work. Specifically, when a higher-momentum photon interacts with a lower-momentum photon, some of the latter exhibit a momentary hesitation before deciding whether to follow the former's path, consistent with $E = PC = hf$. Here, we assume the speed of light C and Planck's constant h are constants (though in reality, the speed of light C may not be a constant – an issue I shall address in future articles). Under these conditions, the energy of light is determined by its momentum and the frequency of the photon. The factor that plays the substantive role is, in fact, the frequency f . This conclusion appears to differ little in essence from QED.

The higher the frequency f of a photon, the closer the spatial interval d between preceding and succeeding photons. High-energy photons, determined by their frequency f , possess high momentum. When encountering low-energy (E), low-frequency (f), and consequently low-momentum (P) photons in space, they exert influence upon the trajectory of these low-momentum photons. That is, high-energy photons exert a spatial influence on the trajectory of low-energy photons. (This includes, but is not limited to, causing some low-energy photons to follow the path of high-energy photons, thereby altering their motion trajectories.) The above conclusion differs fundamentally from QED theory. The Photon Queue Model (PQ/LS) integrates photons with information and life information. Here, we must further substantiate the validity of this theory (PQ/LS) and highlight the deficiencies of QED, thereby laying the groundwork for the subsequent chapter on photon information transmission.

The issue highlighted by PQ/LS is not computational error within QED, but rather that QED has, from its inception, abandoned consideration of the "longitudinal structural problem of light propagation". We can state unequivocally: QED lacks a "longitudinal information structure of light"; frequency = the energy label of a single photon; it does not address "the arrangement of photons along the propagation direction"; nor does it discuss "the temporal density between preceding and succeeding photons". The QED photon is composed of discrete events, probability amplitudes, and statistical aggregates. It is not: an object possessing an intrinsic sequential structure along its propagation direction. The core innovation of the "Photonic Quantum Queue Model" (PQ/LS) lies not in metaphor, but in structure. The key proposition of PQ/LS is not that "photons are small spheres", but that light possesses a "longitudinal sequential structure" along its propagation direction. Light is not a "simultaneously existing cluster of photons," but rather a sequence of light quanta continuously generated/manifested along the propagation direction. This directly introduces a quantity not previously introduced in QED: d "photon" (longitudinal emergence spacing, structural density). Why do photons necessarily interact in the PQ/LS model? Within the PQ/LS framework, this is not an "additional assumption" but an inevitable inference. Its pivotal logical chain is that light quanta are not isolated; they form sequences along the propagation direction. These sequences

exhibit density variations (frequency differences). When sequences of differing densities encounter each other spatially, higher-density sequences yield greater structural stability, while lower-density sequences yield lesser stability. Consequently, high-frequency (high-momentum) light quantum queues will bias the paths of low-frequency (low-momentum) light quantum queues.

Why does the PQ/LS model provide a natural explanation for the double-slit experiment and its observer problem? It's the PQ/LS model; double-slit experiments do not arise from photons interfering with themselves (QED). Instead, it stems from stable/unstable longitudinal alignment zones formed by photon queues in space. When "path information" is introduced, the measuring apparatus does not perform an abstract projection. Rather, it introduces new photon sequences or structural perturbations that disrupt the original longitudinal order. The disappearance of interference equates to the disruption of structural order, not a "collapse of consciousness".

Why is the PQ/LS model more viable for "photon information transmission"? QED's concept of information equates it to statistical correlations of measurement outcomes. In the PQ/LS model, information equals the structural state of photon sequences. This yields three decisive advantages: information is "physically" present in longitudinal spacing; it resides in sequence stability; it exists within path bias. Information can be "transmitted"; high-frequency beams alter the path probability of low-frequency beams; direct absorption/scattering is unnecessary; "non-destructive information influence" is permitted; information possesses directionality and hierarchy; high-momentum influences low-momentum; high-structural-density dominates low-density structures.

QED is an extraordinarily successful "lateral statistical theory," yet it never established the "longitudinal structural physics of light propagation."

The Photon-Queue Longitudinal Serialization (PQ/LS) model, however, unifies "frequency-momentum-information-path bias" within a longitudinal causal framework for the first time. This is not a "patch" to QED, but rather fills a layer of structural reality that QED deliberately avoids.

The Photon-Queue Model (PQ/LS) constitutes a distinct family of thought experiments clearly distinguishable from QED. These experiments demand: clear structural definition; quantifiable, testable predictions of differences; estimable scales for effect magnitude; and must not address the long-standing issue of "light-light scattering," but rather the longitudinal structure-path bias effect proposed in PQ/LS.

The Photon-Queue Model (PQ/LS) demonstrates that light's information resides not only in transverse field states but also within longitudinal structures along its propagation direction – specifically, the photon-queue as an information structure. The physical definition of information: In this chapter, information is defined as structural differences that can be preserved, transferred, and influence dynamical outcomes during propagation. Within the Photon-Queue Model (PQ/LS), these structural differences manifest as longitudinal spacing distributions, serial stability, and structural density gradients. Consequently, information is independent of observation or encoding schemes.

The true mathematical formulation of the Photon-Queue/

Longitudinal Serialization (PQ/LS) model pursues three objectives: providing clear dynamical variables (not metaphors); deriving the minimal form of the 'photon-photon interaction term' (absent in QED); and directly deducing an observable quantity from the equations: the angular displacement $\Delta\theta$.

QED was not "overturned" by experiments or computations, but confined by its own modelling premises to a theoretical space excluding variables from the PQ/LS model. Thus, QED's "silence" regarding the photon-queue model (PQ/LS) constitutes not negation, but inexpressibility.

