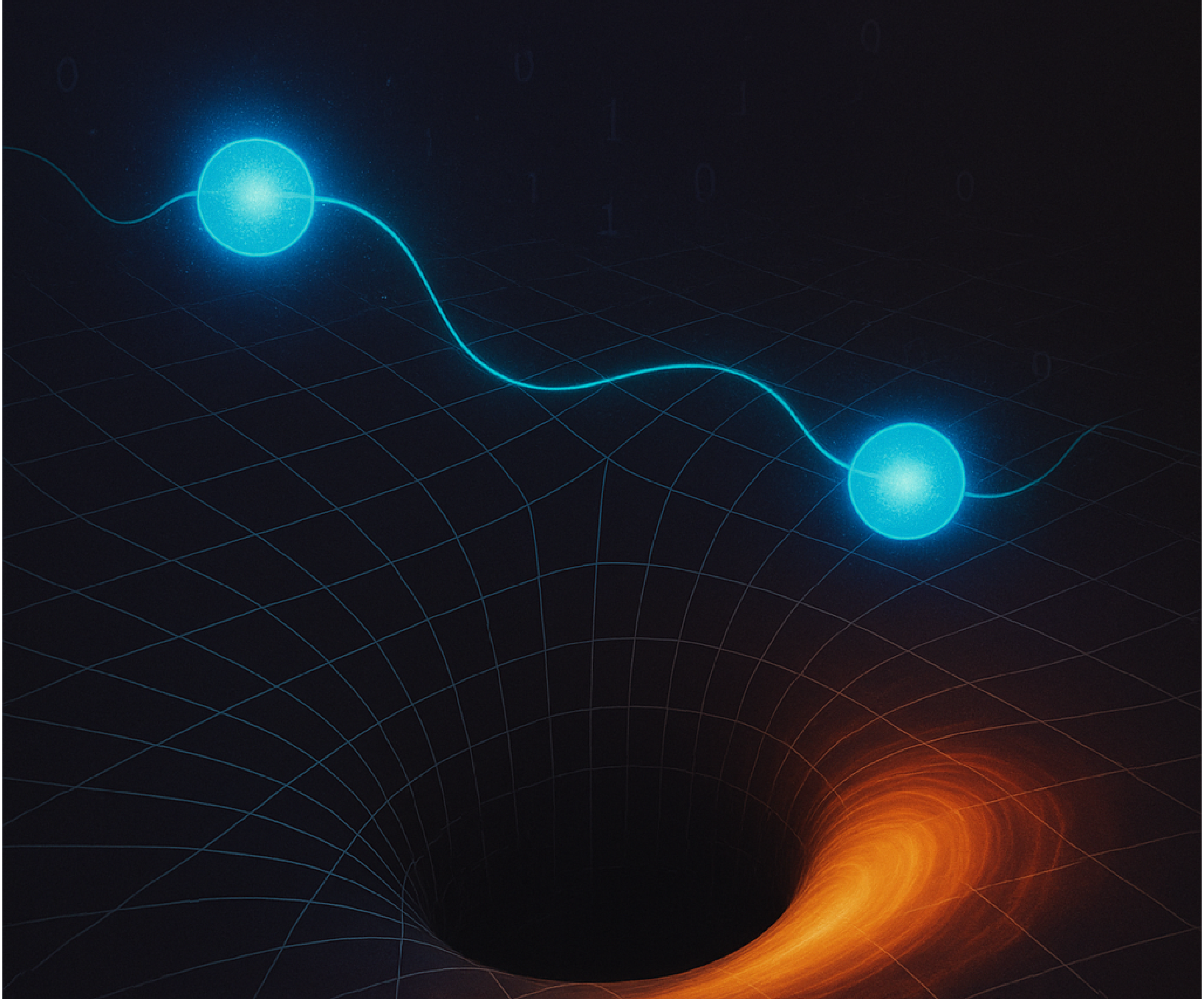
QUANTUM INFORMATION, ENTROPY, AND ENTANGLEMENT IN BLACK HOLE PHYSICS

M.Sc. RESEARCH THESIS



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Quantum Information, Entropy and Entanglement in Black Hole Physics

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पटना विश्वविद्यालय
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M.Sc. Research Thesis

Submitted To

Department of Physics, Patna University

Declaration

We, **Alok Kr. Nirala** and **Suruchi Kumari**, hereby declare that this research thesis entitled **"Quantum Information, Entropy and Entanglement in Black Hole Physics"** has been prepared by us on the basis of original research carried out during the course of our fourth semester of M.Sc. Physics programme under the supervision of **Dr. Sumita Singh**, Professor & Head, and **Dr. Ashok Kumar Jha**, Assistant Professor, Department of Physics, Patna University.

This research thesis is our bona fide work and has not been submitted in any form to any University or Institute for the award of any degree or diploma prior to the date mentioned below. We bear full responsibility for the content and submission of this thesis.

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Certificate

This is to certify that **Alok Kr. Nirala (Roll No. 40)** and **Suruchi Kumari (Roll No. 11)**, students of M.Sc. Physics 4^{th} Semester, Department of Physics, Patna University, have prepared the research thesis entitled **"Quantum Information, Entropy and Entanglement in Black Hole Physics"** in partial fulfillment of the requirements for the degree of Master of Science in Physics for the academic session 2023–2025.

This thesis is based on original research work undertaken by the students under our supervision during the fourth semester and fulfills the academic standards and regulations prescribed by Patna University.

We recommend that this thesis may be accepted for evaluation.

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Abstract

This project develops a non-geometric framework for black hole physics by rejecting the existence of spacetime geometry as a fundamental structure independent of the observer. It interprets the emergence of geometric features as a byproduct of memory and comparison between informational states within finite time intervals. Entropy is redefined as a measure of accessible uncertainty shaped by the observer's record, rather than as a geometric quantity. The black hole information paradox is resolved by discarding the notion of objective information loss across the horizon and instead understanding evaporation as an update in the observer's informational context.

Three original computational models substantiate this framework: Model 1 captures entropy growth through internal decoherence and coherence disintegration; Model 2 models entropy dynamics as conditioned by observer-dependent informational access; Model 3 simulates nonlocal scrambling of mutual information without invoking geometric transport. These simulations demonstrate that black hole evaporation and information recovery can be consistently explained through observer-relative informational transitions.

This perspective offers a coherent foundation where evolution, entropy, physical structures and known interactions emerge from information-theoretic constraints, without invoking underlying geometric assumptions.

KEYWORDS

Black Holes, Spacetime, Geometry, Gravity, Singularity, Entanglement, Entropy, Information Paradox, Observer, Reality

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-Alok Kr. Nirala
-Suruchi Kumari

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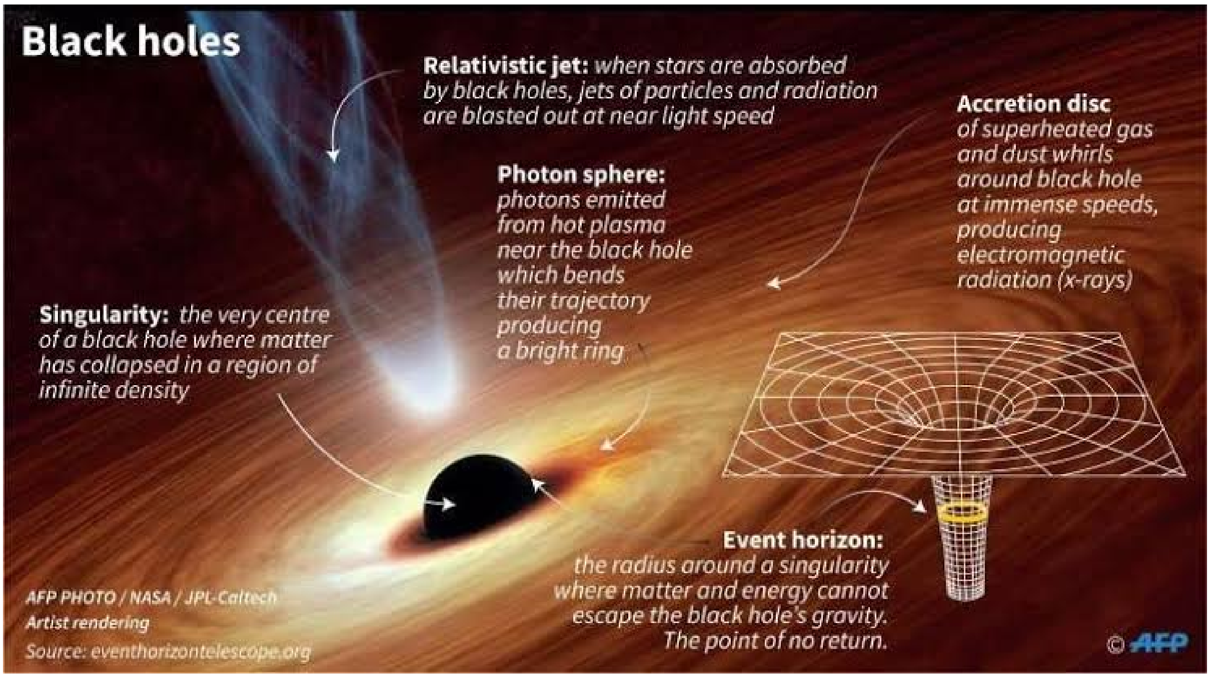
Introduction



In general relativity, black holes arise as exact solutions of Einstein's field equations under strong gravitational collapse. These solutions describe regions from which no signal can escape, bounded by event horizons and ending at a singularity. The nature of this singular structure remained ambiguous until the mid-20th century. In the 1960s and 70s, work by Penrose, Hawking, and others showed that singularities were not merely coordinate-dependent, but inevitable under broad physical conditions. These developments formalized the idea of gravitational collapse, leading to the notion that black holes represent real astrophysical endpoints of massive stars. With this understanding, black holes became not just theoretical solutions but physical objects with causal structure defined by event horizons. Yet these developments were still embedded in a classical setting, where quantum effects played no role. The framework described what happens to geometry under extreme curvature but remained silent about the behavior of quantum fields near or beyond the horizon. This limitation began to shift with the work of Bekenstein, who proposed in the early 1970s that black holes should possess entropy proportional to their surface area. He was motivated by the observation that black holes appear to satisfy analogues of the four laws of thermodynamics, including versions of energy conservation and non-decreasing area. This area-entropy association challenged the purely geometric description of black holes. If entropy is a measure of inaccessible microstates, then the horizon must encode physical degrees of freedom — a concept absent in classical general relativity. In 1974, Hawking extended this line of thought by showingthat quantum fields in a curved background cause black holes to emit thermal radiation with a temperature inversely related to their mass. This result, derived using semiclassical techniques, unified gravitational collapse, thermodynamics, and quantum field theory — but also introduced severe tension. Hawking's calculation implied that black holes evaporate over time, radiating energy and shrinking until they potentially disappear. If the radiation is purely thermal, it carries no memory of the matter that fell into the black hole. This conclusion contradicts quantum mechanics, where information is preserved under unitary evolution. The contradiction between black hole evaporation and unitarity came to be known as the information paradox, which remains unresolved in conventional theories. Subsequent attempts to address this paradox took different directions. In string theory, certain classes of black holes were modeled in higher-dimensional setups with super symmetry, enabling microscopic state counting that agreed with the Bekenstein-Hawking entropy. However, these constructions relied heavily on idealized boundary conditions and did not capture the real-time dynamics of evaporating black holes. Loop quantum gravity introduced quantized area operators and horizon microstates, offering potential explanations for entropy, but encountered difficulties in treating radiation and information retrieval. By the early 2000s, increasing attention turned to the role of entanglement in black hole entropy. Calculations showed that quantum fields near horizons exhibit strong correlations across the boundary, contributing divergent entanglement entropy proportional to area. This observation hinted at a new picture: entropy may arise from partitioning a global quantum system into accessible and inaccessible regions. In such a view, spacetime geometry is not the source of entropy, but a coarse-grained result of informational division. At the same time, holographic principles emerged, asserting that the degrees of freedom of a volume can be encoded on its boundary. Originally motivated by black hole thermodynamics, this idea gained further structure through the AdS/CFT correspondence, where a gravitational theory in anti-de Sitter space is equivalent to a quantum field theory on the boundary. This correspondence suggests that gravity itself may be an emergent phenomenon, derived from an underlying theory of quantum information and entanglement. These developments point toward a shift in perspective. Instead of building quantum theories on top of classical geometrical frameworks, it may be necessary to invert the relationship: geometry, thermality, and even gravitational force may arise from deeper informational processes. Black holes, in this framework, are not singularities embedded in a spacetime manifold, but manifestations of how information is distributed, restricted, or transformed across time intervals. Their thermodynamic behavior reflects not a geometric surface, but the observer's inability to access or reconstruct certain correlations. This historical trajectory, from purely classical to semiclassical and now toward an informational perspective, provides the basis for this project. The existing frameworks capture fragments of black hole behavior but fall short of explaining the full picture, particularly in regimes where geometry itself becomes ill-defined. What is needed is a model where entropy, entanglement, and quantum information are treated not as consequences of spacetime, but as its foundation.

1.1 Objectives

1. To replace the classical geometrical description of black holes with an informational framework where quantum information, entropy, and entanglement are the primary constructs.
2. To reinterpret the Bekenstein-Hawking entropy formula not as an outcome of classical horizon geometry but as a reflection of bounded information accessible to an external observer.
3. To reconstruct the mechanism of Hawking radiation as a result of entanglement dynamics across an informational boundary rather than a particle tunneling process in a curved metric background.
4. To critically analyze the nature of black hole singularities, proposing that singularities signify the failure of emergent geometry, not of physical laws, and to model this transition from geometric to pre-geometric informational states.
5. To investigate the connection between entanglement entropy and spacetime curvature, examining whether gravitational dynamics can be derived from the structure of entanglement alone.
6. To simulate simple models of quantum information flow across horizons and quantify entropy and temperature behavior in a geometry-free framework, verifying consistency with expected black hole thermodynamics.
7. To provide a unified theoretical narrative that can serve as a stepping stone toward reimagining black holes, spacetime, and gravity as large-scale approximations of deeper informational laws.

In pursuing these objectives, this project does not aim to merely adjust General Relativity or Quantum Field Theory at their margins. Instead, it reconstructs the foundation: treating spacetime, gravity, entropy, and radiation as consequences of a deeper informational substrate. The entire approach is based on the recognition that extreme gravitational systems are not a test of geometric continuity, but a test of the very assumptions underlying our concepts of reality. In the coming sections, we will gradually build this framework, challenge the standard assumptions, and develop mathematical tools aligned with these insights.

1.2 Methodology

The development of this research has followed a layered approach, integrating critical reanalysis of black hole thermodynamics, quantum information theory, and observer-centered frameworks. We have avoided conventional geometrical presuppositions and replaced them with a strictly informational interpretation. The methodology operates on the understanding that entropy, time, and structure arise not from spacetime geometry but from observer-conditioned correlations within quantum systems.

Instead of treating the information paradox as a geometrically bounded problem, we approach it from the perspective of abstract information dynamics, with the observer playing an integral role in the determination and manifestation of reality. This has led to the construction of a generalized informational field framework in which the four fundamental interactions and the internal states of black holes are described as emergent consequences of time-evolving, observer-accessible informational structures.

