Hidden Determinism in Quantum Measurement: Interaction-Free Detection and Counterfactual Reality

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Abstract

Interaction-free measurement, counterfactual communication, and Young's double-slit experiment reveal how quantum systems exhibit effects from events that do not physically occur. In this paper, we reinterpret such phenomena through the Hidden Deterministic Interpretation (HDI), which introduces a physically fixed global phase as a hidden variable. HDI employs two principles—the Phase Consistency Criterion (PCC) and the Quantum Hamilton's Principle (QHP)—to determine the particle's definite trajectory within a physically real wavefunction of Heisenberg's picture. Even paths not taken influence outcomes through interference, as seen in the double-slit experiment. Detection ends the particle's trajectory, naturally rendering the prior wavefunction obsolete without invoking stochastic collapse or many-worlds branching. HDI thus provides a unified, deterministic account of quantum counterfactuality within a realist, single-world framework.

1 Introduction

Orthodox quantum mechanics [1], most prominently associated with the Copenhagen interpretation [2,3], has proven immensely successful in its predictive power. Its foundation rests on two core principles:

- **Principle 1:** A quantum state vector, when expressed as a superposition of eigenstates of an observable, collapses to a definite eigenstate upon measurement.
- **Principle 2:** The probability of such a collapse is governed by Born's rule, equating the likelihood of an outcome to the squared modulus of the corresponding amplitude.

The Hidden Deterministic Interpretation (HDI) provides a physical mechanism underlying both principles [4]. While HDI does not invoke the postulated collapse of the wavefunction as in the Copenhagen interpretation—where the entire wavefunction discontinuously reduces to a single eigenstate—it accounts for a form of wavefunction reduction that arises naturally from its deterministic ontology. To formalize this ontology, HDI introduces two foundational principles:

1. **Phase Consistency Criterion (PCC):** The global phase of the Heisenberg state vector $|\psi\rangle$, denoted as $\mathrm{ph}(|\psi\rangle)$, equals the phase of the position eigenstate $|\mathbf{r}_i, t_i\rangle$, $\mathrm{ph}(\langle\mathbf{r}_i, t_i|\psi\rangle)$, at emission:
$$\mathrm{ph}(|\psi\rangle) = \mathrm{ph}(\langle\mathbf{r}_i, t_i|\psi\rangle), \tag{1}$$
where $\mathbf{r}_i$ and t_i are initial position and time of the particle, respectively.

2. **Quantum Hamilton's Principle (QHP):** The path actually taken by the particle makes the accumulated quantum phase (action) stationary:
$$\delta \left\{ \int_{t_i}^{t_f} dt \; L_c(\mathbf{r}(t), \dot{\mathbf{r}}(t)) \right\} = 0, \tag{2}$$
where δ denotes infinitesimal variation, t_f is the final time, and L_c is the classical Lagrangian; $\mathbf{r}(t)$ is the position eigenvalue at time t and $\dot{\mathbf{r}}(t)$ is its time derivative.

HDI, like Bohmian mechanics [5,6], offers a unified, deterministic ontology without invoking additional guiding equations or nonlocal hidden variables.

In HDI, the particle is not collapsed out of a spread-out wavefunction, but rather moves within the Heisenberg picture's wavefunction along a well-defined trajectory guided by the PCC (Eq. (1)) and the QHP (Eq. (2)). This is akin to how a test particle follows a geodesic in the curved spacetime of general relativity [7].

Once the particle is detected, the wavefunction's prior predictive role becomes irrelevant for that event, effectively rendering the earlier wavefunction obsolete. In this precise sense, HDI accommodates a form of wavefunction collapse, not as an ad hoc process, but as a consequence of the completed physical trajectory. Thus, HDI retains deterministic evolution while reproducing the phenomenology traditionally associated with measurement collapse. This deterministic structure provides the foundation for HDI's treatment of measurement, interference, and counterfactuality.

Different interpretations of quantum mechanics offer distinct explanations for interaction-free measurement [8,9] and quantum counterfactuality [10–14]. Collapse-based interpretations invoke discontinuous wavefunction changes upon observation [1–3]; Many-Worlds Interpretation attributes different outcomes to branching universes [15,16]; and Bohmian mechanics [5,6] explains it via particle trajectories guided by a pilot wave. Each approach carries conceptual or metaphysical overhead.

In this paper, the above-mentioned paradigmatic quantum phenomena are examined within the HDI framework. Although paradoxical under standard interpretations, they arise naturally from the deterministic ontology of HDI.

