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Observers as Agents: Relational Epistemology from Physics to Ecology

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Abstract

The ideal of objectivity as observer-independent truth has shaped scientific thought since early modern times. Yet contemporary science reveals that all knowledge is perspective-bound embedded, embodied, and enacted observers participate in constructing coherent accounts of reality. This work develops a synthetic, observer-based epistemology that unifies insights from physics, chemistry, biology, cognitive science, ecology, and philosophy, showing how structured intersubjective mechanisms allow perspectival integration into scientifically valid knowledge across domains.

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1. Introduction

Scientific modeling has traditionally aspired to objectivity by minimizing or eliminating the role of the observer. From classical mechanics through much of twentieth-century physics, models were expected to describe an observer-independent, "objective" reality. Yet insights from quantum mechanics, cognitive science, and systems theory show that this ideal is both conceptually limited and methodologically problematic.

Throughout this work, the term 'observer' is used in a broad, relational sense. Observers are understood not as detached entities standing apart from the systems they observe, but as embedded agents (actors) participating in mutual interactions. Every system or agent may simultaneously observe and be observed; there is no fundamental asymmetry between 'observer' and 'observed.' This framing aligns with an agent-based cosmology grounded in info-computationalism, where all natural processes are modeled as networks of information transformation through interacting agents.

This article argues that embedding observer-dependence as a central feature of knowledge generation and epistemology provides a coherent and unifying framework for addressing long-standing conceptual, methodological, and philosophical conundrums across disciplines. Rather than seeing observer role as subjective and detrimental for science, we position them as structurally essential elements of scientific modeling.

From Immanuel Kant's (1781/1998) Critique of Pure Reason to John Wheeler's (1990) participatory universe, the importance of observation and information as foundational to reality has become increasingly apparent. Carl Friedrich von Weizsäcker's "Ur-Theorie" (1985/2006) anticipates Wheeler's participatory universe by proposing that the fundamental building blocks of reality are not particles or fields, but elementary units of binary alternatives—so-called "Urs." Both perspectives emphasize observation and information as foundational to physical reality, with von Weizsäcker's work laying conceptual groundwork for later information-theoretic approaches such as Wheeler's "it from bit".

Quantum mechanics, particularly through Bohr (1935) and Heisenberg (1927), brought observer effects to the forefront, fundamentally challenging classical notions of objective reality. Modern physics reveals that attempts to model reality without reference to observers encounter conceptual and methodological impasses. Relational epistemology offers a coherent alternative, framing knowledge as inherently tied to structured interactions between observers and systems.

We develop an observer/actor-based operational-relational epistemology that situates agency and perspective as fundamental, objective (i.e., inter-subjective) features of reality. Drawing from Relational Quantum Mechanics (Rovelli, 1996, 2021), Quantum Bayesianism (Fuchs et al., 2014; Von Baeyer, 2016), Operational Probabilistic Theories (Hardy, 2011; Höhn, 2019; Leifer & Spekkens, 2014), information-based observer frameworks (Dodig-Crnkovic, 2011, 2016, 2017; Fields, 2012, 2016), the Gaia Hypothesis (Lovelock & Margulis, 1974), and relativity theory (Einstein, 1905; 1915), we present a unified model that bridges physical foundations, information science, cognitive systems, social theory, ecology, philosophy and related fields.

2. Observer-Based Relational Structures and Knowledge Across Scales

Observer-dependence is not confined to quantum mechanics; it recurs as a central feature across natural and social sciences. From subatomic particles to ecological systems, embedding the observer within models allows for clearer, more robust explanations of complex phenomena.

Observer-Based Relational Epistemology in Physics

In quantum mechanics, both Relational Quantum Mechanics (Rovelli, 1996; 2021) and Quantum Bayesianism (Fuchs et al., 2014; Von Baeyer, 2016) exemplify frameworks where facts are not absolute but relative to the observer's interaction with a system. Relational Quantum Mechanics proposes that all physical quantities are defined relative to a given observer, rejecting the notion of observer-independent facts. It maintains objective consistency through defined interaction protocols while emphasizing that facts are observer-relative and structured through causal interactions.