To support and test this framework, three original computational models were designed and simulated:

Internal Decoherence and Coherence Collapse simulates the transition of pure quantum states within a black hole to increasingly decohered subsystems, tracking entropy growth as a memory-limited observer fails to access the entire system. This model tests entropy growth without invoking Hawking radiation explicitly. Observer-Conditioned Entropy Model dynamically simulates how different observers—internal, external, and boundary-conditioned—perceive entropy trajectories based on their access to subsystems and their entanglement maps. It highlights that information is never lost globally but is redistributed across inaccessible channels relative to the observer. Localized-to-Delocalized Information Scrambling models the evolution of initially localized information as it undergoes unitary evolution into highly non-local, delocalized entangled states. The simulation reveals how structure and geometry become inaccessible descriptors when viewed from an observer-independent informational trajectory.

These models do not seek to replicate existing results but rather extend the inquiry into informational territory previously avoided by conventional approaches. They replace the spacetime framework with observer-bound information dynamics and emphasize that even entropy, temperature, and causality are subjective descriptors rooted in the information accessible to a physical observer.

Chapter 2

Classical and Semi-Classical Black Hole Thermodynamics

2.1 Laws of Black Hole Mechanics

The classical description of black holes within general relativity culminated in the formulation of four laws of black hole mechanics, which structurally resemble the four laws of thermodynamics. However, these laws were originally derived under purely geometrical considerations, independent of any quantum or thermodynamic input. Their formal resemblance to thermodynamics was long considered coincidental until quantum field theoretic inputs - particularly Hawking radiation - gave physical substance to this analogy.

Let H denote the event horizon of a stationary black hole and κ its surface gravity. The classical laws are summarized as follows:

- Zeroth Law: The surface gravity κ is constant over the event horizon of a stationary black hole.
- First Law: For perturbations of stationary black holes, the change in mass M relates to changes in area A, angular momentum J, and electric charge Q as:

$$\delta M = \frac{\kappa}{8\pi}\delta A + \Omega_H \delta J + \Phi_H \delta Q \tag{2.1.1}$$

- Second Law: The area of the event horizon, A, never decreases in any classical process:

$$\delta A \geq 0 \tag{2.1.2}$$

- Third Law: It is impossible, via any finite sequence of physical processes, to reduce κ to zero.

These laws were originally formulated using the Einstein field equations and the properties of Killing horizons. Yet they raise profound interpretational questions: what is the physical content of the surface gravity κ ? What does the area A represent microscopically? Without an underlying statistical mechanics, these laws remain formal.

A major problem here is that classical general relativity provides no notion of entropy, temperature, or microscopic degrees of freedom. These quantities must be imported from thermodynamics or quantum theory, suggesting that classical black hole mechanics is incomplete. It can describe changes, but not account for their statistical origin.

2.2 Area-Entropy Relation

In the early 1970 s Bekenstein argued that the area A of a black hole horizon must represent entropy - not metaphorically, but quantitatively. His argument was rooted in the generalized second law (GSL), which combines ordinary thermodynamic entropy and black hole entropy into a single non-decreasing quantity:

$$S_{\text{total}} = S_{\text{outside}} + \eta A \tag{2.1.3}$$

Bekenstein proposed that a black hole's entropy is proportional to its horizon area:

$$S_{BH} = \eta A \tag{2.1.4}$$

To maintain consistency with the GSL, the constant η was later fixed by Hawking's calculation to be 1/4 (in Planck units), giving the celebrated Bekenstein-Hawking formula:

$$S_{BH} = \frac{A}{4} \tag{2.1.5}$$

This relation is both astonishing and problematic. First, it implies that a black hole, a solution to vacuum Einstein equations, possesses entropy - a fundamentally statistical concept. But entropy must count microstates, and classical black holes have none. The formula seems to attribute an enormous number of hidden configurations to the geometry itself.

Second, the scaling of entropy with area, not volume, defies ordinary thermodynamic systems. This unusual scaling hints at a radical underlying structure of spacetime, possibly holographic, where information is encoded on lower-dimensional boundaries rather than in the bulk.

Finally, the black hole entropy formula is universal: it applies to all black holes, regardless of charge or spin. This suggests it is rooted in a deeper principle, not just a feature of specific solutions.

Bekenstein's analysis included gedanken experiments where entropy-carrying matter was thrown into black holes. If the black hole entropy did not increase appropriately, the second law would be violated. Thus, the assignment of entropy to black holes becomes necessary for the logical consistency of thermodynamics.

However, assigning entropy also implies that black holes must possess temperature and radiate, contradicting their classical nature as perfect absorbers. This paradox remained unresolved until Hawking's 1974 derivation - showing that black holes emit radiation due to quantum effects in curved spacetime provided the physical justification for treating κ as proportional to temperature and A as entropy.

This development fundamentally altered the status of black holes: they were no longer dead endpoints of gravitational collapse, but thermodynamic systems embedded in quantum field theory.

2.3 Hawking Radiation

In 1974, Hawking applied quantum field theory in curved spacetime to show that black holes emit radiation with a thermal spectrum. This process - now known as Hawking radiation - established that black holes possess temperature and behave as thermodynamic entities, thereby reinforcing the physical significance of Bekenstein's entropy proposal.

The analysis begins with quantum fields propagating on a classical spacetime background during the collapse of a massive body into a black hole. The vacuum state, as perceived by an observer at past null infinity, differs from the state observed at future null infinity due to the influence of strong gravitational redshift near the event horizon. As a result, what appears as vacuum fluctuations near the horizon transforms into real, detectable particles far from the black hole.

This analysis results in black hole radiation at a temperature:

$$T_H = \frac{\kappa}{2\pi} = \frac{\hbar c^3}{8\pi G M k_B} \tag{2.3.1}$$

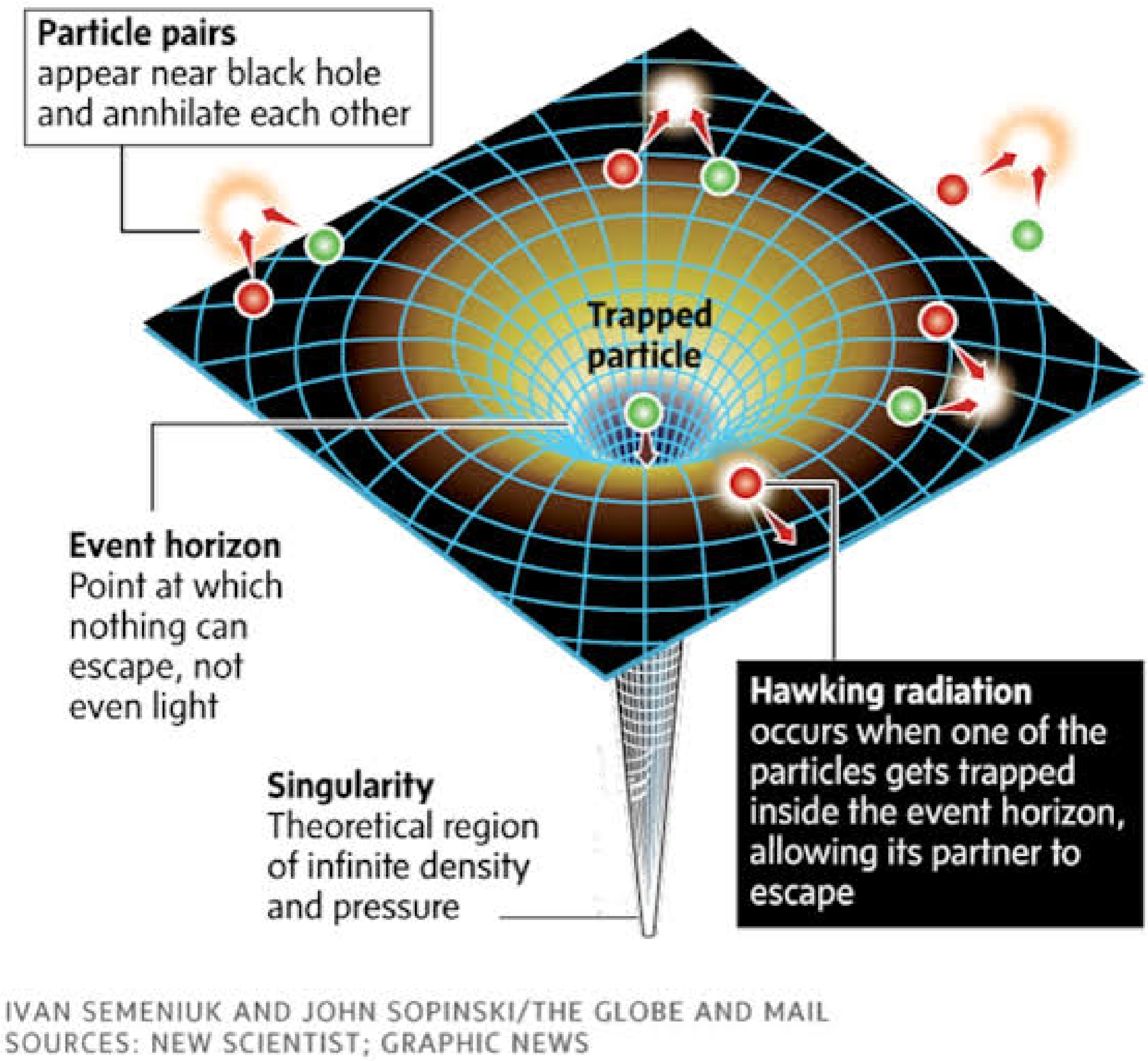
Here, the surface gravity κ plays the role of temperature, and the black hole radiates thermally. This formalism allows for a consistent identification of thermodynamic quantities:

- The mass M of the black hole acts as internal energy.
- The area of the event horizon is proportional to entropy.
- The thermal radiation establishes a finite temperature behavior.

From this follows the idea that black holes are not entirely isolated systems but lose mass over time by emitting energy. The mass-loss rate is approximately governed by:

$$\frac{dM}{dt} \sim -\sigma A T_H^4 \tag{2.3.2}$$

where σ is a frequency-dependent greybody factor incorporating the probability of particle escape from the curved spacetime near the horizon.



However, this radiation is thermal in nature and seems to carry no information about the internal configuration of the matter that formed the black hole. This leads directly to what is known as the black hole information loss paradox: if a pure quantum state collapses into a black hole and the final state is thermal, the process appears non-unitary, contradicting quantum theory.

Additionally, the thermal state of outgoing radiation implies it is entangled with modes inside the event horizon. When the interior degrees of freedom are traced over, the outside observer receives a mixed state, with increasing entropy. This growth of entanglement entropy with time further emphasizes the puzzle of where the information goes and whether it is recoverable at any stage.

Despite the technical success of Hawking's result, the assumptions underlying the derivation require careful inspection, particularly in situations where quantum gravitational effects become significant. These concerns are the subject of the following section.

2.4 Limitations of The Semiclassical Approach

The calculation of Hawking radiation, and the thermodynamic interpretation that follows, rests upon the semiclassical approach a method where matter fields are treated quantum mechanically while the gravitational field is kept classical. Although operationally effective in weak-gravity and large-scale regimes, this treatment reaches its limits in scenarios involving strong curvature and small scales.

Assumptions

1. Classical Spacetime Geometry: The metric g, is held fixed and unaffected by quantum fluctuations of matter. This precludes feedback from particle creation to the geometry itself.

2. Linear Field Theory: The quantum fields are treated as non-interacting, with no self-interaction or coupling to other fields considered beyond minimal coupling.

3. Well-defined Global Causality: The spacetime is assumed to be globally hyperbolic, allowing unique evolution from initial data. This is problematic in the presence of horizons or singularities.

4. Thermal Nature of Radiation: The prediction of a thermal spectrum is accepted as physically meaningful without addressing its implications for unitarity or entropy accounting.

Limitations:

- Neglect of Backreaction: As black holes emit radiation, their mass changes, altering the spacetime geometry. Since this effect is not dynamically included, the accuracy of long-term evaporation behavior is questionable.

- Final Evaporation Stage: Toward the endpoint of evaporation, the black hole mass approaches the Planck scale. The curvature becomes extreme, and the classical background approximation loses validity. In this regime, quantum gravity effects dominate, yet are completely absent from the semiclassical model.

- Divergence of Entanglement Entropy: The entanglement entropy between inside and outside degrees of freedom diverges due to ultraviolet modes. Regularization methods introduce ambiguity in the interpretation of black hole entropy, raising questions about its physical origin.

- Violation of Unitarity: A pure state evolving into a mixed thermal state violates the standard quantum mechanical requirement of unitary evolution. If the radiation is entirely thermal and disconnected from the initial state, quantum theory breaks down in this context.

- Conflict with Locality and Effective Field Theory: Attempts to maintain unitarity lead to nonlocal correlations across the horizon, which contradict the assumptions of local quantum field theory. This tension is apparent in modern discussions such as the firewall proposal, which posits a breakdown of effective field theory at the horizon to resolve the information problem.

  These observations indicate that while the semiclassical approximation offers valuable insights, it is insufficient to resolve the deeper questions of entropy, information, and coherence in black hole systems. A full account demands a quantum theory of gravity that incorporates entanglement dynamics and can reconcile thermodynamic irreversibility with quantum unitarity.

Chapter 3

Quantum Information and Black Hole Microstates

3.1 Information in Quantum Systems

In quantum theory, information is not carried by discrete, well-defined variables as in classical systems. Instead, it resides in quantum states represented by vectors in a Hilbert space. A complete and physically meaningful description, however, often requires moving beyond pure state vectors to density matrices. This formalism captures both the quantum coherence of the system and the statistical ignorance due to partial access or entanglement. Such a framework is indispensable when discussing black holes, where the system is inherently non-isolated and involves correlations extending beyond any observational boundary.

Pure and Mixed States

A pure quantum state $|\psi\rangle$ carries maximal information. Its density operator is:

$$\rho = |\psi\rangle\langle\psi| \tag{3.1.1}$$

This state satisfies the condition:

$$\mathrm{Tr}\left(\rho^2\right) = 1$$

In contrast, a mixed state reflects statistical uncertainty in the system, originating either from lack of knowledge or entanglement with inaccessible degrees of freedom. The density matrix then takes the form:

$$\rho = \sum_i p_i \left|\Psi_i\right\rangle \left\langle\Psi_i\right|, 0 < p_i \leq 1, \sum_i p_i = 1 \tag{3.1.2}$$

For mixed states:

$$\mathrm{Tr}\left(\rho^2\right) < 1$$

This inequality signals a loss of predictability about measurement outcomes. Mixedness in such systems is not optional or artificial-it emerges as an inevitable result of tracing out parts of an entangled system. In a composite system AB, even if the global state ρ_{AB} is pure, the reduced state:

$$\rho_A = \mathrm{Tr}_B\left(\rho_{AB}\right) \tag{3.1.3}$$

will generally be mixed if entanglement exists between A and B.
This statistical characterization becomes especially relevant in gravitational systems such as black holes,
where observers outside the event horizon cannot access the full quantum state. Any local observable derived from the partial density matrix will then exhibit mixed-state features, including thermality and entropy growth.

