



# Information, Relationality, and Thermodynamic Time: Reconstructing Rovelli's Quantum Information Theory

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## Abstract

In classical information theory (represented by Shannon's framework), the study of information transmission typically presupposes a fixed "channel" endowed with absolute attributes. This assumption implicitly holds that the properties of the channel are determinate and observer-independent, remaining unchanged regardless of perspective or the state of the channel itself. However, contemporary physics---particularly the development of quantum mechanics---fundamentally challenges the very notion of "absoluteness." As Carlo Rovelli has emphasized in one of his core arguments, quantum mechanics compels us to abandon the conception of states and properties as "absolute" and "observer-independent." The insistence on such absoluteness is precisely what underlies many of the paradoxes and interpretative difficulties that plague quantum theory. Rovelli extends this general philosophical critique of "absoluteness" consistently into the domain of information theory, thereby provoking a profound re-examination and critique of the classical presupposition of the "absolute channel." From this relational perspective, information should not be conceived as an abstract entity existing independently of physical relations, but rather as an observable measure of relative relations between systems. Accordingly, the reconstruction of classical information theory on the basis of relational ontology---namely, the reconstruction of information theory itself---is not only a demand of theoretical coherence but also a necessary step in responding to the challenge of quantum reality and in building a more universal theory of information.

**Keywords:** Information theory, Relationality, Quantum mechanics, Carlo Rovelli, Thermodynamic time

## 1. Introduction

This paper offers a philosophical analysis of quantum information theory's conceptual foundations rather than presenting new physical results. Our aim is to examine how Rovelli's relational ontology challenges classical epistemological assumptions and its implications for understanding the nature of observation and knowledge.

The United Nations has designated 2025 as the International Year of Quantum Science and Technology, aiming to showcase through global celebrations how quantum theory has

profoundly shaped technological innovation, cultural evolution, and humanity's understanding of nature. In sharp contrast to such large-scale events, however, physicists still remain fundamentally divided over philosophical issues such as the reality of the quantum world (Lalöe, 2012).

Classical physics, rooted in the Western philosophical tradition, upholds that the properties of objects exist inherently, independent of observation. Quantum mechanics, by contrast, reveals that properties are the dynamic result of interactions between measurement contexts and objects. Notably, phenomena such as quantum randomness and entanglement---long subject to suspicion---have now become the central physical resources driving the development of quantum information technology. Over recent decades, concepts once criticized have become indispensable resources in quantum information science.

Against this background, physics is undergoing a profound paradigm shift: from the pursuit of descriptions of absolute objective reality to the exploration of the relational nature of physical systems. This transformation is especially evident in quantum mechanics, where classical assumptions such as "observer independence" and the "absolute channel" reveal their limitations under the challenges posed by quantum nonlocality, the measurement problem, and the thermodynamic arrow of time. Alternative information-theoretic approaches include QBism's agent-centered perspective (Fuchs et al., 2014), Brukner and Zeilinger's foundational information principles (Brukner & Zeilinger, 2009), and Spekkens' epistemic restrictions framework (Spekkens, 2007), each offering distinct ontological commitments. Recent developments have further refined these perspectives, including cross-perspective extensions of RQM (Adlam & Rovelli, 2023), recent reassessments of the current RQM debate (Calosi & Riedel, 2024), and new work on the scope and universality of information thermodynamics (Minagawa et al., 2025).

In 1996, Carlo Rovelli proposed Relational Quantum Mechanics (RQM) (Rovelli, 1996). This theory laid a relational-ontological foundation for quantum theory by redefining information as physical correlations between systems rather than as abstract entities. This interpretive framework philosophically dissolves the measurement problem and reinterprets the long-debated puzzle of time as thermodynamic time, interpreting the arrow of time as the emergent phenomenon of informational asymmetry. In this way, it builds a unified conceptual bridge between quantum mechanics, thermodynamics, and gravitational theory, with the aim of showing that the essence of the world is interaction.

RQM has faced important challenges that must be acknowledged. Frauchiger and Renner (2018) extended the Wigner's friend thought experiment to argue that agents using quantum theory to reason about each other's measurements arrive at contradictory predictions, potentially undermining RQM's self-consistency. Rovelli's response is that the apparent contradiction dissolves once one recognizes that statements made by different observers cannot be simultaneously accessed or verified by any single agent without a physical interaction serving as mediation — cross-observer comparisons are themselves physical events subject to relational description (Di Biagio & Rovelli, 2021).

This paper takes Rovelli's technical reconstruction of quantum information theory as its focus, systematically introducing his core viewpoint---namely that the essence of physical reality is a dynamic network of informational relations (van Fraassen, 2010).