Quantum Bayesianism complements this relational perspective by interpreting quantum probabilities as reflecting individual belief updates based on new information. The wavefunction is treated not as an ontological entity but as an expression of subjective knowledge. Measurement, within this view, becomes an inherently observer-dependent process.

These insights extend naturally into fundamental physics challenges, such as quantum gravity and cosmology. Loop Quantum Gravity (Rovelli, 2021) models spacetime itself as a network of quantized relations—spin networks—applying relational principles from Relational Quantum Mechanics (Rovelli, 1997) to the scale of spacetime geometry. Internal time frameworks (Höhn, 2019) further develop this relational approach by proposing models where time itself is an emergent, observer-relative phenomenon.

Special and general relativity (Einstein, 1905; 1915) embed observer-dependence through the formalization of reference frames. In special relativity, measurements of time, length, and simultaneity depend on the observer's state of motion relative to what is being measured. In general relativity, gravitational effects further shape the structure of spacetime; see Misner, Thorne, and Wheeler (1973) as perceived by different observers. While relativity preserves objectivity through invariant quantities like the spacetime interval and Einstein field equations, it simultaneously demonstrates that many physical properties are observer-relative in precisely defined ways. Relativity thus reinforces the core insight of relational epistemology: facts about systems, including those as fundamental as temporal duration and spatial extension, are conditioned by structured interactions with observers. Observer-dependence is not a conceptual issue in quantum theory alone but a structural feature evident across physics as a whole.

Observer-Based Relational Epistemology in Chemistry

Relational dependence in chemistry becomes especially clear in fields like supramolecular and systems chemistry, where chemical identity and behavior emerge from context-dependent interactions rather than fixed intrinsic properties. Host–guest binding, for example, depends not

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solely on the molecular structures involved but also on environmental conditions such as solvent, temperature, and competing molecules (Lehn, 1995).

Philosophers of chemistry, including Harré (1970), Hendry (2006), and (Scerri & McIntyre, 2015), formalize this insight through relational ontologies. They argue that chemical kinds should be defined by their roles within broader interaction patterns, rather than as immutable essences derived strictly from physics. This challenges reductionist approaches and aligns chemistry more closely with systems biology and complex systems theory.

In this context, even molecules may be considered observers in a minimal sense: through interaction, a molecule may undergo a state change that reflects the state of its environment. While such interactions are not cognitive, they function as informational exchanges that alter the system's structure—thus satisfying the criteria for relational observation within the logic of processes.

This perspective aligns with the account developed in Dodig-Crnkovic (2025), which proposes that natural laws should be understood as embedded logics of physical, chemical, and biological processes. In that view, laws do not stand apart from phenomena but instead constitute structured constraints guiding transitions between states. Observation—whether by molecules or cognitive agents—participates in and reflects this process logic, reinforcing the view that knowledge and structure co-emerge from agent-based interaction.

Modern computational methods in cheminformatics and machine learning reinforce this relational view. Molecules are represented as graph-theoretic networks where nodes and edges encode relational information about atomic arrangements and bonds (Gilmer et al., 2017). These models foreground relational definitions of chemical identity, aligning computational practice with observer-based epistemology.

Relational chemistry has applications in areas like systems chemistry and origins-of-life research (Scerri & McIntyre, 2015). Studies of autocatalytic sets and chemical evolution, extending earlier work (Hordijk & Steel, 2004) (Kauffman, 1993) illustrate how relational frameworks support the co-emergence of structure and function, focusing on patterns of interaction rather than isolated molecular features.

Observer-Based Relational Epistemology in Biology and Cognitive Science

A parallel development is evident in biology. Living systems, from single cells to complex organisms, observe their environment through sensory and signaling pathways. Bayesian inference models (Knill & Pouget, 2004; Helland, 2021) describe how organisms update internal models to predict and respond to environmental stimuli. Observation supports a survival mechanism, embedding epistemic processes within biological structures.