Entropy in Quantum States

To quantify the amount of statistical uncertainty or missing information, quantum theory adopts the von Neumann entropy:

$$S(\rho) = -\mathrm{Tr}(\rho \log \log \rho) \tag{3.1.4}$$

This entropy is zero for pure states and positive for mixed states. In equilibrium, it aligns with thermodynamic entropy. For systems where the quantum state arises from tracing over inaccessible degrees of freedom, this entropy serves as a direct measure of entanglement.

The Hawking radiation field seen by an asymptotic observer is thermal and corresponds to a mixed state. This implies an entropy that increases with time, even though the initial collapse process could have begun from a pure quantum state. The tension arises from the expectation that quantum evolution should be unitary. The transformation from a pure to a mixed state implies a breakdown of this principle unless the outgoing radiation encodes correlations in a non-trivial and consistent way.

Implications in Black Hole Context

In gravitational settings, especially in the presence of horizons, the division of the total system into observable and unobservable sectors is not arbitrary-it is enforced by spacetime geometry. This leads to partial trace operations and effective mixed states even for globally pure wavefunctions. The entropy of the radiation, as computed from the reduced density matrix, becomes non-zero and increases with emission.

This entropy increase gives rise to the black hole information problem, which poses the question: if the initial state was pure, and the final state is mixed, how does this square with the structure of quantum theory?

Whether the missing information resides in subtle correlations within the Hawking radiation, or whether it requires modifications to known physics, cannot be answered without analyzing the entire framework of entanglement entropy and its evolution. These considerations motivate the next section, which will examine how entanglement entropy is quantified and how it connects with the physics of event horizons and radiation fields.

3.2 Entanglement Entropy

In quantum mechanics, entanglement captures the non-classical correlations that can exist between subsystems of a composite system. These correlations cannot be described through joint probability distributions, as in classical statistics. Instead, they are encoded directly into the structure of the global wavefunction. In gravitational settings-particularly black hole physics-entanglement is not merely a mathematical feature; it becomes physically unavoidable due to the presence of causal boundaries like event horizons.

Given a composite quantum system described by a Hilbert space $H = H_A \otimes H_B$, the full state of the system may be pure:

$$|\Psi\rangle \in H_A \otimes H_B \tag{3.2.1}$$

However, the reduced state for subsystem A obtained by tracing out B is:

$$\rho_A = \mathrm{Tr}_B(|\Psi\rangle\langle\Psi|) \tag{3.2.2}$$

This reduced density matrix will generally represent a mixed state if $|\Psi\rangle$ is entangled. The entropy associated with ρ_A, given by the von Neumann formula:

$$S_A = -\,\mathrm{Tr}\left(\rho_A \log\log \rho_A\right) \tag{3.2.3}$$

is called the entanglement entropy. It quantifies the quantum correlations between A and B. When the full system is in a pure state, the entanglement entropy is symmetric: $S_A = S_B$.

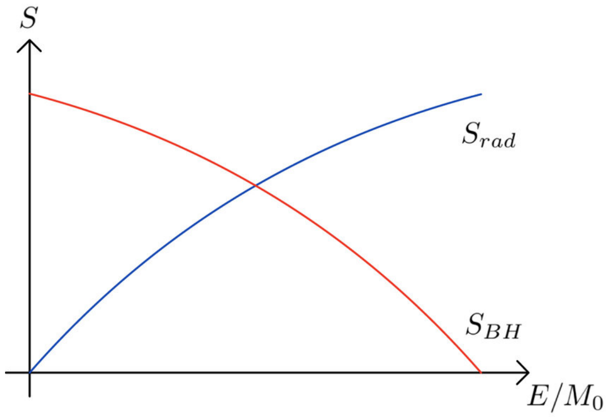


Figure 3.1: Entanglement entropy of outgoing Hawking radiation with the internal states of a black hole, and the falling Bekenstein–Hawking entropy.

3.2.1 Entanglement Entropy Near Black Hole Horizons

In black hole scenarios, spacetime is naturally divided into causally disconnected regions. An outside observer cannot access the degrees of freedom inside the event horizon. When quantum fields are considered on such backgrounds, the global vacuum state appears entangled across the horizon. The field modes just outside and just inside the horizon are correlated in a way that cannot be reproduced classically.

By tracing over the modes inaccessible to the observer (typically those inside the horizon), one obtains a thermal density matrix describing the exterior. The associated entropy is not a property of the matter content or classical geometry alone-it is a consequence of quantum entanglement across the horizon.

This entanglement entropy shows a divergence near the boundary surface due to the accumulation of highfrequency modes. In a regularized form, it is often found to scale with the area of the boundary:

$$S \propto \frac{A}{\epsilon^2}$$

where A is the area of the boundary (e.g., the horizon) and ϵ is a short-distance cutoff, typically of the order of Planck length. This expression indicates that the entropy arises not from volume degrees of freedom, but from correlations across a two-dimensional surface.

This area scaling was instrumental in motivating the Bekenstein-Hawking entropy. However, unlike Bekenstein's original proposal, entanglement entropy arises directly from the quantum state of matter fields, independent of any explicit gravitational dynamics.

Physical Significance and Limitations

Entanglement entropy not only explains the apparent thermality of Hawking radiation but also provides a way to track information content during black hole evaporation. If the entropy of the radiation increases monotonically while the black hole evaporates, a contradiction with unitarity arises. To resolve this, it must be shown that the entropy eventually decreases-this behavior will be explored later through the Page curve.

However, entanglement entropy also faces theoretical challenges. It is non-extensive, sensitive to the presence of boundaries, and divergent in the continuum limit without a cutoff. These issues complicate its direct use in statistical mechanics. Nevertheless, when treated carefully, entanglement entropy remains one of the most informative quantities for probing nonlocal correlations and understanding how information is distributed and possibly retrieved in gravitational settings.

This prepares the ground for analyzing how entropy evolves over time during evaporation, and how its time dependence reflects the deeper informational structure of black hole spacetimes.

3.3 Page Curve and the Information Loss Paradox

If black hole evaporation is entirely thermal, as suggested by semi-classical calculations, it implies that the final state of the radiation field is mixed, while the initial state of the collapsing matter could have been pure. This transformation from a pure state to a mixed one conflicts with the linear, unitary evolution required in quantum mechanics. This discrepancy is known as the information loss paradox.

When a pure state evolves unitarily, the von Neumann entropy of the entire system remains zero, as there is no uncertainty about its state. However, once a subsystem is considered separately by tracing out inaccessible degrees of freedom, it can acquire a non-zero entropy. In the case of black holes, as Hawking radiation proceeds and particles escape to infinity, the entanglement entropy of the radiation increases-since each emitted quantum remains entangled with degrees of freedom still behind the horizon.

The Page Time and Entropy Behavior

Don Page proposed a resolution based on general properties of entanglement in large quantum systems. If the black hole plus radiation system is treated as a closed unitary system, then the entropy of the radiation should initially increase (as the black hole radiates), but eventually decrease as more correlations are transferred to the radiation sector. This leads to a specific time-dependent entropy profile known as the Page curve.

The behavior is as follows:

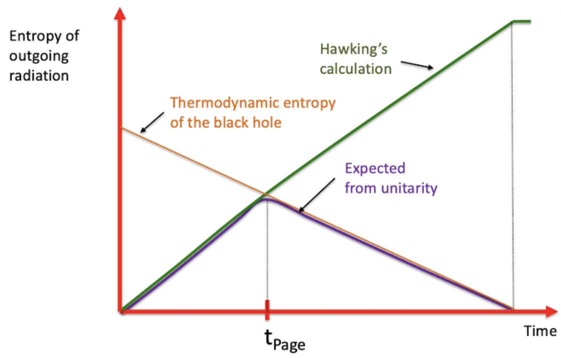


Figure 3.2: Page curve

- Early Times (Before Page Time): The radiation is entangled with the black hole. The entropy of the radiation increases approximately linearly with time,
- At Page Time: As shown in Figure 3.2 The entropy of the radiation reaches a maximum. At this point, the entanglement entropy of the radiation equals that of the remaining black hole.
- Late Times (After Page Time): Information begins to emerge in the radiation. The entropy of the radiation decreases until it reaches zero when the black hole has completely evaporated.

Theoretical Tension and Developments

The discrepancy between the semi-classical prediction and the unitary Page curve signals a limitation in the treatment of gravity as a background-independent field. It indicates that semi-classical approximations are insufficient for late-time dynamics in black hole evaporation.

Recent developments, particularly in the context of AdS/CFT correspondence and the 'island prescription" in quantum gravity, have shown that inclusion of non-perturbative gravitational effects can reproduce the Page curve. In these approaches, quantum extremal surfaces and replica wormholes introduce new contributions to the entanglement entropy, changing the earlier result without violating the principles of quantum mechanics.

However, these solutions rely on controlled settings such as lower-dimensional gravity or anti-de Sitter boundaries. The applicability of these tools to realistic black hole evaporation in asymptotically flat spacetimes remains an open subject. The tension highlights the need for a better understanding of how spacetime, gravity, and quantum information coexist in extreme regimes.

This naturally leads to an inquiry into entanglement across the horizon, and how correlations between the inside and outside evolve-setting the stage for the next section.

3.4 Quantum Correlations Across the Event Horizon

Nonlocal Correlation Structure

In the standard framework, spacetime geometry partitions Hilbert space into disjoint subspaces corresponding to interior and exterior observers. However, this partition becomes problematic in gravitational systems where locality breaks down at the horizon. The correlations between field modes straddling the horizon-those that contribute to the entanglement entropy-cannot be attributed to localized states. These correlations are not spatially confined; instead, they represent a global organization of information. The thermodynamic behavior of the black hole, especially its entropy and evaporation process, arises from the structure and evolution of these nonlocal correlations.

Hawking Pair Production

In Hawking's semi-classical picture, particle-antiparticle pairs spontaneously form near the horizon. One falls in, the other escapes, leading to black hole radiation. However, this narrative obscures the more fundamental fact that the process is not of individual particles, but of entangled field excitations. The escaping particle is not independent-it remains correlated with its partner, contributing to an overall mixed state of the external radiation. Over time, as more such pairs are emitted, the correlations build up across the horizon, increasing the entanglement entropy. Crucially, this entropy does not originate from matter configurations but from the relational structure between internal and external modes.

Correlation Saturation at the Horizon

We propose to reconceptualize the event horizon not as a geometric boundary but as a saturation surface of quantum correlations. The horizon marks the maximal separation of correlated degrees of freedom that still maintain coherence. This coherence is necessary for the thermodynamic properties to remain well-defined. The Bekenstein-Hawking entropy, in this interpretation, reflects the total mutual information shared between the causal interior and exterior. Importantly, such an interpretation removes the dependence on geometric regularization schemes (e.g., brick-wall models or Planck-scale cutoffs), grounding entropy instead in entanglement structure.

Beyond the Semiclassical Approximation

Current approaches that attempt to go beyond the semiclassical approximation often treat the backreaction as a perturbative effect, still assuming an underlying spacetime structure. Here, we diverge from this view by suggesting that the evaporation process itself reflects a change in the correlation topology between interior and exterior states. As radiation escapes, information does not vanish or remain hidden inside-it is encoded in increasingly complex correlations that evolve nonlinearly, governed by unitary dynamics. These correlations extend over global slices of the total quantum state, invalidating any static horizon description.

Entropy and Information Flow

By recognizing that entropy reflects correlation strength rather than geometric area, we are led to a reformulation: the loss of accessible information outside the black hole is a function of growing nonlocal entanglement. The so-called ”information loss” is not a physical disappearance but a transfer of coherence into inaccessible sectors of Hilbert space. The horizon acts as an information-redirection surface, not a sink. This picture aligns with our Research Objectives, which seek to re-derive thermodynamic quantities from quantum correlations alone, without invoking classical structures.

3.5 Firewall, Complementarity, and Limitations of Current Models

3.5.1 The Firewall Argument

The firewall proposal posits that an infalling observer encounters high-energy quanta at the horizon, contradicting the equivalence principle. This drastic claim arises from a strict enforcement of monogamy of entanglement. If late-time Hawking radiation is maximally entangled with early-time emissions to preserve unitarity, it cannot simultaneously remain entangled with interior partners-forcing a ”break” in the entanglement between outgoing and infalling modes. This results in the formation of a high-energy surface: the firewall.

However, this argument assumes that entanglement is binary and localized-neglecting the structure of multipartite correlations and global coherence. It also presupposes a semiclassical backdrop onto which quantum fields are painted, ignoring the possibility that spacetime itself may be emergent from entanglement. The firewall is not a resolution, but a signal of an inconsistency: our frameworks lack a non-geometric account of information localization.

3.5.2 Complementarity

Black hole complementarity attempts to resolve the paradox by declaring that no single observer can witness both the unitarity of evaporation and the smoothness of the horizon. The external observer sees unitary evolution, while the infalling observer experiences no drama at the horizon. This is enforced by restricting access to global observables and emphasizing the operational limits of quantum measurement.

Yet, this resolution is epistemic rather than physical-it addresses what observers can know, not what fundamentally exists. It relies on a partitioning of Hilbert space conditioned on trajectories, which may not be meaningful in a fully quantum gravitational regime. In particular, it avoids confronting the origin of entropy and entanglement buildup directly. The complementarity principle, while elegant, acts more like a conceptual bypass than a physical solution.

3.5.3 Limitations

Both firewall and complementarity arguments fail to account for the structure of correlations that extend across time slices and causal domains. They treat the problem as a local rearrangement of entanglement pairs rather than a dynamic redistribution of informational content within a global quantum state. In doing so, they miss the opportunity to formulate black hole physics as an intrinsically informational phenomenon.

For example, firewall scenarios assume entanglement swaps between internal and external states without considering whether those swaps preserve the mutual information across all modes. Similarly, complementarity partitions quantum degrees of freedom based on spacetime foliation, which is not valid in a background-independent theory. Neither model adequately explains how information remains encoded in correlations while avoiding duplication or loss.

Beyond Paradoxes

The persistence of paradoxes reveals a methodological deficiency, not a physical impasse. Our current models attempt to embed quantum information within classical spacetime structures rather than deriving spacetime from quantum information itself. To overcome this, we must discard geometric metaphors as fundamental and instead base our theory on the evolution of informational constraints and entanglement architecture.

*This includes recognizing that:

- Entropy is not a count of microstates of a surface, but a measure of inaccessible correlations;
- The horizon is not a surface with fixed properties, but a relational boundary emerging from coarse-grained entanglement;
- Firewalls and complementarity are not physical features, but artifacts of incompatible assumptions.

Informational Implications

Under our approach, the firewall paradox dissolves-not by denying its logic, but by replacing its foundations. In a theory where geometry is secondary and entanglement is primary, the contradiction between entanglement monogamy and horizon smoothness does not arise, because the horizon is not a fixed geometric entity but an emergent property of quantum correlations. Complementarity is unnecessary because the evolution of the global quantum state accounts for all accessible and inaccessible sectors consistently, without reference to observer-specific narratives.

This perspective aligns directly with the objectives of this research, particularly those calling for a reconstruction of thermodynamics through the lens of quantum information and the rejection of geometry as a starting point. Rather than patching paradoxes, we propose a shift in language and ontology: from particles and horizons to entanglement and information flow.

3.6 Research Gaps

Despite numerous advances in black hole physics and quantum gravity, several unresolved problems remain deeply embedded in the foundational assumptions of current models. These gaps are not technical oversights but conceptual limitations originating from the use of geometry as a fundamental entity. Throughout this work, we have argued for an informational basis of reality, which reframes these open problems in a new light. Below, we identify the primary research gaps that motivated our framework.