The original contributions of this paper are threefold. First, we offer a synthetic philosophical framework — which we term *informational relationalism* — that integrates Rovelli's relational quantum mechanics, his perspectival account of thermodynamic time, and his quantum gravitational work into a unified conceptual structure. This cross-domain synthesis, and the

identification of informational asymmetry as the common thread, constitutes the primary original contribution. Second, Section 5 provides an original philosophical analysis — explicitly the authors' own extrapolation, not attributable to Rovelli — of how the relational approach may bear on the black hole information paradox and the ER=EPR conjecture. These remain speculative proposals; the section clearly flags where the argument goes beyond Rovelli's published positions and where it engages with conjectural physics. Third, Table 1 is an original comparative synthesis constructed by the authors. The remaining content — including the exposition of the two postulates, the formal sketch in Section 2.3, and the discussion of decoherence — is expository, situating Rovelli's published work within a broader philosophical context, and is clearly attributed throughout.

## 2. Theoretical Framework for Relational Information Theory

### 2.1 Core Concept: Information as Relation

The American engineer Claude Shannon, in his seminal 1948 work, defined information operationally as a measure of the reduction of uncertainty, mathematically tied to probability distributions (Shannon, 1948). While revolutionary for communication engineering, Shannon's framework was philosophically neutral regarding the nature of the "channel" and the "message." It implicitly inherited a classical ontology: information flows through a pre-defined, absolute channel between distinct sender and receiver systems. Today, many scientists, inspired by Wheeler's "it from bit," speculate that "information" may become the key to future advances in physics, serving as a foundational primitive (Wheeler, 1989). Rovelli adopts Shannon's quantitative definition but performs a crucial ontological reframing: information is not something that *flows through* relations but is *constituted by* them. Information measures the capacity of one physical system to communicate with another, and this capacity is *physically manifested* as specific correlations between variables of the interacting systems.

In Relational Quantum Mechanics, Rovelli points out that the persistent "unease" produced by quantum mechanics arises from our deeply ingrained habit of assuming an observer-independent, absolute system state. Such a concept, however, is as invalid at the quantum level as the notion of "absolute simultaneity" was shown to be in special relativity. The core move of RQM is to elevate this relativity from spacetime coordinates to *all* physical properties. Therefore, Rovelli defines information not as a representation of an independent reality but as a *relation* between physical systems---specifically, the information that one system (which can be any physical entity, not necessarily conscious) has about another system. This information is not merely epistemological (about our knowledge) but is physical, instantiated as concrete, measurable correlations (e.g., between a detector's pointer position and a particle's spin).

He emphasizes that any statement about a system's state (e.g., " $q = 1$ ") must be understood as relative to some specific observer. Once we recognize that networks of interactive information exist throughout the universe, it becomes natural to describe the world in terms of informational exchanges.

Table 1: Comparative schematic contrast between classical information theory and Rovelli's relational quantum information theory. The table highlights differences in ontology, state description, measurement, and channel conception; it is an interpretive synthesis by the authors based on Rovelli (1996).

Dimension	Classical Information Theory	Rovelli's Quantum Information Theory
Channel	Absolute, fixed	Relational, dependent on interacting systems
Information Capacity	Infinite, unlimited	Finite, constrained by system interactions and Planck's constant
State Description	Observer-independent, absolute	Observer-dependent, relative to reference system
Ontological Assumption	Information exists independently of relations	Information is a physical correlation between systems
Measurement Perspective	Reveals pre-existing state	Creates relational information through interaction

From Tab.1, it is evident that classical information theory is built upon a metaphysical foundation of absoluteness and independence, inherited from classical physics. Rovelli's quantum information theory, in contrast, is built upon a foundation of relationality and finitude. This shift is not merely technical but ontological. The "absolute channel" presupposes a fixed stage, while the "relational channel" implies that the stage itself emerges from the actors' interactions. This fundamental difference in starting points constitutes the logical and philosophical bedrock for Rovelli's proposal of the *two basic postulates*, which serve as the axioms for his reconstruction.

## 2.2 Two Basic Postulates

Postulate 1 (Limited information): The amount of relevant information that can be extracted from a system is finite. This postulate directly confronts the classical ideal of infinite precision. It implies that the complete description of a quantum state is not just practically but *principally* constrained by the system's finite information capacity. This finiteness is not arbitrary; it is quantitatively linked to Planck's constant  $\hbar$ , which sets the fundamental scale of action. "Relevant information" is defined operationally: it is the information we possess about a system, acquired through past interactions, which enables us to predict the outcomes of *future* interactions with it. This captures the core discreteness of quantum mechanics---for any given degree of freedom (like spin along an axis), only a finite set of possibilities (e.g., up or down) can be distinguished, corresponding to a finite number of bits. This is experimentally manifested in quantized measurements and the resolution limits implied by the uncertainty principle.

