Light as a Case Study within an Empirical-Axiomatic Framework

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Abstract

Scientific understanding proceeds through experiments that reveal how systems behave and through abstract models constructed to account for those behaviors. Persistent conceptual and philosophical confusions arise, however, when the distinction between empirical reality and its abstract representations is left implicit. This issue is particularly evident in the study of light, where multiple, mutually non-equivalent models coexist, each successful within specific limits, yet none capable of exhausting all observed phenomena.

In this work, light is analyzed as a case study using the empirical–axiomatic self framework. Light is treated first as an empirical self: a system that exists and behaves in reality and constrains observation through experimental interaction. Experimental outcomes are taken as empirical facts, understood not as explanations but as constraints imposed by reality on representation. From these constraints, multiple axiomatic selves ray, wave, classical electromagnetic, particle, quantum, and quantum field models are constructed as abstract, internally coherent structures, each defined by assumptions and restricted domains of validity.

The analysis shows that domains of validity are determined directly by experimental results and indirectly by comparison with more general axiomatic selves, though experimental constraint remains the ultimate authority. More general models clarify, but do not replace, earlier ones, explaining their success within restricted regimes. No axiomatic self, regardless of generality, is identified with the empirical self itself.

By maintaining a strict distinction between empirical reality and abstract representation, the framework dissolves several long-standing philosophical confusions, including realism versus instrumentalism, wave–particle duality, theory replacement, determinism versus probability, and the measurement problem. These issues are shown to arise from category mistakes rather than from deep features of nature.

Although light serves as the central example, the principles extracted are not specific to optical phenomena. The empirical–axiomatic distinction applies broadly across physical systems and extends naturally to complex systems. The work thus offers a clarified account of scientific understanding: to understand a system is to know the empirical constraints it imposes, the axiomatic structures used to represent it, the domains in which those structures apply, and the limits beyond which they fail. [Pawar, 2026a, Pawar, 2026b]

Keywords: light, models of light, empirical facts, scientific models, domain of validity, experimental constraints, wave–particle duality, philosophy of physics, foundations of physics, quantum mechanics interpretation

1 Introduction

The central aim of physics, and more generally of science, is to understand reality at the most fundamental level accessible to us. In practice, this understanding proceeds through experiments

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that reveal how systems behave and through models constructed to account for those behaviors. However, persistent conceptual and philosophical confusions arise when the distinction between what is observed in reality and how it is represented in abstract structures is not made explicit. These confusions are particularly visible in the case of light, where multiple, mutually non-equivalent models coexist, each successful within certain limits, yet none capable of exhausting all observed phenomena. This paper takes light as a case study to articulate a framework that clarifies this situation by separating empirical reality from axiomatic representation in a disciplined and operational manner.

In this work, light is treated first and foremost as an empirical self: a system that exists and behaves in reality and constrains our observations through experiments. The empirical self of light is unique and invariant; it is not a theory, not a model, and not an abstract structure. Experimental outcomes such as propagation, interaction with matter, spatial pattern formation, polarization effects, and discrete detection events are understood as empirical facts arising from interactions with this empirical self. These facts are taken as primary. They are not explanations, nor are they derived from theory; instead, they function as constraints on any attempt to represent or explain the behavior of light.

From these empirical constraints, humans construct multiple axiomatic selves abstract, internally structured models designed to account for selected aspects of empirical behavior. Ray optics, wave optics, classical electromagnetic theory, particle models, quantum models, and quantum field theory are all examples of such axiomatic selves in the context of light. Each is defined by its assumptions, its internal coherence, and its domain of validity. No axiomatic self is identified with light itself, and no axiomatic self is assumed to be complete. Instead, each model is evaluated by how and where it successfully tracks empirical facts, where it remains silent, and where it becomes inconsistent with experimental results.

A central theme of this paper is that domains of validity are not arbitrary. They are determined directly by experimental results and indirectly by comparison with other axiomatic selves, particularly more general ones. However, these two sources are not independent: more general axiomatic selves derive their authority from empirical success, and therefore experimental results are the ultimate arbiters of validity. This perspective explains how scientific progress occurs through refinement and hierarchical organization of models rather than through simple replacement of false theories by true ones.

The case study of light is used not to privilege a particular model, but to demonstrate how conceptual clarity emerges when empirical facts, descriptive language, and abstract modeling are carefully separated. In doing so, the paper shows that several long-standing philosophical problems such as the realism versus instrumentalism debate, wave–particle duality, the question of what light "really is," determinism versus probability, and the measurement problem—arise from category mistakes rather than from deep features of nature. When the distinction between empirical self and axiomatic selves is maintained, these problems dissolve rather than require resolution.

What is new in this work is not the proposal of a new physical theory of light, but a refined and operational articulation of the empirical–axiomatic self framework grounded in a detailed case study. In particular, this paper makes explicit the separation between empirical facts and the language used to express them, classifies model assumptions into analytically enabling and domain-restricting categories, clarifies the hierarchical relationship among axiomatic selves without granting ontological privilege, and distinguishes clearly between model silence and model inconsistency. These refinements sharpen the framework and make its application transparent.

Although light serves as the primary example, the framework developed here is not specific to optical phenomena. The empirical–axiomatic distinction applies equally to other physical systems, such as electrons and fields, and extends naturally to complex systems, including biological organisms. In this sense, the paper aims to contribute not only to the conceptual understanding of light, but also to a more general account of what it means to understand a system scientifically: to know what is empirically given, how it constrains representation, which abstract structures apply under which conditions, and where the limits of those structures lie. [Pawar, 2026b, Pawar, 2026a]

Note on the Relationship to Earlier Work

The conceptual framework employed in this paper was introduced and developed in detail in two earlier works: A Foundational Framework for Understanding the Universe and the Self [Pawar, 2026a] and A Framework-Guided Conceptual Analysis of Foundational Philosophical Questions [Pawar, 2026b]. Those papers present the core structure of the framework, its fundamental distinctions, and its application to a range of foundational philosophical questions.

The present work builds on that framework and extends it in a specific and operational manner. While the underlying conceptual commitments remain unchanged, several distinctions that were previously implicit are made explicit here through a detailed case study of light. In particular, this paper clarifies the operational separation between empirical facts and descriptive language, refines the classification of assumptions within axiomatic selves, articulates the hierarchical organization of axiomatic selves in terms of domain of validity, and makes explicit the role of experimental results as the ultimate authority constraining abstract representation.

These extensions do not alter the framework's foundations, but they sharpen its methodological content and demonstrate how it functions in scientific practice. The case study of light thus serves both as an illustration of the framework and as a means of refining it, allowing general principles to be extracted that apply beyond the specific system under consideration.

2 Methodological Clarification and Framework Recap

This case study proceeds from a clear methodological distinction between reality as it exists and our abstract representations of it. The central claim is that any system under investigation must first be treated as an empirical self, meaning the system as it exists and behaves in reality, independently of language, theory, or explanation. In the present case study, light is treated as such an empirical self. Experimental observations are understood as interactions with this empirical self, and the outcomes of these interactions are taken as empirical facts. These facts are not explanations, models, or theoretical claims; they are constraints imposed by reality on any attempt at representation.

To state empirical facts, language is necessarily used. However, the use of language including mathematical or descriptive terms does not by itself constitute modeling. Describing an observed pattern or regularity is not equivalent to explaining it. At the empirical level, concerns such as axiomatic circularity or derivability are not relevant. What matters instead are coherence, consistency, precision, and reproducibility. Terms commonly associated with particular models may appear at this stage purely as descriptive labels, without implying commitment to any underlying framework.

Models enter only at a later stage, where they are treated as axiomatic selves. An axiomatic self is an abstract structure defined by assumptions and internal relations, constructed to account for a selected subset of empirical facts. Multiple axiomatic selves may correspond to the same empirical self, each capturing different aspects of behavior under different conditions. No axiomatic self is identified with the empirical self itself. Each model has a domain of validity, meaning the conditions under which it successfully tracks empirical behavior. Outside this domain, a model may become silent or inconsistent.

Domains of validity are determined in two ways: directly through experimental results and indirectly through comparison with other axiomatic selves, especially more general ones. However, these two sources are not independent. Other axiomatic selves derive their authority from empirical success, and therefore experimental results are the ultimate arbiter of domain of validity. More general models may impose constraints on earlier ones, but they do not replace reality, nor do they eliminate the need for domain-restricted models.