2 Interaction-Free Measurement: The Elitzur–Vaidman Bomb Experiment

Elitzur and Vaidman [8,9] introduced the bomb-testing thought experiment to demonstrate that it is possible to detect the presence of a sensitive bomb without triggering it.

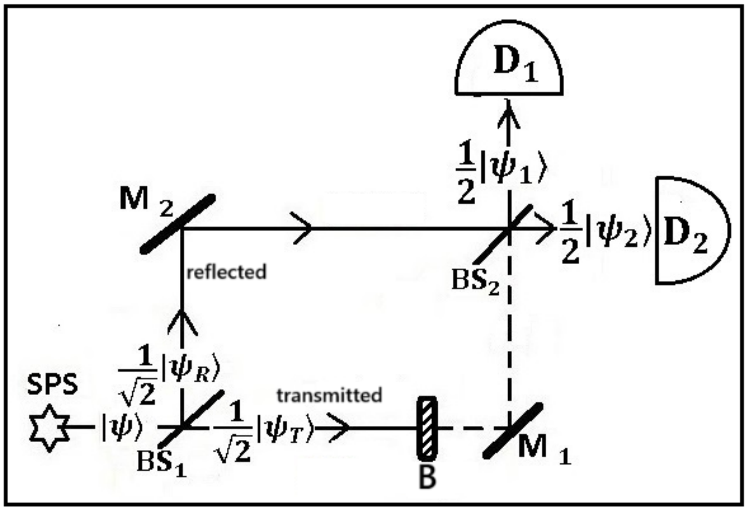

Figure 1: **Schematic of the Elitzur–Vaidman bomb experiment**: SPS is the single-particle source. BS_1 and BS_2 are 50:50 beam splitters. M_1 and M_2 are 100% reflecting mirrors. D_1 and D_2 are single photon detectors. $|\psi\rangle$ is the Heisenberg state vector. $|\psi\rangle = \frac{1}{\sqrt{2}}(|\psi_R\rangle + |\psi_T\rangle)$ where $|\psi_R\rangle$ and $|\psi_T\rangle$ are the reflected and transmitted components of $|\psi\rangle$. B is the bomb (or obstacle). A single photon from the source (SPS) enters the interferometer via BS_1, splitting equally into two paths. The presence of a functional bomb in transmitted-path absorbs the photon if it takes that path. Otherwise, if the photon takes reflected-path, it reflects off M_2 and recombines at BS_2. When the bomb is present, interference is disturbed and a click at D_1 confirms the bomb's presence without any interaction.

Let a photon enter the interferometer from a single-photon source (SPS) as shown in Figure 1. At BS_1, it evolves into an equal superposition:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\psi_R\rangle + |\psi_T\rangle), \tag{3}$$

where $|\psi_R\rangle$ follows reflected-path and $|\psi_T\rangle$ follows transmitted-path.

If no bomb is present, both components reach BS_2 and interfere. The resulting amplitudes cause "destructive interference" at D_1 and "constructive interference" at D_2, so the photon always reaches D_2.

Now suppose a bomb is placed in transmitted-path. If the photon takes this path, it triggers the bomb (absorbed). But if it takes reflected-path, it reaches BS_2 alone, with no interference. This means it has a "25% chance" of reaching D_1. Hence, if D_1 clicks and the bomb did not explode, we know the photon could not have taken transmitted-path. We have "inferred the presence of the bomb without interaction"—an interaction-free measurement.

The apparent paradox in this experiment is elegantly resolved within the HDI framework. The presence of the bomb imposes a boundary condition that prevents the transmitted component of the wavefunction from reaching BS_2. Only the reflected component reaches BS_2, where it is further split into parts directed toward detectors D_1 and D_2. As a result, the constructive and destructive interference that would otherwise occur at D_1 and D_2—in the absence of the bomb—is disrupted. Regardless of the bomb's presence, the particle follows a definite trajectory determined by the Phase Consistency Criterion (PCC) and the Quantum Hamilton's Principle (QHP). If the bomb is present and the particle takes the transmitted path, the bomb explodes, which occurs with probability 1/2. If the particle instead takes the reflected path, it may be detected at D_1 with probability 1/4.

3 Quantum Counterfactuality and Computation

Quantum counterfactuality refers to situations in which the presence or state of a system is inferred by detecting what *would have happened* had an interaction occurred—even though no such interaction takes place. Nested interferometers, such as those proposed in counterfactual communication protocols [10, 11] allow the detection or transmission of information without the transmitting particle ever traveling to the receiving location. A related and notable application of this principle is *counterfactual quantum computation*, in which the result of a quantum algorithm can be inferred even though the computer did not physically run [12–14].