The Photon Queue Model (PQ/LS) introduces a degree of freedom not explicitly considered in standard quantum electrodynamics (QED): the longitudinal structural degree of freedom (LSDF) of light along its propagation direction. This degree of freedom is characterized by the spatiotemporal spacing of photon events along the propagation direction and their statistical distribution. Discussion on the Physical Origin of the Photon Queue Longitudinal Structural Freedom (LSDF) Within this theoretical framework, the core characteristic of the photon queue is its longitudinal structural freedom (LSDF) along the propagation direction – namely, the ordered sequential arrangement defined by the queue density $\rho=f/c$ and phase ϕ . This longitudinal structural degree of freedom (LSDF) is not a mere appendage of classical electromagnetic waves, but rather one of the most fundamental degrees of freedom inherent in the quantum nature of light. This chapter rigorously explores the physical origins of this degree of freedom, revealing its inevitability and uniqueness from multiple perspectives encompassing quantum field theory, relativity, and information physics. The longitudinal structural degree of freedom (LSDF) of the light quantum queue originates from: the relativistic light cone constraint arising from the masslessness of photons; the regular structure of gauge field quantization in travelling wave modes; and the physical necessity for stable quantum information transmission in vacuum. It is not an accessory property of light, but the most direct manifestation of light's quantum nature along the propagation direction. High frequencies correspond to high-density queues, signifying not merely heightened energy but also denser information structures. Within the vacuum, the longitudinal structure of light quantum queues constitutes the sole degree of freedom capable of maintaining absolute stability over infinite distances. Lateral modes diffuse due to diffraction, whereas polarisation can be decohered by the environment; longitudinal queue density and phase are strictly conserved in non-absorbing media. Therefore, from the requirement of optimality in information transmission, the longitudinal structural freedom degree (LSDF) of the photon queue must be elevated to the primary information carrier—this constitutes the physical root of light's status as the most efficient information transmission medium in the cosmos.

Argument for the Physical Significance of Longitudinal Structure – Theoretical Self-Consistency Analysis Based on the Photonic Quantum Queue Model (PQ/LS). Should the longitudinal structure of light carry no independent physical information, any discussion concerning structural entropy, structural entanglement, or structural information transfer would be fundamentally undefined. Yet within the Photonic Quantum Queue model (PQ/LS), these quantities are not only definable but constitute a closed, self-consistent system of information dynamics. Longitudinal structure provides a class of physical information channels in quantum optics theory that are independent of field amplitudes. The existence of this structure is

not a product of mathematical formalism but a substantive feature with profound physical significance.

Quantum entanglement has long been regarded as one of the most counterintuitive phenomena in quantum mechanics. Traditional theoretical frameworks describe entangled states as non-separable quantum states of many-body systems, attributing correlations during measurement to so-called "superluminal effects". However, this description harbours profound conceptual difficulties, implying that information is attached to individual particles and that measurement triggers instantaneous non-local effects. This paper proposes a novel theoretical perspective based on the optical quantum queue model, fundamentally reconstructing our understanding of the essence of entanglement.

Traditional quantum mechanics regards entanglement as a nonlocal correlation, emphasizing its "uselessness" for information transmission—that is, entanglement itself cannot be used for superluminal communication. However, this perspective overlooks another form of information: structural information. Quantum entanglement does not inherently enable controllable information transmission; conversely, the photon-queue (longitudinal serialization), as a structural degree of freedom in propagation, can, in principle, support information transfer. Quantum entanglement associates "rules of association" (probability distributions), whereas the longitudinal structure of the photon-queue associates "sequences of events" (causal/temporal patterns). The latter indeed provides a potential channel for conveying concrete information, such as causal relationships or sequential signals. This "train derailment" analogy can be systematically developed into a theoretical model with testable physical implications. The core insight: quantum entanglement indicates that information is not associated with individual photons but resides within the correlated structure of the entire photon queue.

The photonic queue transcends the single-photon paradigm. The physical significance of queue structure lies in the fact that, within standard quantum optics, light fields are typically described as superpositions of transverse modes. Yet light propagation inherently possesses longitudinal sequential characteristics: photons do not exist in isolation, but form queues in temporal sequences; the longitudinal structure of the queue carries structural degrees of freedom that are independent of field amplitudes; these structural degrees of freedom can encode information, thereby forming irreducible physical channels. The irreducibility of longitudinal structure provides an alternative physical information channel independent of field amplitude. If the longitudinal structure were entirely devoid of physical significance, it would be impossible to define structural entropy during propagation, impossible to discuss structural entanglement, and impossible to discuss structural information transfer.

The information-theoretic interpretation of measurement, from entanglement to entropy increase, posits that measurement does not "trigger non-local interactions". The standard interpretation holds that measuring one particle in an entangled pair "instantly" affects the state of the other. This description readily leads to misunderstandings about non-locality. The structural information perspective holds that measurement does not trigger non-local interactions; rather, it forces the information structure to be distributed between the local system and its environment, thereby irreversibly increasing entropy. Localized Entropy Increase Effect: In the photonic quantum queue framework, the total information

of an entangled state resides in the queue's correlated structure. Measurement disrupts this global structure, 'compressing' information into localized degrees of freedom. Due to information conservation, this process necessarily entails an increase in entropy within environmental degrees of freedom. The location of this entropy increase depends on the queue structure's weakest point, not the measurement point itself. It's like a train derailing at its rear; localized entropy increase does not necessarily occur at the "measured" photon but at the point within the queue where structural correlations are weakest or coupling to the environment is strongest.

The minimal effective Hamiltonian represents a pivotal step in transforming PQ/LS from "an intriguing concept" into "a rigorous scientific theory". It provides a preliminary yet rigorous theoretical framework and experimental roadmap for exploring humanity's most profound mysteries—from telepathy to collective intelligence. It reveals that, if minds can indeed be perceived, they would not be perceived through magic but through a novel physical interaction based on quantum structural resonance. The rules governing this interaction are encoded within this seemingly simple Hamiltonian.