Postulate 2 (Unlimited questions): It is always possible to obtain new information about a system. This postulate injects openness and indeterminism into the framework. It asserts that the quantum-mechanical description is inherently incomplete for any single observer/system pair. There always exist alternative experimental questions (incompatible observables) that can be asked, the answers to which may reveal entirely new information. Crucially, asking these new questions (performing new measurements) is not a passive reading but an interactive process that can make previous information *irrelevant*---it no longer helps predict the future state relative to the new context. This is the informational essence of quantum non-commutativity.

The interplay of these postulates is key. When new information is obtained (Postulate 2), Postulate 1 enforces that the total stock of *relevant* information cannot balloon indefinitely. Therefore, gaining new information often necessitates the *erasure* or obsolescence of old information. This dynamic process of information acquisition and displacement is at the heart of quantum state update upon measurement. Rovelli argues that much of the formal structure of quantum mechanics---superposition, complementarity, the probability rules---can be seen as logical consequences of these two simple, physically motivated principles. The theory thus naturally admits an expression in the language of information, not as an add-on but as its core logic.

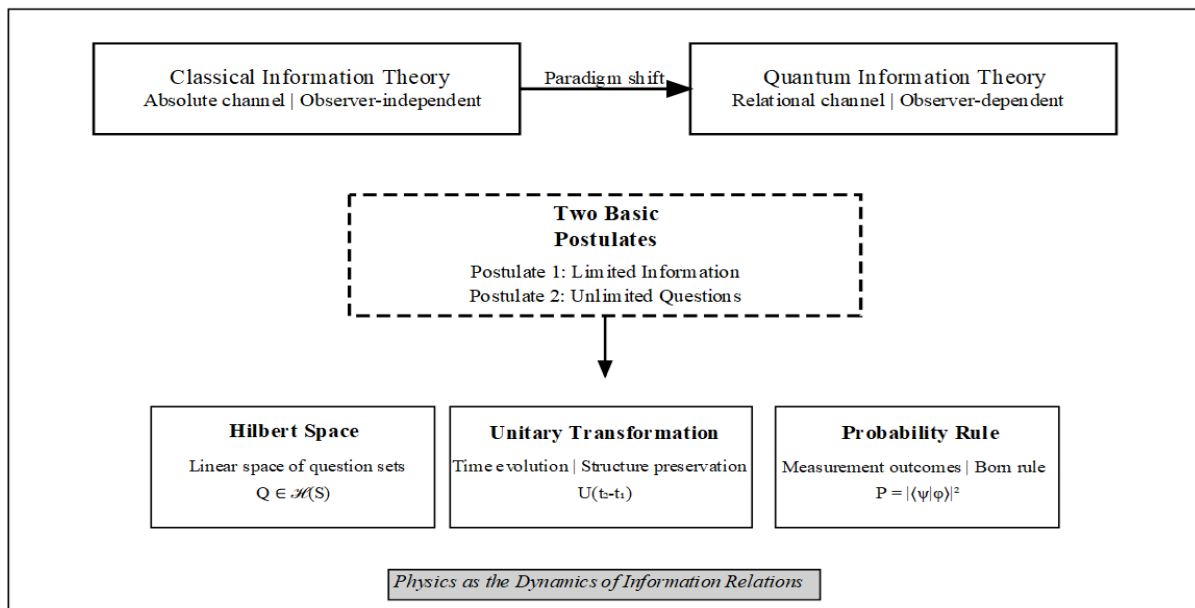


Figure 1: Conceptual roadmap of the relational reconstruction. The figure summarizes the argumentative role of the two postulates—finite information and unlimited questions—in motivating, at a schematic level, Hilbert-space structure, unitary evolution, and probabilistic assignment. It is intended as a conceptual map rather than a formal derivation.

Fig.1 illustrates the paradigm shift: starting from the relational postulates of finite information (P1) and unlimited questions (P2), combined with information-theoretic concepts, one can derive the abstract space of questions ( $\mathcal{H}(S)$ ), which is shown to possess the structure of a Hilbert space. Unitary transformations emerge as symmetries of this question structure over time, and the Born rule arises as the rule for assigning probabilities to answers, given a specific informational context.

It is worth noting the relationship between RQM and the Pusey–Barrett–Rudolph (PBR) theorem (Pusey et al., 2012), which constrains epistemic interpretations of the quantum state by showing that any theory in which quantum states represent mere subjective probability distributions leads to empirical contradictions. RQM is not straightforwardly a  $\psi$ -epistemic theory in the PBR sense: it does not claim that the quantum state is a classical probability distribution over hidden variables. Rather, RQM holds that quantum states possess a form of 'relational reality' — they are real relative to a given observer-system interaction. Laudisa (2019) provides a detailed analysis confirming that RQM's ontology is compatible with the constraints imposed by the PBR theorem.

