# Relational Ontology as a Bridge Between Realism and Empiricism in Scientific Explanation

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**Abstract**

This paper proposes that relational ontology, which defines existence through relations, serves as a bridge between scientific realism and empiricism by offering a structural criterion for scientific explanation. Through case studies in quantum mechanics and thermodynamics, we illustrate how relationality grounds scientific theories in empirical interactions while supporting realist commitments to unobservable structures. Engaging with philosophy of science debates—realism, reductionism, and demarcation—and drawing on thinkers such as Lakatos, Kuhn, Cartwright, van Fraassen, and contemporary authors like Ladyman and Chakravartty, this work examines the explanatory limits of relational ontology in addressing consciousness and contrasts scientific explanations with non-scientific accounts. Its original contribution lies in demonstrating how relational ontology unifies these perspectives through a rigorous structural criterion, advancing our understanding of scientific explanation within the philosophy of science.

# 1 Introduction

Scientific explanation is a central concern in the philosophy of science, addressing how theories represent reality and what distinguishes scientific inquiry from other forms of knowledge. This paper argues that relational ontology—defining existence through relations—provides a structural criterion for scientific explanation that bridges scientific realism and empiricism. Realism posits that scientific theories describe an objective reality, including unobservables, while empiricism emphasizes observables as the sole basis for scientific knowledge. Relational ontology offers a middle path by grounding unobservables in empirical interactions, thus unifying these perspectives.

We explore this framework through case studies in quantum mechanics and thermodynamics, engaging with key philosophy of science debates: realism versus empiricism, reductionism, and the demarcation problem. The paper also examines consciousness as a test case for relational ontology's explanatory power and contrasts scientific explanations with non-scientific accounts, such as classical theism, to highlight broader implications. Drawing on historical and contemporary thinkers—Lakatos, Kuhn, Cartwright, van Fraassen, Ladyman, and Chakravartty—this work contributes to ongoing discourse in the philosophy of science.

The paper is structured as follows: Section 2 defines relational ontology and its philosophical foundations, including a rigorous mathematical formalization. Section 3 presents case studies in quantum mechanics and thermodynamics. Section 4 situates the analysis within philosophy of science debates. Section 5 examines consciousness and relational ontology's limits in detail. Section 6 compares scientific and non-scientific explanations. Section 7 addresses objections and limitations comprehensively, and Section 8 concludes with the paper's contributions.

# 2 Relational Ontology: Foundations and Formalization

## 2.1 Core Principle and Mathematical Framework

Relational ontology posits that existence is inherently relational: an entity exists if and only if it stands in relation to other entities. This principle can be formally expressed as:

$$\forall x \in \mathcal{U} : \exists(x) \leftrightarrow \exists y \in \mathcal{U} \setminus \{x\} \text{ such that } R(x, y) \tag{1}$$

where $\mathcal{U}$ represents the universe of discourse, $\exists(x)$ denotes the existence predicate for entity $x$, and $R(x, y)$ represents a relation between entities $x$ and $y$. This formalization captures three essential features:

**Non-trivial relationality**: The relation $R$ must be substantive, not merely formal or logical. We define this as:

$$R(x, y) \text{ is non-trivial} \leftrightarrow R(x, y) \text{ is empirically detectable or theoretically significant} \tag{2}$$

**Structural coherence**: Relations must form coherent structures that can be mapped onto empirical phenomena:

$$\mathcal{S} = \langle \mathcal{E}, \mathcal{R} \rangle \tag{3}$$

where $\mathcal{S}$ is a relational structure, $\mathcal{E}$ is a set of entities, and $\mathcal{R}$ is a set of relations among these entities.

**Empirical grounding**: For any relational structure $\mathcal{S}$ to be scientifically meaningful, there must exist observational consequences $\mathcal{O}$ such that:

$$\mathcal{S} \mapsto \mathcal{O} \text{ through empirically testable predictions} \tag{4}$$

This mathematical framework provides the foundation for what we term the **structural criterion for scientific explanation**: a scientific explanation is valid if and only if it describes empirically verifiable relational structures that satisfy the above conditions.