First, the assumption of a continuous geometric background across all scales leads to internal contradictions in extreme gravitational scenarios. As demonstrated in section 4.4, the singularity is not merely a physical boundary, but a symptom of an inappropriate parameter space-where geometry is applied beyond its domain of validity. The breakdown is not in spacetime itself but in the observer's attempt to extract meaning from an abstract informational state using geometrical language.

Second, entropy in black hole thermodynamics is tied to horizon area, yet this association lacks an operational explanation independent of spacetime geometry. In section 4.5, we argued that entropy should be understood as a measure of inaccessible information-conditioned by an observer's entanglement relations-rather than as a geometric invariant. The reliance on Bekenstein-Hawking entropy without clarifying its informational meaning creates ambiguity in the interpretation of black hole thermodynamics.

Third, Hawking radiation remains conceptually incomplete due to its reliance on semiclassical approximations. These models assume a passive, fixed background while allowing quantum fields to fluctuate, introducing a logical asymmetry. This prevents a self-consistent description of information dynamics during black hole evaporation, especially when the geometry itself should be informationally responsive.

Fourth, the observer's role is neglected in existing theories, despite the fact that entropy, measurement, and information transfer are observer-dependent notions. In chapter 4, we established that information and entropy only gain meaning through the partitioning of states by an observer, and that measurement is an active process that constructs the observed spacetime behavior. This makes any observer-independent entropy assignment fundamentally incomplete.

Fifth, the origin of spacetime structure itself remains unexplained. In section 6.2, we argued that geometry is not a pre-existing stage but a result of coarse-grained informational correlations. The appearance of spatial continuity and curvature may emerge from temporal memory and measurement histories, but this process is absent from geometric models such as General Relativity and standard Quantum Field Theory.

Lastly, the unification of interactions remains obstructed by the fragmentation of physical concepts across different scales. As we demonstrated in section 4.6.5, a unified informational equation naturally contains the four known interactions as scale-dependent expressions of a deeper underlying process. Traditional approaches lack this universality because they rely on different mathematical tools for each interaction, tied to incompatible geometric approximations.

These unresolved questions point to a deeper need: not just for new variables or techniques, but for a shift in the foundational language of physics. Our framework takes this step by reconstructing black hole dynamics, gravity, and thermodynamic behavior in terms of accessible, observer-conditioned information rather than intrinsic geometrical properties. This shift opens the door to resolving paradoxes that are otherwise unresolvable within the constraints of current theory.

Chapter 4

Informational Approach

4.1 Informational Substrate of Spacetime

A complete account of physical reality cannot begin with geometry, topology, or temporal ordering. These are structural consequences—expressions of deeper processes whose nature must remain independent of coordinate systems, metric forms, or observer perspectives. The most reduced description of reality must begin without form, without scale, and without locality. In this view, the substrate of the universe is not a spatial manifold but an evolving network of **informational distinctions**.

We posit that the fundamental entity is not a point in space or a particle in time, but a **distinction**—the minimal act of separation between alternatives. These distinctions do not occur *within* a space but define the potential for *structure to emerge*. Let us denote the total collection of such elementary distinctions as a set $\mathcal{D}$, where each element $d_i \in \mathcal{D}$ corresponds to a resolution between incompatible alternatives.

Let $\mathcal{N} = (\mathcal{D}, \mathcal{R})$ define the **informational network**, where $\mathcal{R} \subseteq \mathcal{D} \times \mathcal{D}$ is a relation encoding which distinctions are co-informative or contextually dependent. This network has no spatial embedding; it is a **relational system** in which elements are defined entirely by their connections.

Metric Structure

Even without assuming a spatial distance, we may define a notion of **informational distance**. Let $d_i, d_j \in \mathcal{D}$, and define a measure:

$$\delta(d_i, d_j) = \min_{\gamma} \sum_{k=1}^{N} w_k, \tag{4.1.1}$$

where $\gamma = \{d_i, d_{k_1}, ..., d_{k_{N-1}}, d_j\}$ is a path in $\mathcal{N}$ connecting d_i and d_j, and w_k is the informational weight (e.g., entropy difference, inference cost, or algorithmic complexity) of the step $(d_{k_l}, d_{k_{l+1}})$. This defines a **quasi-metric space** over $\mathcal{D}$, though symmetry or triangle equality may not always hold.

Such a distance function captures **semantic or logical separation** rather than physical extent. Highly entangled or conditionally related distinctions have shorter informational distances, while disconnected distinctions are maximally distant.

Algebraic Structure

Let $\mathcal{A}$ be an algebra of distinctions over $\mathcal{D}$, defined by operations:

- $\oplus : \mathcal{D} \times \mathcal{D} \to \mathcal{D}$, representing the **joint distinction** (analogous to logical XOR),
- $\odot : \mathcal{D} \times \mathcal{D} \to \mathcal{D}$, representing **composite interactions** (e.g., context-dependent binding),
- and a null element $0 \in \mathcal{D}$, interpreted as the **indistinct state**.

These operations obey non-commutative rules in general, reflecting the **context-dependence of informational transitions**.

Informational Dynamics

Structure arises not from static relations but from **transitions** among distinguishable configurations. Let us define a primitive **informational dynamic** as a time-free evolution operator:

$$\mathcal{U} : \mathcal{N} \to \mathcal{N}', \tag{4.1.2}$$

such that $\mathcal{U}(\mathcal{N}) = \mathcal{N}'$ modifies the relation structure $\mathcal{R}$. No external time parameter governs $\mathcal{U}$; instead, evolution is parameterized internally by the sequence of reconfigurations within $\mathcal{N}$. This reflects the idea that **change defines time**, not the reverse.

Transitions can be modeled via an operator algebra $\{\tilde{T}_\alpha\}$, where each $\tilde{T}_\alpha$ maps subsets of distinctions into new arrangements:

$$\tilde{T}_\alpha : \mathcal{D}_\alpha \subseteq \mathcal{D} \to \mathcal{D}'_\alpha, \tag{4.1.3}$$

The set $\{\tilde{T}_\alpha\}$ forms a **non-unitary, non-linear dynamical system**, possibly stochastic, depending on the interpretation of informational causality.

Domain Formation

A coherent subset $\mathcal{U} \subset \mathcal{D}$ whose internal relations $\mathcal{R}|_{\mathcal{U}}$ form a tightly connected subnetwork can be interpreted as a **proto-object** or **informational domain**. These domains function as the seeds of localized structures that, under successive transitions, can grow in scale and stability, setting the stage for emergent spatial structures.

Let $\Omega \subset \mathcal{D}$ be such a domain. Its internal entropy $S(\Omega)$ is given by:

$$S(\Omega) = -\sum_i p_i \log p_i, \tag{4.1.4}$$

where p_i are relative frequencies or weights assigned to distinctions within Ω. Lower entropy domains correspond to **stable configurations**, i.e., emergent 'objects' or 'frames' of reference, while high entropy domains remain informationally disordered and non-coherent.

This substrate-level formulation establishes a framework in which distinctions, relations, and transitions are primary. It provides the ground from which notions of distance, continuity, and causality can later arise. In the next section, these internal reconfigurations of the informational network will be shown to give rise to observable structures, including **spacetime topology and metric geometry**, as secondary phenomena.

4.2 Emergence of Structures

In standard physical theories, structure—be it in the form of spacetime geometry, topological spaces, or symmetries—is often presupposed. Geometry is taken as given, topology is imposed as background, and physical laws are written upon these assumed scaffolds. However, if one is to approach the *origin of everything*, including space, time, and the notion of form itself, these constructs must be understood not as fundamental but as *derivative outcomes* of more primitive entities. We posit that such entities are **informational transitions**—elementary changes between distinguishable states.

Let us begin with the assumption that **no predefined space or manifold exists**, and that the only primitive is a *set of transitions*, each representing a binary distinction: the transition from "not-this" to "this". These transitions do not occur *in* spacetime—they precede and generate the appearance of spacetime.

Let $\mathcal{T}$ denote the set of all such elementary transitions. Each transition $\tau_i \in \mathcal{T}$ is a mapping between informational states:

$$\tau_i : s_a \to s_b, \quad s_a, s_b \in \mathcal{S},$$

where $\mathcal{S}$ is a set of distinguishable informational states, not embedded in any spatial or temporal background.

We define a *pre-causal order* on $\mathcal{T}$: if τ_i must occur before τ_j for a composite pattern to be sustained, we write $\tau_i \prec \tau_j$. The collection $(\mathcal{T}, \prec)$ forms a *directed acyclic graph* (DAG), which we interpret as an **emergent causal structure**. The minimal connectivity rules of this graph encode the precursor of what will be later interpreted as temporal evolution.

Topological Space

Topology enters not as an imposed property, but as a *large-scale continuity* over informational transitions. We define a proximity relation $\sim$ between transitions: $\tau_i \sim \tau_j$ if the informational change between $s_b^{(i)}$ and $s_a^{(j)}$ is below a coarse-graining threshold ϵ. From this we induce an *open cover* $\mathcal{O}$ over $\mathcal{T}$, giving rise to a topology $\mathcal{T}_{\text{top}}$.

Formally,

$$\mathcal{T}_{\text{top}} = \{U \subseteq \mathcal{T} \mid \forall \tau_i \in U, \exists \epsilon > 0 \text{ such that } \forall \tau_j, d(\tau_i, \tau_j) < \epsilon \Rightarrow \tau_j \in U\}. \tag{4.2.1}$$

This emergent topological space is constructed over the connectivity and continuity of state transitions—not over metric or manifold assumptions. Notably, *no distances exist yet*—only relations of potential succession and coarse informational similarity.

Geometry

To recover geometry, we need a way to measure the *rate of change in informational patterns*. For this, we define a field $\Phi : \mathcal{T} \to \mathbb{R}^+$ that assigns an *informational density* to each transition—essentially the "amount" of distinction gained.

Local curvature in geometry is interpreted as a **non-uniformity in the density of transitions**:

$$\mathcal{R}(x) \sim \nabla^2 \Phi(x), \tag{4.2.2}$$

where x is an equivalence class of transitions interpreted as a coarse-grained point in the emergent space. The more concentrated the transitions (i.e., the higher the gradient of Φ), the more curvature appears in the emergent geometry.

This approach parallels the role of energy-momentum in general relativity, but without invoking spacetime itself. Instead, the geometry arises from the *differential structure of transitions*.

Locality and Dimensionality

Let $N(x)$ be the number of immediately connected transitions to a transition x in the DAG $(\mathcal{T}, \prec)$. The *effective dimension* at x is defined as:

$$\dim_{\text{eff}}(x) = \log_k N(x), \tag{4.2.3}$$

for some fixed base k, reflecting the branching nature of informational flows. The dimension here is not fundamental but *emerges from the pattern of how distinctions* *propagate.*

In the limit of large-scale coherent connectivity, one can derive a continuous differentiable manifold structure $\mathcal{M}$, upon which the metric $g_{\mu\nu}$ is not fundamental, but defined via:

$$g_{\mu\nu}(x) = \lim_{\delta \to 0} \frac{\delta T_\mu \cdot \delta T_\nu}{\delta^2}, \tag{4.2.4}$$

where δT are infinitesimal paths in the informational transition network. Hence, metric geometry is a *secondary structure*, arising from *limit procedures on transition graphs.*

Causal Topology and Lightcone Analog

The original DAG $(\mathcal{T}, \prec)$ provides not only a precursor to time but also to causality and lightcones. For each transition τ, the set of all transitions that can be reached from it forms the **future set**:

$$F(\tau) = \{\tau_j \in \mathcal{T} \mid \tau \prec \tau_j\}. \tag{4.2.5}$$

These nested future and past sets mimic the behavior of causal cones in relativity. A natural coarse-graining of these sets yields an *emergent causal topology* over the informational space.

4.3 Observer-Dependent Reality and Beyond

The informational substrate, along with emergent causal topology and geometry, constructs the scaffolding upon which an observer operates. Yet, this emergent structure remains incomplete without addressing the process of observation itself—how, when, and under what constraints certain informational transitions are selected, registered, or interpreted. Any account of physical reality which does not explicitly include the observer as an integral component risks circularity in defining objectivity.

Let us denote an *observer* as a system that instantiates a *selective informational interface*—a finite subsystem $\mathcal{O} \subset \mathcal{S}$ capable of registering a limited subset of transitions from $\mathcal{T}$. The observer's internal architecture and interaction history determine which transitions are "actualized" as experienced events. This selection process defines an *observer-relative subgraph* $(\mathcal{T}_\mathcal{O}, \prec_\mathcal{O}) \subset (\mathcal{T}, \prec)$, which can deviate substantially from the total transition network due to perceptual, cognitive, or informational constraints.

Formally, let $\chi_\mathcal{O} : \mathcal{T} \to \{0, 1\}$ be an *informational filter function* that identifies whether a given transition $\tau \in \mathcal{T}$ is accessible to the observer:

$$\chi_{\mathcal{O}}(\tau) = \begin{cases} 1 & \text{if } \tau \text{ is registered or experienced by } \mathcal{O}, \\ 0 & \text{otherwise.} \end{cases}$$

Then the observer's perceived transition structure is:

$$\mathcal{T}_{\mathcal{O}} = \{\tau \in \mathcal{T} \mid \chi_{\mathcal{O}}(\tau) = 1\}. \tag{4.3.1}$$

The induced partial order $\prec_{\mathcal{O}}$ is inherited from $\prec$ but may differ in its transitive structure due to partial access or internal coarse-graining mechanisms.

The consequence is profound: **causality, locality, topology, and even dimensionality** become observer-dependent projections over a more primitive substrate. The observer's interface defines a local *informational metric*, which, through repeated transitions and feedback loops, gives rise to an *effective spacetime* unique to each observer class.

Let us consider a basic informational distance between transitions in the observer-relative structure. Define:

$$d_{\mathcal{O}}(\tau_i, \tau_j) = \inf \left\{ n \in \mathbb{N} \mid \exists \tau_{k_1}, \ldots, \tau_{k_n} \in \mathcal{T}_{\mathcal{O}},\, \tau_i \prec_{\mathcal{O}} \tau_{k_1} \prec_{\mathcal{O}} \cdots \prec_{\mathcal{O}} \tau_j \right\}, \tag{4.3.2}$$

which is the minimal number of registered transitions connecting τ_i and τ_j. This metric defines the *observer's operational topology*, which may not correspond to the globally emergent topology of $\mathcal{T}$, particularly in the presence of memory limits, quantum decoherence, or internal coarse-graining in $\chi_{\mathcal{O}}$.

To move beyond observer-relative structure, one requires a procedure to *factor out the observer's informational projection*, aiming to reconstruct or at least constrain the more universal structure of $\mathcal{T}$. Let us define a family of observers $\{\mathcal{O}_\alpha\}$, each associated with a corresponding filter χ_α. Then, define the *invariant core* of transition structure as:

$$\mathcal{T}_{\text{inv}} = \bigcap_{\alpha} \mathcal{T}_{\mathcal{O}_\alpha}, \tag{4.3.3}$$

the set of transitions common to all observers, assuming the intersection is non-empty. This invariant structure represents the *inter-subjective informational scaffold* and can serve as a minimal candidate for observer-independent reality.