### 2.3 Consistency of Quantum Formalism with Relational Postulates

This section does not attempt a formal derivation of quantum mechanics from the two postulates. Such a derivation requires additional mathematical assumptions and has been

pursued elsewhere (Hardy, 2001; Dakić & Brukner, 2011). Our aim here is more limited: to indicate how Hilbert-space structure, unitary evolution, and the Born rule can be conceptually motivated as consistent with the relational information-theoretic principles articulated in Postulates 1 and 2.

First, Postulate 1 implies that the amount of relevant information obtainable from a system is finite. At the conceptual level, this supports a non-classical state description in which elementary systems are represented not by infinitely precise classical states, but by structured sets of limited informational alternatives. In this sense, Hilbert-space formalism may be understood as an appropriate mathematical framework for representing finite, observer-relative informational distinctions.

Second, if information is constituted by correlations established in physical interaction, then temporal evolution must preserve the structural relations among possible questions and answers. This provides the conceptual motivation for unitary evolution: the formalism must conserve internal consistency and probabilistic normalization while relating different informational contexts over time.

Third, measurement probabilities must connect prior information with future possible outcomes without reintroducing an observer-independent absolute state. Within this roadmap, the Born rule functions as the rule that assigns probabilities to answers relative to a given informational context. Different observers may assign different states or probabilities because these are indexed to different physical interactions, but the formal probabilistic structure remains the same.

Accordingly, the claim made here is deliberately modest. We do not derive quantum mechanics from the two postulates alone; rather, we argue that Hilbert-space structure, unitarity, and the Born rule are conceptually compatible with Rovelli's relational postulates and can be motivated within an information-theoretic reading of quantum theory. Readers seeking rigorous reconstructions are referred to Hardy (2001) and Dakić and Brukner (2011).

### 3. Results: The Relational Toolkit and Its Implications

#### 3.1 Relational Encoding, Coarse-Graining, and Quantum Entropy

Rovelli places information at the core of quantum mechanics. To say "system S possesses information about system Q" means there exists a physical correlation between their states. In the modern language of quantum information, this is akin to saying S and Q share (classical or quantum) correlation, quantified by mutual information. Rovelli uses Shannon's framework but reinterprets it: the information an observer O has about a system S is the set of correlations between O's variables and S's variables established through past interactions. This information is encoded in the *relative state* of S with respect to O. In quantum computing terms, the state of a qubit is never "absolute"; its meaning ( $|0\rangle$  or  $|1\rangle$ ) is always defined relative to a chosen basis, which corresponds to a specific measurement apparatus (the "observer" in RQM).

A pivotal technical tool in this framework is *coarse-graining*. In statistical mechanics, coarse-graining is the deliberate ignoring of microscopic degrees of freedom to define macroscopic variables like temperature and pressure. Rovelli generalizes this concept quantum-information-theoretically. Here, coarse-graining corresponds to *restricting attention to a subsystem*. When we focus only on subsystem A of a larger system (A+B), we are effectively ignoring (tracing over) the degrees of freedom of B. Even if the global state of (A+B) is pure (zero von Neumann entropy), the state of A alone, described by its reduced density matrix  $\rho_A = \text{Tr}_B(\rho_{AB})$ , is generally mixed.

This leads to a uniquely quantum source of entropy: *entanglement entropy*. If A and B are entangled, then ignoring B results in a loss of information about A's correlations, rendering A's state uncertain. This uncertainty is quantified by the von Neumann entropy of the reduced density matrix:

$$S = -\text{Tr}[\rho \log \rho] \quad (1)$$

This entropy is purely quantum; it exists even in the absence of any classical ignorance or thermal disorder. Rovelli emphasizes that this quantum coarse-graining---choosing a subsystem and its associated observables---is not just a calculational tool but a fundamental physical act that defines a perspective. Different ways of partitioning a universe (different choices of "subsystem A") yield different entropy profiles over time.

Rovelli's central insight, linking this to thermodynamics, is the conjecture that for any sufficiently complex, interacting quantum system, *there exist natural subsystem decompositions whose associated entanglement entropy increases monotonically in one time direction* (Rovelli, 2017). This increase defines a local, perspectival arrow of time that aligns with the thermodynamic arrow. The "low-entropy past" is then the past where, relative to our chosen coarse-graining (e.g., the degrees of freedom relevant to life on Earth), the relevant subsystems were less entangled. Recent developments in quantum thermodynamics (Goold et al., 2016; Huber et al., 2015) provide complementary perspectives on information-entropy relations in quantum systems.

