

Quantum Conditional Reality: A Synthetic Realist Interpretation of Quantum Foundations

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Abstract

Quantum mechanics is the most empirically successful theory in modern science, yet its conceptual and ontological foundations remain deeply contested. Persistent disagreements over the status of the quantum state, the nature of measurement, and the role of the observer bifurcate the field into realist, instrumentalist, and constructivist camps. This article proposes Critical Synthetic Realism (CSR) as a coherent philosophical framework for resolving these foundational tensions. CSR integrates a stratified metaphysics of Conditional Reality—where quantum phenomena are understood as real but manifest only under specific theoretical, experimental, and contextual conditions—with an expanded epistemology of Critical Fallibilism, which acknowledges the profound underdetermination of ontological interpretation by empirical data. Rejecting both the naïve realist treatment of theory as a direct mirror of nature and the anti-realist reduction of theory to a mere predictive instrument, CSR articulates a *via media*: it affirms an objective reality accessible to science while taking full account of the epistemic limits imposed by theory-dependence, contextuality, and observer involvement. The paper situates CSR within contemporary quantum foundations, compares it to dominant interpretations, and explores its implications for the measurement problem, theory choice, and emerging quantum technologies. By offering a fallibilist yet robustly realist account of quantum knowledge, CSR aims to stabilize foundational discourse without foreclosing future theoretical development.

Keywords: Quantum Foundations, Scientific Realism, Conditional Reality, Quantum Measurement, Theory-Dependence, Critical Fallibilism, Philosophy of Quantum Mechanics

1. Introduction: The Conceptual Tension at the Heart of Quantum Theory

Few scientific theories rival the empirical success of quantum mechanics; fewer still have generated such enduring philosophical disquiet. From its inception, quantum theory has systematically challenged classical assumptions about physical reality, causality, locality, and observation. While its predictive accuracy is confirmed across an extraordinary range of domains—from atomic spectroscopy to quantum electrodynamics and beyond—the theory's ontological meaning remains fundamentally unsettled. For over a century, physicists and philosophers have disputed whether the quantum state represents a physical entity, encodes epistemic information, or functions merely as a calculational device.¹

This constitutive tension places quantum mechanics in a unique position within the philosophy of science. Unlike classical mechanics or even relativity, quantum theory does not merely invite philosophical interpretation; it appears to demand it. The formalism operates with impeccable precision, yet the ontological commitments it entails remain radically ambiguous. Competing interpretations—from realist and instrumentalist to relational and information-theoretic—each claim conceptual coherence, but none commands consensus.² The result is a productive yet potentially fragmenting foundational pluralism.

This article argues that these interpretive impasses often stem from an unresolved conflict between two philosophically untenable extremes. On one side stands a *naïve scientific realism* that

treats the mathematical structures of quantum theory as literal representations of mind-independent reality, frequently reifying the wavefunction or the multiverse without sufficient epistemic warrant.³ On the other stands a *strict instrumentalism* or strong constructivism, which reduces quantum theory to a predictive algorithm devoid of ontological commitment, thereby undermining the explanatory aspirations that motivate foundational inquiry.⁴

In response, we advance *Critical Synthetic Realism* (CSR) as a framework designed to mediate between these poles. CSR rests on two interdependent pillars. First, it proposes a stratified metaphysics of *Conditional Reality*, wherein quantum phenomena are objectively real but become manifest only under specific experimental, theoretical, and contextual conditions. Second, it adopts an expanded epistemology of *Critical Fallibilism*, recognizing that while quantum theory tracks real structures of the world, our interpretations of those structures remain provisional, theory-laden, and historically contingent.

Our aim is not to adjudicate definitively between existing interpretations but to provide a meta-framework for their evaluation and comparison. By grounding realism in a conditional ontology and tempering it with a fallibilist epistemology, CSR seeks to preserve the objectivity of quantum science without overstating the finality of any particular interpretive stance. In doing so, this paper contributes to ongoing debates in quantum foundations and clarifies the philosophical assumptions underpinning emerging quantum technologies.