The purpose of this case study is therefore not to identify what light "really is," nor to privilege one model over others as ontologically fundamental. Instead, the goal is to show how empirical facts give rise to multiple axiomatic selves, how their domains of validity are established, and how philosophical confusions arise when the distinction between empirical self and axiomatic selves is not maintained. The analysis is intentionally qualitative, focusing on conceptual clarity rather than quantitative derivation, and is meant to illustrate how understanding emerges from disciplined separation between reality, experiment, and abstraction. [Pawar, 2026b, Pawar, 2026a, van Fraassen, 1980]

Reader's Guide

This work introduces a conceptual framework intended to clarify how physical systems are studied, modeled, and understood, rather than to propose new physical laws. The terms empirical self and axiomatic self are used to distinguish between a system as it exists and behaves in reality, and the abstract structures constructed to represent, explain, or predict aspects of that behavior. The term self is employed not to imply agency, consciousness, or metaphysical status, but to emphasize continuity across physical, biological, and cognitive systems, and to avoid treating models as ontologically identical with the systems they describe. Throughout, experimental observations are treated as empirical constraints, while models are understood as abstract, domain-limited representations. A detailed case study of light is used to demonstrate how multiple axiomatic descriptions can coexist for a single empirical system without contradiction.

3 The Empirical Self of Light: A Catalogue of Empirical Facts

Human interaction with light begins with direct sensory observation, but the empirical behavior of light can be articulated independently of any explanatory framework. Under ordinary conditions, light propagates in such a way that sharp shadows are formed, and illumination patterns are predictable. This establishes the empirical fact that light travels along well-defined paths in homogeneous environments. When light encounters smooth reflective surfaces, it is observed that the outgoing direction is related to the incoming direction in a regular manner, such that the angle at which light departs equals the angle at which it arrives. This regularity is reproducible and does not depend on the nature of the light source. Light is also observed to pass through certain materials designated as transparent, while undergoing a systematic change in direction when transitioning between different media. This change in direction is an empirically observable effect, evident in everyday phenomena such as apparent bending at interfaces, and is reproducible under controlled conditions.

Light is further empirically observed to originate from sources and to enter the eye or detector, rather than emanating from the observer. Vision itself is therefore constrained by the empirical fact that light propagates from emitting systems toward receiving systems. Additionally, light does not propagate instantaneously. There exists a finite propagation time between emission and detection, and this time delay is measurable and consistent across repeated observations. This establishes the empirical constraint that light propagates at a finite, invariant speed under given conditions.

When light is directed through arrangements involving closely spaced openings or bounded apertures, the spatial distribution of detected brightness on a distant screen exhibits stable patterns consisting of alternating regions of higher and lower detection density. These patterns are reproducible and depend on the geometry of the experimental setup. Importantly, these spatial regularities are empirical facts of detection outcomes; they exist independently of how they are explained. Similarly, when light encounters narrow apertures or obstacles, it spreads into regions that would not be illuminated if it traveled strictly along straight paths, producing structured spatial distributions dependent on boundary geometry. These spreading behaviors are stable, repeatable, and geometry-dependent.

Light is also empirically observed to exhibit orientation-dependent transmission when interacting with certain materials. When light passes through specific substances, its subsequent transmission depends on the relative orientation of those substances. Two similarly oriented elements allow transmission, while orthogonally oriented elements suppress it almost entirely. This establishes the empirical fact that light possesses internal directional structure that affects how it interacts with matter, regardless of any interpretation of that structure.

Measurements further establish that the speed at which light propagates depends on the medium through which it travels. Under otherwise identical conditions, light travels at different speeds in different materials, while maintaining consistent directional and geometric behavior. At the same time, experiments show that light can propagate through vacuum without the need for any material carrier. Moreover, it is empirically established that the measured speed of light in vacuum is invariant with respect to the motion of the source or the observer. This invariance is an experimental fact that constrains all descriptions of light propagation.

Light is empirically observed to interact dynamically with matter. When light encounters material systems, it can transfer energy in a way that leads to observable physical effects, such as the emission of electrons from material surfaces. These interactions occur without measurable delay and depend on properties of the light such as frequency rather than merely the overall amount of incident light. This establishes that light–matter interaction is not continuous in time or space in the manner of smooth energy flow, but instead exhibits discrete interaction outcomes.

Detection experiments further reveal that light transfers momentum to matter. When light impinges on material systems, measurable mechanical effects are produced, demonstrating that light carries momentum and exchanges it with matter upon interaction. This momentum transfer is empirically detectable and quantitatively reproducible.

Crucially, the act of detecting light does not produce a continuous spatial or temporal record. Instead, detection occurs as localized, countable events. Each detection event is confined to a specific region of the detector and occurs at a definite time. Even in experimental arrangements that yield stable spatial patterns, individual detection events remain localized and isolated. The spatial patterns emerge only statistically, after many such events are accumulated. This establishes a fundamental empirical distinction between propagation behavior and detection records.

Further experiments show that detection events are not statistically independent in all configurations. Under certain conditions, correlations are observed between detection events occurring at spatially separated detectors. These correlations are reproducible and depend on experimental configuration, revealing higher-order statistical structure in detection outcomes beyond single-event localization.

Experiments using controlled emission conditions confirm that even when detection events occur one at a time, the same spatial and statistical regularities emerge when many events are collected. This demonstrates that the observed patterns are not the result of collective emission or detector saturation, but arise from the statistical structure of many localized detection events.

In addition to the statistical regularities observed in single-detector and intensity-correlation experiments, further empirical facts have emerged from experiments involving correlated detection outcomes across spatially separated measurement systems. In a wide class of experiments, pairs of detection events associated with jointly prepared emission processes exhibit correlations that cannot be reduced to independent local statistics at each detector. These correlations persist even when the detection events are spacelike separated and when no direct interaction occurs between the detectors after emission. Importantly, these experiments do not establish that "light itself is entangled" as an intrinsic property of an isolated system. Rather, they establish an empirical fact about joint detection statistics: under specific preparation and measurement conditions, detection outcomes associated with light-mediated processes exhibit nonclassical correlations that cannot be reproduced by models assuming independent local variables alone. These correlations are revealed only at the level of aggregated detection records and do not manifest in individual detection events. As with other empirical facts, this behavior constrains possible axiomatic descriptions without itself constituting a model, interpretation, or ontological claim about the nature of light.

Across the entire electromagnetic spectrum from radio frequencies through visible light to X-rays and gamma rays the same categories of empirical behavior are observed. Light in all these regimes exhibits propagation, reflection, refraction, orientation-dependent interaction, energy transfer, momentum transfer, finite propagation speed, invariant vacuum speed, localized detection events, and statistical regularities in detection outcomes. Differences across the spectrum manifest as changes in scale, interaction strength, and material response, not as fundamentally different kinds of behavior.

Taken together, these observations constitute the empirical self of light. They are facts obtained through interaction with reality, expressed using language and descriptive labels, but not derived from any axiomatic structure. These empirical facts constrain all possible models of light, but they are not themselves models. They define what must be accounted for, not how it must be explained. [Bell, 1987, Feynman et al., 1964, Michelson and Morley, 1887, Hecht, 2016]

4 Construction of Axiomatic Selves of Light

This section constructs the major axiomatic theories of light by treating them explicitly as axiomatic selves abstract, internally consistent representational structures constructed to account for selected subsets of empirical facts associated with the empirical self of light. The purpose of this section is not to present these theories as competing descriptions of what light "really is," but to analyze their assumptions, domains of validity, successes, silences, and inconsistencies. Each axiomatic theory is examined with respect to the empirical facts established earlier, with particular attention paid to how its domain of validity is constrained both by experimental results and by the emergence of more general axiomatic theories. Throughout, the empirical self of light is taken as fixed and unique; only the abstract structures representing it are varied.

4.1 Ray (Geometrical) Model of Light

The ray model of light is one of the earliest axiomatic theories constructed to represent the behavior of light. Its core analytical assumptions are that light propagates along well-defined paths, called rays, and that these rays travel in straight lines in homogeneous environments. Reflection and refraction are treated as geometric redirections of these rays at interfaces. These assumptions are not derived from deeper principles within the model; they are taken as primitives that allow straightforward geometric analysis of light propagation and image formation.

The assumptions that restrict the domain of validity of the ray model are largely implicit. The model assumes that any internal structure of light is irrelevant to the phenomena under consideration and that spatial dimensions involved in the experiment are large compared to any characteristic scale associated with light. These restrictions are not stated within the model itself but are imposed retrospectively through experimental results and clarified by more general axiomatic theories, particularly wave-based and electromagnetic models. Within its domain of validity, the ray model successfully accounts for empirical facts such as straight-line propagation in homogeneous media, the formation of sharp shadows, specular reflection, refraction at interfaces, and image formation by mirrors and lenses. These successes arise precisely because the experimental configurations involved suppress or average out effects that depend on the internal structure of light. The ray model is silent about phenomena that involve spatial spreading, geometry-dependent intensity distributions, polarization, discrete detection events, or energy transfer mechanisms. It does not attempt to address these facts; they lie entirely outside its representational scope.