#### Example 1: Coarse-Graining and Thermodynamic Entropy

Consider a two-qubit system in the entangled state:

$$|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \quad (2)$$

Observer A (coarse-grained): Tracks only total spin, ignoring individual spins. The reduced density matrix is:

$$\rho_A = \text{Tr}_B(|\Psi\rangle\langle\Psi|_{AB}) = \frac{1}{2}(|0\rangle\langle 0| + |1\rangle\langle 1|) \quad (3)$$

Thermodynamic entropy:

$$S_A = -\text{Tr}(\rho_A \log \rho_A) = \log 2 = 1 \text{ bit} \quad (4)$$

Observer B (fine-grained): Has access to the full pure state  $|\Psi\rangle_{AB}$ , so  $S_B = 0$ .

This demonstrates how coarse-graining creates thermodynamic entropy for observer A, while the global state remains pure.

#### Example 2: Perspectival Entropy in EPR Systems

Consider three particles in a GHZ state:

$$|\Psi\rangle_{ABC} = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle) \quad (5)$$

Observer  $O_1$  (accesses particles A and B only):

$$\rho_{AB} = \text{Tr}_C(|\Psi\rangle\langle\Psi|_{ABC}) = \frac{1}{2}(|00\rangle\langle 00| + |11\rangle\langle 11|) \quad (6)$$

$$S_{O_1} = -\text{Tr}(\rho_{AB} \log \rho_{AB}) = 1 \text{ bit} \quad (7)$$

Observer  $O_2$ (accesses all three particles): Has the complete pure state, so  $S_{O_2} = 0$ .

Observer  $O_3$ (accesses particle C only):

$$\rho_C = \text{Tr}_{AB}(|\Psi\rangle\langle\Psi|_{ABC}) = \frac{1}{2}(|0\rangle\langle 0| + |1\rangle\langle 1|) \quad (8)$$

$$S_{O_3} = -\text{Tr}(\rho_C \log \rho_C) = 1 \text{ bit} \quad (9)$$

This illustrates that entropy depends on the observer-system partition, not absolute properties.

### 3.2 Decoherence as Information Localization and Delocalization

The process of decoherence, a cornerstone of modern quantum foundations, receives a clear informational reinterpretation within RQM. Decoherence explains how quantum superpositions in a system (S) are rapidly suppressed through interaction with an environment (E). In Rovelli's terms, this is a process of *information localization and delocalization*. When S interacts with E, information about S's state (e.g., which path in a superposition it is in) is not destroyed; instead, it becomes *encoded in the correlations* between S and the myriad degrees of freedom of E. From the perspective of an observer who only has access to S (another form of coarse-graining), this information is effectively lost---it is delocalized into the environment and becomes practically unrecoverable. This loss of *local* accessibility of information manifests as the disappearance of interference terms (decoherence) and the emergence of classical, probabilistic behavior for S alone.

This connects directly to **Postulate 1 (Limited information)**. An observer localized in space and time has finite information capacity and can only monitor a finite number of degrees of freedom. They cannot track the exact quantum state of a vast environment. Therefore, for such an observer, the information that has leaked into E becomes irrelevant for predicting S's future behavior, effectively erasing quantum coherence. Planck's constant  $\hbar$  enters by setting the scale at which this information exchange becomes significant---it quantizes the phase space, meaning that complete, infinite-precision localization of a system's state (a point in classical phase space) would require infinite information, which is forbidden. This perspective complements Zurek's quantum Darwinism, where preferred observables emerge through environmental interaction (Zurek, 2001), though Rovelli emphasizes the relational rather than selective nature of this process.

## 4. Discussion: The Informational Arrow of Time and Quantum Gravity

### 4.1 Thermodynamic Time from Informational Asymmetry

Rovelli offers a quantum informational interpretation that "thermodynamic time arises from the asymmetry of information." Quantum phenomena provide a distinct source of entropy---entanglement entropy. He notes that a system (e.g., the biosphere) exploits information asymmetries through interactions with its environment (e.g., electromagnetic radiation), harnessing entropy increase to build complexity, manifesting time's directionality.

Rovelli discusses David Albert's perspective: given a universal evolving state  $\Psi(t)$ , a decomposition into subsystems exists such that von Neumann entropy is zero initially and increases over time. Entropy growth and decay depend on how we partition the universe, not on the global state itself (Albert, 1992). The growth of von Neumann entropy is a manifestation of asymmetry in information distribution among subsystems. When a quantum system becomes entangled, information is shared asymmetrically, increasing entanglement entropy. The observed entropy growth defining the arrow of time emerges from specific subsystem decompositions (coarse-grainings), providing a quantum informational explanation of thermodynamic time.