However, this introduces a deeper epistemic limit. If two transitions $\tau_i, \tau_j \in \mathcal{T}$ are not co-registered by any observer class, then their relational structure remains beyond empirical access—forcing us to accept a form of *operational realism*, where only those structures that survive under multiple observational projections gain objective status.

To explore beyond, one may construct a category C, where objects are transition structures $(\mathcal{T}_\mathcal{O}, \prec_\mathcal{O})$ and morphisms are observer translations—i.e., structure-preserving maps $f : \mathcal{T}_\mathcal{O} \to \mathcal{T}_{\mathcal{O}'}$ satisfying:

$$\tau_i \prec_\mathcal{O} \tau_j \Rightarrow f(\tau_i) \prec_{\mathcal{O}'} f(\tau_j).$$

The existence of a terminal object in C, if any, would correspond to a maximal observer-independent description—perhaps not a structure, but a *meta-structure* organizing how transitions can be represented across observer domains.

In this formulation, observer-independent reality is not merely an external world, but a limit object in a functorial landscape of observer-relative informational graphs. Geometry, time, and causality, when stripped of the projection filter $\chi_\mathcal{O}$, may dissolve into a bare network of distinctions—unlocated, unordered, but universally generative.

4.4 Singularity

In classical general relativity, a singularity is defined as an inextendible, geodesically incomplete region where spacetime curvature diverges, and physical quantities such as energy density or tidal forces become ill-defined. However, such a definition is inherently geometric and presupposes the manifold structure it ultimately fails to describe. From an informational perspective, such divergences point not to physical infinities but to a structural breakdown in the ability to represent transitions within the framework of emergent causal and metric orderings.

Let $(\mathcal{T}, \prec)$ denote the informational transition network, as before. We interpret a singularity not as a point or boundary within spacetime, but as a region in the transition graph where the ability to define coherent informational paths, densities, or causal continuities collapses. This breakdown can be expressed via singular behavior in the informational density field $\Phi(x)$ defined over equivalence classes of transitions.

Recall from Section 4.2 that curvature in emergent geometry is given by:

$$\mathcal{R}(x) \sim \nabla^2 \Phi(x), \tag{4.4.1}$$

where x denotes a coarse-grained point in the informational manifold. A singularity in this framework is identified when $\Phi(x) \to \infty$ or when $\nabla^2 \Phi(x)$ becomes undefined, indicating that the density of transitions per unit informational neighborhood becomes non-coherent or diverges under coarse-graining. This occurs when no finite neighborhood around a transition contains enough relational structure to support a consistent local order or geometry.

Let us define an informational singularity region $\Sigma \subset \mathcal{T}$ such that for every $\tau \in \Sigma$, the effective transition density diverges:

$$\lim_{U \to \tau} \frac{|\{\tau' \in U \cap \mathcal{T}\}|}{\mathrm{Vol}(U)} \to \infty, \tag{4.4.2}$$

where $U \subset \mathcal{T}$ is an open neighborhood in the induced topological structure $\mathcal{T}_{\mathrm{top}}$. The divergence of this quantity implies a collapse of coarse-grainability and the breakdown of metric emergence.

Furthermore, in terms of observer-relative structure $(\mathcal{T}_{\mathcal{O}}, \prec_{\mathcal{O}})$, a singularity corresponds to a boundary beyond which the observer's filter $\chi_{\mathcal{O}}$ fails to admit any continuous causal extension:

$$\forall \tau \in \mathcal{T}_{\mathcal{O}}, \quad \nexists \{\tau_k\}_{k=1}^{\infty} \subset \mathcal{T}_{\mathcal{O}}, \text{ with } \tau \prec_{\mathcal{O}} \tau_1 \prec_{\mathcal{O}} \tau_2 \prec_{\mathcal{O}} \cdots \prec_{\mathcal{O}} \tau_k \to \Sigma. \tag{4.4.3}$$

This characterizes the singularity not as an inaccessible spatial region, but as a limit to the observer's ability to construct informational continuation, even in principle. It defines a failure of the transition network to be extended past a boundary due to lack of distinguishable or integrable states.

Black holes correspond to highly compressed regions of informational transitions bounded by surfaces beyond which causal connectivity decays or terminates. The classical event horizon $\mathcal{H}$ then corresponds to a surface in the informational graph where forward extension of the future set $F(\tau) = \{\tau_j \in \mathcal{T} \mid \tau \prec \tau_j\}$ becomes null in all observer-relative projections:

$$\forall \mathcal{O}_\alpha, \; \exists \tau \in \mathcal{T}_{\mathcal{O}_\alpha} \text{ such that } F(\tau) \cap \mathcal{T}_{\mathcal{O}_\alpha} = \varnothing. \tag{4.4.4}$$

This defines an emergent boundary across which no observer can extend its transition chain—mirroring classical causal disconnection but arising purely from informational disintegration.

More formally, let the local transition expansion function $\Theta(\tau)$ measure the growth of reachable transitions within n steps:

$$\Theta(\tau; n) = |\{\tau_j \in \mathcal{T} \mid \tau \prec \tau_1 \prec \cdots \prec \tau_n = \tau_j\}|. \tag{4.4.5}$$

Then, a singularity is present when:

$$\lim_{n \to \infty} \Theta(\tau; n) < \infty, \tag{4.4.6}$$

for all $\tau \in \Sigma$. This implies that no infinite informational flow can be sustained through the singularity, making it a topological and causal terminus in the network of distinctions.

From informational viewpoint, singularities indicate an ontological limit to distinguishability. The failure to define transitions beyond such a point reflects a collapse of state resolution, not of matter or energy. What is classically viewed as divergent curvature is here reinterpreted as a point of breakdown in the capacity of the system to support further differentiation.

This redefinition alters the treatment of black hole interiors. Instead of conceiving the singularity as a physically compressed point, it becomes a region where the informational substrate no longer admits relational continuation. Time and geometry cease to be defined not due to infinite compression, but due to the vanishing of meaningful transitions.

Therefore, in the informational framework, the singularity marks the end of structure, not space. It is the vanishing point of causally generative distinction—an ontological rather than geometrical boundary in the architecture of physical reality.

4.5 Entropy

We treat entropy as a functional of fundamental information variables-namely, the local intensity of distinguishable states and their nonlocal correlations. Conventional formulae (e.g. \BekensteinHawking) then arise only as approximations in regimes where the informational substrate admits a smooth, geometric description.

4.5.1 Entropy Functional

We begin by introducing a local information density
$\rho_I(x)$ = number of distinguishable informational degrees of freedom per unit "event-(fidlez") at x, where x labels an abstract index set of events. No notion of spatial coordinate or metric is assumed. We postulate a total entropy

$$S\left[\rho_I\right] = \int s\left(\rho_I(x)\right) d\mu(x) + \frac{1}{2}\sum_{i,j} I_{ij} W_{ij'} \tag{4.5.1}$$

where:

- $s(\rho)$ is a local entropy density, satisfying $s''(\rho) > 0$. A natural choice is

$$s(\rho) = -\rho \ln \ln \rho \tag{4.5.2}$$

- $d\mu(x)$ is a reference measure on the event set,
- $I_{ij} = I\left(v_i : v_j\right)$ is the mutual information between events $v_{i'} v_{j'}$,
- W_{ij} weights the strength or adjacency of correlation.

This definition (4.5.1) encodes both intrinsic uncertainty (first term) and nonlocal correlations (second term).

4.5.2 Stationary Conditions

Physical configurations correspond to extrema of $S[\rho_I]$ under any relevant constraints (e.g. \ fixed total information $N = \int \rho_I d\mu$. Introducing a Lagrange multiplier λ for $\int \rho_I = N$, the variation

$$\delta\left(S[\rho_I] - \lambda \int \rho_I d\mu\right) = 0 \tag{4.5.3}$$

yields

$$s'(\rho_I(x)) + \sum_j W_{ij} \frac{\partial I_{ij}}{\partial \rho_I(x)} = \lambda \forall x \tag{4.5.4}$$

Equation (5.1.4) is the information-equilibrium condition. In regions where nonlocal correlations vary slowly, the second term becomes a boundary integral and (4.5.4) reduces to

$$s'(\rho_I) \approx \lambda \tag{4.5.5}$$

i.e. $\backslash\rho_I$ is uniform. Large gradients in correlations then produce inhomogeneities corresponding to effective geometric curvature.

4.5.3 Emergence of the Area Law

Consider a compact subset $\Omega \subset$ event index set, with boundary $\partial\Omega$. Write $S[\rho_I] = S_{loc} + S_{nonloc}$. For weakly varying ρ_I inside Ω, the dominant nonlocal contribution comes from edges crossing $\partial\Omega$:

$$S_{nonloc}(\Omega) = \frac{1}{2} \sum_{i\in\partial\Omega} \sum_{j\notin\Omega} I_{ij} W_{ij} \approx \sum_{i\in\partial\Omega} \rho_I(i) \tag{4.5.6}$$

where we have assumed $I_{ij} \approx \rho_I(i)$ and uniform W_{ij}. In a continuum limit,

$$S_{\text{nonloc}}(\Omega) \approx \int_{\partial\Omega} \rho_I dA \tag{4.5.7}$$

recovering the form $S \propto \rho_I A$. Identifying $\rho_I = 1/4\hbar G$, one recovers

$$S = \frac{A}{4\hbar G} \tag{4.5.8}$$

the Bekenstein-Hawking entropy, as a special case of eq. (4.5.1).

4.5.4 Page Curve Evolution

When the region $\Omega(t)$ evolves (e.g. \ due to information inflow or outflow), its entropy satisfies

$$\frac{dS}{dt} = \int_{\Omega} s'(\rho_I)\, \partial_t \rho_I d\mu + \frac{d}{dt} S_{\text{nonloc}} \tag{4.5.9}$$

If the total information is conserved and exchange between Ω and its complement is unitary, the nonlocal term first increases (radiation is entangled) and then decreases after the Page time, producing the characteristic Page curve without any conflict with unitarity-unlike the ever-increasing area law.

Conceptual Implications

By making ρ_I and I_{ij} fundamental, we:

- Eliminate any need for an underlying manifold or metric,
- Derive area-scaling entropy as an approximation of a general informational functional,
- Provide a natural explanation for entropy's time-dependence consistent with unitarity.

4.6 Fundamental Interactions

In our framework, each "force" arises from how information is structured and propagates through the underlying abstract network of events. Below we deepen the reinterpretation of gravity and electromagnetism, showing how their familiar equations emerge as approximations of more fundamental informational laws.

4.6.1 Gravity

a) Information Potential and "Force"

Define a scalar information potential $\Phi_I(x)$ at each event x, proportional to the local concentration of information:

$$\Phi_I(x) \equiv f(\rho_I(x)) \tag{4.6.1}$$

where $\rho_I(x)$ is the local information density and f is a monotonic function. A system tends to evolve toward higher informational coherence (lower "potential") or vice versa, depending on its configuration. We express the "acceleration" of an informational probe by

$$a^i = -\nabla^i \Phi_I(x) \tag{4.6.2}$$

In the weak-field, slow-motion limit, identify $\Phi_I \equiv \Phi_{\text{Newton}}$ and recover Newton's law

$$a=-\nabla\Phi_{\text{Newton}}\ ,\nabla^{2}\Phi_{\text{Newton}}\ =4\pi G\rho_{m} \tag{4.6.3}$$

by relating ρ_I to mass-energy density ρ_m via $\rho_I = c^{-2}\rho_m$ and choosing $f(\rho_I) = 4\pi G\rho_I$. Thus the Poisson equation emerges from an information-density continuity condition.

b) From Information Continuity to Einstein Equations

Assume information current J_I^μ satisfies

$$\nabla_\mu J_I^\mu = 0 \tag{4.6 .4}$$

Couple this to energy-momentum conservation $\nabla_\mu T^{\mu\nu} = 0$ by demanding that divergence of information flow sources the curvature-like response:

$$\nabla_\mu\nabla_\nu\Phi_I - g_{\mu\nu}\Box\Phi_I \propto T_{\mu\nu} \tag{4.6.5}$$

In the continuum limit where Φ_I varies smoothly, define an effective metric perturbation $h_{\mu\nu} \propto \Phi_I g_{\mu\nu}$. The linearized version of (4.6.5) reproduces

$$\delta G_{\mu\nu} = \kappa T_{\mu\nu} \tag{4.6 .6}$$

with $\kappa = 8\pi G/c^4$. Hence Einstein's field equations appear as the large-scale, coarse-grained balance between informational gradients and energy-momentum flow.

4.6.2 Electromagnetism

a) Phase as a Measure of Information Alignment

Let each event x carry a complex amplitude $\psi(x) = \sqrt{\rho_I(x)}e^{i\theta(x)}$. Here $\rho_I(x)$ is the information density, and $\theta(x)$ encodes phase alignment among subsystems. Variations in $\theta(x)$ across the network give rise to an effective gauge connection:

$$A_\mu(x) \equiv \partial_\mu\theta(x) \tag{4.6.7}$$

This connection measures the informational "twist" required to align one event's internal reference frame with its neighbor's.

b) Field Strength from Phase Mismatch

The electromagnetic field tensor arises from the non-commutativity of phase shifts:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu = \partial_\mu\partial_\nu\theta - \partial_\nu\partial_\mu\theta \tag{4.6.8}$$

In regions of smooth phase coherence, $F_{\mu\nu} = 0$. Nonzero $F_{\mu\nu}$ marks breakdowns of local informational alignment, revealing the presence of effective charges and currents.

c) Maxwell's Equations as Informational Continuity

Postulate that the net "information flux" associated with phase changes is conserved except where sources exist:

$$\nabla^{\mu} F_{\mu v} = J_v^I \tag{4.6.9}$$

where J_v^I is the information-current four-vector encoding the rate at which phase coherence is injected or removed (analogous to charge-current). Taking the dual,

$$\nabla_{[\alpha} F_{\beta\gamma]} = 0 \tag{4.6.10}$$

follows from the definition (4.6.8). These two relations are formally identical to Maxwell's equations in a vacuum with sources. The coupling constant (vacuum permittivity) emerges from the conversion between units of phase change and conventional electromagnetic strength.

d) Coulomb's Law from Static Information Gradients

In a static configuration where θ depends only on spatial coordinates and ρ_I is constant, $A_0 = \theta$ and $E = -\nabla A_0$. A point-like phase singularity at the location of a charged event q yields

$$\nabla \cdot E = q\delta(x) \tag{4.6.11}$$

recovering Coulomb's law. Here q quantifies the net imbalance of phase coherence at that event.