The model becomes inconsistent when it is applied to situations where empirical facts explicitly contradict its assumptions, such as diffraction through narrow apertures or stable spatial patterns formed by multiple openings. In these cases, the ray model does not merely fail to explain the observations; it makes predictions that are incompatible with experimental results. These inconsistencies mark the limits of its domain of validity, as determined by experiment and clarified by more general axiomatic selves. [Feynman et al., 1964, Born and Wolf, 1999]

4.2 Wave Model of Light

The wave model introduces a different axiomatic self, in which light is represented as a continuous wave-like disturbance capable of superposition. Its primary analytical assumptions are that multiple contributions of light can overlap in space and that the resulting behavior depends on their combined effect. Spatial distributions of detected intensity are treated as arising from this superposition. These assumptions enable the analysis of geometry-dependent patterns without invoking localized trajectories.

The domain of validity of the wave model is restricted by assumptions of continuity and smooth interaction with matter. It assumes that light energy is distributed continuously and that matter responds proportionally to local wave intensity. These assumptions are not imposed arbitrarily; they are validated within specific experimental regimes and later restricted by both experimental results and more general axiomatic theories, particularly quantum models.

Within its domain, the wave model successfully accounts for empirical facts such as diffraction through apertures, stable spatial patterns produced by multiple openings, polarization-dependent transmission, and many features of reflection and refraction when treated as limiting cases. These successes arise because the experimental arrangements probe spatial structure rather than localized interaction events.

The wave model is silent about the discrete nature of detection events, instantaneous energy transfer, and the accumulation of spatial patterns from individual detection events. It does not address the mechanism by which energy is transferred in localized interactions, nor does it attempt to describe single-event detection statistics.

The model becomes inconsistent when it is applied to empirical facts that explicitly contradict its continuity assumptions, such as the photoelectric effect or the observation that spatial patterns persist even when detection events occur one at a time. In these regimes, the wave model speaks by predicting smooth energy accumulation but contradicts experimental results. These inconsistencies define the limits of its domain of validity. [Feynman et al., 1964, Hecht, 2016, Young, 1804, Born and Wolf, 1999]

4.3 Classical Electromagnetic Model of Light

The classical electromagnetic model represents light as a propagating configuration of coupled electric and magnetic fields. Its analytical assumptions include the continuity of fields, deterministic field evolution, and interaction with charged matter through well-defined force laws. These assumptions allow the unification of a wide range of optical phenomena under a single abstract structure.

The domain of validity of this model is restricted by its assumption of continuous fields and deterministic interactions. These restrictions are not internal failures of the model but are imposed by experimental results at microscopic scales and clarified by quantum axiomatic theories. The electromagnetic model remains valid where field descriptions accurately track empirical behavior, particularly at macroscopic scales. Within its domain, the classical electromagnetic model successfully accounts for propagation in vacuum, reflection, refraction, polarization, momentum transfer, radiation pressure, and the unification of optical phenomena across the electromagnetic spectrum. Its success lies in its ability to represent continuous propagation and interaction effects over large ensembles and time scales.

The model is silent about discrete detection events, probabilistic interaction outcomes, and the microscopic mechanisms of energy exchange. It does not address why energy transfer occurs in localized events or why detection statistics follow specific distributions. The model becomes inconsistent when applied to empirical facts such as instantaneous photo-emission or single-event detection behavior. In these cases, it predicts gradual energy accumulation or continuous interaction where experiments show discrete outcomes. These contradictions mark the experimentally enforced boundaries of its validity. [Jackson, 1999, Maxwell, 1873, Feynman et al., 1964, Born and Wolf, 1999]

4.4 Modern Corpuscular Model of Light

The modern corpuscular model of light is an axiomatic self in which light is represented as a collection of localized entities that propagate through space and interact with matter as individual units. In this model, light is not treated as a continuous field spread over space, nor as an abstract wave with phase and amplitude, but as discrete carriers of energy and momentum that move along definite paths between interactions. These entities are not defined mathematically as quantum fields or operators; they are conceptualized as particles in the ordinary classical sense.

The core analytical assumption of the modern corpuscular model is that light consists of localized units that travel through space and can exchange energy and momentum with material systems upon interaction. Propagation is treated kinematically: particles move from source to detector, typically along straight lines in homogeneous media. Interaction with matter is treated as a direct exchange process, analogous to collisions in classical mechanics.

Another analytical assumption is that optical phenomena can be explained by tracking these particles' trajectories and interactions, without invoking extended spatial structure, interference, or superposition. The model does not include intrinsic phase, coherence, or field structure. Each particle is treated independently, and collective behavior is explained, if at all, by averaging over many independent particles.

The domain of validity assumptions of this axiomatic self are implicit but restrictive. The model assumes:

- That light–matter interaction can be treated as localized exchange events.
- That spatial patterns can be understood as aggregates of many independent particle impacts.
- That wave-like effects are negligible or can be ignored.
- That relativistic constraints (such as invariant speed) are either not required or can be imposed externally.

These assumptions sharply limit where the model can be applied.

Within this domain, the modern corpuscular model successfully accounts for certain empirical facts. It explains why light transfers energy and momentum to matter. It naturally accommodates radiation pressure and mechanical effects of light. It provides an intuitive description of localized detection events, where light is absorbed at a specific place and time. It also fits naturally with experiments showing that light–matter interaction occurs in discrete events rather than as continuous deposition.

This success is important: the modern corpuscular model captures the discreteness of interaction, which earlier wave-based axiomatic selves fail to represent.

However, the modern corpuscular model is silent about many central empirical properties of light. It does not speak about interference patterns, diffraction, or polarization as intrinsic phenomena. It has no internal resources to describe coherence, phase relations, or orientation-dependent transmission. It does not address statistical correlations between detection events, such as intensity correlations or entanglement. It also does not encode relativistic structure internally; finite or invariant speed must be imposed by hand rather than emerging from the model.

More importantly, the modern corpuscular model becomes inconsistent when it is applied to phenomena that empirically require extended spatial structure or correlation. When used to explain interference or diffraction, the model predicts additive intensity patterns that contradict observed spatial regularities. When applied to correlation experiments, it fails to reproduce empirically observed statistical relationships. In these cases, the model does not merely remain silent; it actively contradicts empirical facts if taken seriously beyond its domain. [Feynman et al., 1964, Born and Wolf, 1999, Einstein, 1905]

Important Note

The localized interaction model of light or corpuscular or modern corpuscular model is not a historical theory proposed by any single individual, nor is it a standard textbook model of light. It is introduced in this work purely as an illustrative axiomatic self, constructed to isolate and represent a specific empirically established aspect of light: namely, that light interacts with matter through localized, discrete interaction events. This model is not intended as a complete or foundational description of light, and it should not be identified with Newton's corpuscular theory, Einstein's photon hypothesis, or any quantum or field-theoretic framework. Rather, it is a deliberately simplified abstract structure, retrospectively constructed from experimental constraints, used here to demonstrate how an axiomatic self can successfully capture one aspect of the empirical self while remaining silent or inconsistent with others. Its role is methodological rather than historical or explanatory, serving to clarify the empirical–axiomatic distinction central to the framework employed in this paper.

4.5 Quantum Model of Light

The quantum mechanical model of light is an axiomatic self in which light is described using the general principles of quantum mechanics state vectors, superposition, probability amplitudes, and measurement postulates without elevating light to the status of a fundamental quantum field. In this model, light is treated as a quantum system whose behavior is encoded in abstract states defined in a Hilbert space, and whose interaction with measuring devices produces probabilistic outcomes. The purpose of this axiomatic self is not to assert what light is in reality, but to provide a mathematically consistent abstract structure capable of reproducing a wide range of empirically observed regularities, particularly those involving interference, discreteness of detection, and statistical correlations.

The foundational analytical assumptions of the quantum mechanical model are the standard axioms of quantum mechanics. First, the state of light is represented by a quantum state (or wavefunction) that encodes probabilities for possible outcomes of measurement. Second, these states can exist in superposition, allowing multiple mutually exclusive possibilities to coexist at the level of abstract description. Third, physical observables associated with light such as energy, momentum, or polarization are represented by operators acting on the state space. Fourth, measurement is treated as a fundamental operation that yields definite outcomes probabilistically, according to rules intrinsic to the formalism.

An important analytical assumption in this axiomatic self is that empirical detection events are not continuous processes, but discrete outcomes of measurement. The model does not attempt to describe the detailed physical mechanism of detection; instead, it treats detection as an interaction whose outcome is governed by probabilistic rules. In this sense, the quantum mechanical model abstracts away the internal dynamics of detectors and focuses on statistically reproducible regularities in outcomes.

The domain of validity assumptions of the quantum mechanical model are significant and restrictive. The model assumes:

- That spacetime can be treated as a fixed background, without requiring a dynamical or quantum description of spacetime itself.
- That relativistic effects can either be neglected or incorporated approximately, rather than being fundamental to the axiomatic structure.
- That the number of light quanta involved in a process can be treated as fixed or externally specified, rather than dynamically variable.
- That light–matter interactions can be treated through effective rules rather than fully relativistic field interactions.