Bacterial quorum sensing exemplifies relational agency within living systems. Individual bacteria release and detect signaling molecules, adjusting their behavior based on the local concentration of these signals. The transition from individual to collective behavior occurs when a critical threshold—quorum—is detected, but this threshold is not an absolute property. It is defined relative to each bacterium's local environment, making bacterial coordination a biologically grounded example of observer-relative knowledge (Bassler & Losick, 2006).

Human cognition presents scaled-up observation systems, integrating sensory-motor input-outputs with abstract reasoning, language, and culture. Artificial intelligence systems mirror this structure through reinforcement learning and neural networks that adjust based on feedback, such as neural message passing systems (Gilmer et al., 2017). Both biological and artificial observers highlight the principle of structured, adaptive information processing (Dodig-Crnkovic, 2011, 2016), (Dodig-Crnkovic & von Haugwitz, 2017).

Observer-Based Relational Epistemology in Social and Ecological Systems

Observer-dependence extends beyond individual cognition and biological systems into collective, distributed systems such as societies and ecosystems. In social systems, observation occurs through structured communication. Niklas Luhmann (1995) proposed that social systems observe

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through communication, creating second-order observations that structure norms and institutions. This contrasts with Habermas's (1984) emphasis on human agency within communicative action. Integrating both views illustrates how observation extends from individual agents to emergent social structures, operating through recursive feedback mechanisms.

In ecological systems, observer-dependence manifests as distributed sensing across scales. The Gaia Hypothesis (Lovelock & Margulis, 1974) describes Earth's biosphere as a self-regulating system wherein atmospheric, biological, and geological components adjust to maintain life-supporting conditions. Coherence emerges from relational structures distributed across subsystems.

Panarchy theory models ecological systems as nested adaptive cycles (Gunderson & Holling, 2002), integrating local feedback loops conditioned by observer-relative measurements into broader regulatory patterns. Ostrom's framework for commons governance (Ostrom, 2009) formalizes how local observational perspectives contribute to coherent collective management.

In ecological and social systems, multi-agent observational frameworks—such as distributed sensor networks or participatory governance models—make explicit the need to integrate diverse observer perspectives into a coherent whole. Scientific models in these domains rely on formal translation mechanisms that reconcile observer-relative reports into shared, inter-subjective, operationally consistent knowledge.

Observer-Based Relational Multi-Scale and Multi-Agent Integration

Across all domains—quantum systems, biological organisms, social networks, and ecosystems—observers function as embedded agents. Observer-relative facts are systematic structural features of knowledge generation. Relational Quantum Mechanics and Quantum Bayesianism demonstrate this in physics. In social and ecological systems, distributed sensing, participatory governance, and ecological monitoring rely on integrating multiple observer perspectives into intersubjectively valid frameworks (Friston, 2010; Luhmann, 1995; Lovelock & Margulis, 1974; Ostrom, 2009; Gunderson & Holling, 2002).

Formal multi-agent operational models, dynamic epistemic logic (van Benthem, 2011), and algorithmic information theory (Müller, 2017) provide theoretical scaffolding. Embedding observer agency is not optional: it is structurally necessary for coherent modeling across complex adaptive systems. These examples across scales are summarized as follows:

Table 1. Summary of observer types across different scales.

Domain	Type of Observer	Characteristics	Example
Quantum Physics	Quantum System (Rovelli, 1996; Fuchs et al., 2014)	Relational state, observer-dependent	Electron spin measurement
Chemistry	Enzyme, Protein (Friston, 2010)	State adaptation	Protein folding
Biology	Cell, Organism (Knill & Pouget, 2004)	Sensory pathways, Bayesian inference	Immune cell detecting pathogen
Cognitive Domain	Living systems, AI (Friston, 2010; Dodig-Crnkovic, 2011, 2016)	Sensing, reasoning, learning, feedback adaptation	Bacterial quorum sensing, self-driving car updating route
Social	Communication systems	Second-order observations,	Legal system adapting to new laws

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	(Luhmann, 1995)	recursive communication	
Ecological	Ecosystem, Gaia hypothesis (Lovelock & Margulis, 1974)	Self-regulating feedback, dynamic equilibrium	Forest carbon regulation

Informational and Computational Aspects

Integrating multi-scale observer theory with operational-relational physics requires acknowledging both informational (structural) and computational (dynamic) aspects of observation. *Informational aspects* concern the structures generated by observers—objects, categories, and stable representations while *computational aspects* concern the processes through which observers adapt and update these structures via continuous interaction and feedback. Dodig-Crnkovic's (2011, 2016) and (Dodig-Crnkovic & von Haugwitz, 2017), dual-aspect info-computational model captures this balance, illustrating how observers/actors/agents co-create stability and adaptability across organizational levels.