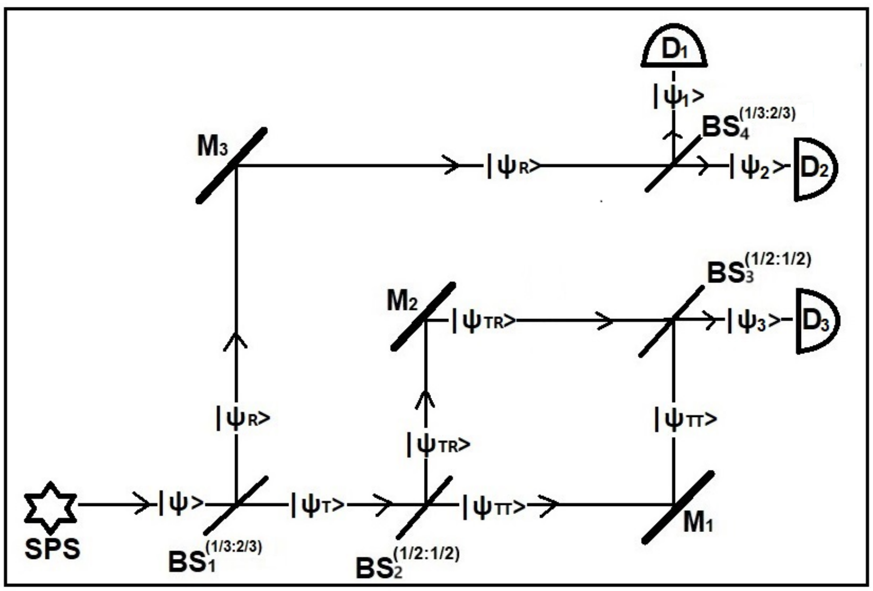

Figure 2: **A nested interferometric configuration demonstrating counterfactual inference**: SPS denotes a single-photon source. BS_1 and BS_4 are asymmetric beam splitters with reflectivity-to-transmissivity ratio of 1:2. BS_2 and BS_3 are symmetric (50:50) beam splitters. Mirrors M_1, M_2, and M_3 are perfect reflectors. Detectors D_1, D_2, and D_3 are ideal single-photon detectors. The quantum state after BS_1 evolves as $|\psi\rangle = \frac{1}{\sqrt{3}}|\psi_R\rangle + \sqrt{\frac{2}{3}}|\psi_T\rangle$, where the subscripts R and T denote reflected and transmitted components, respectively. The transmitted state further evolves via BS_2 as $|\psi_T\rangle = \frac{1}{\sqrt{2}}(|\psi_{TR}\rangle + |\psi_{TT}\rangle)$. Inserting an obstacle (e.g., a bomb) into the inner interferometer disrupts this interference, resulting in a zero detection probability at D_1. This enables interaction-free detection of the obstacle, highlighting the counterfactual nature of quantum inference.

A nested interferometric configuration enabling counterfactual inference is illustrated in Figure 2. In this setup, SPS denotes a single-photon source that emits individual quantum