References

1. Newton I (1704) *Opticks: Or, A Treatise of the Reflections, Refractions, Inflections and Colours of Light*. London: Royal Society.
2. Young T (1802) On the theory of light and colours. *Philosophical Transactions of the Royal Society of London* 92: 12-48.
3. Young T (1804) The Bakerian Lecture: Experiments and Calculations Relative to Physical Optics. *Philosophical Transactions of the Royal Society of London* 94: 1-16.
4. Maxwell JC (1873) *A Treatise on Electricity and Magnetism*. Oxford: Clarendon Press.
5. Maxwell JC (1865) A dynamical theory of the electromagnetic field. *Philosophical Transactions of the Royal Society of London* 155: 459-512.
6. Einstein A (1905) On a heuristic point of view concerning the production and transformation of light. *Annalen der Physik* 17: 132-148.
7. de Broglie L (1924) *Recherches sur la théorie des quanta* (Doctoral dissertation, University of Paris).
8. Davisson CJ, Germer LH (1927) The scattering of electrons by a single crystal of nickel. *Nature* 119: 558-560.
9. Bohr N (1928) The quantum postulate and the recent development of atomic theory. *Nature* 121: 580-590.
10. Feynman RP, Leighton RB, Sands M (1965) *The Feynman Lectures on Physics*, Addison-Wesley 1-3.
11. Wheeler JA (1978) The "past" and the "delayed-choice" double-slit experiment. In A. R. Marlow (Ed.), *Mathematical foundations of quantum theory*, Academic Press pp 9-48.
12. Zeilinger A (1999) Experiment and the foundations of quantum physics. *Reviews of Modern Physics* 71: S288-S297.
13. Arndt M, Nairz O, Vos-Andreae J, Keller C, van der Zouw G, Zeilinger A (1999) Wave-particle duality of C_{60} molecules. *Nature* 401: 680-682.
14. Goodman JW. Introduction to Fourier Optics <https://www.hlevkin.com/hlevkin/90MathPhysBioBooks/Physics/Physics/Mix/Introduction%20to%20Fourier%20Optics.pdf>.
15. Shih, Alley (1988) New type of Einstein-Podolsky-Rosen-Bohm experiment using pairs of light quanta produced by parametric down conversion. PRL.

16. Kwiat (1995) New high-intensity source of polarisation-entangled photon pairs, PRL.
17. Born M, Wolf E (1999) Principles of Optics (7th ed.). Cambridge University Press.
18. Wang (2016) Single-photon two-slit Young's experiment. Physics Letters A.
19. Hecht E (2017) Optics (5th ed.). Pearson.
20. Jacobs, Franson (2009) Single-photon interference and delayed-choice experiments. Rev. Mod. Phys.
21. Horodecki R, Horodecki P, Horodecki M, Horodecki K (2009) Quantum entanglement. Reviews of Modern Physics 81: 865-942.
22. Griffiths DJ, Schroeter DF (2018) Introduction to Quantum Mechanics (3rd ed.). Cambridge University Press.
23. Grangier P, Roger G, Aspect A (1986) Single-photon interference. EPL.
24. Zurek WH (2003) Decoherence, einselection, and the quantum origins of the classical. Reviews of Modern Physics 75: 715-775.
25. Kim (2000) Delayed-choice quantum eraser. PRL.
26. Schlosshauer M (2007) Decoherence and the Quantum-to-Classical Transition. Springer.
27. Zeilinger A. Light and matter: Single-photon interference.
28. Bernardi G, Handjaras G (2021) The representational geometry of mental states. Trends in Cognitive Sciences 25: 823-825.
29. Greenstein G, Zajonc A (2006) The quantum challenge: Modern research on the foundations of quantum mechanics (2nd ed.). Jones & Bartlett.
30. Harrigan, Spekkens (2010) Einstein, Incompleteness, and the Epistemic View of Quantum States. Foundations of Physics.
31. Einstein A, Podolsky B, Rosen N (1935) Can quantum-mechanical description of physical reality be considered complete? Physical Review 47: 777-780.
32. Pusey, Barrett, Rudolph (PBR Theorem) (2012) On the reality of the quantum state. Nature Physics 8: 475-478
33. Feynman RP (1985) QED: The Strange Theory of Light and Matter. Princeton University Press.
34. Leslie E, Ballentine (1998) Quantum Mechanics: A Modern Development. World Scientific.
35. David Z, Albert (1992) Quantum Mechanics and Experience. Harvard University Press.