Informational Limits and Algorithmic Information Theory

Algorithmic information theory, as discussed by Müller (2017), proposes that certain physical laws may arise from intrinsic constraints on the informational capacity of observer states. This suggests a possible unification between information theory and physical epistemology, framing the limits of knowledge as conditioned by algorithmic compressibility and observer-dependent state spaces. Müller's proposal emphasizes subtleties in how observer states relate to physical structure, beyond simplified summaries.

This connection between observer theory and algorithmic limits aligns with broader perspectives in complex systems and information science. Observers are not omniscient entities; their knowledge is constrained by both physical embodiment and computational resources. These limits must be formalized within multi-agent, multi-scale models.

Moving beyond compartmentalized scientific domains, observer-based relational epistemology offers a unified lens. Whether in quantum measurement, chemical reaction networks, cognitive systems, or ecological feedback loops, the observer is a necessary structural component shaping both the process and content of knowledge generation.

3. Epistemological Puzzles Solved by Observer-Centric Approach: Quantum Entanglement, and Continuum–Discrete Controversy

While the theoretical value of observer-based epistemology is substantial, its explanatory power becomes especially clear when applied to specific conceptual challenges that have persisted in scientific discourse. Two such cases, quantum entanglement and the discrete–continuous controversy, highlight how relational models offer coherent solutions where traditional, observer-independent frameworks encounter difficulties.

Quantum Entanglement Revisited

Quantum entanglement has long been portrayed as one of the most mysterious aspects of quantum theory, often framed as implying non-local physical connections between distant particles. From an observer-based perspective, however, entanglement reflects structured correlations in the knowledge and information available to observers rather than direct physical links between objects of observation. Relational Quantum Mechanics (Rovelli, 1996; 2021) and Quantum Bayesianism (Fuchs et al., 2014; Von Baeyer, 2016) both interpret entangled states as relative to specific observer interactions and measurements.

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Consider two observers interacting with an entangled system. When one observer measures the spin of a particle, their knowledge about the system updates according to the relational structure defined by conservation laws. A second observer, uninformed of the first measurement, still treats both particles as being in an undetermined superposition. The coherence of these differing accounts is maintained through operational translation rules: when observers compare notes, they find no contradictions. This reframing of entanglement not as a paradox but as an epistemological structure based in observation and measurement resolves longstanding debates over locality and realism in quantum theory (Fuchs et al., 2014; Brukner, 2015).

From the perspective of relational quantum mechanics and Quantum Bayesianism (Fuchs et al., 2014), this interpretation is reframed: entanglement expresses structured correlations in the knowledge and expectations of observers, rather than absolute, observer-independent facts about systems themselves (Rovelli, 1996; Fuchs et al., 2014).

From an information-theoretic perspective, this relational framing connects directly to Shannon's channel capacity theorem. Any noisy interaction—including quantum measurement—can transmit only a finite amount of information about the system in question. While "a finite amount of information" is standard phrasing, this does not imply it must be representable in a finite number of bits. Here, "information" refers to the reduction in the observer's uncertainty about the system — that is, a change in the observer's knowledge, not an intrinsic property of the system itself. This distinction is elaborated by Lee (2017, Chapter 8), who discusses how even continuous measurements convey finite entropy, although they cannot be finitely represented in bits.

Observers are structurally limited in what they can access; entanglement correlations reflect these structured informational constraints rather than an exhaustive description of system properties. This perspective is elaborated in Lee (2017, Chapter 7), where the relationship between continuous and discrete information in the context of Shannon's channel capacity is discussed in depth, emphasizing that relational knowledge is inherently coarse-grained and perspectival.