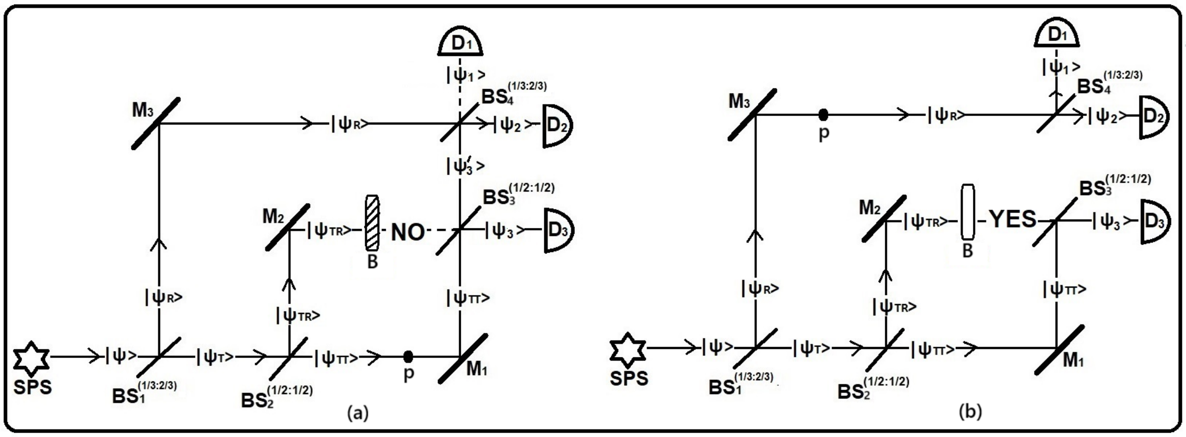

Figure 3: **Counterfactual communication using nested interferometers**: The p stands for "photon". (a) In the configuration labeled "NO," an obstacle, B, is placed in the inner path. "NO" indicates that no photon passes through B. If a photon takes the path $BS_1.M_3.BS_4$, then it is detected by D_2. If a photon takes the path $BS_1.BS_2.M_1.BS_3.BS_4$, then it is detected by either D_3 or D_2. (b) In the configuration labeled "YES," the channel is unobstructed. If a photon takes the path $BS_1.BS_2$, then it is detected by D_3. If a photon takes the path $BS_1.M_3.BS_4$, then it is detected by either D_1 or D_2. The presence or absence of the obstacle determines the D_1 click, thereby encoding a bit of information.

particles into the interferometric network. BS_1 and BS_4 are asymmetric beam splitters with a reflectivity-to-transmissivity ratio of 1:2, while BS_2 and BS_3 are symmetric 50:50 beam splitters. The mirrors M_1, M_2, and M_3 are assumed to be perfect reflectors, and D_1, D_2, and D_3 are ideal single-photon detectors. One arm of the outer interferometer contains the inner interferometer formed by BS_2, M_1, M_2, and BS_3, while its second arm is formed by BS_1, M_3, and BS_4.

The initial quantum state $|\psi\rangle$ from SPS is split at BS_1 into a coherent superposition of reflected and transmitted components: $|\psi\rangle = \frac{1}{\sqrt{3}}|\psi_R\rangle + \sqrt{\frac{2}{3}}|\psi_T\rangle$, where $|\psi_R\rangle$ and $|\psi_T\rangle$ denote the reflected and transmitted branches, respectively. The transmitted component $|\psi_T\rangle$ encounters another 50:50 beam splitter BS_2, resulting in further coherent splitting into $|\psi_T\rangle = \frac{1}{\sqrt{2}}(|\psi_{TR}\rangle + |\psi_{TT}\rangle)$.

The system is tuned such that, when a bomb is placed in the path corresponding to $|\psi_{TR}\rangle$ (as shown in Figure 3(a)), it imposes a boundary condition that disturbs the interference in the inner interferometer. This disruption propagates to the outer interferometer, altering the phase relations among the wavefunction components. Consequently, the detection probabilities at D_1, D_2, and D_3 are given by 0, 1/2, and 1/6, respectively.

However, when no obstacle (e.g., a bomb or an absorbing object) is placed in the inner interferometer path, as shown in Figure 3(b), the detection probabilities at D_1, D_2, and D_3 are given by 1/6, 1/6, and 2/3, respectively. The non-zero probability at D_1 provides interaction-free evidence of the bomb's presence.

From the HDI perspective, the wavefunction evolves through all arms of the interferometer, while the particle follows a definite trajectory determined by the PCC and the QHP.

When an absorber is introduced, it alters the boundary conditions of the wavefunction, modifying interference patterns even if the particle does not traverse that path. This results in a form of counterfactual inference: information about the presence of an object is obtained without any physical interaction between the particle and the object itself. Such outcomes arise not from probabilistic collapse or branching, but from the deterministic evolution of a particle within a physically real wavefunction that is globally shaped by all interaction possibilities.