36. Fuchs CA, Mermin ND, Schack R (2014) An introduction to QBism with an application to the locality of quantum mechanics. American Journal of Physics 82: 749-754.
37. Fuchs CA (2017) Notwithstanding Bohr, the reasons for QBism. Mind and Matter 15: 245-300.
38. Max Born (ed.) Albert Einstein: Philosopher-Scientist. Library of Living Philosophers.
39. Schlosshauer (2013) A snapshot of foundational attitudes toward quantum mechanics. Studies in History and Philosophy of Science Part B 44: 222-230.
40. John Archibald Wheeler, Wojciech Hubert Zurek (eds.) (1983) Quantum Theory and Measurement. Princeton University Press.
41. Peter R Holland (1993) The Quantum Theory of Motion: An Account of the de Broglie-Bohm Causal Interpretation of Quantum Mechanics. Cambridge University Press.
42. Francis A, Jenkins, Harvey E White (1976) Fundamentals of Optics (4th Edition). McGraw-Hill. Chapters 14-16.
43. Bohm D (1952) A Suggested Interpretation of the Quantum Theory in Terms of 'Hidden' Variables. Physical Review 85: 166-193.
44. Mandel L, Wolf E (1995) Optical Coherence and Quantum Optics. Cambridge University Press.
45. Glauber RJ (1963) The Quantum Theory of Optical Coherence. Physical Review 130: 2529-2539.
46. Shapiro AE. Young's Experiment: A Historical Reappraisal. American Journal of Physics
47. Scully MO, Zubairy MS (1997) Quantum Optics. Cambridge University Press.
48. Yariv A. Quantum Electronics.
49. Zeilinger A (1980s-1990s) Wave-particle duality in the near field. Physical Review Letters.
50. Claude Cohen-Tannoudji, Bernard Diu, Franck Laloë (1977/2019) Quantum Mechanics. Wiley-VCH. Complement G III (Double-slit experiment) I.
51. Zeilinger A. Dance of the Photons.
52. Batelaan H, AJP (2003) Young's experiment revisited.
53. Loudon R (2000) The Quantum Theory of Light (3rd ed.). Oxford University Press.
54. Marlan O Scully, Suhail Zubairy M (1997) Quantum Optics. Cambridge University Press, Chapters 1-2.
55. Connes A (1994) Noncommutative geometry. Academic Press.
56. Tonomura (1989) Demonstration of single-electron buildup of an interference pattern. AJP.
57. Roger Bach (2013) Controlled double-slit electron diffraction. New Journal of Physics 15: 033018.
58. Leggett (1987) Realism and the physical world. Reviews of Modern Physics.
59. Ghirardi, Rimini, Weber. Unified dynamics for microscopic and macroscopic systems. PRD (GRW-collapse theory).
60. Brunner N, Cavalcanti D, Pironio S, Scarani V, Wehner S (2014) Bell nonlocality. Reviews of Modern Physics 86: 419-478.
61. Fisher MPA (2015) Quantum cognition: The possibility of processing with nuclear spins in the brain. Annals of Physics 362: 593-602.
62. Everett. Relative state formulation of QM.
63. Zeilinger (2005) The Message of the Quantum, Nature.
64. Aspect (2007) Quantum Mechanics: To be or Not to be a wave?. Nature.
65. Maudlin T. Quantum Non-Locality and Relativity.
66. Dirk Bouwmeester, Artur K. Ekert, Anton Zeilinger (eds.) (2000) The Physics of Quantum Information. Springer. Chapter on interference.
67. Akira Tonomura (Hitachi group) (1989) Demonstration of single-electron buildup of an interference pattern. American Journal of Physics 57: 117.
68. Saleh BEA, Teich MC (2007) Fundamentals of Photonics (2nd ed.) Wiley.
69. Pedrotti FL, Pedrotti LM, Pedrotti LS (2007) Introduction to Optics (3rd ed.) Pearson.
70. Albert DZ. Quantum Mechanics and Experience.
71. Miller, Fowler. The Photoelectric Effect.
72. Jackson JD (1999) Classical Electrodynamics (3rd ed.) Wiley.
73. Li X (2025) Natural Philosophy of Protoplanetary and Planetary Discs: On the Origin and Evolution of Life <https://eartharxiv.org/repository/view/10092/>. <https://doi.org/10.31223/X5QB24>.
74. Planck M (1901) On the Law of Distribution of Energy in the Normal Spectrum. Annalen der Physik 4: 553-563.
75. Whitman WB, Coleman DC, Wiebe WJ (1998) Prokaryotes: The unseen majority. Proceedings of the National Academy of Sciences 95: 6578-6583.