2. Literature Review: Realism, Instrumentalism, and the Quantum Problem

2.1. Scientific Realism and its Discontents in Quantum Theory

Scientific realism maintains that mature scientific theories aim to describe a mind-independent reality and that their empirical success is best explained by their approximate truth.⁵ In classical domains, this position is intuitively compelling: entities like electrons and electromagnetic fields are treated as real constituents of the world. In the quantum domain, however, realism confronts unique obstacles.

The quantum state, represented by the wavefunction ψ , resists straightforward ontological categorization. Is it a physical field, a dispositional property, or an informational construct? Attempts to preserve realism by assigning direct physical reality to ψ often lead to counterintuitive consequences, including action-at-a-distance, ontological proliferation (as in many-worlds interpretations), or a mysterious collapse process.⁶ While such models are logically coherent, they raise the question of whether realism has been preserved at the cost of parsimony and explanatory restraint.

Furthermore, quantum contextuality—where the value of an observable depends on the measurement context—challenges the classical realist assumption that properties exist independently of measurement. The Kochen-Specker theorem and Bell's inequalities formally constrain the kinds of hidden-variable models that can be sustained, suggesting that any realist interpretation

must accommodate non-classical features.⁷ These results have led some to conclude that realism in its classical form is untenable in quantum mechanics.⁸

2.2. Instrumentalist and Anti-Realist Responses

In reaction to these difficulties, instrumentalist and anti-realist approaches have found renewed appeal. From this perspective, quantum theory is a powerful instrument for prediction, but its formal elements need not correspond to physical reality. Theories are judged by empirical adequacy, and ontological questions are deferred or dismissed as metaphysically speculative.⁹

While instrumentalism sidesteps certain metaphysical puzzles, it does so at a significant cost. It undermines the explanatory depth that drives fundamental research and theoretical unification. Moreover, it sits uneasily with actual scientific practice, wherein hypothesis formation, experimental design, and technological application routinely presuppose a degree of realism about the systems under investigation.¹⁰

More recent pragmatic, information-theoretic, and relational interpretations attempt to soften instrumentalism by recasting quantum states as representations of knowledge or relations between systems.¹¹ Although these approaches offer valuable insights, they often stop short of articulating a coherent account of what quantum theory reveals about the structure of reality *itself*.

2.3. Toward a Mediating Framework

The persistent stalemate between realism and instrumentalism suggests the problem may lie not solely with quantum theory, but with the philosophical binaries brought to its interpretation. Classical realism assumes a direct correspondence between representation and reality; strong anti-realism denies the possibility of such correspondence. Both, we argue, rely on an impoverished ontology.

What is required is a framework that acknowledges the conditionality of quantum phenomena without denying their reality—one that affirms the objectivity of scientific inquiry while explicitly recognizing its epistemic limits. Critical Synthetic Realism is proposed as just such a framework, synthesizing insights from the philosophy of science to articulate a more nuanced account of quantum reality.

3. Methodology: A Synthetic Realist Framework for Quantum Foundations

This article employs a conceptual-analytic and meta-theoretical methodology to clarify the ontological and epistemological assumptions underlying contemporary debates in quantum foundations. The approach is philosophical rather than empirical, operating through logical reconstruction and synthesis. This is appropriate given that core issues—the status of the quantum state, the nature of measurement, and the meaning of contextuality—are not resolvable by data alone but require sustained conceptual analysis.¹²

Our methodology, Critical Synthetic Realism (CSR), functions as a meta-framework comprising three integrated components: (1) stratified ontological analysis, (2) critical fallibilist epistemology, and (3) comparative interpretive evaluation.

3.1. Conceptual Analysis and Ontological Clarification

The first component is a conceptual analysis of key, often tacit, terms in quantum foundations: “reality,” “measurement,” “observer,” “state,” and “context.” CSR treats the divergent usage of these terms not as a mere semantic confusion but as evidence of unresolved ontological ambiguity. Analysis proceeds by examining how different interpretations implicitly answer two questions: What kinds of entities does quantum theory commit us to? Under what conditions do these entities manifest determinate properties?