Feature / Principle	**Elitzur–Vaidman Bomb Experiment**	**Quantum Counterfactuality**	**Counterfactual Quantum Computation**
Objective	Detect presence of a light-sensitive bomb	Transmit information without particle entering channel	Determine computation output without running computer
Setup Type	Mach–Zehnder interferometer with potential bomb	Nested interferometers with open/closed communication	Nested interferometers simulating logical gates
Interaction-Free Inference	Yes (detects bomb without explosion)	Yes (message decoded from absence of photon transit)	Yes (result inferred without photon in computation arm)
Counterfactual Nature	Spatial (infers obstacle's presence remotely)	Spatial (infers binary message from path avoidance)	Logical (infers result from potential computational path)
Photon Behavior	May avoid bomb yet indicate its presence	Avoids blocked channel yet allows message decoding	Avoids computation path yet reveals correct output
Key Mechanism	Disturbance of interference due to potential interaction	Interference shift caused by blocking channel	Interference shift from hypothetical computation path
Measurement Location	Detection at D_1 implies bomb is live	Detection or no detection at D_1 indicates message bit	Detection or no detection at D_1 reveals computed result
Original Proposal	Elitzur and Vaidman (1993)	Salih et al. (2013), Hosten et al. (2006)	Jozsa (1998), Hosten et al. (2006)
HDI Interpretation	Wavefunction explores both arms; particle avoids bomb deterministically	Wavefunction explores all paths; particle avoids blocked channel	Wavefunction explores all paths; particle deterministically avoids computation path

Table 1: Comparison of Elitzur–Vaidman Bomb Experiment, Quantum Counterfactuality, and Counterfactual Quantum Computation from both operational and HDI perspectives.

4 Counterfactuality in Young's Double-Slit Experiment under HDI

The HDI reveals that counterfactual quantum phenomena are not limited to intricate interferometric arrangements but are fundamentally embedded even in the canonical Young's double-slit experiment [2]. In this view, a particle follows a definite trajectory through one of the slits—say, slit 2—while the wavefunction (PRQSV) evolves through both slits simultaneously; here, PRQSV stands for the position representation of the quantum state vector, i.e., Heisenberg picture's wavefunction. Despite the particle not traversing slit 1, the amplitude associated with that untraveled path interferes with the one that is traversed, producing an observable interference pattern at the detection screen. This interpretation naturally

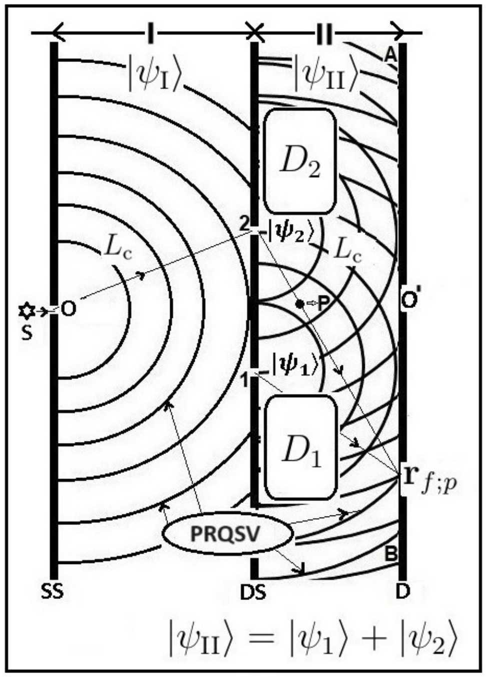

Figure 4: **Schematic Diagrams of Young's Double-Slit Experiment**: S represents the single-particle source, D_1 and D_2 are single-particle detectors, and p denotes the particle. SS denotes the single slit, DS the double-slit assembly, and D the detection screen. L_c is the free-particle Lagrangian. $|\psi_\mathrm{I}\rangle$ and $|\psi_\mathrm{II}\rangle$ are the state vectors corresponding to regions I and II. The relation $|\psi_\mathrm{II}\rangle = |\psi_1\rangle + |\psi_2\rangle$ holds, where $|\psi_1\rangle$ and $|\psi_2\rangle$ are the projections of $|\psi_\mathrm{I}\rangle$ through slit-1 and slit-2. The points O′ and $\mathbf{r}_{f;p}$ lie in the central bright fringe and another bright fringe. Here, PRQSV stands for the position representation of the quantum state vector, i.e., Heisenberg picture's wavefunction.

extends the idea of counterfactuality: the "non-event" of the particle not passing through slit 1 still exerts a measurable influence, shaping the interference pattern observed on the detection screen. If the particle had instead gone through slit 1, then slit 2 would become the non-event, and its associated amplitude would still contribute. Thus, the very presence of interference embodies the physical effect of a counterfactual path.