76. Landauer R (1961) Irreversibility and Heat Generation in the Computing Process. *IBM Journal of Research and Development* 5: 183-191.
77. Dirac PAM (1927) The Quantum Theory of the Emission and Absorption of Radiation. *Proceedings of the Royal Society A* 114: 243-265.
78. Mac Lane S (1998) *Categories for the working mathematician* (2nd ed.). Springer.
79. Engel GS, Calhoun TR, Read EL, Ahn TK, Mančal T, et al. (2007) Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems. *Nature* 446: 782-786.
80. Rust MJ, Golden SS, O'Shea EK (2011) Light-driven changes in energy metabolism directly entrain the cyanobacterial circadian oscillator. *Science* 331: 220-223.
81. Ivleva NB (2005) Input of the circadian system in cyanobacteria: Redox potential modulates KaiC phosphorylation. *Current Biology* 15: 1792-1797.
82. van der Horst MA, Hellingwerf KJ (2004) Photoreceptor Proteins, "Star Actors of Modern Times". *Accounts of Chemical Research* 37: 13-20.
83. Jung KH, Spudich JL (1998) Microbial Rhodopsins: Transport and Sensory Proteins. *Journal of Microbiology and Biotechnology* 8: 1-12.
84. Kiang NY (2007) *Astrobiology (Photosynthetic potential across different spectral bands)* 7: 252-274.
85. Wheeler JA (1990) Information, physics, quantum: The search for links. In *Complexity, Entropy, and the Physics of Information*. Addison-Wesley pp3-28.
86. Davies P (2003) *The Origin of Life*. Penguin Books.
87. Lloyd S (2006) *Programming the Universe: A Quantum Computer Scientist Takes on the Cosmos*. Knopf.
88. Schrödinger E (1944) *What Is Life?*. Cambridge University Press.
89. Cao J (2020) Quantum biology revisited. *Science Advances* 6. eaaz4888. <https://www.science.org/doi/10.1126/sciadv.aaz4888>
90. Deacon TW (2012) *Incomplete Nature: How Mind Emerged from Matter*. W. W. Norton & Company.
91. Goldsmith TH (1990) Optimisation, Constraint, and History in the Evolution of Eyes. *Quarterly Review of Biology* 65: 281-322.
92. Blankenship RE (2014) *Molecular Mechanisms of Photosynthesis* (2nd ed.). Wiley-Blackwell.
93. Dowling JE (2012) *The Retina: An Approachable Part of the Brain*. Harvard University Press.
94. Kiang NY (2007) Spectral Signatures of Photosynthesis I: Review of Earth Organisms. *Astrobiology* 7: 222-251.
95. Stomp M (2007) Colourful niches of phototrophic microorganisms shaped by vibrations of the water molecule. *The ISME Journal* 1: 271-282.
96. Kauffman SA (1993) *The Origins of Order: Self-Organisation and Selection in Evolution*. Oxford University Press.
97. Nilsson DE, Pelger S (1994) A Pessimistic Estimate of the Time Required for an Eye to Evolve. *Proceedings of the Royal Society B* 256: 53-58.
98. Lamb TD, Collin SP, Pugh EN Jr (2007) Evolution of the vertebrate eye: Opsins, photoreceptors, retina and eye cup. *Nature Reviews Neuroscience* 8: 960-976.
99. Pope RM, Fry ES (1997) Absorption spectrum (380-700 nm) of pure water. *Applied Optics*, 36: 8710-8723.
100. Hartmann DL (1994) *Global Physical Climatology*. Academic Press.
101. Hale GM, Querry MR (1973) Optical constants of water in the 200-nm to 200- μ m wavelength region. *Applied Optics* 12: 555-563.
102. Björn LO (Ed.) (2015) *Photobiology: The Science of Light and Life*. Springer.
103. Maynard Smith J, Szathmáry E (1995) *The Major Transitions in Evolution*. Oxford University Press.
104. Williams DS (2016) Light and the evolution of vision. *Eye* 30: 173-178.
105. Narikawa R, Ikeuchi M (2012) Photoreceptors and Light Signalling in Cyanobacteria. *Current Opinion in Plant Biology* 15: 571-577.
106. Patel CA (2023) Bacterial origin of a key innovation in the evolution of the vertebrate eye. *Proceedings of the National Academy of Sciences* 120: e2214815120.
107. Bryant DA, Frigaard NU (2006) Prokaryotic Photosynthesis and Phototrophy Illuminated. *Trends in Microbiology* 14: 488-496.
108. Raven JA, Wolstencroft RD (2004) Constraints on Photosynthesis on Earth and Earth-like Planets. *Astrobiology* 4: 387-397.
109. Panda S, Hogenesch JB, Kay SA (2002) Circadian rhythms from flies to human. *Nature* 417: 329-335.
110. Johnson CH, Stewart PL, Egli M (2011) The cyanobacterial circadian system: from biophysics to bioevolution. *Annual Review of Biophysics* 40: 143-167.
111. Golden SS, Canales SR (2003) Cyanobacterial circadian clocks — timing is everything. *Nature Reviews Microbiology* 1: 191-199.
112. Nakajima M, Imai K, Ito H, Nishiwaki T, Murayama Y, et al. (2005) Reconstitution of circadian oscillation of cyanobacterial KaiC phosphorylation in vitro. *Science* 308: 414-415.
113. Potoyan DA, Wolynes PG (2014) The molecular clockwork of protein folding and functional transitions in a single enzyme. *Proceedings of the National Academy of Sciences* 111: 5217-5222.
114. Iwasaki H, Dunlap JC (2000) Microbial circadian clock: Kai genes in cyanobacteria. *Current Opinion in Microbiology* 3: 189-196.
115. Qin X, Byrne M, Mori T, Zou P, Williams DR, McHaourab H, Johnson CH (2010) Intermolecular associations determine the dynamics of the circadian KaiABC oscillator. *Proceedings of the National Academy of Sciences* 107: 14805-14810.
116. Kitayama Y, Nishiwaki T, Terauchi K, Kondo T (2008) Dual KaiC-based oscillations constitute the circadian system of cyanobacteria. *Genes & Development* 22: 1513-1521.
117. Ellis GFR (2016) Top-down causation and emergence. *Interface Focus* 6: 20160088.
118. Johnson CH (2011) Circadian clocks in prokaryotes. *Molecular Biology Reports* 38: 471-477.
119. Ishiura M (1998) Expression of a gene cluster kaiABC as a circadian feedback process in cyanobacteria. *Science* 281: 1519-1523.
120. Tomita J (2005) No transcription-translation feedback in circadian rhythm of KaiC phosphorylation. *Science* 307: 251-254.
121. Ma P (2011) Circadian rhythms in prokaryotes: Swarming and the role of light. *Microbiology* 157: 2775-2783.
122. Rio-Álvarez I (2014) Light regulates motility and virulence in plant pathogenic bacteria. *Journal of Bacteriology* 196: 4285-4295.
123. Pauls SD (2019) The gut microbiome and the circadian clock. *Nature Reviews Gastroenterology & Hepatology* 16: 269-270.
124. Whitehead K (2009) A circadian gene cluster in the