Seth Lloyd's work on quantum time travel through post-selected teleportation supports this view (Lloyd et al., 2011). Lloyd showed that entanglement could connect forward and backward segments of time, with post-selection establishing a quantum channel to the past. Lloyd proved, through asymmetry of quantum channel capacity, that the essence of the arrow of time lies in the initial state of the universe imposing directional constraints on quantum information transfer, supporting Rovelli's claim that "thermodynamic time originates from informational asymmetry."

This informational interpretation of thermodynamic time is technically grounded by the thermal time hypothesis of Connes and Rovelli (1994). Working within the algebraic formulation of quantum field theory, they propose that physical time flow is not a fundamental feature of the world but emerges as the modular flow associated with a KMS thermal state — a state describing a system in thermal equilibrium. In this framework, the notion of 'temperature' and 'time' become deeply intertwined: time is the flow generated by the thermal state itself. This provides a precise mathematical realization of the claim, central to this paper, that thermodynamic time arises from informational asymmetry rather than from a fundamental time parameter in the laws of physics (Martinetti & Rovelli, 2003).

#### 4.2 The Low-Entropy Initial State

Rovelli emphasizes the universe's low-entropy initial state is crucial for the arrow of time. From an informational perspective, this beginning is the necessary condition for recording and preserving information. A high-entropy initial state would permit no discernible distinctions, no concept of the "past," and no possibility for memory or learning. The existence of information-acquiring organisms requires a low-entropy initial condition to drive evolution, learning, and information accumulation. This view contrasts with Price's symmetry-based analysis (Price, 1996) and Barbour's timeless formulation (Barbour, 2001), while sharing common ground with Carroll's cosmological approach to time's arrow (Carroll, 2010).

Thus, the informational significance of the low-entropy initial state lies in its role as the foundation for informational order, memory formation, and complex system evolution---prerequisites for our perception of the arrow of time.

Table 2. Information-theoretic mechanisms associated with the emergence of the arrow of time. The table summarizes how radiation flow, biological coarse-graining, entanglement, memory formation, and decoherence contribute to entropy increase and temporal asymmetry in the relational framework, based on Rovelli (2017).

Physical Process	Information-Theoretic Description	Entropy Change	Manifestation of Time Directionality
Solar Radiation Input	High-frequency photons (low entropy) $E/h\nu_1$ photons	$S_1 = k \log N_1$ (input entropy)	Ordered energy input
Biological Processing	Coarse-graining operations, ignoring micro details	$\Delta S > 0$ (entropy production)	Irreversible process
Earth Radiation Output	Low-frequency photons (high entropy) $E/h\nu_2$ photons	$S_2 = k \log N_2, S_2 > S_1$	Disordered energy output
Quantum Entanglement	Subsystem entanglement $ \psi\rangle \neq  \psi_1\rangle \otimes  \psi_2\rangle$	$S_{ent} = -Tr[\rho \log \rho]$ (entanglement entropy)	Localization of quantum information
Memory Formation	Establishment of correlations $I(past : present) > 0$	Local reduction, global increase	Past-future asymmetry
Decoherence	Information spreading into environment, loss of phase coherence	$S_{environment}$ increases	Emergence of classical behavior

As shown in Tab.2, whether energy flow, life processes, or quantum evolution, their common feature is that acquisition and loss of information are accompanied by unidirectional entropy

growth, the root of the arrow of time. Time is therefore a macroscopic manifestation of information dynamics.

## 5. Information in Quantum Gravity

### 5.1 Relational Resolution of the Black Hole Information Paradox

The analysis in this section represents the authors' own philosophical extrapolation of Rovelli's relational framework to the black hole information paradox and the ER=EPR conjecture. These interpretations go beyond Rovelli's own published statements and should be read as speculative philosophical proposals rather than established results. Competing approaches to the information paradox remain actively debated (see below), and no resolution currently commands consensus. The black hole information paradox arises because Hawking radiation suggests information loss, contradicting quantum unitarity. Rovelli's relational approach offers one possible resolution: information may be encoded in the correlation between Hawking radiation and the black hole horizon. In loop quantum gravity, the horizon consists of discrete "quanta of space"; infalling matter changes their arrangement, potentially encoding information. Radiation particles are entangled with horizon quanta, forming mutual information. Although an external observer cannot recover information from radiation or horizon alone, their correlation may preserve it. However, this remains a speculative proposal competing with other approaches including the AMPS firewall hypothesis (Almheiri et al., 2013), island formula methods addressing the Page curve (Penington, 2020; Almheiri et al., 2019, 2020; Penington et al., 2022), soft hair mechanisms (Hawking et al., 2016), black hole complementarity (Susskind et al., 1993), and fuzzball proposals (Mathur, 2005).