These assumptions define the regime in which the quantum mechanical model is applicable and explain why it remains empirically successful in many laboratory-scale experiments while failing to generalize universally.

Within its domain of validity, the quantum mechanical model successfully accounts for a large class of empirical facts. It explains the formation of interference and diffraction patterns as consequences of superposition and probability amplitudes. It accounts for polarization phenomena through the structure of quantum states. It accommodates the discreteness of detection events and the accumulation of spatial patterns from individual localized outcomes. It reproduces statistical regularities observed in correlation experiments, including intensity correlations and certain forms of entanglement, by assigning joint probability amplitudes to composite systems. For a wide range of experimentally accessible conditions, this axiomatic self reproduces the same empirical predictions as more general models.

However, despite this success, the quantum mechanical model is not maximally general, and its limitations are conceptually important.

First, the model is structurally silent about the field nature of light. It does not treat light as something that exists everywhere in space as a field; instead, it treats light as a quantum system described by states and observables. As a result, phenomena involving spontaneous emission, vacuum structure, or particle creation and annihilation are not naturally represented within this axiomatic self and must be introduced through additional rules or external assumptions.

Second, the quantum mechanical model is silent or incomplete with respect to fully relativistic structure. Lorentz invariance and causal locality are not intrinsic axioms of the model but must be imposed separately. This makes the model unsuitable for regimes where relativistic consistency is essential, even if it remains empirically adequate in low-energy or non-relativistic limits.

Third, the model does not explain why certain empirical regularities hold; it encodes them. Like all axiomatic selves, it provides relations between abstract quantities and empirical outcomes, not an ontological account of light itself. Individual detection events remain empirical facts, not necessities derived from axioms.

When the quantum mechanical model is extended beyond its domain of validity such as when it is treated as a fundamental description of light independent of field structure or relativistic constraints it becomes conceptually inconsistent with known empirical and theoretical constraints. These inconsistencies do not indicate failure of the model within its proper scope; they arise only from misuse.

In the language of this framework, the quantum mechanical model of light is therefore a highly successful but domain-limited axiomatic self. It captures essential empirical features superposition, statistical regularity, and discreteness of outcomes while remaining silent about deeper structural aspects that are addressed by more general axiomatic selves. Its success does not diminish the need for other models; instead, it demonstrates how multiple axiomatic selves can coexist, each constrained by empirical facts and each valid within a specific domain. [Feynman et al., 1964, Hecht, 2016, Dirac, 1930, Planck, 1901]

4.6 Quantum Field Model of Light (QED)

Light is described by Quantum Electrodynamics (QED), which is a specific relativistic quantum field theory within the general framework of QFT.The quantum field model of light represents the most general and empirically successful axiomatic self currently available for describing light. In this axiomatic self, light is not treated as a classical wave propagating in space, nor as a stream of localized particles following trajectories, but as an excitation of an underlying quantum field. This field is defined over spacetime and is governed by quantum principles that encode both probabilistic structure and relativistic constraints. Importantly, this axiomatic self is not introduced to answer the question "what light really is," but to construct an abstract structure capable of accounting for the widest range of empirically observed behaviors of light under experimentally accessible conditions.

The foundational analytical assumptions of the quantum field model are explicit and structural. First, spacetime is treated as a background arena (typically flat spacetime, or curved spacetime when extended), over which quantum fields are defined. Second, physical quantities associated with light such as energy, momentum, and interaction probabilities are represented by operators acting on abstract state spaces. Third, light–matter interaction is encoded through coupling between the electromagnetic field and other quantum fields, allowing the calculation of probabilities for detection events and energy–momentum exchange. Fourth, the model assumes relativistic invariance, ensuring consistency with empirically established invariance of the speed of light and with relativistic causal structure.

A crucial analytical assumption is that what is empirically observed in experiments such as detector clicks, energy transfer, and correlation statistics is not identified with the field itself, but with interaction outcomes between the field and measuring systems. This separation between abstract field structure and empirical detection outcomes is central to the internal coherence of the axiomatic self.

The domain of validity assumptions of the quantum field model are equally important. The model assumes:

- That spacetime structure can be treated as a fixed or semi-classical background (i.e., quantum gravity effects are negligible).
- That experimentally accessible energies remain well below the Planck scale.
- That detectors and measuring apparatus can be treated as effective quantum systems without requiring a full microscopic account of consciousness, observation, or macroscopic emergence.
- That renormalization procedures yield finite, stable predictions within the tested energy regimes.

These assumptions restrict the domain of validity of the model. They are not arbitrary; they are imposed jointly by experimental constraints and by the recognition made explicit through comparison with other axiomatic selves that the model ceases to be applicable in regimes where spacetime itself must be quantized or where unknown interactions dominate.

Within its domain of validity, the quantum field model successfully accounts for an exceptionally broad range of empirical facts. It reproduces all empirically established propagation behaviors of light, including finite and invariant propagation speed and compatibility with relativistic causality. It accounts for reflection, refraction, diffraction, interference, and polarization phenomena as statistical regularities emerging from field interactions. It explains energy and momentum transfer to matter, including radiation pressure and photoelectric effects, without invoking classical trajectories. It accounts for the discreteness of detection events and the emergence of spatial patterns only through statistical accumulation. It explains intensity correlations, single-event randomness, and joint detection statistics, including entanglement correlations, in a unified abstract structure. Across the entire electromagnetic spectrum, the same field-theoretic structure applies, differing only in scale and coupling strength.

In this sense, the quantum field model is maximally general relative to currently known empirical facts. No other axiomatic self currently matches its scope.

However, despite this breadth, the quantum field model is not equivalent to the empirical self of light, and it is not complete. Its limitations must be stated explicitly.

First, the model is silent about the ultimate structure of spacetime itself. While it can be formulated on curved spacetime backgrounds, it does not explain the quantum nature of spacetime or gravity. Phenomena involving black hole singularities, spacetime topology change, or Planck-scale physics lie outside its domain of validity.

Second, the model does not explain why specific empirical facts hold; it encodes how they are related. For example, it provides probability distributions for detection events, but it does not generate individual detection outcomes as necessities. The occurrence of a particular detector click remains an empirical fact, not an axiomatic consequence.

Third, the model does not exhaust the empirical self. Future experiments may reveal new regularities, correlations, or interaction regimes that are not representable within the current axiomatic structure. The framework explicitly allows for this possibility; historical precedent strongly supports it.

Fourth, while the model is internally consistent and empirically constrained, it relies on idealizations such as perfectly defined fields, asymptotic states, and renormalized quantities that are abstract constructs, not direct features of empirical reality.

When misapplied outside its domain of validity such as by treating it as a final theory of reality or by extending it into regimes where spacetime quantization is unavoidable—the model becomes conceptually inconsistent with empirical expectations. These inconsistencies do not arise from internal failure, but from violation of domain constraints.

In the language of this framework, the quantum field model of light is therefore an axiomatic self of the highest current generality, but it remains an axiomatic self nonetheless. It is a powerful abstract structure constrained by empirical facts, not a replacement for them. Its success does not diminish the distinction between empirical self and axiomatic self; it reinforces it. The very fact that the model must specify assumptions, domains of validity, and idealizations demonstrates that it cannot collapse into the empirical reality it seeks to represent. [Feynman and Hibbs, 1965, Jackson, 1999, Dirac, 1930, Peskin and Schroeder, 1995]

4.7 General Relativistic Description of Light(Geometric Optics in Curved Spacetime)

In the general relativistic description, light is represented within the axiomatic framework of general relativity, where gravity is not treated as a force acting on light, but as a manifestation of spacetime geometry. In this axiomatic self, spacetime itself is taken as a dynamical entity whose curvature is determined by the distribution of mass–energy, and light is described as responding to this curvature. The behavior of light is thus encoded not in forces or fields acting on light, but in the geometric structure of spacetime through which light propagates.

The core analytical assumption of this axiomatic self is that spacetime is a four-dimensional differentiable manifold equipped with a metric, and that the paths followed by light correspond to null geodesics of this metric. A null geodesic is not a physical trajectory in the everyday sense, but an abstract geometric object defined within the spacetime structure. This assumption allows the behavior of light to be analyzed purely geometrically, without reference to electromagnetic field dynamics or particle-like interactions.

A second analytical assumption is that gravity is identified with spacetime curvature. In this framework, there is no separate gravitational force acting on light. Instead, light follows the geometry of spacetime itself. This is a radical conceptual shift relative to Newtonian thinking, but within this axiomatic self it is not a philosophical claim; it is a structural assumption that enables analysis.

A third analytical assumption is that light can be treated in the geometric optics limit, meaning that its wavelength is assumed to be negligibly small compared to the characteristic length scales over which spacetime curvature varies. This assumption allows light to be represented as rays (null geodesics) rather than as extended waves or quantum objects. Importantly, this is an assumption introduced for analytical tractability, not a claim about the ultimate nature of light.