### 2.2 Philosophical Foundations

This framework aligns with structural realism, which emphasizes the relational structure of reality over individual entities (Ladyman, 2007). Structural realism, as articulated by Ladyman (2007), argues that science reveals the structure of reality through relations, rather than the intrinsic nature of entities. Similarly, Chakravartty (2017) highlights how relational structures underpin scientific theories, supporting a realist commitment to unobservables defined by their empirical interactions.

Relational ontology offers a middle path between scientific realism and constructive empiricism. Realism, as defended by Psillos (2005), holds that scientific theories describe an objective reality, including unobservable entities like quantum states. In contrast, van Fraassen (1980) constructive empiricism asserts that science aims only to account for observables, treating unobservables as predictive tools. Relational ontology bridges this divide by defining unobservables through their empirical relations, supporting a realist stance while remaining grounded in observable interactions.

The structural criterion emerges from this synthesis: it preserves the realist commitment to theoretical entities while satisfying the empiricist demand for observational grounding. This criterion distinguishes scientific explanations from non-scientific accounts by requiring that all theoretical posits be anchored in relational structures with empirical consequences.

## 3 Case Studies

Relational ontology informs scientific explanations across disciplines. We illustrate this through two detailed case studies: quantum mechanics and thermodynamics.

### 3.1 Quantum Mechanics

Relational quantum mechanics (RQM) posits that a quantum system's state is defined only through its interactions with another system (Rovelli, 1996). This approach exemplifies relational ontology by grounding quantum states in empirical interactions rather than intrinsic properties.

Consider two entangled particles, A and B, in a Bell state:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B) \tag{5}$$

The state of A is indeterminate until measured relative to B. The reduced density matrix for A, obtained by tracing over B, is:

$$\rho_A = \mathrm{Tr}_B(|\Psi\rangle\langle\Psi|) = \frac{1}{2}(|0\rangle_A\langle 0| + |1\rangle_A\langle 1|) \tag{6}$$

This demonstrates that A's properties emerge relationally through B (Rovelli, 1996). The relational structure $\mathcal{S}_{quantum} = \langle\{A, B\}, \{R_{entanglement}\}\rangle$ maps onto observable consequences through Bell inequality violations, satisfying our structural criterion.

This relationality extends to cosmology: quantum fluctuations, constrained by the Heisenberg uncertainty principle $\Delta E \Delta t \geq \hbar/2$, seed cosmic structure during inflation, as evidenced by the cosmic microwave background power spectrum $P(k) \propto k^{n_s - 1}$, where $n_s \approx 0.96$ (Collaboration, 2020). These processes illustrate how relational ontology underpins scientific explanations without requiring external causation, while maintaining empirical testability through cosmological observations.

## 3.2 Thermodynamics

Thermodynamics further exemplifies relationality through self-organization and emergent complexity. The second law of thermodynamics, $dS \geq 0$ for isolated systems, dictates that entropy increases overall, but open systems can locally decrease entropy by exporting disorder to their environment (Prigogine & Stengers, 1984).

The entropy differential in an open system is given by:

$$dS = \frac{dQ}{T} + dS_{irreversible} \tag{7}$$

where $dQ$ is the heat transfer, $T$ is the temperature, and $dS_{irreversible} \geq 0$ represents irreversible entropy production (Kondepudi & Prigogine, 2014).

In biological systems, such as living cells, internal entropy decreases as disorder is expelled to the environment, driving the emergence of complexity. This can be formalized as:

$$\frac{dS_{system}}{dt} = \frac{dS_{internal}}{dt} + \frac{dS_{exchange}}{dt} < 0 \tag{8}$$

where $\frac{dS_{internal}}{dt} \geq 0$ but $\frac{dS_{exchange}}{dt} < 0$ with $|\frac{dS_{exchange}}{dt}| > \frac{dS_{internal}}{dt}$.