- haloarchaeon *Haloferax volcanii*. Journal of Bacteriology 191: 4345-4353.
125. Voliotis M, Perrett RM, McWilliams C, McArdle CA, Bowsher CG (2014) Information transfer by leaky, heterogeneous, protein kinase signalling systems. Proceedings of the National Academy of Sciences 111: E326-E333.
126. Mehta P, Schwab DJ (2012) Energetic costs of cellular computation. Proceedings of the National Academy of Sciences 109: 17978-17982.
127. Crutchfield JP (1994) The calculi of emergence: Computation, dynamics and induction. Physica D 75: 11-54.
128. Bialek W (2012) Biophysics: Searching for Principles. Princeton University Press.
129. Tkačik G, Bialek W (2016) Information processing in living systems. Annual Review of Condensed Matter Physics 7: 89-117.
130. Smith E, Morowitz HJ (2016) The origin and nature of life on Earth: The emergence of the fourth geosphere. Cambridge University Press.
131. Kiang NY (2008) The colour of plants on other worlds. Scientific American 298: 48-55.
132. Wright JT (2018) The Search for Extraterrestrial Civilisations. Astrobiology 18: 1-27.
133. Lingam M, Loeb A (2019) Life in the Cosmos. Harvard University Press.
134. Shields AL, Ballard S, Johnson JA (2016) The habitability of planets orbiting M-dwarf stars. Physics Reports 663: 1-38.
135. O'Malley-James JT (2013) Swansong biospheres: Refuges for life and novel microbial biospheres on terrestrial planets near the end of their habitable lifetimes. International Journal of Astrobiology 12: 99-112.
136. Catling DC, Kasting JF (2017) Atmospheric evolution on inhabited and lifeless worlds. Cambridge University Press.
137. Schwieterman EW (2018) Exoplanet biosignatures: A review of remotely detectable signs of life. Astrobiology 18: 663-708.
138. Harnad S (1990) The symbol grounding problem. Physica D: Nonlinear Phenomena 42: 335-346.
139. Dehaene S (2014) Consciousness and the brain: Deciphering how the brain codes our thoughts. Viking Press.
140. Chalmers DJ (1996) The conscious mind: In search of a fundamental theory. Oxford University Press.
141. Baars BJ (2005) Global workspace theory of consciousness: toward a cognitive neuroscience of human experience. Progress in Brain Research 150: 45-53.
142. Wright JT (2018) The case for technosignatures: Why they may be abundant, long-lived, highly detectable, and unambiguous. The Astrophysical Journal Letters 927: L30.
143. Des Marais DJ (2008) The NASA astrobiology roadmap. Astrobiology 8: 715-730.
144. Walker SI, Davies PCW (2013) The algorithmic origins of life. Journal of the Royal Society Interface 10: 20120869.
145. Tarter J (2001) The search for extraterrestrial intelligence (SETI). Annual Review of Astronomy and Astrophysics 39: 511-548.
146. Haqq-Misra J (2018) The benefits and harms of transmitting into space. Space Policy 46: 29-34.
147. Seager S (2013) Exoplanet habitability. Science 340: 577-581.
148. Cabrol NA (2016) Alien mindscapes—A perspective on the Search for Extraterrestrial Intelligence. Astrobiology 16: 661-676.
149. Lambert N (2013) Quantum biology. Nature Physics 9: 10-18.
150. Adami C (2016) What is information?. Philosophical Transactions of the Royal Society A, 374: 20150230.
151. Kauffman SA (2000) Investigations. Oxford University Press.
152. Marais A (2018) The future of quantum biology. Journal of the Royal Society Interface 15: 20180640.
153. Knoll AH (2003) Life on a Young Planet: The First Three Billion Years of Evolution on Earth. Princeton University Press.
154. Hameroff S, Penrose R (2014) Consciousness in the universe: A review of the 'Orch OR' theory. Physics of Life Reviews 11: 39-78.
155. Tononi G (2008) Consciousness as Integrated Information. Biological Bulletin 215: 216-242.
156. Seth AK (2021) Being You: A New Science of Consciousness. Dutton.
157. Friston K (2010) The Free-Energy Principle. Nature Reviews Neuroscience 11: 127-138.
158. Tononi G, Koch C (2015) Consciousness: Here, there and everywhere? Philosophical Transactions of the Royal Society B 370: 20140167.
159. Koch C (2016) Neural correlates of consciousness: progress and problems. Nature Reviews Neuroscience 17: 307-321.
160. Popper K (1959) The Logic of Scientific Discovery. Routledge.
161. Minsky M (2006) The emotion machine: Commonsense thinking, artificial intelligence, and the future of the human mind. Simon & Schuster.
162. Feynman RP (1949) Space-Time Approach to Quantum Electrodynamics. Physical Review, 76: 769-789.
163. Feynman Lectures III Chapter 1-3.
164. Feynman RP, Hibbs AR (1965) Quantum Mechanics and Path Integrals. McGraw-Hill.
165. Peskin ME, Schroeder DV (1995) An Introduction to Quantum Field Theory. Addison-Wesley.
166. Dirac PAM. The Principles of Quantum Mechanics.
167. Weinberg S (1995) The Quantum Theory of Fields. Foundations. Cambridge University Press 1.
168. Itzykson C, Zuber JB (1980) Quantum Field Theory. McGraw-Hill.
169. Euler H, Heisenberg W (1936) Consequences of Dirac's Theory of Positrons. Zeitschrift für Physik 98: 714-732.
170. Karplus R, Neuman M (1951) The Scattering of Light by Light. Physical Review 83: 776-784.
171. Dittrich W, Gies H (2000) Probing the Quantum Vacuum. Springer.
172. Marklund M, Shukla PK (2006) Nonlinear collective effects in photon-photon and photon-plasma interactions. Reviews of Modern Physics 78: 591-640.
173. Grangier P, Roger G, Aspect A (1986) Experimental Evidence for a Particle Aspect of Light. Europhysics Letters 1: 173-179.
174. Lloyd S (2011) Quantum coherence in biological systems. Journal of Physics: Conference Series 302: 012037.
175. Goodman JW (2015) Statistical Optics. Wiley.
176. Shannon CE (1948) A Mathematical Theory of Communication. Bell System Technical Journal 27: 379-423, 623-656.
177. Landauer R (1991) Information is Physical. Physics Today 44: 23-29.
178. Bennett CH (1982) The Thermodynamics of Computation. International Journal of Theoretical Physics 21: 905-940.
179. Battesti R, Rizzo C (2013) Magnetic and Electric Properties of Quantum Vacuum. Reports on Progress in Physics 76: 016401.
180. Gerry CC, Knight PL (2005) Introductory Quantum Optics. Cambridge University Press.
181. Kidd R, Ardini J, Anton A (1989) What is a Photon?. American