The domain of validity assumptions of this axiomatic self are crucial and restrictive. This model assumes:

- The wavelength of light is much smaller than spacetime curvature scales.
- Wave phenomena such as diffraction, interference, and coherence effects are negligible.
- Quantum effects in light–matter interaction are negligible.
- The electromagnetic field structure of light does not need to be explicitly represented.

These assumptions define the domain of validity of this axiomatic self. They are not arbitrary. They are imposed and justified by experimental results and by comparison with more general axiomatic selves, such as classical electromagnetic theory in curved spacetime and quantum field theory in curved spacetime. When these assumptions fail, the model does not merely become incomplete; it ceases to be applicable.

Within its domain of validity, the general relativistic geometric optics model successfully accounts for a distinct class of empirical facts that cannot be explained within flat-spacetime ray optics or Newtonian gravity. These include:

- The bending of light in the presence of massive bodies.
- Gravitational lensing, including multiple images and magnification.
- The Shapiro time delay, where light takes longer to traverse curved spacetime.
- Gravitational redshift and blueshift of light.
- The apparent deflection of light near compact objects.

These are not predictions derived in isolation from experiment; they are empirical facts that constrain the axiomatic self and confirm its validity within the appropriate regime. The success of this model is therefore empirical, not metaphysical.

The model is explicitly silent about many aspects of the empirical self of light. It does not address:

- Interference and diffraction phenomena.
- Polarization dynamics.

- Coherence and phase relations.
- Discrete detection events.
- Energy quantization or probabilistic outcomes.
- The electromagnetic field structure of light.

This silence is not a weakness. It reflects the fact that these phenomena lie outside the domain of validity defined by the model's assumptions. The axiomatic self simply does not speak about them.

The model becomes inconsistent when applied outside its domain of validity. For example, if one attempts to use geometric null geodesics to explain interference patterns or quantum detection statistics, the model makes claims that contradict empirical facts. In such cases, the inconsistency is not a failure of general relativity as a theory of spacetime, but a misuse of this particular axiomatic self beyond its applicable regime.

The domain of validity of this axiomatic self is determined in two ways. First, experimental results directly constrain where the geometric optics approximation holds. Second, more general axiomatic selves such as classical electromagnetic theory in curved spacetime and quantum field theory in curved spacetime clarify why and when the geometric approximation is valid. However, these more general axiomatic selves themselves derive their authority from experimental success. Ultimately, experimental results remain the final arbiter of validity.

Despite its conceptual depth and empirical success, the general relativistic geometric optics model remains an axiomatic self, not the empirical self of light. It is an abstract structure that represents how light behaves under specific conditions, using specific assumptions. It does not exhaust the empirical reality of light, nor does it replace other axiomatic selves. Instead, it occupies a well-defined position within the hierarchy of representations, extending earlier ray-based models to curved spacetime while remaining subordinate to more general field- and quantum-based descriptions where its assumptions break down. [Michelson and Morley, 1887, Einstein, 1954, Misner et al., 1973]

5 The Framework Explained Through the Case Study of Light

This section explains the proposed framework by applying it directly to the case study of light. The aim here is not to introduce new physical results, but to clarify how the framework operates in practice and how its core concepts acquire meaning when applied to a concrete system. Light is chosen not because it is exceptional, but because it is empirically rich and historically associated with multiple, mutually non-equivalent models. This makes it an ideal system for illustrating the distinction between empirical reality and abstract representation.

At the foundation of the framework lies the distinction between the empirical self and axiomatic selves. In the case of light, the empirical self refers to light as it exists and behaves in reality: it propagates, interacts with matter, produces observable effects, and constrains experiments. The empirical self of light is not a description, not a theory, and not an abstract structure. It is simply light as it is encountered in experiments. There is only one empirical self of light, regardless of how many models we construct to represent it. All experimental facts such as propagation speed, reflection, spatial pattern formation, polarization effects, discrete detection events, and energy transfer are interactions with this single empirical self.

Empirical facts are the outcomes of these interactions. Within this framework, an empirical fact is not an explanation but a constraint imposed by reality. For example, the appearance of a stable spatial pattern on a screen in a two-opening experiment is an empirical fact. Describing this pattern using language, symbols, or even mathematical terms does not turn it into a model. Language is an already existing abstract structure that allows us to express facts, but expression itself is not explanation. At the level of empirical facts, the framework does not require axiomatic non-circularity; it requires only coherence, consistency, precision, and reproducibility.

From these empirical facts, we construct axiomatic selves. An axiomatic self is an abstract structure defined by assumptions that allow us to represent and analyze a selected subset of empirical behavior. In the case of light, ray optics, wave optics, classical electromagnetic theory, particle models, quantum models, and quantum field theory are all axiomatic selves. Each of these is internally coherent and analytically powerful within its own scope, but none of them is identical to the empirical self of light. They exist in abstract space, not in physical reality, and they are evaluated by how well they track empirical constraints within specific conditions.

A crucial concept in the framework is the domain of validity of an axiomatic self. The domain of validity specifies the conditions under which a given axiomatic self successfully represents empirical behavior. In practice, domains of validity are not fixed purely from within a model. They are determined in two ways: directly by experimental results and indirectly by comparison with other axiomatic selves. For example, experiments reveal when a model fails to match observed behavior, while more general axiomatic selves clarify why earlier models worked under restricted conditions. However, these two sources are not independent. More general axiomatic selves derive their authority from experimental success, and therefore experimental results are the ultimate arbiters of domain of validity. [Pawar, 2026b, Pawar, 2026a, Feynman et al., 1964, Cartwright, 1983]

5.1 Domains of Validity and Hierarchy of Axiomatic Selves

Axiomatic selves can be arranged in a hierarchy of generality. In the case of light, more general axiomatic selves do not simply replace earlier ones; instead, they subsume them as limiting cases. For instance, wave-based axiomatic selves clarify the conditions under which ray optics is valid, while quantum axiomatic selves clarify the limits of classical wave and electromagnetic descriptions. This hierarchy is epistemic rather than ontological. A more general axiomatic self is superior in scope and constraint-awareness, not because it is closer to reality itself, but because it applies across a wider range of conditions.

The domain of validity of a less general axiomatic self is often understood only after a more general one is constructed. However, the authority of the more general model ultimately rests on experimental results. Experiments decide whether a model succeeds, fails, or remains silent. Other axiomatic selves help articulate these limits, but they do not override empirical constraint. This hierarchical structure explains why older models remain useful and correct within restricted domains even after more general models are developed.

5.2 Why No Axiomatic Self Equals the Empirical Self

A central claim of the framework is that no axiomatic self is equivalent to the empirical self. Even the most general and empirically successful axiomatic theory of light remains an abstract structure defined by assumptions, idealizations, and representational choices. It does not become light itself. Expecting a model to exhaust the empirical self is a category mistake: it confuses representation with reality.

In the case of light, this mistake manifests in questions such as “What is light really?” or in attempts to privilege a single model as ontologically final. The framework rejects this demand. The empirical self of light is richer than any abstract structure we can construct. Models track behavior; they do not replace reality. This distinction explains why multiple axiomatic selves can coexist without contradiction and why no amount of theoretical generality eliminates the need for domain awareness. [Pawar, 2026a, Pawar, 2026b]

6 Philosophical Implications

The analysis presented in the preceding sections was primarily methodological and case-based, focusing on the relation between empirical facts, abstract models, and domains of validity through the example of light. This section draws out the philosophical implications that follow from that analysis. The discussion proceeds within the empirical–axiomatic framework introduced and developed by the author i.e me, which is referred to throughout this paper as the empirical–axiomatic framework. When this framework is mentioned in what follows, it should be understood as referring to the author's own conceptual framework, as developed in earlier foundational work and extended in the present study. The aim of this section is not to introduce additional theoretical commitments or to resolve philosophical debates by proposing new metaphysical claims. Rather, it is to clarify how several well-known philosophical problems arise in the first place and how they are transformed once the empirical–axiomatic distinction is maintained consistently. The framework does not compete with existing philosophical positions by offering alternative answers; instead, it reorganizes how questions about reality, representation, and understanding are posed.

Each of the issues discussed in this section such as realism versus instrumentalism, wave–particle duality, theory replacement, determinism versus probability, and the measurement problem has traditionally been treated as reflecting deep tensions about the nature of reality. Within the empirical–axiomatic framework, these issues are examined as consequences of conflating empirical reality with abstract representation, or of attributing to axiomatic structures a role they are not meant to play. When empirical self and axiomatic selves are kept conceptually distinct, the problems do not require independent resolution; instead, they lose their original force.