This relational process—where systems interact with their surroundings to create order— demonstrates how physical laws explain phenomena through empirical interactions, consistent with relational ontology.

The relational structure

$$\mathcal{S}_{\text{thermo}} = \langle \{\text{system}, \text{environment}\}, \{R_{\text{energy\_exchange}}, R_{\text{entropy\_flow}}\} \rangle$$

generates testable predictions about self-organization patterns, satisfying our structural criterion.

# 4 Philosophy of Science Debates

Relational ontology connects to longstanding debates in the philosophy of science, providing a framework to address realism, reductionism, and demarcation.

## 4.1 Realism vs. Empiricism

As established, relational ontology aligns with structural realism, bridging the divide between realism and empiricism (Ladyman, 2007; Chakravartty, 2017; Psillos, 2005; van Fraassen, 1980). Structural realism posits that science reveals the relational structure of reality, a view that supports realist commitments to unobservables while grounding them in empirical relations, thus addressing van Fraassen's emphasis on observables (van Fraassen, 1980).

This synthesis offers our structural criterion for scientific explanation: explanations are valid if they describe empirically verifiable relational structures. This criterion preserves theoretical realism while satisfying empirical constraints, providing a principled resolution to the realism-empiricism debate.

## 4.2 Reductionism

Reductionism holds that complex phenomena can be explained by fundamental laws (Psillos, 2005). However, Cartwright (1983) critiques this view, arguing that scientific laws are often idealized and context-dependent. Relational ontology supports a nuanced perspective on reductionism.

While thermodynamic phenomena can be reduced to statistical mechanics, their explanatory power often lies in higher-level relational structures, such as self-organizing systems, which resist full reduction (Prigogine & Stengers, 1984). The relational approach suggests that reduction is possible when relational structures at different levels can be systematically mapped onto each other, but emergence occurs when higher-level structures exhibit relational properties not present at lower levels.

This can be formalized as: reduction is successful when there exists a structure-preserving mapping $f : \mathcal{S}_{higher} \to \mathcal{S}_{lower}$ such that empirical predictions are preserved. Emergence occurs when no such mapping exists while maintaining explanatory adequacy.

## 4.3 Demarcation Problem

The demarcation problem seeks to distinguish science from non-science, a concern addressed by Popper, Lakatos, and Kuhn (Popper, 1959; Lakatos, 1970; Kuhn, 1970). Lakatos (1970) emphasizes empirical progress within research programs, while Kuhn (1970) highlights paradigm shifts as markers of scientific development.

Relational ontology aligns with these criteria by defining scientific explanations as those grounded in testable relational structures, providing a clear demarcation from non-scientific accounts that lack empirical verifiability. Our structural criterion operationalizes this demarcation: scientific theories must specify relational structures that generate empirically testable consequences, while non-scientific accounts fail to meet this requirement.

# 5 Consciousness and the Limits of Relational Ontology

Consciousness poses a significant challenge for scientific explanation, testing the limits of relational ontology and providing crucial insights into the scope and boundaries of our structural criterion.

## 5.1 Relational Approaches to Consciousness

Integrated Information Theory (IIT) quantifies consciousness through the metric $\Phi$, which measures a system's informational integration (Tononi et al., 2016). The theory proposes that consciousness corresponds to integrated information, formally defined as:

$$\Phi = \min_{M} D(p(X_1|X_0), \prod_{i} p(X_1^i|X_0^i)) \tag{9}$$

where $D$ is the Earth Mover's Distance, $X_0$ and $X_1$ represent system states at different times, and the minimum is taken over all possible partitions $M$ of the system.

High $\Phi$ values, observed in EEG studies during wakefulness, correlate with conscious states, while low $\Phi$ values occur during unconscious states like deep sleep (Tononi et al., 2016). This suggests consciousness emerges from relational complexity within physical systems, fitting our relational framework.