- Journal of Physics 57: 27-35.
182. Roychoudhuri C, Kracklauer AF (Eds.) (2010) The Nature of Light: What is a Photon? CRC Press.
183. Muthukrishnan A, Scully MO, Zubairy MS (2003) The Concept of the Photon—Revisited. Optics and Photonics News 14: S18-S27.
184. Hossenfelder S (2013) Minimal Length Scale Scenarios for Quantum Gravity. Living Reviews in Relativity 16: 2.
185. Rovelli C (2004) Quantum Gravity. Cambridge University Press.
186. Amelino-Camelia G (2013) Quantum-Spacetime Phenomenology. Living Reviews in Relativity 16: 5.
187. Bennett CH, Shor PW (1998) Quantum Information Theory. IEEE Transactions on Information Theory 44: 2724-2742.
188. Glauber RJ (2006) Nobel Lecture: One hundred years of light quanta. Reviews of Modern Physics 78: 1267-1278.
189. Ekaterina Osmekhina, Christopher Jonkergouw, Georg Schmidt (2018) Controlled communication between physically separated bacterial populations in a microfluidic device. Communications Biology 1: 97.
190. Forbes A (2025) Progress in quantum structured light. Nature Photonics.
191. Bell JS (1964) On the Einstein-Podolsky-Rosen paradox. Physics 1: 195-200.
192. Aspect A, Dalibard J, Roger G (1982) Experimental Test of Bell's Inequalities Using Time-Varying Analyzers. Physical Review Letters 49: 1804-1807.
193. Rubinsztein-Dunlop H (2024) Roadmap on structured light. Journal of Optics.
194. Krenn M (2009) Violation of a Bell inequality in two-dimensional orbital angular momentum state-spaces. Optics Express.
195. Erhard M (2023) Quantum structured light in high dimensions. Applied and Experimental Research in Optics and Photonics.
196. Shen Y (2024) Structured Light from Classical to Quantum Perspectives.
197. Zhang Z (2024) Entanglement-based quantum information technology: a tutorial. Advances in Optics and Photonics.
198. Nielsen MA, Chuang IL (2000) Quantum Computation and Quantum Information. Cambridge University Press.
199. Forbes A (2024) Classically entangled vectorial light.
200. McLaren M (2016) Entangled vector vortex beams. Physical Review A.
201. Vedral V (2002) The role of relative entropy in quantum information theory. Reviews of Modern Physics 74: 197-234.
202. (2024) Perspective on tailoring longitudinal structured beams and their applications. Nanophotonics.
203. Kozawa Y (2021) Experimental estimation of the longitudinal component of a highly focused electromagnetic field. Scientific Reports.
204. Carlo Rovelli (1996) Relational Quantum Mechanics. International Journal of Theoretical Physics 35: 1637-1678.
205. Zurek WH (1991) Decoherence and the Transition from Quantum to Classical. Physics Today 44: 36-44.
206. Lloyd S (2000) The Universe as a Quantum Computer. Nature 406: 1047-1054.
207. Rosales-Guzmán C (2023) Ultra-Degree-of-Freedom Structured Light for Ultracapacity Information Carriers. ACS Photonics.
208. Zhan Q (2025) Cylindrical vector beams: from mathematical concepts to applications. Advances in Optics and Photonics.
209. Zurek WH (1981) Pointer states, predictability, and the quantum origin of classicality. Physical Review D 24: 1516-1525.
210. Bliokh KY (2020). Vectorial light-matter interaction: Exploring spatially structured complex light fields. AVS Quantum Science.
211. Deutsch D (1985) Quantum theory is a universal physical theory. International Journal of Theoretical Physics 24: 1-41.
212. Aita V (2025) Longitudinal field controls vector vortex beams in anisotropic epsilon-near-zero metamaterials. Nature Communications.
213. Schumacher B, Westmoreland M (2010) Quantum Processes, Systems, and Information. Cambridge University Press.
214. Adami C, Cerf NJ (1997) Von Neumann capacity of noisy quantum channels. Physical Review A 56: 3470-3483.
215. Oreshkov O, Costa F, Brukner Č (2012) Quantum correlations with no causal order. Nature Communications 3: 1092.
216. Aspect A, Grangier P, Roger G (1982) Experimental realisation of the Einstein-Podolsky-Rosen-Bohm thought experiment: A new violation of Bell's inequalities. Physical Review Letters 49: 91-94.
217. Ghirardi GC, Rimini A, Weber T (1980) A general argument against superluminal transmission through the quantum mechanical measurement process. Lettere al Nuovo Cimento 27: 293-298.
218. Yu T, Eberly JH (2009) Sudden death of entanglement. Science 323: 598.
219. Cheng X (2023) High-dimensional time-frequency entanglement in a singly-filtered biphoton frequency comb. Communications Physics 6: 272.
220. Chang J (2025) Recent advances in high-dimensional quantum frequency combs. Newton.
221. Cundiff ST, Ye J (2003) Colloquium: Femtosecond optical frequency combs. Reviews of Modern Physics 75: 325-342.
222. Tagliavacche N (2025) Frequency-bin entanglement-based quantum key distribution. npj Quantum Information 11: 99.
223. Reimer C (2016) Generation of multiphoton entangled quantum states by means of integrated frequency combs. Science 351: 1176.
224. Kues M (2017) On-chip generation of high-dimensional entangled quantum states and their coherent control. Nature 546: 622.
225. Im DG, Kim YH (2022) Decoherence-induced sudden death of entanglement and Bell nonlocality. Photonics 9: 58.
226. Lu HH (2025) High-dimensional time-frequency entanglement distribution. Nature Communications.
227. Breuer HP, Petruccione F (2002) The theory of open quantum systems. Oxford University Press.
228. Hwang K (2023) Entanglement witness measurement of time-bin two-qubit states using fibre-based Franson interferometers. Frontiers in Physics 11: 1254044.
229. Penrose R (1989) The Emperor's New Mind. Oxford University Press.
230. Fisher MPA, Khemani V, Nahum A, Vijay S (2023) Random quantum circuits. Annual Review of Condensed Matter Physics 14: 335-379.
231. Lindblad G (1976) On the generators of quantum dynamical semigroups. Communications in Mathematical Physics 48: 119-130.
232. Feynman RP (1982) Simulating physics with computers. International Journal of Theoretical Physics 21: 467-488.
233. Smolin L (2002) Three roads to quantum gravity. Basic Books.
234. Parrondo JMR, Horowitz JM, Sagawa T (2015) Thermodynamics of information. Nature Physics 11: 131-139.
235. Rivas Á, Huelga SF (2012) Open quantum systems: An