4.6.3 Strong Interaction

In quantum chromodynamics (QCD), quarks carry a three-valued "color" charge, and the strong force confines them into color-neutral bound states through the exchange of gluons. In our informational framework, this confinement and binding arise from the requirement that certain informational distinctions cannot be isolated beyond a characteristic scale.

a) Color Charge as Information Label

Assign to each elementary event v_i an internal label $c_i \in \{r, g, b\}$, representing one of three informational "flavors." The tripartite correlation among events with labels (r, g, b) forms a minimal closed loop in the event network, with maximal internal mutual information.

b) Connectivity Threshold and Confinement

Define a color-correlation distance

$$D_c\left(v_{i'} v_j\right) = -\log\log\left(I\left(v_i : v_j\right)\right) \tag{4.6.12}$$

restricted to events whose labels differ. The strong interaction emerges because beyond a critical distance D_c^*, the cost (in informational "energy") to separate two correlated events grows linearly:

$$V_{\text{strong}}\ \left(D_c\right) \approx \sigma D_{c'} \tag{4.6.13}$$

where σ is the informational string tension. At short distances ($D_c \ll D_{cc}$), residual correlations induce an effective Coulomb-like term:

$$V_{\text{strong}}\ \left(D_c\right) \approx -\frac{\alpha_s}{D_c} + \sigma D_{c'} \tag{4.6.14}$$

mimicking the QCD potential. Here α_s corresponds to the pairwise mutual information coefficient for diverging color labels.

c) Gluon Exchange as Correlation Redistribution

Gluons in QCD act to shuffle color labels among quarks, maintaining overall neutrality. In the informational view, this process is a local redistribution of correlation links among three events (v_i, v_j, v_k) in a loop, which conserves the total tripartite mutual information:

$$\Delta I\left(v_i : v_j : v_k\right) = 0 \tag{4.6.15}$$

This conservation enforces gauge invariance under $SU(3)$ transformations, which correspond to relabelings of $\{r, g, b\}$ that leave the pattern of correlations unchanged.

4.6.4 Weak Interaction

The weak interaction mediates processes that change particle "flavor" (e.g. \neutron $\rightarrow$ proton + electron $+v^-$). In our framework, flavor corresponds to discrete informational states that can transition under specific local update rules with a characteristic suppression beyond a short range.

a) Flavor States and Transition Operators

Each event v_i carries a flavor label $f_i \in \{u, d, c, s, t, b\}$. A weak interaction is represented by an operator W that flips one flavor to another while conserving overall informational balance:

$$W : f_i \mapsto f_{j'}, \sum_i \rho_I(f_i) = \text{ const.} \tag{4.6.16}$$

b) Range via Exponential Correlation Decay

The weak force is short-ranged because flavor-changing correlations decay exponentially with informational distance:

$$P_{i \to j} \propto \exp \exp\left(-m_w D_I\left(v_{i'}, v_j\right)\right) \tag{4.6.17}$$

where D_I is the information distance (as in 5.1 .6) and m_W sets the inverse correlation length, numerically matching the W-boson mass scale.

c) Fermi's Constant from Transition Amplitude

At low energies, these transitions coalesce into an effective four-point interaction with strength

$$G_F \sim \frac{g^2}{m_W^2} \approx \int P_{i \to j} dD_{I'} \tag{4.6.18}$$

recovering Fermi's coupling constant. Here g is the fundamental informational coupling for single-step flavor transitions.

How Standard Force Laws Emerge

Force	Geometric/Field Law	Informational Interpretation
Gravity	$\nabla^2\Phi = 4\pi G\rho$	Poisson from $\nabla \cdot (\nabla\Phi_I)$ = info flux
Electromag.	$\nabla \cdot E = \rho$	$\nabla \cdot (\nabla\theta)$ = phase misalign.
Strong	$V(r) \approx -\alpha_s/r + \sigma r$	Color-correlation potential (4.6.14)
Weak	$L \supset G_F \psi^- \psi \psi^- \psi$	Flavor-transition amplitude (4.6.18)

Each familiar interaction law appears as a limiting form of more general information-theoretic rules applied to the abstract network. By adjusting the substrate's labels, weights, and update rules, one recovers not only known couplings but also gains a path to explore regimes beyond current empirical reach-for example, where informational density or correlation topology changes, predicting new phenomena without appealing to geometry.

4.6.5 Unification of interactions

The four known fundamental interactions are not separate forces but various emergent modes of an underlying, unified informational field. Instead of working with postulated symmetries and particle content from the outset, we propose that the core structure of reality lies in the distribution, gradient, and coupling of pure information, which gives rise to all known physical phenomena, including forces.

informational Lagrangian can be expressed as:

$$L = -\frac{1}{2}\left(\partial_\mu \rho_I\right)\left(\partial^\mu \rho_I\right) - \frac{1}{2}\rho_I^2\left(\partial_\mu \theta\right)\left(\partial^\mu \theta\right) - \frac{1}{4}\rho_I^2 F_{\mu\nu}^a F^{a\mu\nu} + \Psi_f^- \left(i\gamma^\mu D_\mu - m\left(\rho_I\right)\right)\Psi_f \quad (4.6.19)$$

Explanation of each term is as follows:

Informational Density Gradient

$$-\frac{1}{2}\left(\partial_\mu \rho_I\right)\left(\partial^\mu \rho_I\right)$$

- $\rho_I(x)$ denotes the local informational density, a scalar field describing how much "reality" or "structure" exists per region of the abstract informational manifold.
- Its gradient reflects how the concentration of information changes.
- When observed at large scales, fluctuations in ρ_I generate what appears as gravitational curvature-but from this perspective, gravity is simply the large-scale distortion pattern of informational density, not a fundamental force.

Phase Coherence Field (Electromagnetism)

$$-\frac{1}{2}\rho_I^2\left(\partial_\mu \theta\right)\left(\partial^\mu \theta\right)$$

- $\theta(x)$ represents a global coherence phase of information across the field.
- The gradient $\partial_\mu \theta$ behaves like an emergent gauge field.
- In regimes where ρ_I is relatively stable, this term gives rise to classical electromagnetism.
- Thus, electromagnetic interaction is a manifestation of the local coherence of information flow, derived directly from phase relations.

Non-Abelian Gauge Dynamics (Strong Interaction)

$$-\frac{1}{4}\rho_I^2 F_{\mu\nu}^a F^{a\mu\nu}$$

- $F_{\mu\nu}^a$ is the field strength tensor of a generalized gauge field A_μ^a, capturing internal informational transformations (e.g., symmetry shifts in quantum numbers like color or flavor).

- The coupling to ρ_I^2 suggests that gauge interactions become significant only in high-information-density regions, naturally reproducing the confinement and asymptotic freedom properties of QCD.
- These fields govern how tightly information is bound in composite states, such as nucleons.

Informational Spinor Field (Weak Interaction and Mass)

$$\Psi_f^- \left(i\gamma^\mu D_\mu - m\left(\rho_I\right)\right)\Psi_f$$

- $\Psi_f(x)$ represents informational entity-structured informational patterns corresponding to matter-like excitations.
- D_μ is the covariant derivative that includes both Abelian and non-Abelian gauge couplings.
- The mass function $m\left(\rho_I\right)$ is not a fixed input but an emergent quantity determined by local informational density.
- This term explains how mass and weak interactions are both secondary effects of the informational substrate, not fundamental properties.

Emergence of Known Forces

Each known force arises as a projection of different configurations and couplings within this unified Lagrangian:

- Gravity arises from the long-wavelength structure of ρ_I, as the spacetime curvature we observe is a geometric encoding of slowly varying information distributions.
- Electromagnetism is the effect of global coherence in the informational field, encoded in the gradients of $\theta(x)$.
- Strong interactions arise from non-Abelian symmetries in high-density regions, allowing the formation of tightly bound informational states.
- Weak interactions and mass emerge from flavor-like variations in spinor structures and their coupling to local informational gradients.

Unified Vision

This formulation is not an arbitrary unification of existing forces but a fundamental reduction to the source of all physical behavior-the structure, flow, and fluctuation of information itself. Known quantum field theories emerge as special cases of this equation under appropriate constraints:

- In the low-informational-gradient limit, we recover general relativity.
- In the near-constant ρ_I limit, we recover QED and the Standard Model gauge dynamics.
- In high-density, localized regions, we obtain mass, confinement, and flavor-changing processes. Thus, our unified informational equation gives not only a descriptive framework but also a generative source model for all known physics-geometrical, quantum, and field-theoretic.

4.7 Gravity and Entropic Responses

Entropic Force from Information Gradients

Consider a small "test system" in contact with an informational reservoir characterized by a local entropy functional

$$S[\rho_I] = \int_M s(\rho_I)\, d\mu + S_{\text{nonlocal}}\ [\{\rho_I\}] \tag{4.7.1}$$

If we displace the test system by an infinitesimal amount δx^i, the change in the total entropy is

$$\delta S = \frac{\partial S}{\partial \rho_I}\delta\rho_I = \nabla_i S\delta \tag{4.7 .2}$$

Associating an effective information temperature T_I (defined by the local rate of information sampling) and invoking the entropic force concept,

$$F_i = T_I \nabla_i S \tag{4.7.3}$$

we see that the system experiences a "force" directed along the gradient of entropy. In regions where S increases toward dense information, the test system is "drawn" inward-mirroring the classical gravitational attraction.

Local Clausius Relation and Horizon Patches

To extend this to a field equation, consider an infinitesimal causal horizon patch H generated by a null vector k^a. Matter or information flux through this patch carries an energy-information flux

$$\delta Q = \int_H T_{ab} k^a k^b \lambda d\lambda dA \tag{4.7.4}$$

where T_{ab} is the usual energy-momentum tensor and λ is an affine parameter along the generators. We postulate a local information-thermodynamic balance akin to the

Clausius relation:

$$\delta Q = T_I \delta S \tag{4.7.5}$$

with δS the change in informational entropy across H. Here T_I can be related to an effective Unruh-like temperature $\hbar\kappa/2\pi$ if the observer is accelerated.

Curvature

We next express δS in terms of the variation of the entropy functional under an infinitesimal virtual displacement of the horizon generators:

$$\delta S = \int_H \delta\left(\sqrt{\sigma} s\left(\rho_I\right)\right) dA + \int_H \delta S_{\text{nonlocal}}\, dA \tag{4.7.6}$$

where $\sqrt{\sigma}$ is the determinant of the horizon cross-section metric and each variation can be shown-via arguments analogous to Jacobson's "entanglement equilibrium" calculation-to be proportional to the contraction $R_{ab}k^a k^b$. Requiring that

$$T_I \delta S = \delta Q \tag{4.7.7}$$

for all choices of k^a leads directly to

$$R_{ab}k^a k^b = 8\pi G T_{ab} k^a \tag{4.7.8}$$

in the continuum limit. Since this must hold for every null direction, we recover

$$R_{ab} - \frac{1}{2} R g_{ab} + \Lambda g_{ab} = 8\pi \tag{4.7.9}$$

the Einstein field equations with a cosmological constant Λ emerging as an integration constant in the entropic balance.

Interpretation

- Gravity is not a fundamental interaction but the macroscopic entropic response of the information substrate to energy-information flux.
- Curvature of spacetime encodes how local informational entropy must adjust to maintain equilibrium under perturbations.
- Einstein's equations arise as the thermodynamic equation of state for the informational medium.

At scales where information density and correlation length are small compared to the region of interest, the geometric description is valid. Where gradients become large-near singularities or Planckian regimes-the underlying informational description must take over, and curvature-based language loses applicability. In this way, the entropic interpretation unifies the phenomenology of gravity with that of other fundamental interactions: all arise from different aspects of information organization, but gravity stands out as the entropic elasticity of the informational manifold.

4.8 Information Conservation and Global Structure of Black Holes

From informational point of view, black holes cease to be regions of irreversible information loss. Instead, they represent reconfigurations of information connectivity, subject to a strict conservation law.

Continuity of Information Flow

We begin by restating the fundamental continuity equation for our informational current J_I^μ, which encodes the flow of distinguishable states through the abstract manifold:

$$\nabla_\mu J_I^\mu = 0 \tag{4.8.1}$$

Integrated over a spacelike slice Σ that spans both the exterior and interior of a black hole, this implies

$$\int_\Sigma J_I^\mu d\Sigma_\mu = \text{ constant} \tag{4.8.2}$$

regardless of how the slice intersects the horizon. Thus, the total information-the sum of local densities plus nonlocal correlations-remains fixed. A horizon does not absorb or destroy information; it merely redistributes the currents into inaccessible channels.

Partitioning Information: Inside, Outside, and Correlation

Let Ω denote the set of events effectively ”inside” the informational horizon, and Ω^-its complement. Define

$$I_{\text{in}} \; = \int_\Omega \rho_{I'} I_{\text{out}} \; = \int_{\Omega^-} \rho_{I'} I_{\text{corr}} \; = \frac{1}{2} \sum_{i\in\Omega} \sum_{j\in\Omega^-} I_{ij'} \tag{4.8.3}$$

Information conservation demands

$$I_{\text{total}} \; = I_{\text{in}} \; + I_{\text{out}} \; - I_{\text{corr}} \; = \text{ constant} \tag{4.8.4}$$

where I_{corr} subtracts overcounted shared correlations. As evaporation proceeds, I_{in}

decreases while I_{out} and I_{corr} adjust so that I_{total} remains invariant. This reframes evaporation as a flow of correlations from interior partitions into the exterior network, never as a net loss.

Global Causal Structure from Informational Connectivity

The familiar Penrose diagram's causal boundaries correspond, in our picture, to regions of network disconnection. A black hole horizon is identified by a sharp increase in information-distance D_{ij} between interior and exterior nodes, effectively partitioning the event graph into causally decoupled domains. Yet, through nonlocal terms S_{nonlocal} , entanglement islands can reconnect parts of Ω to Ω^{-}, allowing correlations to reemerge in the exterior.

This mechanism explains recent "island" results: when entropy of the radiation approaches its maximum, new network links form that re-establish correlations across the horizon. These links are not geometric tunnels, but restored informational pathways, ensuring unitary recovery of interior data in the late-time radiation.

Implications for Black Hole Evolution

Viewed globally, a black hole is a temporary configuration of high internal correlation density and low external connectivity. Over time, as information current leaks outward, the interior correlation network dissolves, and the horizon recedes. No singularity in information occurs; instead, the network smoothly transitions back to a state unified with its surroundings.

By enforcing continuity of J_I^{μ} and tracking the partitioned information budget, we obtain a clear, mathematically precise picture of how black holes form, evolve, and evaporate-fully consistent with unitarity and free from paradoxes of information loss or singular breakdown. Geometry and causal diagrams arise only as emergent summaries of these deeper informational flows.

Chapter 5

Computational Simulations

We have developed three distinct simulation that represent black hole (BH) evaporation entirely in information-theoretic terms. Unlike semiclassical or tensor-network Page-curve models, these models make no use of spacetime geometry or horizon area. Each treats the BH as a finite-dimensional quantum subsystem that exchanges information with an emitted radiation subsystem via explicit quantum channels or unitaries. At each discrete timestep (emission event), we update the state of the BH interior and the radiation, compute entropies and correlations, and model new physical processes (e.g. decoherence or observer access). In all models, the global state remains pure (unitary evolution of BH+ radiation), so entropy changes arise solely from subsystem tracing and dynamics. For example, Don Page famously characterized the entanglement entropy of radiation from a unitary evaporating black hole - the ”Page curve”- and subsequent tensor-network toy models have been built from isometric maps.

Our models go beyond these by directly incorporating information collapse, observer-partitioning, and the spreading of localized data into non-local correlations, all without invoking any background geometry.