The subsections that follow should therefore be read as diagnostic rather than adjudicative. Each subsection briefly recalls the conventional formulation of a given philosophical problem, clarifies what is and is not at stake, and then shows how the problem is re-interpreted or dissolved within the empirical–axiomatic framework. The intent is to guide the reader through these implications in a structured manner, demonstrating that the framework's contribution lies not in adding new answers, but in clarifying the conceptual structure underlying scientific understanding. [Pawar, 2026a, Pawar, 2026b, Feynman et al., 1964]

6.1 Realism versus Instrumentalism

The realism–instrumentalism problem concerns the ontological status of scientific theories. Realism claims that successful scientific theories describe what actually exists in the world, while instrumentalism claims that theories are merely tools for organizing observations and making predictions, without committing to what is real. The debate presupposes that a theory must occupy one of these two roles: either it corresponds to reality or it is only a pragmatic device.

This problem is not a dispute about the existence of reality itself, nor about the validity of experimental facts. Both realists and instrumentalists accept that experiments yield real, reproducible outcomes and that the world constrains what we observe. The disagreement is specifically about whether abstract theoretical structures should be granted the same ontological status as the phenomena they successfully organize.

The problem arises because theories are implicitly treated as if they must be candidates for reality itself. When no distinction is made between the empirical self and axiomatic selves, models are expected either to be reality (realism) or to be completely detached from it (instrumentalism). This false dichotomy is generated by conflating representation with what is represented.

Within this framework i.e Empirical-Axiomatic Framework, this dichotomy dissolves naturally. Reality is assigned exclusively to the empirical self, which exists independently of description or theory. Axiomatic selves are abstract, internally consistent structures constructed to represent selected aspects of the empirical self within specific domains of validity. Once this separation is maintained, there is no tension in being realist about the empirical self and instrumentalist about axiomatic selves. The question "Is the theory real or merely a tool?" is revealed as ill-posed, because it incorrectly demands a single ontological status for entities that belong to different conceptual levels.

In the case of light, this dissolution is clear. Light exists and behaves in reality regardless of whether it is described using rays, waves, particles, or quantum fields. These descriptions are axiomatic selves with specific domains of applicability. None of them is required to be ontologically identical to light itself. As a result, the realism–instrumentalism debate loses its force, not because one side is chosen, but because the framework shows that the debate arises from a category mistake. [van Fraassen, 1980]

6.2 Wave-Particle Duality

The wave–particle duality problem is usually framed as the claim that light behaves sometimes like a wave and sometimes like a particle, leading to the question of what light really is. This is often presented as a deep paradox, suggesting that reality itself possesses mutually incompatible properties.

This problem is not rooted in experimental inconsistency. The experimental results are coherent, reproducible, and well established. Nor is it merely a linguistic ambiguity. The difficulty persists even when terminology is carefully defined, because the underlying assumption remains unexamined.

The paradox arises from treating "wave" and "particle" as competing ontological descriptions of the same reality. Each is implicitly assumed to be a candidate for what the empirical self truly is. When both descriptions successfully account for different experimental behaviors, their incompatibility appears mysterious.

This framework i.e Empirical-Axiomatic Framework dissolves this problem by reclassifying wave and particle descriptions as distinct axiomatic selves rather than ontological claims. Each axiomatic self is constructed to represent a particular subset of empirical facts under specific experimental conditions. Neither is the empirical self, and neither competes for that role. The empirical self is singular; the axiomatic selves are plural. The apparent duality arises only when one mistakenly demands that a single axiomatic self exhaust all aspects of empirical behavior.

In the case of light, spatial pattern formation under certain experimental arrangements is effectively represented by wave-based axiomatic selves, while discrete detection events and localized energy transfer are effectively represented by particle or quantum axiomatic selves. The empirical self of light exhibits both behaviors. Once the representational status of models is recognized, the notion of wave–particle duality ceases to be a paradox and becomes an expected consequence of plural, domain-limited modeling. [Bohr, 1928]

6.3 What is light ?

A persistent philosophical discomfort in physics arises from the question "What is light really, beyond all models?" This question expresses the expectation that science should ultimately provide a single, final description that reveals the true nature of light as it exists independently of representation.

This problem is not motivated by a failure of prediction, explanation, or experimental success. Physics accounts for an enormous range of optical phenomena with remarkable precision. The dissatisfaction arises even in the presence of successful theories.

The anxiety emerges from the assumption that an axiomatic self should be equivalent to the empirical self. Abstract models are implicitly expected to replace reality rather than to represent it. When this expectation is left implicit, no model no matter how general or successful—can ever appear sufficient.

This framework removes this expectation entirely. It explicitly denies that any axiomatic self can be identical to the empirical self. Axiomatic selves are constrained representations, not mirrors of reality. Once this is accepted, the demand for a final answer to "what light really is" is revealed as illegitimate within the framework itself.

Quantum field theory, for example, may be the most general available axiomatic self for light, but it remains an abstract structure with assumptions, idealizations, and a domain of validity. It is not expected to exhaust the empirical self of light. The ontological anxiety dissolves because the framework never promises what the question demands. [Heisenberg, 1958, Einstein, 1954]

6.4 Theory Replacement and Scientific Progress

Scientific progress is often described as a sequence in which false theories are replaced by true ones. This narrative suggests that older theories were simply wrong and that newer theories progressively reveal deeper layers of reality.

This is not a claim that older theories fail in practice. Classical theories continue to work remarkably well in many domains. The confusion lies in how their status is interpreted once more general theories are introduced.

The problem arises when axiomatic selves are treated as truth claims about reality rather than as domain-limited representations. When a new model appears, the older one is assumed to be false instead of restricted. This creates the illusion of wholesale replacement.

Empirical-Axiomatic framework reframes scientific progress as the refinement and reorganization of domains of validity. More general axiomatic selves do not invalidate earlier ones; they impose constraints on where those earlier models apply and explain why they were successful within those limits. These domain constraints are determined directly by experimental results and indirectly by other axiomatic selves, which themselves derive their authority from experimental success.

In the case of light, geometrical optics remains valid in regimes clarified by wave and quantum models. The empirical self remains unchanged throughout. What evolves is our understanding of which axiomatic self applies under which conditions. Progress becomes representational refinement rather than convergence to final truth. [Kuhn, 1962]

6.5 Determinism versus Probability

In quantum contexts, the question is often posed whether reality is fundamentally deterministic or fundamentally probabilistic. This question is usually interpreted as making a deep metaphysical claim about the nature of the universe.

This is not a debate about whether deterministic equations or probabilistic predictions are useful. Both approaches are empirically successful in appropriate contexts.

The confusion arises when properties of axiomatic selves are projected onto the empirical self. Probabilistic structure in a model is interpreted as indeterminacy in reality itself, while deterministic structure is interpreted as ontological necessity.

Empirical-Axiomatic framework dissolves this projection. Determinism and probability are properties of axiomatic selves, reflecting representational choices, assumptions, and epistemic constraints. They do not directly characterize the empirical self. The empirical self produces outcomes; axiomatic selves encode how those outcomes are represented and predicted.

In the case of light, probabilistic predictions describe detection statistics, not randomness inherent in light itself. Once representation and reality are separated, the determinism–probability debate loses its metaphysical force. [Bell, 1987]

6.6 The Measurement Problem

The measurement problem asks what really happens during measurement and why definite outcomes occur when theories involve abstract states, superpositions, or fields. It is often treated as a deep problem about the nature of reality or observation.

This is not a question about whether measurement outcomes exist. The outcomes are empirically undeniable and reproducible.

The problem arises when axiomatic constructs are treated as if they must directly correspond to empirical events. When abstract states are reified, the emergence of definite outcomes appears mysterious and problematic.

Empirical-Axiomatic framework treats measurement outcomes as empirical facts belonging to the empirical self. Measurement theories are axiomatic selves constructed to represent these facts. There is no mystery about the reality of outcomes; the only issue is whether a given axiomatic self adequately represents them within its domain of validity. [von Neumann, 1955]

In light experiments, a detector click is an empirical fact. Wavefunctions, fields, or quantum states are axiomatic constructs. The measurement problem dissolves once these roles are not confused. [Pawar, 2026b, Pawar, 2026a]

7 Conclusion

This work has used light as a case study to articulate and demonstrate the empirical–axiomatic self framework as a disciplined way of understanding scientific knowledge without conflating reality with representation. By treating light first as an empirical self and only subsequently as the object of multiple axiomatic selves, the analysis has shown how experimental facts constrain understanding independently of any particular theoretical commitment. The empirical self of light remains unique and invariant throughout the discussion, while the plurality of axiomatic selves reflects the diversity of abstract structures constructed to represent different aspects of its behavior under different conditions.

The systematic separation between empirical facts and axiomatic representation clarifies how scientific models function and why no single model exhausts the reality it represents. Axiomatic selves are shown to be internally coherent, domain-limited, and hierarchically related, with more general models clarifying but not replacing the domains of validity of earlier ones. These domains are ultimately determined by experimental results, even when articulated through more general theoretical frameworks. This structure explains both the enduring usefulness of older models and the emergence of more general ones, without invoking theory replacement or convergence to a final description of reality.