Rather than seeking a single reductive answer, CSR employs a *stratified ontological analysis*, distinguishing between the mathematical, physical, experimental-contextual, and epistemic layers of description. This allows for the assessment of realist claims without presupposing a direct isomorphism between formalism and ontology.¹³

3.2. Stratified Ontology as Methodological Principle

The second component adopts stratified ontology as an organizing principle. CSR assumes reality is structured in multiple, irreducible layers, each with its own explanatory norms. For quantum theory, this entails a methodological refusal to collapse explanation into either pure formalism or raw data.

Methodologically, stratification allows us to ask which layer a given interpretive claim addresses. For instance, claims about the wavefunction may pertain to the mathematical layer (a vector in Hilbert space), the physical layer (a guiding field), or the epistemic layer (a state of knowledge). CSR treats conflation across these layers as a primary source of foundational disagreement.

3.3. Critical Fallibilism as Epistemic Method

The third component is *Critical Fallibilism*, an epistemic stance treating all interpretive claims as provisional, corrigible, and historically situated. In quantum foundations, where empirical data radically underdetermines ontology, such fallibilism is a necessity, not a concession.¹⁴

Within this method, no interpretation is taken as final. Interpretations are instead assessed for coherence, explanatory power, empirical consistency, and ontological economy. This functions as a safeguard against metaphysical overreach, allowing for realist commitment without dogmatism. CSR thus advances *conditional* realist claims—claims about what quantum theory plausibly describes, given specific conceptual and experimental constraints.

3.4. Comparative Interpretive Evaluation

Finally, the methodology includes a comparative evaluation of interpretive frameworks (e.g., Bohmian, Everettian, Copenhagen, QBist). This comparison does not seek a “winner” but aims to identify shared assumptions, points of divergence, and conceptual

blind spots. CSR serves as a meta-lens, applying the same stratified and fallibilist criteria to each interpretation to illuminate how different positions negotiate the theory-reality-measurement relationship.

4. Conditional Reality and the Ontology of Quantum Phenomena

4.1. The Problem of Ontology in Quantum Foundations

Interpretive disputes signal that the quantum problem is not merely epistemic but ontological. The theory predicts precisely while leaving indeterminate *what exists*. Classical ontology assumes systems possess determinate properties independently of observation. Quantum mechanics systematically violates this assumption. Observable quantities lack simultaneous definite values, and outcomes depend on experimental arrangements.¹⁵

Attempts to preserve a classical ontology via hidden variables or a real wavefunction incur substantial metaphysical costs. Conversely, approaches that dissolve ontology into epistemology fail to justify the realist intuitions driving quantum research and technology. This stalemate necessitates an alternative ontology that accommodates contextuality without abandoning realism.

Conditional Reality is proposed as this alternative. It reframes the ontological question: Under what conditions do quantum phenomena manifest as determinate features of the world? This shift allows an ontology faithful to quantum practice, avoiding both naïve realism and skepticism.

4.2. Defining Conditional Reality

Conditional Reality denotes a mode of existence where entities or properties are objectively real but not universally manifest. In quantum mechanics, systems are real, but properties like position or spin are not intrinsic possessions. They become determinate only within specific measurement contexts defined by physical interactions and formal constraints.¹⁶

This differs from instrumentalism and idealism. Quantum properties are not mere observer beliefs. The conditions for determinacy are physical and structural. The quantum state, therefore, is best interpreted not as a direct physical object nor a mere bookkeeping tool, but as a *conditional representation* of a system’s potential manifestations under specified constraints. The wavefunction encodes real structural relations between a system and its possible interactions, without cataloging intrinsic properties.¹⁷

4.3. Stratification and Conditional Manifestation

Conditional Reality gains clarity within a stratified model. In the quantum domain, we can distinguish:

- The **Formal Layer** (Hilbert space, operators).
- The **Physical Layer** (quantum systems, apparatus).
- The **Experimental-Contextual Layer** (measurement setup, decoherence environment).
- The **Epistemic Layer** (inference, models).

Confusion arises when claims from one layer are imported into another. Conditional Reality mediates, respecting each layer's autonomy while accounting for their interaction. Quantum phenomena are conditionally instantiated *across* layers. Measurement does not create reality but actualizes particular aspects of a system constrained by indeterminacy. Reality lies in structured patterns of conditional manifestation.