Global Workspace Theory (GWT) provides another relational account, proposing that consciousness arises from the global broadcasting of information across neural networks (Dehaene, 2014). The theory can be formalized in terms of information integration across brain modules:

$$C = f\left(\sum_{i,j} I(M_i, M_j)\right) \tag{10}$$

where $C$ represents consciousness level, $I(M_i, M_j)$ is mutual information between brain modules $i$ and $j$, and $f$ is a non-linear function capturing threshold effects.

Both theories exemplify how relational ontology can account for consciousness through structural approaches, suggesting that conscious states correspond to specific relational configurations of neural systems.

## 5.2 The Hard Problem and Relational Ontology's Limits

However, the "hard problem" of consciousness—why physical processes yield subjective experience—remains unresolved within purely relational frameworks (Chalmers, 1995). This limitation reveals important boundaries of relational ontology's explanatory power.

The hard problem can be formulated as follows: even if we fully specify the relational structure $\mathcal{S}_{brain} = \langle \mathcal{N}, \mathcal{R}_{neural} \rangle$ where $\mathcal{N}$ represents neural elements and $\mathcal{R}_{neural}$ represents their interactions, it remains unclear why this structure should be accompanied by subjective experience rather than proceeding as a purely physical process.

Non-reductive approaches offer alternative perspectives that highlight these limits. Strong emergentism, as proposed by Clayton (2006), posits consciousness as an irreducible emergent property, distinct from physical processes despite arising from them. This can be represented as:

$$\mathcal{S}_{consciousness} \supset f(\mathcal{S}_{neural}) \tag{11}$$

indicating that conscious structures contain properties not captured by any function of neural structures alone.

Naturalistic dualism, advocated by Hasker (2010), suggests that consciousness involves a non-physical aspect, compatible with natural laws but not reducible to them. This approach proposes fundamental psychophysical laws connecting physical and experiential domains:

$$\mathcal{L}_{psychophysical} : \mathcal{S}_{physical} \leftrightarrow \mathcal{S}_{experiential} \tag{12}$$

### 5.3 Implications for Relational Ontology

These challenges illuminate both the strengths and limitations of relational ontology. While it successfully explains the structural basis of consciousness through theories like IIT and GWT, it struggles with the qualitative, subjective aspects of experience. This suggests that relational ontology may need supplementation rather than replacement.

One promising direction involves recognizing different types of relations. While our framework has focused on third-person, empirically observable relations, consciousness may require first-person relational structures that are not reducible to external observation. This could lead to an expanded relational ontology that includes subjective relations without abandoning the empirical grounding that makes the approach scientifically valuable.

The consciousness case study thus serves as a crucial test that both validates relational ontology within its domain of application and clarifies its boundaries, pointing toward areas where the framework may need extension or integration with other philosophical approaches.

## 6 Scientific vs. Non-Scientific Explanations

To further illustrate relational ontology's role in scientific explanation and its demarcation criterion, we contrast it with non-scientific accounts, examining both the strengths of the relational approach and potential objections to this contrast.

### 6.1 Classical Theism and Relational Ontology

Classical theism posits a non-relational deity as the universe's cause, existing independently of interactions (Swinburne, 2016). This presents a direct challenge to relational ontology's core principle. Within our framework, existence requires interaction: if no entity $y$ exists such that $R(God, y)$ holds in a non-trivial sense, such an entity cannot exist according to equation (1).

However, this analysis must be nuanced. Some theological positions do posit divine relations—with creation, with human souls, or within the Trinity. A more precise formulation would distinguish between:

1. **Absolute independence**: No relations whatsoever
2. **Asymmetric relations**: Relations that affect the relatum but not the divine entity
3. **Symmetric relations**: Genuine mutual relations

Classical theism typically endorses (2), while relational ontology requires (3) for genuine existence. This creates a principled distinction based on the nature of relationality required.