By applying this framework to light, the work has demonstrated that several long-standing philosophical confusions arise from category mistakes rather than from deep features of nature. Debates concerning realism and instrumentalism, wave–particle duality, determinism and probability, and the measurement problem dissolve once the distinction between empirical self and axiomatic selves is maintained. The framework does not resolve these debates by choosing sides, but by showing that their framing presupposes an improper identification of abstract representation with empirical reality.

Finally, although light serves as the central example, the framework is not specific to optical phenomena. The empirical–axiomatic distinction applies equally to other physical systems, such as electrons and fields, and extends naturally to complex systems, including biological organisms. In this sense, the framework offers a general account of understanding in science: understanding consists not in identifying a final model of reality, but in knowing how empirical facts constrain representation, how multiple axiomatic structures relate to one another, and where the limits of each representation lie. This perspective preserves the integrity of empirical reality while acknowledging the indispensable role of abstraction in scientific inquiry.

Appendix A: Clarifications and Extensions Introduced in the Present Articulation of the Framework

This appendix records conceptual clarifications, refinements, and extensions that emerge in the present articulation of the empirical–axiomatic self framework, particularly through its application to the case study of light. These elements were implicit or absent in earlier expressions of the framework and are made explicit here to improve precision, operational clarity, and methodological transparency. The purpose of this appendix is not to introduce a new framework, but to document how the existing framework has been sharpened and extended through concrete analysis.

A first clarification introduced in this work is the explicit separation between empirical facts and the language used to express them. While earlier formulations distinguished empirical self from axiomatic self, the present articulation makes it explicit that empirical facts are always reported using pre-existing abstract structures such as natural language or mathematical symbolism. The use of such language does not itself constitute modeling. Terms historically associated with particular theories (for example, “interference” or “diffraction”) may appear at the empirical level purely as descriptive labels for observed regularities, without importing the axiomatic commitments of the theories from which those terms originate. This clarification removes ambiguity about whether empirical reporting is already a form of theoretical commitment.

A second refinement concerns the internal classification of assumptions within axiomatic selves. In this articulation, assumptions are explicitly distinguished into two categories: those that are analytically enabling, allowing the construction and manipulation of the model at all, and those that function as domain-restricting assumptions, limiting the conditions under which the axiomatic self is expected to track empirical behavior. This distinction clarifies how an axiomatic self can be internally consistent yet empirically limited, and why empirical failure outside a domain of validity does not undermine the internal coherence of the model.

A third extension is the explicit articulation of hierarchical generality among axiomatic selves. While earlier expressions acknowledged the plurality of models, the present articulation clarifies that axiomatic selves can be ordered by generality, with more general models subsuming earlier ones as limiting or approximate cases. This hierarchy is explicitly identified as epistemic rather than ontological. A more general axiomatic self is superior in scope and constraint-awareness, not because it is closer to reality itself, but because it applies across a wider range of conditions and clarifies the domains of validity of less general models.

Closely related is a fourth clarification regarding the determination of domains of validity. The present articulation makes explicit that domains of validity are constrained in two ways: directly by experimental results and indirectly by comparison with other axiomatic selves, especially more general ones. However, this work emphasizes that this duality is asymmetric. Other axiomatic selves derive their authority from empirical success, and therefore experimental results are the ultimate and final arbiters of domain of validity. This clarification resolves potential ambiguity about whether theoretical considerations can override experimental constraint.

A fifth refinement introduced here is the explicit distinction between silence and inconsistency in axiomatic selves. An axiomatic self may be silent about certain empirical facts, meaning it does not attempt to represent them at all, or it may be inconsistent with them, meaning it makes predictions that contradict experimental outcomes. This distinction is methodologically significant: silence does not count against a model within its domain of validity, whereas inconsistency marks the boundary of that domain. Earlier formulations treated model failure more generically; the present articulation sharpens this evaluative criterion.

A sixth extension is the explicit demonstration that several traditional philosophical problems dissolve under the framework rather than being resolved by additional theoretical commitments. Through the light case study, debates such as realism versus instrumentalism, wave–particle duality, determinism versus probability, theory replacement, and the measurement problem are shown to arise from category mistakes specifically, from conflating empirical self with axiomatic selves. The present articulation strengthens the framework by showing that, once these categories are kept distinct, the debates themselves lose their footing.

Finally, the present articulation strengthens the universality claim of the framework. By grounding the analysis in a detailed case study of light and then explicitly generalizing the empirical–axiomatic distinction to other physical systems (such as electrons and fields) and to complex systems (such as biological organisms), the framework is shown to be independent of scale, complexity, and disciplinary context. This universality was suggested earlier but is demonstrated more concretely here.

Taken together, these clarifications and extensions do not alter the core commitments of the framework. Instead, they make explicit several distinctions that are essential for its consistent application, sharpen its methodological implications, and clarify its philosophical consequences. [Pawar, 2026a, Pawar, 2026b]

Appendix B: General Principles Derived from the Case Study

The purpose of this appendix is not to introduce a new framework or to modify the conceptual structure developed in the main text. The framework employed throughout this work remains the same. What is done here is analogous to a common practice in physics: after analyzing a concrete system in detail, one abstracts a set of general principles that capture the essential methodological features of that analysis. These principles are not imposed a priori; they are distilled from how the framework operates when applied to a specific case, in this instance, the case study of light.

In physics, principles often serve as compact statements of regularities that guide analysis across diverse systems without being tied to any single phenomenon. The principles presented in this appendix should be understood in that sense. They summarize, in a general form, how empirical facts, abstract models, domains of validity, and experimental constraints relate to one another within the framework already in use. While these principles are made explicit here, they reflect practices that are already implicitly present in standard physical reasoning, particularly in contexts where multiple models coexist and are applied under different conditions.

The case study of light provides a particularly transparent setting for extracting these principles because it involves a rich empirical self and a well-developed plurality of axiomatic selves. However, nothing in the principles themselves depends on features unique to light. The same considerations apply when studying other physical systems, such as electrons, fields, or composite systems, and extend naturally to more complex domains. In this sense, the principles listed below are not conclusions about light, but methodological guidelines for understanding how scientific models relate to empirical reality in general.

Accordingly, the principles that follow should be read as general statements about scientific understanding within the existing framework. They articulate how empirical behavior constrains representation, why multiple axiomatic structures are inevitable, how domains of validity are established and refined, and why experimental results retain ultimate authority. Together, they provide a compact summary of the framework's operational content and its applicability across different case studies in physics.

Principle 1: Distinction Between Empirical Self and Axiomatic Selves

For any system under study, a fundamental distinction must be maintained between the empirical self and the axiomatic selves constructed to represent it. The empirical self refers to the system as it exists and behaves in reality, independent of description, language, or theory. It is unique: there is only one empirical self corresponding to a given system. In contrast, axiomatic selves are abstract structures models defined by assumptions, relations, and internal rules constructed to account for selected aspects of the system's observed behavior. No axiomatic self is identical to, equivalent to, or exhaustive of the empirical self.

Principle 2: Empirical Facts as Constraints, Not Explanations

Empirical facts arise from experimental interaction with the empirical self. These facts are not explanations, models, or theories; they are constraints imposed by reality on any attempt at representation. Expressing empirical facts necessarily involves language and abstract descriptors, but such expression does not constitute modeling. At the level of empirical facts, the relevant criteria are coherence, consistency, precision, and reproducibility—not axiomatic derivability or non-circularity. Circularity concerns apply to abstract constructions, not to the reporting of empirical behavior.

Principle 3: Axiomatic Selves Are Domain-Limited Abstract Structures

Every axiomatic self is defined by a set of assumptions or axioms that specify its internal structure and scope. These axioms implicitly or explicitly restrict the domain of validity of the model that is, the range of conditions under which the model can successfully track empirical behavior. An axiomatic self may be empirically successful within its domain while remaining silent about, or inconsistent with, behaviors outside that domain. Such limitations do not invalidate the model; they characterize its applicability.

Principle 4: Plurality of Axiomatic Selves Is Inevitable

Because empirical behavior is rich, multi-aspectual, and context-dependent, no single axiomatic self can account for all empirical facts simultaneously. The existence of multiple axiomatic selves corresponding to the same empirical self is therefore not a failure of scientific understanding, but a necessary consequence of finite epistemic capacity interacting with complex reality. Each axiomatic self captures certain regularities while abstracting away others, and different axiomatic selves may coexist without contradiction when their domains of validity are respected.

Principle 5: Hierarchical Generality Among Axiomatic Selves

Axiomatic selves can differ in generality. A more general axiomatic self typically applies across a wider range of conditions and may recover earlier axiomatic selves as limiting or approximate cases. In this sense, later or more general models can be considered epistemically superior: they explain why earlier models worked within restricted regimes and clarify the conditions under which those models fail. However, this superiority is structural and representational, not ontological. Even the most general axiomatic self remains an abstract construction and does not collapse into the empirical self.

