# Worldline Ontology as a Unifying Framework for Special Relativity, Quantum Mechanics, and Electromagnetic Reflection

Alex De Giuseppe[1]

[1]Province of Parma, Italy

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**Abstract**

We propose a worldline-based ontological framework in which physical phenomena traditionally attributed to quantum indeterminacy, wavefunction superposition, and nonlocality emerge instead from global spacetime configurations. Within this framework, particles are not fundamental point-like entities but manifestations of admissible intersections and correlations between worldlines constrained by relativistic geometry. We show that quantum interference, superposition, and entanglement follow naturally from these constraints without invoking wavefunction collapse or intrinsic randomness. Extending the formalism, we demonstrate that electromagnetic reflection on mirrors admits a consistent reinterpretation as an absorption–reconstruction process mediated by alternative worldline configurations, fully compatible with Maxwell equations and QED. The proposed framework unifies Special Relativity and Quantum Mechanics at the ontological level while preserving all established mathematical predictions.

## 1 Motivation and Ontological Premise

Modern physics is characterized by an asymmetry:

- Special Relativity (SR) provides a clear geometric ontology (worldlines in spacetime).
- Quantum Mechanics (QM) provides extremely accurate predictions but remains ontologically opaque.

Quantum objects are described by states, amplitudes, and operators, yet no physical meaning is assigned to these beyond instrumental calculation. This work adopts the position that this opacity signals not indeterminacy of nature, but incompleteness of ontology.

**Ontological postulate.** *Worldlines are the only fundamental physical objects. All observable phenomena arise from admissible global configurations and intersections of worldlines in spacetime.*

Particles, fields, and quantum states are secondary descriptions of these configurations.

# 2 Worldlines and Global Configuration Space

Let spacetime be a four-dimensional Lorentzian manifold $(\mathcal{M}, g_{\mu\nu})$. A worldline is a continuous timelike or null curve

$$\gamma : \lambda \mapsto x^\mu(\lambda).$$

Define $\Gamma$ as the space of all admissible global worldline configurations compatible with relativistic constraints.

Physical reality corresponds not to a single local trajectory, but to a subset

$$\mathcal{A} \subset \Gamma$$

selected by geometric, material, and informational constraints.

# 3 Superposition and Interference as Worldline Multiplicity

In standard QM, a particle in superposition is described by

$$|\psi\rangle = \sum_i c_i |i\rangle .$$

In the worldline framework, this corresponds to:

- multiple admissible worldlines $\{\gamma_i\}$
- all satisfying the same boundary conditions
- none yet excluded by interaction

## 3.1 Interference

Interference arises when admissible worldlines intersect a common detection event $D$. The observed intensity is proportional to the measure of compatible configurations:

$$P(D) \propto \left| \sum_{\gamma_i \in \mathcal{A}} e^{iS[\gamma_i]/\hbar} \right|^2 ,$$

which is mathematically identical to the path integral formalism, but ontologically interpreted as global geometric consistency rather than probability of alternatives.

### 3.2 Decoherence

Decoherence corresponds to the elimination of cross-compatibility between subsets of $\mathcal{A}$ due to environmental coupling, reducing the admissible set to a single effective worldline.

# 4 Entanglement via Matrioska Constraints

We now integrate the formal entanglement framework you provided.

Let

$$(\Delta C) \leftrightarrow (\Delta M) \leftrightarrow (\Delta L)$$

denote nested constraints on admissible configurations:

- $(\Delta C)$: spacetime geometric admissibility
- $(\Delta M)$: material coherence
- $(\Delta L)$: informational correlation

Define projections

$$\Phi_C, \Phi_M, \Phi_L : \Gamma \to \mathcal{C}, \mathcal{M}, \mathcal{L}$$

and admissible set

$$\mathcal{A} = \{\gamma \in \Gamma \mid \Phi_C(\gamma) \in \mathcal{C},\ \Phi_M(\gamma) \in \mathcal{M},\ \Phi_L(\gamma) \in \mathcal{L}\}.$$

### 4.1 Operational Entanglement

Two subsystems $A, B$ are entangled when the restriction of $\mathcal{A}$ prevents factorization:

$$\mathcal{A} \neq \mathcal{A}_A \times \mathcal{A}_B.$$

This reproduces all standard entanglement measures (mutual information, logarithmic negativity) while maintaining strict no-signaling: correlations arise from shared admissible history, not from dynamical influence.