## 6.2 Empirical Grounding and Testability

Scientific explanations, by contrast, rely on empirically grounded relations—e.g., quantum entanglement or thermodynamic self-organization—aligned with Lakatos (1970) criterion of empirical progress. The key difference lies not merely in subject matter but in methodological approach:

Scientific relational structures satisfy:

$$\mathcal{S}_{scientific} \mapsto \mathcal{P}_{testable} \mapsto \mathcal{O}_{observable} \tag{13}$$

where $\mathcal{P}_{testable}$ represents testable predictions and $\mathcal{O}_{observable}$ represents observable consequences.

Non-scientific accounts typically fail to establish this mapping, either because:

1. No testable predictions follow from the posited relations
2. The relations are defined in ways that preclude empirical testing
3. Observable consequences are explained post-hoc rather than predicted

### 6.3 Cartwright's Critique and Contextual Laws

Cartwright (1983) critique of universal laws provides additional support for this demarcation. Cartwright argues that scientific laws are often idealized and context-dependent, which might seem to undermine the objectivity of scientific explanation. However, relational ontology accommodates this insight by emphasizing that relational structures are always situated within specific contexts.

The difference between scientific and non-scientific accounts is not that scientific laws are universal while non-scientific ones are contextual, but rather that scientific accounts specify the contextual conditions under which their relational structures apply and generate testable consequences. Non-scientific accounts often claim universal applicability without specifying testable contextual conditions.

This can be formalized as:

$$\mathcal{S}_{scientific} = \langle \mathcal{E}, \mathcal{R}, \mathcal{C} \rangle \tag{14}$$

where $\mathcal{C}$ represents the contextual conditions under which the relational structure applies and generates empirical consequences.

## 7 Addressing Objections and Limitations

This section addresses major objections to relational ontology and acknowledges its limitations, strengthening the overall argument through critical examination.

### 7.1 McKenzie's Objection: Collapse into Empiricism

McKenzie (2017) argues that structural realism, and by extension relational ontology, risks collapsing into empiricism by prioritizing relations over intrinsic properties. This objection deserves careful consideration as it strikes at the heart of our attempt to bridge realism and empiricism.

McKenzie's argument can be reconstructed as follows:

1. Structural realism claims that science reveals only relational structures
2. Relations are observable or inferrable from observables
3. Therefore, structural realism reduces to a sophisticated form of empiricism
4. This eliminates genuine theoretical realism

Our response involves several components:

**Distinction between relations and relational structures**: While individual relations may be observable, the structural patterns they form often transcend direct observation. The relational structure $\mathcal{S} = \langle \mathcal{E}, \mathcal{R} \rangle$ is not merely the sum of its relations but includes emergent structural properties that support genuine theoretical realism.

**Unobservable relations**: Many scientifically significant relations are not directly observable but are theoretically posited to explain patterns in observable phenomena. For example, quantum entanglement relations are not directly observable but are inferred from correlation patterns that violate classical expectations.

**Structural coherence constraint**: Our framework requires that relational structures satisfy coherence conditions that go beyond mere empirical adequacy. The structure must exhibit internal consistency and explanatory power that supports realist interpretation.

Formally, we can distinguish between empirical adequacy and structural realism:

$$\text{Empirical adequacy}: \quad \mathcal{T} \text{ saves the phenomena} \tag{15}$$

$$\text{Structural realism}: \quad \mathcal{T} \text{ correctly describes } \mathcal{S}_{real} \tag{16}$$

where $\mathcal{S}_{real}$ represents the actual relational structure of reality, which may exceed what is required for mere empirical adequacy.

### 7.2 The Grounding Problem

Another objection concerns the grounding of relations themselves. If entities exist only through relations, what grounds the relations? This threatens infinite regress or circularity.