4.4. Measurement and Contextuality

The measurement problem is often a dilemma between collapse and no-collapse interpretations. Conditional Reality reframes it as an ontology of *manifestation*. Measurement is a contextual interaction that renders specific properties manifest within a given experimental arrangement.¹⁸

Contextuality is thus a structural feature of quantum reality, not a defect. Properties exist as conditionally constrained potentials, becoming determinate when appropriate physical conditions obtain. This aligns with empirical content while avoiding observer mysticism or classical rigidity. Objectivity is preserved at the level of lawful conditional relations.

4.5. Realism Without Reification

A central virtue of Conditional Reality is that it enables realism without reification. Quantum systems are real, and their behavior is lawfully constrained. However, the theory does not force us to treat every formal element as a literal physical component. By distinguishing conditional manifestation from intrinsic possession, CSR sustains the realist intuition that science reveals the world's structure while respecting quantum phenomena's inherent limits.¹⁹

5. Implications for Quantum Science and Emerging Technologies

The CSR framework has practical implications beyond philosophy, offering conceptual clarity for research and technology.

5.1. Quantum Measurement and Experimental Design

Conditional Reality conceptualizes measurement as contextual actualization. This aligns with and reinforces rigorous experimental practice. It encourages detailed modeling of contextual variables (apparatus configuration, environmental coupling) as ontologically significant, not merely as noise. This promotes transparency and reproducibility as reflections of quantum ontology itself.²⁰

5.2. Quantum Information and Computation

In quantum information science, abstract entities like qubits are often reified. CSR cautions against this while affirming their operational reality. A qubit is a conditionally defined system whose informational properties manifest within specific physical and operational contexts. This supports a pragmatic realism: quantum states are real operational resources without demanding contentious metaphysical claims about their ultimate nature. It also clarifies that information is conditionally instantiated through physical systems, emphasizing material and environmental constraints in developing scalable technologies.²¹

5.3. Theory Choice and Interpretive Restraint

As quantum technologies mature, interpretive narratives can influence funding, research directions, and public communication. CSR's Critical Fallibilism introduces a principle of *interpretive restraint*. It encourages presenting ontological claims as provisional and condition-bound, explicitly tied to domains of application. This allows the use of interpretations where they are heuristically useful (e.g., visualizing entanglement) without presenting them as final truths. This restraint also has an ethical dimension, helping to mitigate hype and skepticism by presenting quantum science as a fallible yet truth-tracking enterprise.²²

5.4. Interdisciplinary Integration

Quantum science increasingly intersects with materials science, biology, and cognitive science. CSR's stratified ontology provides a framework for navigating these interactions. Different disciplines can be seen as engaging different layers of reality, allowing for integration without premature reduction. Quantum phenomena can be fundamental at one level while compatible with higher-level, classical, or emergent descriptions.²³

6. Conclusion

Quantum mechanics presents a unique confluence of empirical triumph and conceptual ambiguity. Foundational pluralism persists because the theory challenges deep-seated philosophical assumptions about reality and knowledge.

This article has argued that Critical Synthetic Realism (CSR), grounded in the metaphysics of Conditional Reality and the epistemology of Critical Fallibilism, offers a coherent path forward. Conditional Reality reorients quantum ontology away from intrinsic properties and toward conditioned manifestation, affirming the reality of quantum systems while taking contextuality seriously. Critical Fallibilism situates this ontology within a disciplined epistemic stance, treating interpretations as provisional tools rather than final revelations.

Beyond foundational debate, CSR provides conceptual resources for experimental practice, quantum information science, and responsible communication about emerging technologies. It clarifies the ontological significance of measurement contexts and supports pragmatic realism in application.

The contribution of CSR is not a resolution to the quantum riddle but the provision of a stable, flexible philosophical framework within which foundational inquiry can proceed productively. It affirms that quantum theory tracks the structure of an objective world—a world that is, in its quantum dimension, irreducibly conditional [1-22].