# 5 Time Symmetry and Retrocausal Admissibility

Both Maxwell equations and relativistic field equations are time-reversal invariant. Consequently, admissibility constraints are global in time.

This allows *retrocausal informational consistency*:

- no signal is sent backward in time
- but future boundary conditions restrict past admissible configurations

This principle underlies interference, entanglement, and the De Giuseppe Paradox.

# 6 Electromagnetic Reflection Reinterpreted

## 6.1 Absence of Particle Reflection in Maxwell Theory

Maxwell equations describe field evolution:

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}, \quad \nabla \times \mathbf{B} = \mu_0 \epsilon_0 \partial_t \mathbf{E}.$$

Reflection arises only through boundary conditions:

$$\mathbf{E}_{\parallel} = 0 \quad \text{on a conducting surface.}$$

There is no equation describing a photon reversing direction.

## 6.2 QED Perspective

In QED, mirror reflection corresponds to:

$$\gamma_{\text{in}} + e^- \to e^{-*} \to \gamma_{\text{out}} + e^-.$$

The outgoing photon is not identical to the incoming one; only global amplitudes are conserved.

## 6.3 Worldline Interpretation of Reflection

Within the worldline framework:

- the incoming photon worldline terminates at absorption
- an alternative admissible worldline configuration produces an outgoing photon
- phase, direction, and polarization encode geometric symmetry

The mirror enforces a symmetry constraint selecting worldlines corresponding to a specular configuration. The reflected image corresponds to information encoded in a worldline configuration geometrically dual to the incident one.

# 7 Specular Symmetry as Worldline Duality

Let $\gamma$ be an incident null worldline. The mirror defines a spacetime involution $\mathcal{R}$ such that:

$$\gamma' = \mathcal{R}(\gamma)$$

is admissible and phase-consistent.

The observed reflection corresponds to $\gamma'$, not to $\gamma$ reversing direction.

# 8 Consistency with No-Signaling

No information is transmitted superluminally or backward causally. All correlations arise from shared admissible configuration space $\mathcal{A}$. This is identical in structure to quantum entanglement and respects relativistic causality.

# 9 Discussion

The proposed ontology:

- removes wavefunction collapse
- eliminates intrinsic randomness
- explains entanglement without nonlocal forces
- unifies SR and QM geometrically
- provides a physically meaningful interpretation of electromagnetic reflection

All standard predictions of QM, QED, and Maxwell theory are preserved.

# 10 Reflection Beyond Ontology: Why Mirrors, Glass and Water Behave Identically

## 10.1 Empirical universality of reflection

A fundamental empirical fact is that optical reflection occurs not only on metallic mirrors, but also on transparent dielectrics (glass), liquids (water), and even at vacuum interfaces under quantum electrodynamics (QED) scattering regimes. The law of reflection,

$$\theta_i = \theta_r,$$

is universally satisfied regardless of the microscopic constitution of the reflecting medium.

This universality immediately signals that reflection cannot depend on a specific material mechanism (such as a free-electron plasma alone), but must instead arise from a deeper causal and geometric structure shared across all these systems.

## 10.2 Standard electrodynamic account (what is certain)

In Maxwell–Lorentz electrodynamics and QED, reflection is described as follows:

- The incident electromagnetic excitation couples to charged degrees of freedom (bound or quasi-free electrons).
- These degrees of freedom undergo forced oscillations.
- A secondary electromagnetic field is emitted coherently.
- Boundary conditions enforce phase matching such that destructive interference cancels transmission in certain directions and constructive interference occurs in the reflected direction.