Principle 6: Dual Sources of Domain of Validity Constraints

The domain of validity of an axiomatic self is constrained by two sources: Experimental results, which directly reveal where a model succeeds, fails, or becomes silent. Other axiomatic selves, particularly more general ones, which indirectly impose domain restrictions by showing earlier models to be limiting cases under specific assumptions. However, these two sources are not independent. Other axiomatic selves themselves derive their authority from empirical success. Therefore, while domain restrictions may appear to be imposed by theoretical comparison, experimental results are the ultimate and final arbiter of domain of validity.

Principle 7: Experimental Results as Ultimate Authority

All axiomatic selves ultimately answer to empirical facts. Models may constrain one another, refine one another, and hierarchically organize one another, but none of these relations supersede experimental constraint. When a conflict arises between an axiomatic self and empirical behavior, it is the axiomatic self that must be revised, restricted, or abandoned. The empirical self never fails; only representations do.

Principle 8: Scientific Progress Without Model-Reality Collapse

Scientific progress does not consist in replacing false models with true ones, nor in approaching a final axiomatic structure identical to reality. Instead, progress consists in: expanding the range of empirically constrained axiomatic selves, increasing their generality, clarifying their domains of validity, and understanding the relations among them. Understanding a system, within this framework, means knowing which axiomatic selves apply where, why they apply there, and why they fail elsewhere, while maintaining a strict distinction between abstract representation and empirical reality.

Across all systems, empirical reality constrains representation, but representation never exhausts reality. Multiple axiomatic selves may coexist, some more general than others, each valid within domains ultimately determined by experimental results. No axiomatic self however general becomes equivalent to the empirical self. The role of theory is not to replace reality, but to organize, contextualize, and discipline our interaction with it. [Pawar, 2026b, Pawar, 2026a]

Appendix C: Empirical Facts About Light

- Existence and detectability
  1. Light exists as something that can be emitted by physical sources.
  2. Light propagates through space and can be detected at locations distant from the source.
  3. Light can be detected by biological systems (eyes), chemical reactions, photographic plates, and electronic detectors.
  4. Detection of light produces reproducible and measurable effects on matter.
- Propagation
  1. Light propagates with a finite speed.
  2. The speed of light in vacuum is constant within experimental precision.
  3. Light propagation does not require a material medium.
  4. In homogeneous environments, light propagates along well-defined directions.
  5. Obstructions block light and produce sharp shadow boundaries.
- Interaction with matter (directional behavior)
  1. Light changes direction when it encounters reflective surfaces.
  2. The angle at which light departs a reflecting surface equals the angle at which it arrives (within precision).
  3. Light changes direction when passing between different transparent materials.
  4. The amount of directional change depends on the materials involved.
  5. Light propagation depends on the properties of the surrounding medium.

- Spatial distribution and geometry dependence
  1. Light spreads as it propagates away from a source.
  2. Detected intensity decreases with distance from the source.
  3. When light passes through narrow openings, it spreads beyond the geometric shadow.
  4. The spreading pattern depends on the size and shape of the opening.
  5. When light encounters edges or obstacles, structured spatial distributions appear near those boundaries.
  6. When light passes through multiple openings, stable spatial patterns of alternating high and low detection regions appear on screens.
  7. These spatial patterns depend on the arrangement and geometry of the openings.
  8. These patterns are reproducible under identical experimental conditions.
- Intensity and internal properties
  1. Light intensity can be varied continuously by changing source conditions or filters.
  2. Certain materials transmit light differently depending on orientation.
  3. Rotating such materials changes the detected intensity.
  4. Two such materials can fully block light depending on their relative orientation.
  5. Light possesses internal directional properties that affect its interaction with matter.
- Energy transfer
  1. Light transfers energy to matter.
  2. Light can raise the temperature of objects it illuminates.
  3. Light can induce chemical reactions.
  4. Light incident on certain materials causes the emission of electrons.
  5. The emitted electrons appear without measurable time delay.
  6. The energy of emitted electrons depends on properties of the incident light.
  7. Increasing light intensity does not always increase electron energy.
  8. Light–matter interactions can occur in discrete events.
- Momentum transfer
  1. Light exerts pressure on matter.
  2. Objects can be pushed or deflected by exposure to light.
  3. Light transfers momentum to matter during interaction.
- Detection characteristics
  1. Light detection often occurs as localized events.
  2. Individual detection events are spatially confined.
  3. Detectors register discrete detection events (“clicks”).
  4. Continuous illumination patterns emerge only after accumulation of many detection events.
  5. Reducing light intensity does not eliminate spatial pattern formation.
  6. The same spatial detection patterns emerge even when detections occur one at a time.

- Statistical and correlation properties
  1. Detection events exhibit statistical regularities.
  2. Detection rates depend on experimental configuration.
  3. Correlations can exist between detection events at separated locations.
  4. These correlations depend on how the light is produced and detected.
  5. Some correlations exceed those expected from independent random events.
- Spectral universality
  1. Light exists across a wide range of frequencies (radio to gamma).
  2. The same kinds of propagation, reflection, refraction, spreading, polarization, energy transfer, and momentum transfer occur across this range.
  3. Differences across the spectrum are differences of scale and interaction strength, not of basic behavior.
- Robustness and reproducibility
  1. All the above behaviors are reproducible.
  2. The same experimental arrangements yield the same outcomes under the same conditions.
  3. These behaviors do not depend on human observation.
  4. These behaviors occur whether or not a theoretical explanation is available. [Jackson, 1999, Hecht, 2016, Feynman et al., 1964, Heisenberg, 1958]

Appendix D: Matrix of Axiomatic Selves vs Empirical Properties of Light

In the table below, each entry represents the status of a given axiomatic self (model) with respect to a given empirical property of light. The entries are to be interpreted strictly within the empirical–axiomatic framework used in this paper.

Explained (E)

An entry marked E indicates that the axiomatic self successfully accounts for the corresponding empirical fact within its domain of validity. This means that, given the assumptions defining the axiomatic self, the model provides a consistent abstract representation that reproduces the observed behavior under the relevant experimental conditions. An explanation in this sense does not imply completeness, uniqueness, or ontological identity with the empirical self. It indicates only domain-restricted empirical adequacy.

Silent (S)

An entry marked S indicates that the axiomatic self does not address the corresponding empirical fact at all. The model neither explains nor contradicts the phenomenon; it simply lacks the conceptual resources to speak about it. Silence is not a failure of the axiomatic self, nor does it imply incorrectness. It reflects a limitation of scope imposed by the model's foundational assumptions and domain of validity.

Inconsistent (I)

An entry marked I indicates that the axiomatic self makes claims that contradict empirical facts when applied to the corresponding phenomenon. Inconsistency arises only when a model is extended beyond its legitimate domain of validity. In such cases, the empirical facts constrain the model, not the reverse. Inconsistency does not imply that the axiomatic self is globally false; it indicates misuse outside its applicable regime.

These three categories exhaust all meaningful relations between an axiomatic self and an empirical fact within this framework.

Empirical Property of Light	**Ray Optics**	**Wave Optics**	**Classical EM**	**GR Optics**
Straight-line propagation (ordinary conditions)	E	E	E	E
Reflection (angle equals angle)	E	E	E	E
Refraction (direction change in media)	E	E	E	E
Finite speed of light	I	I	E	E
Invariant vacuum speed	I	I	I	E
Gravitational bending of light	I	I	I	E
Interference patterns (spatial regularities)	I	E	E	S
Diffraction and spreading	I	E	E	S
Polarization effects	S	E	E	S
Energy transfer to matter	S	S	E	S
Momentum transfer (radiation pressure)	S	S	E	S
Localized detection events	I	I	I	S
Discrete detection statistics	I	I	I	S
Intensity correlations	S	I	I	S
Entanglement correlations	S	S	S	S
Universality across electromagnetic spectrum	E	E	E	E

Table 1: Relation between empirical properties of light and Different Models of light. [Misner et al., 1973, Born and Wolf, 1999, Young, 1804]

Empirical Property of Light	**Modern Corpuscles**	**Quantum Model**	**QFT (QED)**
Straight-line propagation (ordinary conditions)	E	E	E
Reflection (angle equals angle)	E	E	E
Refraction (direction change in media)	E	E	E
Finite speed of light	E	E	E
Invariant vacuum speed	I	E	E
Gravitational bending of light	I	E	E
Interference patterns (spatial regularities)	I	E	E
Diffraction and spreading	I	E	E
Polarization effects	S	E	E
Energy transfer to matter	E	E	E
Momentum transfer (radiation pressure)	E	E	E
Localized detection events	E	E	E
Discrete detection statistics	E	E	E
Intensity correlations	I	E	E
Entanglement correlations	I	E	E
Universality across electromagnetic spectrum	E	E	E

Table 2: Relation between empirical properties of light and different models of light. [Bell, 1987, Born and Wolf, 1999, Peskin and Schroeder, 1995]

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