Toward a Superdeterministic Path-Integral Model of Quantum Mechanics

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July 1, 2025

Abstract

This paper outlines a superdeterministic interpretation of quantum mechanics rooted in Feynman's path integral formalism. We argue that quantum indeterminacy is epistemic rather than ontological, arising from the observer's inability to account for the complete state of the universe. By rejecting the assumption of measurement independence in Bell's theorem, we demonstrate that a coherent, deterministic framework can explain quantum phenomena without invoking true randomness. In this framework, the outcome of any quantum event is fully determined by the total physical configuration of the universe, including microstates such as air molecule positions, field fluctuations, and detector geometry. The apparent randomness observed in experiments is a result of our practical inability to access or control these contributing factors.

1 Introduction

Quantum mechanics is conventionally interpreted as inherently probabilistic, with randomness built into the outcomes of measurements. However, superdeterminism — the hypothesis that all events in the universe, including experimental choices and detector settings, are predetermined by past conditions — offers a deterministic alternative [1].

Bell's theorem [2] demonstrates that no local hidden variable theory can reproduce the predictions of quantum mechanics unless one is willing to reject at least one of its core assumptions. Among these is *measurement independence*: the idea that hidden variables governing particle behavior are statistically independent of the settings chosen by experimenters. Superdeterminism challenges this assumption.

This paper aims to articulate a version of superdeterminism grounded in Feynman's path integral formulation [3]. We argue that quantum indeterminacy reflects a lack of complete knowledge of initial and boundary conditions and that the deterministic sum over all paths, influenced by the total physical configuration of the universe, governs quantum behavior.

2 Bell's Inequality and the Role of Measurement Independence

Bell's inequality is derived under several assumptions, including locality, realism, and measurement independence. If measurement settings are statistically correlated with hidden variables — as superdeterminism suggests — Bell inequalities may be violated without invoking quantum indeterminacy [4].

In a superdeterministic framework, both the particle properties and measurement apparatus are causally determined by the universal initial state, nullifying the independence assumption and preserving locality. While some critics argue this makes the theory unfalsifiable, we argue it redirects falsifiability toward environmental sensitivity and detailed modeling of experimental boundary conditions.

3 Path Integrals and Global Environmental Sensitivity

In Feynman's formulation, the amplitude for a particle to travel from point A to point B is given by a sum over all possible paths:

$$\langle B|A\rangle = \int \mathcal{D}[x(t)]\, e^{\frac{i}{\hbar}S[x(t)]}, \tag{1}$$

where $S[x(t)]$ is the action functional for a given path $x(t)$.

To account for deterministic environmental effects, we propose a generalized modification of the standard formulation:

$$\langle B|A;\mathcal{E}\rangle = \int \mathcal{D}[x(t)]\, e^{\frac{i}{\hbar}(S[x(t)]+\Delta S[x(t),\mathcal{E}])}, \tag{2}$$

where $\mathcal{E}$ denotes the total environmental configuration and $\Delta S[x(t),\mathcal{E}]$ represents an additional phase contribution dependent on the environment.

This ΔS term captures deterministic, microscopic effects on phase relationships between paths — for example, through boundary geometries, field gradients, or particle configurations — even if their full structure is practically inaccessible. Though we do not specify its detailed form, one can express it abstractly as:

$$\Delta S[x(t),\mathcal{E}] = \int_0^T V_{\text{eff}}(x(t),t;\mathcal{E})\, dt, \tag{3}$$

where V_{eff} is an effective potential encapsulating the environmental modulation of path phases.

This environmental term encodes how dynamic, possibly distant, elements of the universe influence which paths interfere constructively. Even a potential path extending a kilometer—or theoretically across the universe—may be affected by transient environmental factors such as air molecules, moving machinery, or gravitational perturbations. These elements may block, deflect, or modify paths that would otherwise destructively interfere. In doing so, they alter the interference landscape and change the outcome of the measurement. Thus, no two runs of an experiment are ever truly identical, as $\mathcal{E}$ is never held constant. This makes quantum randomness a reflection of our ignorance of the total configuration, not of any inherent indeterminacy in the underlying physics.

Constructive interference among these modified paths leads to the observed outcome. If the environment were fixed and identical across trials, the same outcome would result, as only one path (or narrow family) would constructively interfere. This deterministic selection is consistent with a block-universe ontology, wherein all outcomes are fixed by global boundary conditions. However, it would be inconsistent, for example, with the many-worlds interpretation, where quantum indeterminacy is ontological—that is, where each quantum event causes the universe to branch into multiple, non-interacting histories.

4 Quantum Randomness as an Epistemic Phenomenon

Quantum mechanics traditionally interprets measurement outcomes probabilistically. However, in a superdeterministic framework, this randomness arises from practical ignorance:

- The detector position, environment temperature, and positions of air molecules all affect which paths interfere constructively.
- If we knew the entire state of the universe — including microscopic environmental details — the final measurement result would be predictable.

Thus, we interpret quantum probabilities as epistemic: emergent from ignorance of $\mathcal{E}$ and $\Delta S[x(t), \mathcal{E}]$, not from any fundamental stochasticity in nature.

5 Implications and Experimental Outlook

Possible avenues to test or explore the consequences of this framework include:

- **Extreme environmental control:** Experiments in high vacuum and cryogenic environments may suppress environmental variables and expose deterministic behavior.
- **Path interference modeling:** Simulations could model sensitivity of interference patterns to small changes in geometry or field.
- **Non-standard boundary effects:** Introducing perturbations (e.g., diffraction barriers or nearby materials) far from the main path could reveal the role of long-range constraints.

6 Conclusion

We have outlined a superdeterministic framework that incorporates Feynman's path integral formalism to explain quantum behavior as a deterministic outcome of universal boundary conditions. By rejecting the assumption of measurement independence, we bypass Bell's constraint and allow for a local, causal, and deterministic reinterpretation of quantum events.

In this view, quantum randomness is not a fundamental feature of nature but arises from the practical impossibility of knowing the universe's complete state at any moment. We propose a modified path integral formulation where environmental contributions determine which paths constructively interfere, thereby selecting the outcome deterministically. This view is consistent with a four-dimensional block universe and offers a promising direction for reconciling quantum mechanics with a fully deterministic ontology.

References

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