Discrete–Continuous Duality as an Epistemological Structure

The enduring debate over whether reality is fundamentally discrete or continuous presents a further epistemological puzzle. This question has deep philosophical roots stretching from ancient atomism to modern quantum mechanics and general relativity. In quantum theory, discrete elements such as quantized spin states and energy levels coexist with continuous structures like wavefunctions and probability distributions. Similarly, in cosmology and quantum gravity, questions about the granular structure of spacetime remain unresolved: does space consist of continuous fields or discrete units such as spin networks in Loop Quantum Gravity?

From a relational, observer-based perspective, this duality is reframed as an epistemological question. Observers interact with systems using finite cognitive and physical means, conditioning how information about reality is structured. Discrete and continuous models reflect complementary modes of epistemic structuring: discretization emerges through measurement processes and operational constraints, while continuous models capture relational gradients and probabilities. The puzzle is resolved not by privileging one mode over the other but by recognizing that both arise from observer-relative perspectives embedded in different contexts.

The solution is in the mechanism of observation. In human perception, cognitive science has documented dual modes of perceptual experience, such as temporal segmentation (Pöppel, 1994). Neural oscillation research shows that the human brain alternates between perceiving discrete events and continuous flows, depending on context and attentional demands (VanRullen, 2016). Neurocognitive studies (Lundqvist & Wutz, 2022; Fingelkurts & Fingelkurts, 2006) suggest that switching between these modes is regulated by oscillatory brain rhythms and nonlinear control models (Tyson, 1989). Perceptual cycles segment continuous sensory streams into discrete moments, while integrative background activity supports continuous awareness.

4. Philosophical and Methodological Foundations of Observer-Based Epistemology

Observer-centric frameworks, while offering robust models for epistemology and physics, face persistent philosophical scrutiny. Two central concerns include the tension between instrumentalist interpretations and relational realism, and the challenge of avoiding solipsism while affirming intersubjectivity.

From Universal Objectivity to Structured Intersubjectivity

Historically, observer-dependence has been viewed as a threat to scientific objectivity—a source of unwanted subjectivity or bias. Since early modern science of Descartes and Newton, objectivity was equated with eliminating the physical observer, aspiring to universal laws detached from particular circumstances, reducing the observer to a point of view, Nagel's (1986) "view from nowhere". Kant's Critique of Pure Reason (1781/1998) introduced a more nuanced understanding: objectivity depends not on erasing perspective but on structuring it through universally shared categories of understanding, embedding the observer's role in epistemology.

Relativity theory (Einstein, 1905; 1915) and quantum mechanics made observer-dependence unavoidable. Reichenbach (1958) showed how simultaneity depends on frames of reference, while Nagel (1986) described this as a tension between the "view from nowhere" and perspectival knowledge.

Relational Realism versus Instrumentalism

Although observer-centric frameworks might appear aligned with instrumentalism where theories serve merely as predictive tools without describing reality, operational-relational epistemology instead aligns with relational realism, such as Carlo Rovelli's Relational Quantum Mechanics (1997) and Michela Massimi's (2022) moderate perspectival realism, where relational objectivity is preserved through structured coherence. Observer capacities are framed as structurally embedded features of the world. Data/information /knowledge are intersubjectively structured through causal interactions and relational constraints.

Avoiding Solipsism through Intersubjectivity

A core philosophical challenge is ensuring that observer-relative facts do not devolve into solipsism. Operational-relational frameworks address this through intersubjective translation mechanisms: coherence conditions and shared operational protocols allow independent observers to reconcile differing perspectives into mutually comprehensible knowledge (Fuchs et al., 2014; Brukner, 2015).

In observer-based epistemological frameworks, scientific objectivity does not imply the elimination of observer-dependence. Instead, objectivity emerges through structured relational translation rules that allow different observers to compare, reconcile, and validate their measurements and descriptions. This process is foundational in both theoretical constructs like Relational Quantum Mechanics (Rovelli, 1996; 2021) and Quantum Bayesianism (Fuchs et al., 2014) and broader philosophical perspectives (Von Baeyer, 2016), as well as in broader scientific practice.