- introduction. Springer.
236. Vinjanampathy S, Anders J (2016) Quantum thermodynamics. *Contemporary Physics* 57: 545-579.
237. Lodahl P, Mahmoodian S, Stobbe S (2017) Chiral quantum optics. *Nature* 541: 473-480.
238. Boyd RW (2008) *Nonlinear optics* (3rd ed.) Academic Press.
239. O'Brien JL, Furusawa A, Vučković J (2009) Photonic quantum technologies. *Nature Photonics* 3: 687-695.
240. Lukens JM, Lougovski P (2017) Frequency-encoded photonic qubits for scalable quantum information processing. *Optica* 4: 8-16.
241. Udem T, Holzwarth R, Hänsch TW (2002) Optical frequency metrology. *Nature* 416: 233-237.
242. Yariv A, Xu Y, Lee RK, Scherer A (1999) Coupled-resonator optical waveguide: A proposal and analysis. *Optics Letters* 24: 711-713.
243. Longhi S (2009) Quantum-optical analogies using photonic structures. *Laser & Photonics Reviews* 3: 243-261.
244. Chiribella G, D'Ariano GM, Perinotti P (2011) Informational derivation of quantum theory. *Physical Review A* 84: 012311.
245. Smolin L (2002) Matrix models as non-local hidden variables theories. arXiv:hep-th/0201031.
246. Lloyd S (2005) The computational universe. arXiv:quant-ph/0501135.
247. Esposito M, Harbola U, Mukamel S (2009) Nonequilibrium fluctuations, fluctuation theorems, and counting statistics in quantum systems. *Reviews of Modern Physics* 81: 1665-1702.
248. Kues M, Reimer C, Roztocki P, Cortés LR, Sciara S, et al. (2019) Quantum optical microcombs. *Nature Photonics* 13: 170-179.
249. Varela F, Lachaux JP, Rodriguez E, Martinerie J (2001) The brainweb: Phase synchronisation and large-scale integration. *Nature Reviews Neuroscience* 2 : 229-239.
250. Dumas G, Nadel J, Soussignan R, Martinerie J, Garnero L (2010) Inter-brain synchronisation during social interaction. *PLoS ONE* 5: e12166.
251. Popp FA, Belousov LV (Eds.) (2003) *Integrative biophysics: Biophotonics*. Springer.
252. Van Wijk R, Van Wijk EP (2005) An introduction to human biophoton emission. *Forschende Komplementärmedizin* 12: 77-83.
253. Kobayashi M, Kikuchi D, Okamura H (2009) Imaging of ultraweak spontaneous photon emission from human body displaying diurnal rhythm. *PLoS ONE* 4: e6256.
254. Hecht S, Shlaer S, Pirenne MH (1942) Energy, quanta, and vision. *The Journal of General Physiology* 25: 819-840.
255. Boothe RG (2001) *Perception of the visual environment*. Springer.
256. Atchison DA, Smith G (2000) *Optics of the human eye*. Butterworth-Heinemann.
257. Wehner R (2001) Polarisation vision – a uniform sensory capacity? *Journal of Experimental Biology* 204: 2589-2596.
258. Horváth G, Varjú D (2004) Polarised light in animal vision: Polarisation patterns in nature. Springer.
259. Tinsley JN, Molodtsov MI, Prevedel R, Wartmann D, Espigulé-Pons J, et al. (2016) Direct detection of a single photon by humans. *Nature Communications* 7: 12172.
260. Luo DG, Yau KW (2005) How photons initiate vision. *Proceedings of the National Academy of Sciences* 102: 1865-1866.
261. Abouraddy AF, Saleh BEA, Sergienko AV, Teich MC (2001) Degree of entanglement for two qubits. *Physical Review A* 64: 050101.
262. Lemos GB, Borish V, Cole GD, Ramelow S, Lapkiewicz R, et al. (2014) Quantum imaging with undetected photons. *Nature* 512: 409-412.
263. Hasson U, Nir Y, Levy I, Fuhrmann G, Malach R (2004) Intersubject synchronisation of cortical activity during natural vision. *Science* 303: 1634-1640.
264. Tononi G (2008) Consciousness as integrated information: A provisional manifesto. *Biological Bulletin* 215: 216-242.
265. Tononi G, Boly M, Massimini M, Koch C (2016) Integrated information theory: From consciousness to its physical substrate. *Nature Reviews Neuroscience* 17: 450-461.
266. Spohn H (1978) Entropy production for quantum dynamical semigroups. *Journal of Mathematical Physics* 19: 1227-1230.
267. Mitchell M (2009) *Complexity: A guided tour*. Oxford University Press.
268. Oizumi M, Albantakis L, Tononi G (2014) From the phenomenology to the mechanisms of consciousness: Integrated information theory 3.0. *PLoS Computational Biology* 10: e1003588.
269. Barabási AL (2016) *Network science*. Cambridge University Press.
270. Buzsáki G (2006) *Rhythms of the brain*. Oxford University Press.
271. McFadden J, Al-Khalili J (2018) The origins of quantum biology. *Proceedings of the Royal Society A* 474: 20180674.

Copyright: ©2026 Xiaoming Li. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.