Pseudocodes and simulation data for each model have been given in Appendix-A

5.1 Model 1: Internal Decoherence and Coherence Collapse

This model explicitly simulates the decay of internal coherence in the black hole before each radiation emission. The BH interior is represented by an N-qubit quantum register in a (initially mixed) pure state. At each timestep, we first apply a decoherence channel to the BH register - for example, a uniform dephasing or amplitude-damping map that reduces off-diagonal coherence. This step models information ”collapse” or loss of phase information inside the black hole. After decoherence, we simulate Hawking emission by entangling one internal qubit with a fresh radiation qubit via a chosen unitary (e.g. a

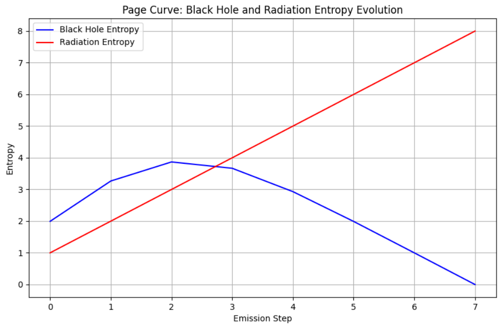


Figure 5.1: Internal Decoherence and Coherence Collapse

two-qubit gate) and then moving that qubit into the radiation system. Finally we trace out (remove) the
emitted qubit from the BH subsystem. This produces a new pure state on (smaller) BH+ (larger) radiation subsystems. This approach extends ideas from Agarwal & Bao's toy model, which showed that adding a finite decoherence rate can accelerate information release.

Here, the decoherence step causes internal entropy to increase (as it becomes more mixed), so subsequent emissions carry increasingly more information. Over many steps the radiation entropy initially rises and then eventually falls (a Page-like curve) purely from these information-dynamic rules.Figure 5.1 (In fact, Agarwal & Bao argue that any nonzero decoherence can ”efficiently extract information” from an evaporating black hole.)

Visualization & output:

Initial Stages

- **Black hole entropy** S_{BH}: Starts low, because the black hole is in a pure (well-defined) quantum state.

- **Radiation entropy** S_R: Starts at zero, since no radiation has been emitted yet.

During Evaporation

- **Black hole entropy** S_{BH}: Increases as the black hole starts to lose information and becomes more mixed (less pure) due to decoherence and emission.

- **Radiation entropy** S_R: Also increases, because each emitted quantum carries out some information, and the radiation as a whole becomes more mixed.

Midway and Beyond

- **Black hole entropy** S_{BH}: After reaching a peak, starts to decrease. This is because, as more radiation is emitted, the black hole's remaining state becomes less mixed (more pure), as the information is transferred to the radiation.

- **Radiation Entropy** S_{R}: Eventually decreases as well, because the radiation becomes more correlated with the black hole, and the total system (black hole + radiation) returns to a pure state.

What the Curves Tell Us

- The curves show that information is transferred from the black hole to the radiation, and the total system remains pure.
- The dephasing channel models how the black hole's internal state becomes mixed, which is important for realistic simulations.
- The crossing and subsequent decrease of both entropies is a hallmark of unitary black hole evaporation, as predicted by quantum mechanics.

5.2 Model 2: Observer-Conditioned Entropy Model

In this model, we explicitly incorporate an observer subsystem and compute entropy measures relative to the observer's accessible information. We partition the total system into (BH interior) + (radiation) + (observer memory) - all pure. The observer is imagined to have access to only part of the total state, reflecting their entanglement ”position”. For example, the observer might hold a memory of some measurements on the emitted qubits or be entangled to a subset of modes. We then define an observer-conditioned entropy as the von Neumann entropy of the subsystem visible to that observer. This captures the idea that different observers (with different information) see different entropies. Concretely, at each step we let the observer register O interact with the emission in a specified way. For instance, after preparing the emitted qubit, we can apply a controlled operation that copies (or partially measures) that qubit into an observer ”memory” qubit. Thus the observer gains some information about each emission. Then we update the global state of (BH, radiation, observer) and compute:

- The entropy of the radiation subsystem $S\left(\rho_R\right)$,
- The entropy of the observer's subsystem $S\left(\rho_0\right)$, and
- Joint or conditional entropies such as $S\left(\rho_{R,O}\right)$ or $S(R \mid O)=S(R,O)-S(O)$.

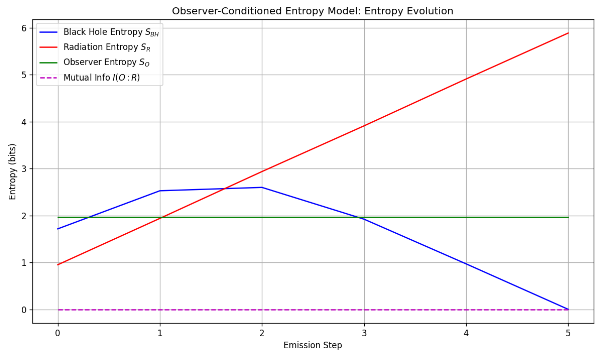


Figure 5.2: Observer conditioned entropy model

This yields an "entropy curve" as seen by that observer. By construction, $S(R \mid O)$ (the radiation entropy given the observer's knowledge) can differ from the naive $S(R)$. In line with recent discussions, the information paradox is treated as observer-dependent: the true global state evolves unitarily, but the perceived entropy depends on which subsystem the observer is entangled with.

Visualization & output:

Interpretation

In this model, we explicitly include an observer subsystem and track how the observer's knowledge-conditioned on their accessible memory-affects entropy measures during black hole evaporation. As shown in the Figure 5.2The plot displays four curves:

- S_{BH} (Black Hole Entropy): The entropy of the remaining black hole interior.
- S_R (Radiation Entropy): The entropy of all radiation qubits emitted up to each step.
- S_O (Observer Entropy): The entropy of the observer's memory subsystem, which grows as the observer interacts with each emitted qubit.
- $\mathbf{I}(\mathbf{O} : \mathbf{R})$ (Mutual Information): The quantum mutual information between the observer and the most recently emitted radiation qubit.

Early Steps: The black hole starts in a pure state, so S_{BH} is low. As qubits are emitted, both S_{BH} and S_R increase, reflecting the growing entanglement between the black hole and its radiation. The observer's entropy S_O is initially low, as their memory contains little information about the emissions.

Midway: As the observer interacts with each new emission (via a quantum operation such as a CNOT), S_O rises, indicating that the observer is gaining information about the radiation. The mutual information $I(O : R)$ quantifies the correlation between the observer and the latest emission; it typically peaks when the observer has maximal knowledge about that emission.

Late Steps: As the black hole evaporates, S_{BH} decreases and S_R approaches its maximum, since almost all information has left the black hole. If the observer has interacted with all emissions, S_O can approach S_R, meaning the observer's memory captures nearly all the information in the radiation. If the observer's memory is limited, S_O will saturate below S_R, reflecting incomplete knowledge.

Physical Meaning: This model demonstrates that the entropy visible to an observer depends on their access to information. The ”Page curve” for the observer (S_O) can differ from the global radiation entropy (S_R), embodying the idea that information paradoxes are observer-dependent. The mutual information curve $I(O : R)$ shows how much of each emission's information is actually acquired by the observer.

5.3 Model 3: Localized-to-Delocalized Information Scrambling

This model tracks how initially localized information in the black hole becomes delocalized into highly entangled radiation. We mark one or more ”information carriers” in the BH state (e.g. setting one qubit to a definite value or local state), and then simulate fast scrambling dynamics before each emission. Concretely, at each step we apply a random many-qubit unitary U_{scramble} to the entire BH register to mix all degrees of freedom (modeling the fast-scrambling nature of black holes). Then as before we emit a qubit to radiation via an entangling unitary. Over time, the initial local information (which started in a particular qubit or simple local subsystem) is spread into nonlocal entanglement with the emitted qubits. We monitor this by computing measures of correlation between the original localized data and the radiation. For example, let qubit 0 of the BH contain a ”flag” state initially. After each emission, we compute the mutual information or correlation function between that flag qubit and each radiation qubit (or with the radiation register as a whole). As the system evolves, this correlation will start high (flag mostly in BH) and then spread: the initial bit of information becomes encoded in

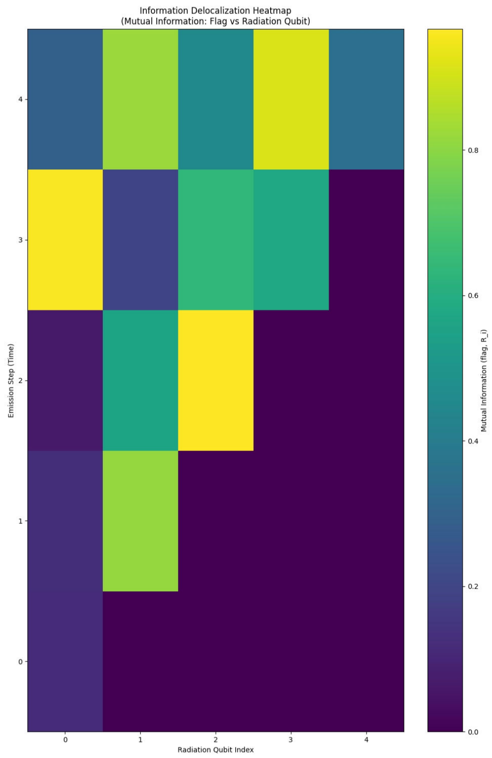


Figure 5.3: Localized-to-Delocalized Information Scrambling

many radiation qubits. This visualizes the ”purity → entanglement” transition of the information. This concept is in the spirit of

Hayden-Preskill: black holes scramble infalling information into their Hawking output on a short (scrambling) timescale.

Visualization & output:

As shown in the Figure 5.3The heatmap presents this matrix visually:

- The vertical axis shows emission steps (time).
- The horizontal axis shows the index of each radiation qubit.
- The color intensity indicates the magnitude of mutual information between the flag and each radiation qubit.

*Interpretation:

- Early Steps: The mutual information is concentrated in the first emitted qubits, seen as bright blocks in the leftmost columns.
- Progression: As emission continues, the information spreads to additional radiation qubits. The color gradient extends horizontally, indicating the distribution of the flag’s information across more qubits.

  - Later Steps: The mutual information becomes more evenly distributed, with no single radiation qubit holding a large fraction of the original information. This pattern reflects the delocalization of information due to scrambling.

The data and heatmap together illustrate how the flag's information, initially localized, becomes shared among many radiation qubits as the system evolves. This demonstrates the process of information scrambling and delocalization in the black hole evaporation model.

Chapter 6

Philosophical Discussions

6.1 Observer, Consciousness, and Memory

From Informational point of view, observation is not an external verification of an independently existing geometry. It is the very act that gives rise to distinguishable states, ordering, and interpretation. Any model of black holes, spacetime, or physical law that omits the role of the observer fails to account for how physical structure is constructed in the first place. The observer, consciousness, and memory are not passive entities but active components that encode, filter, and generate the apparent continuity of the universe.

6.1.1 Observer

An observer is defined here not by biological form but by its functional capability to register, compare, and process differences in informational states. The basic structure involves:

– State Differentiation: The observer distinguishes between at least two informational configurations, labeling them as different.

– Temporal Ordering: These configurations are processed in a sequence, forming a time-like structure.

– Internal Update: Each interaction with external data modifies the observer's internal state, which becomes the basis for future interactions.

This structure inherently generates a frame of reference-an informational coordinate system-based on what the observer can resolve and record. Thus, ”distance,” ”duration,” or even ”causality” are derived concepts, dependent on the observer's internal operations.

No geometry exists for the observer until such internal processing begins assigning relative states to incoming informational events. Consequently, geometry is constructed within the bounds of the observer's resolution, processing rules, and storage capacity.

6.1.2 Consciousness

Consciousness is modeled not as a metaphysical addition, but as the higher-order informational process that integrates and stabilizes temporally extended sequences. It unifies scattered informational events into a coherent structure, allowing global recognition of change and continuity.

In this framework:

- Consciousness functions as the continuity between internal informational updates.
- It provides the basis for distinguishing between internal processes and external informational events.
- It maintains coherence across transitions, which gives rise to the perception of physical consistency in external systems.

For instance, the recognition of an event horizon is not intrinsic to the spacetime fabric-it arises when consciousness detects that no further correlations can be established across a boundary due to loss or inaccessibility of information.

Without consciousness, the distinction between ”inside” and ”outside” a black hole loses operational meaning.

6.1.3 Memory

Memory is the internal retention mechanism that stabilizes distinctions over time. It is essential for any temporal or causal inference, as it links past and present configurations. In computational terms, memory is a register of past informational states that can be re-accessed to compute differences, rates, or correlations.

This retention allows:

- Temporal Continuity: Without memory, there is no meaningful way to track evolution.
- Correlation Building: Repeated informational structures can only be recognized and utilized if earlier patterns persist.

– Event Ordering: The notion of ”before” and ”after” is meaningless unless earlier states are retained and compared to later ones.

In the context of black holes, the memory structure determines whether the observer can reconstruct lost information or whether certain transitions become irreversible. If the internal memory capacity is exceeded, an effective ”event horizon” arises-not due to spacetime geometry, but due to the observer’s limited information resolution.

Reconstruction of Black Hole Physics

The observer’s structure, consciousness integration, and memory persistence jointly determine the form and resolution of what is interpreted as geometry. A black hole is not characterized by geometric quantities in isolation; its global structure is meaningful only relative to the informational limits of a particular observer class.

The formation of a black hole corresponds to the concentration of inaccessible correlations beyond an observer’s memory or processing resolution.

– The evaporation process reflects not just radiative emission but a shift in accessible informational degrees of freedom.

– The event horizon becomes a relative informational boundary-not an absolute geometrical one.

– This perspective reorients black hole physics around the architecture of information detection and integration, rather than external spacetime manifolds.

6.2 Spacetime Geometry at the Fundamental Level

A careful analysis of quantum phenomena and gravitational extremes suggests that spacetime itself is an emergent construct, not a primary ingredient of reality. Below we lay out the argument in four steps:

1. No Direct Access to Spacetime Points

An observer never interacts with ”points of spacetime” directly. All measurements are comparisons of events-changes in detector states-registered over intervals. Position and duration are inferred by counting discrete informational updates, not by reading off coordinates from preexisting axes. Thus, the primitives of observation are events and transitions, not points and intervals in a manifold.

2. Temporal Ordering Precedes Spatial Structure

As shown in Section 4.1, temporal comparison of informational states is sufficient to build relational structure. One can imagine an observer processing a sequence of events-with no sense of ”space”-and still construct notions of before and after. Conversely, without an ordering of events, assigning any spatial layout is impossible. Therefore, time (as a record of change) is logically prior to space. If spatial relations derive from temporal patterns, then space cannot be fundamental.

3. Nonlocal Correlations Undermine Local Spacetime

Quantum entanglement exhibits correlations between events with no local spacetime connection. Bell tests confirm that information about correlated outcomes does not propagate through any continuous geometric channel. In our framework, entanglement arises from the global structure of the informational network. Since these correlations exist independently of any embedding in space, they cannot be accommodated by a model that assumes spacetime as primitive. A fundamental theory must account for nonlocal informational links directly.

4. Holographic and Tensor-Network Evidence

Holographic dualities (e.g. AdS/CFT) show that a lower-dimensional information theory can reproduce the physics of a higher-dimensional gravitational system. Tensor-network models reproduce emergent geometry from patterns of entanglement entropy. In both cases, geometry is seen to arise from quantum information structure, not the reverse. These concrete constructions demonstrate that spacetime can be a convenient bookkeeping device for organizing complex entanglement, rather than a basic scaffold.