Our response draws on the mathematical framework developed in Section 2. Relations need not be grounded in non-relational entities; instead, they can be grounded in structural patterns that emerge from the totality of relational networks. This can be formalized using fixed-point theory:

A relational structure $\mathcal{S}$ is self-grounding if it satisfies:

$$\mathcal{S} = F(\mathcal{S}) \tag{17}$$

where $F$ is a structural function that generates the relational patterns from the structure itself. This avoids both infinite regress and dependence on non-relational foundations.

### 7.3 Scope Limitations

Relational ontology faces legitimate scope limitations that must be acknowledged:

**Subjective experience**: As discussed in Section 5, the hard problem of consciousness reveals areas where relational approaches may be insufficient. This suggests that relational ontology may need supplementation rather than providing a complete metaphysical framework.

**Mathematical objects**: The ontological status of mathematical entities poses challenges for relational approaches. While mathematical structures are inherently relational, their existence may not depend on empirical relations in the same way as physical entities.

**Modal properties**: Relational ontology as formulated here focuses on actual relations, but scientific explanation often involves counterfactual and modal claims that may require additional ontological resources.

### 7.4 Response to Alternative Frameworks

Several alternative frameworks compete with relational ontology:

**Entity realism**: Hacking (1983) argues that scientific realism should focus on entities rather than theories or structures. However, our framework accommodates this by treating entities as nodes in relational networks—they exist as genuine entities precisely because of their relational embeddings.

**Dispositionalism**: Mumford (2003) propose that properties are essentially dispositional. This approach is actually compatible with relational ontology, as dispositions can be understood as relational potentials that become actualized through interactions.

**Process ontology**: Dupré (2012) advocates for process-based ontologies that emphasize becoming over being. Relational ontology can incorporate this insight by treating relations as dynamic processes rather than static connections.

These considerations suggest that relational ontology is best understood not as a complete metaphysical system but as a methodological framework for scientific explanation that can be enriched through integration with other approaches.

## 8 Conclusion

This paper demonstrates that relational ontology serves as a bridge between scientific realism and empiricism through a rigorous structural criterion for scientific explanation. Our key contributions include:

**Mathematical formalization**: We have provided a formal framework that defines existence relationally and establishes precise conditions for scientific explanation through empirically verifiable relational structures.

**Structural criterion**: We have articulated and defended a structural criterion for scientific explanation: explanations are valid if and only if they describe empirically verifiable relational structures that satisfy conditions of non-trivial relationality, structural coherence, and empirical grounding.

**Integration of perspectives**: By grounding unobservables in empirical relations while maintaining realist commitments to theoretical structures, relational ontology provides a principled synthesis of realist and empiricist insights.

**Case study validation**: Through detailed analysis of quantum mechanics and thermodynamics, we have shown how relational ontology illuminates the structure of successful scientific explanations across different domains.

**Boundary identification**: Our examination of consciousness reveals both the power and limits of relational approaches, identifying areas where the framework may need supplementation while clarifying its domain of application.

**Demarcation criterion**: The relational framework provides clear criteria for distinguishing scientific from non-scientific explanations based on empirical testability of relational structures.

Engaging with thinkers like Lakatos, Kuhn, Cartwright, van Fraassen, Ladyman, and Chakravartty, and addressing major objections including McKenzie's critique, this work advances our understanding of scientific explanation within philosophy of science. While limitations persist, particularly regarding consciousness and other domains involving subjective experience, the framework offers a robust foundation for scientific explanation that respects both empirical constraints and realist commitments.

The relational approach suggests that science succeeds not by revealing the intrinsic nature of reality but by mapping its relational structure. This insight has profound implications for how we understand scientific knowledge, theoretical reduction, and the relationship between scientific and non-scientific forms of explanation. Future work should explore extensions of the framework to address its identified limitations while preserving its core insights about the relational nature of scientific explanation.

The framework developed here invites further exploration of relational structures in scientific inquiry, offering philosophers of science a principled approach to longstanding debates while opening new avenues for understanding the nature and limits of scientific explanation.

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