Operational-relational epistemology formalizes these translation mechanisms using shared operational protocols and coherence conditions. This principle applies across systems:

In physics, frame-of-reference transformations ensure that observers using different coordinate systems arrive at consistent descriptions of physical phenomena (Brukner, 2015).

In biology and cognitive science, distributed sensing and multi-agent models use shared encoding and decoding schemes to aggregate observer-relative data into collective biological or cognitive states (Friston, 2010).

In social and ecological systems, standardized observation protocols (e.g., ecological monitoring frameworks) enable coherent multi-agent reporting and action despite differing observational perspectives (Luhmann, 1995; Ostrom, 2009).

Perspectives from Contemporary Observer Theories

Stephen Wolfram's recent work (2023) offers a complementary perspective on the observer's role, particularly within his framework of the Wolfram Physics Project and the concept of the ruliad. Wolfram emphasizes that observers are computationally bounded agents who equivalence vast amounts of underlying complexity into reduced, manageable representations. This process is analogous to coarse graining in physics or lossy compression in information theory.

Wolfram proposes that fundamental laws of physics, such as general relativity and quantum mechanics, may emerge from the characteristics of observers, specifically their computational limitations and belief in persistence over time. His observer theory generalizes beyond physical systems, applying equally to mathematical and linguistic domains, *framing observers as systems that extract simplified narratives from complex underlying structures*.

This perspective aligns with operational-relational epistemology by reinforcing the idea that observation is both constrained and constructive. Observers do not merely record pre-existing facts but actively generate coherent perceived realities by reducing and structuring information from the computationally irreducible substrate of the ruliad.

Relational Objectivity as a Foundational Principle

Relational objectivity as a foundational principle builds on earlier insights from cybernetics and second-order systems theory. Maturana's (1988) ontology of the observer emphasizes not only individual observer agency but also the emergence of shared knowledge through linguistic coordination and consensual domains. Von Foerster's work (2003) on self-referential systems complements this view, highlighting that observers are both products and producers of the systems they describe. In short, objectivity arises not from observer-independence but from structured intersubjective processes grounded in language, interaction, and recursive observation.

5. Conclusion

The central claim of this article is that taking observer-dependence seriously in scientific modeling provides conceptual coherence, methodological clarity and philosophical depth across disciplines. From quantum physics to chemistry, biology, cognitive science, and ecology, embedding observer agency as a structural feature helps resolve long-standing logical, methodological, and philosophical problems that static, observer-independent frameworks struggle to address.

Within this observer-based relational epistemology, observers/agents/actors are not conceived as passive or external. They are modeled as embedded, interacting agents—participants in the very systems they help describe. This reflects a broader info-computational perspective, where natural processes across scales are understood as networks of information transformation governed by agent interactions (Dodig-Crnkovic, 2011, 2016) (Dodig-Crnkovic & von Haugwitz, 2017).

Illustrative cases such as quantum entanglement, the discrete–continuous controversy, supramolecular chemistry, and quorum sensing, show that observer-based models do not weaken scientific objectivity understood as inter-subjectivity. On the contrary, they strengthen it by grounding intersubjective coherence in structured operational protocols. Where observer-dependence was once dismissed as incompatible with universal scientific objectivity, it is now recognized as an essential feature: observers are understood as active agents whose interactions with systems determine both the content and validation of knowledge.

Relational epistemology, as articulated through frameworks like Relational Quantum Mechanics, Quantum Bayesianism, and multi-agent systems theory, offers a unifying perspective that bridges traditionally separate scientific and philosophical domains. It challenges naïve realism while avoiding the pitfalls of radical subjectivism, positioning relational realism as a viable and productive approach to knowledge production.

By formalizing observer agency, scientific models gain both greater explanatory power and practical flexibility. Observers are structurally necessary actors within any coherent epistemology. Synthesizing insights from diverse research domains, we advance an observer/actor-based operational-relational epistemology in which agency and perspective are recognized as foundational features of both observation and theory development.

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