Notes

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2. David Wallace, *The Emergent Multiverse: Quantum Theory*

- according to the Everett Interpretation (Oxford: Oxford University Press, 2012), 1-15; Carlo Rovelli, "Relational Quantum Mechanics," *International Journal of Theoretical Physics* 35, no. 8 (1996): 1637–1678.
3. John S. Bell, *Speakable and Unsayable in Quantum Mechanics: Collected Papers on Quantum Philosophy*, 2nd ed. (Cambridge: Cambridge University Press, 2004), 169-172.
 4. Bas C. van Fraassen, *The Scientific Image* (Oxford: Clarendon Press, 1980), 6-7; Christopher A. Fuchs and Asher Peres, "Quantum Theory Needs No 'Interpretation'," *Physics Today* 53, no. 3 (2000): 70–71.
 5. Stathis Psillos, *Scientific Realism: How Science Tracks Truth* (London: Routledge, 1999), xvi-xix.
 6. Hugh Everett, III, "'Relative State' Formulation of Quantum Mechanics," *Reviews of Modern Physics* 29, no. 3 (1957): 454–462; Bohm, *Wholeness and the Implicate Order*, 71-110.
 7. Simon Kochen and Ernst Specker, "The Problem of Hidden Variables in Quantum Mechanics," *Journal of Mathematics and Mechanics* 17, no. 1 (1967): 59–87; Bell, *Speakable and Unsayable*, 14-21.
 8. Bernard d'Espagnat, *Reality and the Physicist: Knowledge, Duration and the Quantum World*, trans. J. C. Whitehouse (Cambridge: Cambridge University Press, 1989), 108-125.
 9. Van Fraassen, *The Scientific Image*, 8-12.
 10. Nancy Cartwright, *How the Laws of Physics Lie* (Oxford: Clarendon Press, 1983), 44-66.
 11. Rovelli, "Relational Quantum Mechanics," 1638-1640; Fuchs and Peres, "Quantum Theory Needs No 'Interpretation'," 70.
 12. Tim Maudlin, *Quantum Non-Locality and Relativity: Metaphysical Intimations of Modern Physics*, 3rd ed. (Chichester: Wiley-Blackwell, 2011), 1-10.
 13. Richard Healey, *The Philosophy of Quantum Mechanics: An Interactive Interpretation* (Cambridge: Cambridge University Press, 1989), 5-20.
 14. Larry Laudan, "A Confutation of Convergent Realism," *Philosophy of Science* 48, no. 1 (1981): 19–49.
 15. Albert Einstein, Boris Podolsky, and Nathan Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?," *Physical Review* 47, no. 10 (1935): 777–780; John von Neumann, *Mathematical Foundations of Quantum Mechanics*, trans. Robert T. Beyer (Princeton, NJ: Princeton University Press, 1955), 417-445.
 16. Werner Heisenberg, *Physics and Philosophy: The Revolution in Modern Science* (New York: Harper & Brothers, 1958), 52-58.
 17. This view shares affinities with Healey's pragmatist interpretation but emphasizes the ontological commitment to conditionally manifest structures. Cf. Healey, *Philosophy of Quantum Mechanics*, 113-130.
 18. Bohr, "Quantum Postulate," 580; John Archibald Wheeler and Wojciech Hubert Zurek, eds., *Quantum Theory and Measurement* (Princeton, NJ: Princeton University Press, 1983), Part I.
 19. Karl R. Popper, *Quantum Theory and the Schism in Physics*, ed. W. W. Bartley III (London: Hutchinson, 1982), 89-105.
 20. This methodological implication echoes the emphasis on "experimental metaphysics" in the wake of Bell's theorem.
 21. David Deutsch, *The Fabric of Reality: The Science of Parallel Universes—and Its Implications* (New York: Allen Lane, 1997), 194-220, discusses the reality of information in quantum computation from a many-worlds perspective; CSR offers an alternative, less ontologically committed grounding.
 22. The need for responsible communication is emphasized in literature on the sociology of science. Cf. Naomi Oreskes and Erik M. Conway, *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming* (New York: Bloomsbury Press, 2010).
 23. This layered, non-reductionist approach is compatible with various philosophies of science that emphasize the autonomy of different scientific domains.

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