Eugenio Bianchi's calculations from loop quantum gravity derive the Hawking radiation formula, showing entropy proportional to horizon area, suggesting black hole entropy may originate from microscopic degrees of freedom (Bianchi, 2012). Within this framework, information is transformed into correlation between horizon quantum states and Hawking radiation, potentially conserved through their entangled mutual-information network.

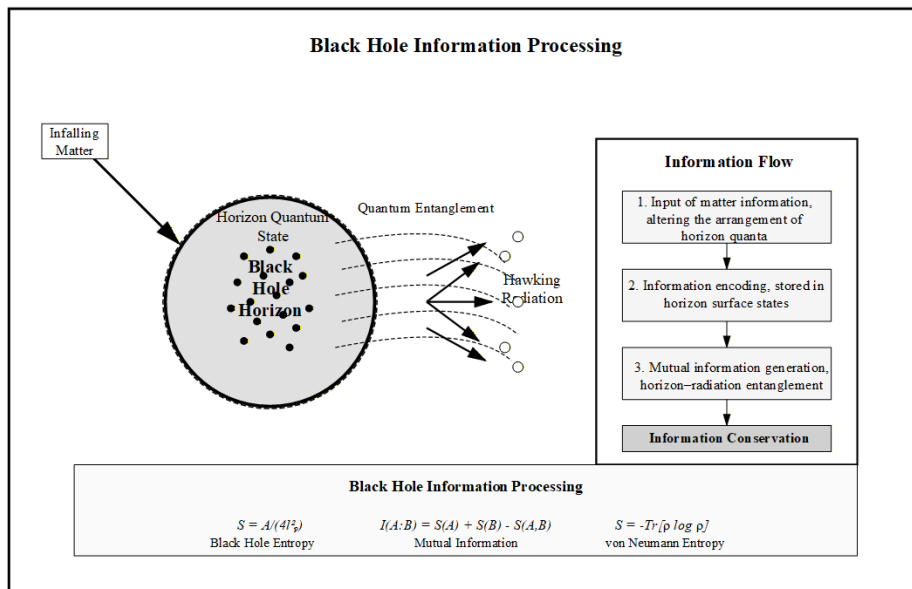


Fig 2. Schematic relational redescription of the black hole information problem. The figure illustrates the interpretive proposal that information carried by infalling matter may be re-described as encoded in correlations between Hawking radiation and horizon degrees of freedom; it is not intended as a complete physical mechanism.

Fig.2 depicts the relational resolution. Infalling matter (information I) interacts with the quantized horizon, changing its microscopic state ( $H \rightarrow H'$ ). The emitted Hawking radiation

(R) is entangled with the new horizon state H'. The original information I is now encoded in the correlation (mutual information) between R and H'. For an observer who could in principle access both R and relevant remnants of H', information would not obviously be destroyed at the level of the relational description, although no concrete recovery mechanism is established here. The paradox arises from assuming a single description valid for both external and infalling observers independently of their relational context.

Important caveats remain: the precise mechanism for information retrieval is not fully understood, and the mathematical relationship between entanglement structure and horizon geometry requires further development. Alternative perspectives on the information paradox continue to be actively debated in the quantum gravity community. The philosophical stake of this relational reformulation is not to replace current physical programs, but to clarify what counts as "information preservation" once observer-independence is no longer assumed at the outset.

### 6. The Informational Origin of Spacetime Geometry

Rovelli explores the relationship between quantum entanglement and spacetime metric, connecting to Maldacena and Susskind's ER=EPR conjecture. This conjecture proposes that geometric properties like area and curvature may originate from macroscopic manifestations of quantum information arrangement. The entanglement network's topology may determine spacetime causality and connectivity.

The ER=EPR conjecture — a speculative but influential proposal lacking formal proof (Maldacena & Susskind, 2013) — proposes that spacetime geometry is not fundamental but emerges from quantum informational correlation networks. In loop quantum gravity, space comprises discrete "space quanta"; geometric properties may represent macroscopic manifestations of quantum information arrangement. Causal structure and metric properties may arise from mutual information correlations. According to this conjecture, quantum entanglement has been proposed to correspond, in a still highly speculative sense, to geometric connectivity through ER bridges (Maldacena & Susskind, 2013).