This insight finds direct analogy in more elaborate phenomena such as the Elitzur–Vaidman bomb test and quantum counterfactual computation. In each case, the path not taken by the particle is crucial to the outcome:

Aspect	**Double-Slit under HDI**	**Elitzur–Vaidman Bomb Test**	**Counterfactual Communication / Computation**
Counterfactual Element	Path not taken by particle	Bomb arm not traversed	Channel or computation path not taken
Interference Disruption	Which-path detection destroys interference	Bomb suppresses interference	Logic encoded via interference disruption
Observable Impact	Loss of interference reveals which-path detector (D_1/D_2)	D_1 click reveals bomb	D_1 click reveals message or result
HDI Mechanism	PRQSV evolves through both slits; particle passes through any one slit	PRQSV explores both arms; particle avoids bomb	PRQSV evolves globally; particle guided deterministically

Table 2: Comparison of counterfactual structures across three paradigmatic quantum scenarios.

Importantly, any attempt to determine through which slit the particle actually travels destroys the interference pattern, converting it to a classical clump distribution. This is entirely analogous to placing a bomb in one arm of an interferometer or encoding a logic gate in a computation path.

In summary, HDI illuminates Young's double-slit experiment as the most fundamental expression of quantum counterfactuality. It affirms that the quantum world is shaped not only by events that do happen, but also by events that do not—yet leave behind unmistakable physical traces.

5 Interpretation Comparison

Interpretation	Collapse Mechanism	Deterministic	Single-World
Copenhagen	Yes (Stochastic)	No	Yes
Many-Worlds	No (Branching)	Yes	No
Bohmian Mechanics	No (Pilot Wave + Hidden Variables)	Yes	Yes
HDI (this work)	**Yes (Deterministic Trajectory)**	**Yes**	**Yes**

Table 3: Comparison of Interpretations for Interaction-Free and Counterfactual Scenarios

HDI matches the empirical predictions of standard interpretations while offering a realist, deterministic alternative. Unlike the Copenhagen interpretation, HDI does not invoke a stochastic or observer-induced wavefunction collapse. Instead, the particle evolves along a definite trajectory, determined by the PCC and the QHP. When the particle is detected, this trajectory concludes, and the wavefunction's earlier predictive role ceases to be relevant. This constitutes a form of wavefunction reduction that is entirely deterministic and intrinsic to the dynamics. Thus, HDI reconciles the appearance of collapse with a fully physical and causal mechanism, without invoking branching worlds or hidden pilot waves.

6 Discussion and Conclusions

The Hidden Deterministic Interpretation (HDI) provides a coherent, deterministic framework for understanding quantum counterfactuality across multiple paradigms. In the Elitzur–Vaidman bomb experiment, the mere possibility of interaction with a bomb modifies the wavefunction's structure by imposing a boundary condition. Even when the particle takes a different path, the interference is disrupted, and detection at D_1 provides conclusive evidence of the bomb's presence. The deterministic evolution guaranteed by the Phase Consistency Criterion (PCC) and the Quantum Hamilton's Principle (QHP) ensures that the detection event arises without invoking any probabilistic collapse. The outcome is the result of interference geometry shaped by the global phase, not stochastic branching or measurement-induced discontinuities.

In more complex nested interferometric configurations used for quantum counterfactual communication and computation, the HDI framework elegantly explains how detector clicks can reveal the presence of an absorber or yield computational outcomes—despite the particle not traversing certain arms of the interferometer. In all such cases, the wavefunction of Heisenberg picture exists through all possible paths, but the particle follows a single, definite trajectory. This trajectory is not randomly chosen; it is selected deterministically by the global phase in such a way that the total quantum action along the path is stationary. This principle aligns the particle's motion with the most physically consistent solution permitted by the boundary conditions.

HDI also reinterprets the well-known Young's double-slit experiment as a primitive and profound expression of counterfactuality. In this experiment, if a particle goes through slit 2, then it simultaneously does not go through slit 1, and vice versa. However, the slit not traversed still affects the interference pattern at the detector. The counterfactual path—though not taken—leaves a physical trace via its influence on the wavefunction's phase structure. Conversely, any attempt to measure which slit the particle passes through collapses the phase structure of the wavefunction, thereby destroying the interference and replacing it with a classical clump distribution. This is the hallmark of a counterfactual mechanism being made factual—an act that breaks the very condition for interference.

In all these cases, HDI shows that counterfactuality is not paradoxical. It is a deterministic consequence of a physically real wavefunction constrained by boundary conditions, including interaction potentials—even those not realized. The particle's actual behavior emerges from the quantum principle of stationary action and the physically meaningful global phase. There is no need to invoke stochastic collapse, observer-induced randomness, or parallel worlds.

Thus, HDI offers a unified ontological foundation for understanding interaction-free measurement, quantum counterfactuality, and computation—anchoring all such phenomena within a single, deterministic, and realist interpretation of quantum mechanics.

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