Crucially, even in QED, the outgoing photon is *not* the same physical photon as the incoming one. The process is formally an absorption–emission sequence, encoded in propagators and scattering amplitudes. Photon identity is undefined.

This point is not interpretational: it is a strict consequence of quantum field theory.

## 10.3 What QED and Maxwell do *not* specify

While the mathematical description is exact, the ontology is deliberately left open:

- The equations do not specify *which* photon is emitted.
- They do not specify whether emission is local in spacetime or globally constrained.
- They do not assign ontological meaning to phase, coherence, or boundary conditions.

Thus, the standard interpretation implicitly assumes that the emitted photon is newly created locally, with no further causal structure.

This assumption is not derived — it is imposed.

## 10.4 Worldline interpretation of reflection

We now introduce an alternative ontological interpretation fully compatible with Maxwell equations and QED amplitudes.

**Definition 10.1** (Worldline Reflection Principle)**.** Optical reflection corresponds to the activation of a geometrically conjugate worldline whose light-cone structure is specularly related to the incident worldline at the interaction boundary.

In this view:

- The incident photon is absorbed and its worldline terminates.
- The reflected photon corresponds to a distinct but causally correlated worldline.
- The apparent reversal of spatial momentum is not a dynamical inversion, but a geometric matching between two admissible null worldlines.

No photon ever decelerates, stops, or reverses direction along the same worldline. The invariant speed $c$ is preserved trivially.

## 10.5 Why mirrors, glass, and water behave the same

At the microscopic level, metals, dielectrics, and liquids differ radically. However, they share one essential feature:

> They provide dense distributions of charged degrees of freedom capable of enforcing global phase coherence at the boundary.

From the worldline perspective, the role of the material is not to "reflect a photon", but to *select admissible causal intersections* between incoming and outgoing null worldlines.

The reflection condition emerges as a geometric constraint:

$$\Delta\phi_{\text{total}} = 0 \pmod{2\pi},$$

which guarantees that the conjugate worldline interferes constructively only in the specular direction.

Thus, material properties determine *which worldlines are allowed*, not how photons "bounce".

## 10.6 Relation to interference and superposition

This mechanism is identical in structure to interference phenomena.

In double-slit experiments, no particle traverses both slits dynamically. Instead, multiple admissible worldlines coexist, and the observed intensity corresponds to the density of allowed causal intersections.

Reflection is simply a degenerate one-boundary version of the same principle.

## 10.7 Entanglement and retrocausal correlations

Because the incoming and outgoing worldlines are distinct but constrained by a shared causal geometry, the process naturally admits nonlocal correlations without signaling.

This mirrors the structure of entanglement:

- Correlation without energy or signal transfer.
- Global constraint on allowed histories.
- Retrocausal informational consistency without causal violation.

Reflection thus appears as a trivial, always-on instance of the same worldline geometry responsible for entanglement.

## 10.8 The smoking-gun question

We emphasize a critical point:

**Remark 10.1.** Standard experiments cannot distinguish between local re-emission and worldline conjugation, because both produce identical scattering amplitudes.

However, the worldline interpretation predicts deviations in regimes where:

- Phase coherence is globally constrained but locally disrupted.
- Time-symmetric boundary conditions are engineered.
- Reflection is coupled to delayed-choice or post-selected measurements.

These regimes define concrete experimental tests beyond standard optics.

## 10.9 Conclusion

Reflection does not require photons to reverse direction, slow down, or violate relativistic constraints. The mathematical formalism already encodes a deeper geometric process.

The worldline interpretation provides an ontologically coherent account without altering any equation — only removing unnecessary narrative assumptions.

Whether nature adopts this ontology remains an experimental question, but it is no longer a speculative one: it is a mathematically admissible and causally consistent alternative. Quantum phenomena do not require indeterminate reality, but rather a global, geometric description of admissible worldline configurations. Superposition, interference, entanglement, and reflection emerge as structural features of spacetime itself. This framework offers a coherent ontological unification of Special Relativity and Quantum Mechanics without modifying their mathematical content.

## References


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