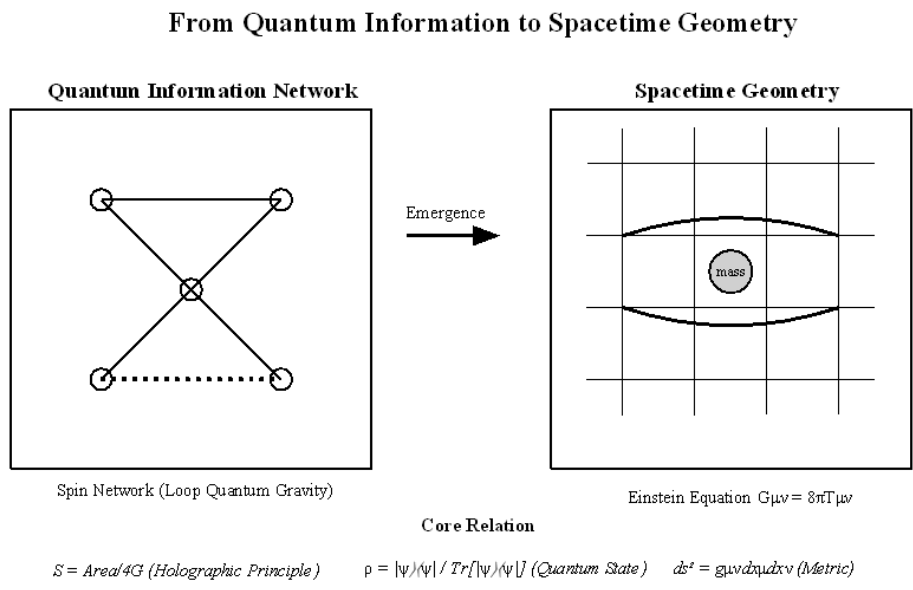


Fig 3. Schematic illustration of a possible informational reading of emergent spacetime. The left panel represents an underlying network of quantum informational relations, while the right panel depicts the coarse-grained appearance of smooth spacetime geometry. The figure is heuristic and philosophical rather than formally derivational.

The relational approach to the black hole paradox aligns with this view: infalling matter information may be preserved through the entanglement network of horizon quanta and radiation. Within this interpretive framework, spacetime geometry might be philosophically understood as a dynamic projection of cosmic-scale information exchange, its metric potentially defined by correlation strength and range. This perspective raises the philosophical possibility that spacetime geometry may emerge from quantum-informational correlation networks; however, the relevant mathematical and physical mechanisms remain open questions (Hawking, 1976).

Fig.3 visualizes the emergence hypothesis. The fundamental reality is a dynamic network of quantum informational relations (left), akin to a constantly evolving spin network with entangled nodes. At a macroscopic scale, when we coarse-grain over these microscopic details, the statistical properties of this network—the average connectivity, the density of links—are perceived as smooth spacetime geometry with metrics and curvature (right). Spacetime is not a container but a derived, thermodynamic picture of informational relations. Alternative frameworks, including Jacobson's thermodynamic gravity and Verlinde's entropic gravity, offer different perspectives on this emergence, though the precise mechanism remains an open research question.

## 7. Conclusion: Physics as the Dynamics of Information Relations

Rovelli's framework interprets physics as the dynamics of information relations between systems. Physics describes the information systems possess about each other, and this information is relative: "the value of a physical quantity is relative to a reference system." Time evolution is described by unitary transformation  $U(t_2 - t_1)$  — the "dynamics of the structure of the set of questions about the system." Thus, quantum mechanics formalizes the dynamical evolution of information relations, emphasizing both the relativity of physical description and the central role of information.

Beyond physics, relational ontology carries implications for epistemology and STS. RQM reconceives measurement as a physical interaction that *constitutes* a relational fact rather than revealing a pre-existing state — resonating with Barad's (2007) "intra-action," in which apparatus and object co-produce the phenomenon. Classical objectivity demands observer-independence; relational objectivity, by contrast, grounds intersubjective agreement in physical interaction itself (Di Biagio & Rovelli, 2021), offering a defensible objectivity without a "view from nowhere." For quantum technology research, this implies that apparatus design is never neutral: it selects a relational context and determines which correlations become manifest. This broader relational emphasis also resonates with recent STS discussions of experimental ontology and situated modelling, which likewise treat knowledge practices as materially mediated and relationally constituted (Braun, 2024; Klein et al., 2024).

Rovelli links information flow, time, and thermodynamics: the biosphere's coarse-graining of solar energy defines an entropy whose increase drives organization and creates a local arrow of time, while quantum entanglement contributes a further entropic source from informational distribution across subsystems. Ultimately, the arrow of time we perceive may be determined by how we, as particular subsystems, interact informationally with the universe — through coarse-graining and coupling — rather than by any globally privileged initial condition.

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