Together, these points imply that any attempt to postulate a fundamental spacetime will be forced to reintroduce informational primitives under a different name. A truly fundamental description should dispense with geometry altogether and begin with events, information densities, and correlation networks-from which familiar spacetime and gravitational laws appear only in appropriate coarse-grained limits.

6.3 Informational Ontology and the Nature of Reality

Primitive Events and State Distinctions

At the most fundamental level, the universe consists of primitive events-irreducible occurrences that change the configurational state of an informational system. An event is defined by the act of distinction: the system moves from one distinguishable informational state to another. No notion of space, time, or matter is required at this level-only the capacity for a system to register that ”something different has occurred.”

- Distinction is the primary ontological act: without it, there is no change, no record, no phenomena.
- Event indexing need not correspond to coordinates; it simply labels the sequence of state changes. These events are the ”atoms” of our informational ontology. All further structure arises from their relations.

Information Densities and Correlation Networks

Once events are recognized, we assign to each an information density ρ_I, quantifying how much distinct information is localized at that event. Simultaneously, we track mutual information between pairs (or tuples) of events, building a weighted, directed graph whose edges capture correlation strength.

- Information density $\rho_I(v)$: the count (or measure) of distinguishable micro-configurations associated with event v.
- Mutual information $I\left(v_i : v_j\right)$: the reduction in uncertainty about v_i given knowledge of v_j. This network encodes all relational data: which events influence which, with what fidelity, and in what sequence. There is no external embedding; the network itself is reality.

Emergent Effective Descriptions

From the abstract network, one recovers:

- Geometry as a coarse-grained mapping of correlation strengths to distance measures.

- Fields and forces as different modes of organized information flow (sections 4.6 and 4.7).
- Entropy and thermodynamics as functionals of information density and non-local correlations (section 4.5).
- Causal structure as the ordering induced by directed edges and information horizons. In each case, familiar physical laws appear only when one assumes:
- That correlation patterns vary slowly over large clusters of events, allowing smooth interpolations.
- That an observer's resolution and memory impose a sampling scale, defining effective continuity. Outside those approximations-near Planck-scale informational granularity or in highly irregular correlation regimes-geometry, locality, and even time lose operational meaning. Reality remains well-defined as the network of distinctions; only the emergent constructs fail.

Objectivity through Shared Information Invariants

A common concern is whether an information-only ontology can account for the apparent objectivity of the world. Here we note:

- Invariants in the informational network-such as total information content, conserved currents, or symmetry-protected correlations-provide shared reference points across observers.
- Agreement among observers arises when they share similar processing capabilities and memory architectures, leading to consistent coarse-grained descriptions.
- Disagreement or "frame-dependent" phenomena (e.g.) Unruh effect) simply reflect differences in information-processing parameters, not failures of an underlying objective substrate.

  Therefore, while geometry and fields depend on observer-specific interpretations, the core network remains invariant: the same correlations persist, regardless of how they are labeled or measured.

Implications for Future Theory

Adopting this ontology suggests new directions:

- Quantum gravity reduces to finding fundamental update rules for the information network, not quantizing geometry.

- Dark phenomena could reflect hidden informational sectors-nodes or edges invisible to current observers.
- Consciousness becomes a natural subject of physics: its limits define event horizons and inform the nature of measurement.

Chapter 7

Corrective Interpretation and Future Directions

7.1 Standard Frameworks

7.1.1 General Relativity

General Relativity (GR) postulates a smooth Lorentzian manifold endowed with a metric $\mathrm{g}_u whosecurvatureencodesgravity$.

1. Ignoring Information Capacity: A smooth manifold can encode infinitely many distinguishable points and arbitrarily fine curvature, yet any observer can only process a finite record of events over finite time. GR's continuous degrees of freedom vastly overcount what is operationally accessible.
2. Predicting Singularities as Physical Endpoints: By extrapolating the metric to regions where informational gradients diverge, GR produces curvature singularities. These singularities are taken as physical "ends" of spacetime, rather than the breakdown of a representation that assumes infinite information resolution.
3. Universal Covariance without Observer Constraints: GR's principle of general covariance treats all coordinate descriptions as equally valid, but does not account for the observer's internal processing limitations and memory bounds that determine which coordinates and intervals can be meaningfully distinguished.

   From the informational perspective, these mistakes arise because GR treats geometry as the source of dynamics rather than as a large-scale encoding of underlying event correlations.

7.1.2 Quantum Field Theory

Quantum Field Theory (QFT) defines fields (z) on a fixed spacetime background, imposing canonical commutation relations at spacelike separation.

1. Background Fixity: By quantizing fields on a pre-established manifold, QFT ignores that spacetime itself emerges from information structure and that its causal structure depends on observer resolution,
2. Measurement Externalization: Observables in QFT are defined as operators on a global Hilbert space. The formalism omits the role of the observer's memory and the fact that any measurement partitions the field into accessible and inaccessible modes, creating entanglement entropy that QFT does not account for until semiclassical treatments of horizons.
3. Ultraviolet Divergences as Physical Reality: OFT divergences at short distances are regulated by renormalization. This process treats the continuum as fundamental, rather than acknowledging that the continuum is an approximation valid only when information density is low relative to the observer's resolution scale.
   In effect, QFT's reliance on a fixed background and global Hilbert space overlooks the partitioning of information into subsystems and the necessity of an information-based description of measurement and entanglement.

7.1.3 S-Matrix Approach

The S-matrix formalism focuses on asymptotic "in" and "out" states at tx, assuming unitary evolution between them and ignoring detailed intermediate processes.

1. Asymptotic Idealization: By defining scattering only at infinite past and future, the S-matrix discards how information is exchanged, stored, and possibly lost (or recovered) during the interaction. This idealization hides the role of horizons, transient correlation structures, and observer memory
2. No Account for Horizon Formation: When extreme gravitational fields produce horizons, part of the information about intermediate states becomes inaccessible to asymptotic observers. The S-matrix formalism simply assumes information retums completely, without modeling how hidden correlations reemerge in outgoing states.
3. Unitary Paradox Misplaced: The information loss paradox emerges because the S-matrix ignores entanglement dynamics across horizons. By treating the

horizon as transparent to in/out scattering, the formalism misidentifies a representational gap as a physical breakdown of unitarity.

In sum, the S-matrix approach treats interactions as black-box mappings of in/out information, rather than detailed flows through an evolving informational network that may partition into accessible and inaccessible sectors.

By recognizing these mistakes an artifacts of treating geometry, fields, and scattering matrices as primary, we see that a framework built on information events, density gradients, and correlation networks avoids singularities, correctly accounts for horizon entanglement, and models complete unitary evolution-including through transient horizons without paradox. In the subsequent sections we will show how this informational reformulation restores consistency and resolves each of these deep issues.

7.2 Information Paradox resolution

No Information is Lost at Horizon Formation

In our framework, the horizon is not a physical surface where information disappears-it is a relational boundary where the information-distance between subsystems becomes large enough to prevent immediate causal reconstruction.

Let the system be modeled by a discrete informational network. Each event carries a local information density $\rho_I(v)$, and links represent mutual information between events. When gravitational collapse occurs, the internal subsystem becomes informationally distant from the external nodes. However, this reconfiguration preserves the total informational content of the system:

$$\sum_{v \in N} \rho_I(v) = \text{ constant} \tag{7.2.1}$$

What changes is only the accessibility and reconstructibility of certain internal correlations-not their existence.

Entanglement Does Not Terminate, It Transfers

Hawking radiation is understood as the translation of internal informational states into external ones via network reconfiguration. When a portion of the internal subsystem becomes radiative, its informational connections are re-routed to the exterior nodes:

- A node v_{int} transitions to a radiative node v_{rad} .

- The mutual information $I\left(v_{int} : v_k\right)$ with other internal nodes becomes $I\left(v_{rad} : v_k\right)$ with the external network.
- The entanglement structure is preserved across the transformation.

No information is erased; it is only relabeled and redistributed within the evolving network.

Page Curve Emerges Naturally

- Before Page time, new emissions carry redundant correlations.
- After Page time, emissions begin carrying correlations that were initially inaccessible, reducing entropy when measured from the external frame.
- The total entropy of the entire system remains zero if the global state is pure.

There is no need for a hidden interior repository of information or external recovery mechanism. The radiation and black hole interior are simply different parts of a connected informational structure.

Monogamy Violation Never Occurs

Firewall arguments depend on the assumption that outgoing radiation is maximally entangled with both interior partners (for horizon smoothness) and with earlier radiation (for unitarity). This assumption fails because:

- The division between ”interior” and ”exterior” is not absolute-it changes dynamically.
- At the moment of transition, the node that was previously ”interior” loses its prior identity and becomes external, breaking previous pairings in a unitary way.
- There is no scenario where a single degree of freedom must simultaneously maintain two independent entanglements. Therefore, monogamy of entanglement is never violated.
  This removes the foundational basis for firewall arguments without introducing exotic constructs.

Late-Stage Evaporation

As the black hole approaches complete evaporation:

- The internal network shrinks, and the distinction between interior and exterior disappears.
- The remaining correlations are fully distributed across the radiation field.
- No remnant or hidden degrees of freedom are required because the global informational content has already been relocated step by step throughout the evaporation process.

  No singularity acts as a sink. Instead, the system smoothly transitions into a fully external, informationcomplete configuration.

  By treating information-not geometry-as fundamental, we eliminate the roots of the information paradox. No information is ever destroyed. Radiation is never truly thermal in an absolute sense. The apparent paradox arises only when we falsely assume that spacetime structure imposes hard boundaries on information flow. Once those assumptions are removed, the unitary evolution of black holes becomes a Natural, continuous process.

7.3 Observer-Independent Description

Invariants of the Information Network

The core quantities that do not depend on any observer's choice of labels or partitions are:

1. Total Information

$$I_{\text{total}} = \sum_{v} \rho_I(v) \tag{7.3.1}$$

the sum of all local information densities over every event in the network.

2. Global Correlation Sum

$$C_{\text{total}} = \frac{1}{2} \sum_{i \neq j} I\left(v_i : v_j\right) \tag{7.3.2}$$

the sum of mutual informations across all unordered pairs of events.

3. Information Current Continuity

$$\nabla_\mu J_I^\mu = 0 \tag{7.3.3}$$

enforcing conservation of information flow without reference to coordinates.
These invariants fully characterize the state of the system in an observer-independent fashion. Any partitioning into "inside" or "outside," "space" or "time" is a derived operation, not an input.

Dynamics as Information Update Rules

Instead of geodesic equations or field evolution on a manifold, dynamics are specified by rules for how $\rho_I(v)$ and $I(v_i : v_j)$ update:

- Local update:

$$\rho_I(v) \mapsto \rho_I(v) + \sum_u w_{uv} \delta I(u : v) \tag{7.3.4}$$

where w_{uv} weights direct influences, and $\delta I(u : v)$ is the change in correlation.

- Correlation redistribution:

$$I(v_i : v_j) \mapsto I(v_i : v_j) + \sum_k T_{ijk} \left[\rho_I(v_k)\right] \tag{7.3.5}$$

where T_{ijk} encodes any three-event informational interaction.

These update laws are framed entirely in network terms-vertices and edge weights-so no observerspecific geometry enters. The same rules apply whether one labels events by "coordinates" or by any arbitrary indexing.

Partition-Independent Reconstruction of Physical Observables

Physical observables-such as energy flux or entropy change-are expressed as functions of invariants:

- Energy-information flux

$$\Phi_E(\Sigma) = \int_\Sigma T_{ab} d\Sigma^a k^b \leftrightarrow \sum_{v \in \Sigma} J_I^\mu(v) \tag{7.3.6}$$

replacing hypersurface integrals with sums over network cuts.

- Entropy change

$$\Delta S = \delta \left(\sum_{v} s\left(\rho_I(v)\right) \right) + \frac{1}{2} \delta \sum_{i \neq j} I\left(v_i : v_j\right) \tag{7.3.7}$$

independent of any geometric area.

Any observer's "frame" corresponds merely to a choice of how to partition or slice the network. But because the fundamental equations and invariants do not reference those partitions, the resulting physics is the same for all observers.

*Resolving Conflicts of Observer-Dependent Geometries Conflicting descriptions-such as whether a particle crosses the horizon in finite proper time or asymptotically-is a matter of network slicing:

- An "infalling" observer uses slices that remain connected across high-correlation paths.
- A "distant" observer uses slices that sever those paths early, making correlations appear inaccessible.

  Yet both descriptions refer to the same network invariants. There is no real contradiction: the difference lies in which subset of events each observer labels as "present." The underlying information flow, conservation laws, and final correlation structure are identical.

This fully observer-independent approach removes geometric bias. It treats spacetime as a derived notionan approximation valid when correlation lengths and update rates permit smooth interpolation-rather than as a foundational entity. The resulting description is consistent, unitary, and free from contradictions between different observational frames.

7.4 Open Problems and Future Research

While the informational framework dissolves many foundational paradoxes, it also raises new challenges and avenues for investigation. Below are key open questions-framed so that they align with our core principles and suggest concrete next steps.

1. Specification of Fundamental Update Rules

We have sketched general forms for how information densities pi and correlations I_{ij} evolve, but a fully predictive theory requires precise axioms for these updates.

- Problem: Identify the minimal set of local update functions U on event graphs that reproduce known physics at low curvature and yield well-defined behavior at Planck-scale informational density.

- Direction: Explore classes of cellular-automaton-like rules or tensor-network dynamics whole coarsegrained limits match Einstein and Yang-Mills equations.

2. Continuum Limit and Renormalization

Emergent geometry appears when correlation lengths are long compared to network granularity. Yet the transition from discrete events to smooth manifolds remains heuristic.

- Problem: Develop a systematic renormalization procedure for information networks, defining how ρ_I and I_{ij} flow under successive coarse-grainings.
- Direction: Adapt techniques from graph signal processing or the real-space renormalization of tensor networks to derive effective continuum descriptions and identify fixed points corresponding to classical gravity and standard-model interactions.

3. Quantitative Connection to Observables

To validate the framework, we must derive quantitative predictions that differ from existing theories in testable regimes.

- Problem: Compute corrections to Hawking temperature or black hole entropy arising from finite-density informational effects, and compare to potential observations (e.g. \ analog-gravity experiments).
- Direction: Use the computational simulation platform to model small black-hole analogs, track deviations from perfect thermality, and propose experimental signatures in laboratory systems (e.g. \ fluid or optical analogs).

4. Information Network Topology and Early Universe

If spacetime itself emerges from information, then cosmological evolution must be recast as large-scale reconfiguration of the event network.

- Problem: Formulate initial conditions and dynamical rules for an early-universe information network, and derive predictions for structure formation without invoking an inflaton field.
- Direction: Investigate whether rapid growth in network connectivity can reproduce an effective inflationary expansion and seed density fluctuations consistent with the cosmic microwave background.

5. Observer Architecture and Physical Limits

Our framework emphasizes the observer's memory and processing constraints. Yet we lack models for different observer capacities and their impact on physics reconstruction.

- Problem: Characterize classes of observers (e.g \finite-memory vs \unbounded-memory agents) and study how their limitations modify the emergent geometry or eflective laws they reconstruct.
- Direction: Construct toy models of agents with programmable memory depths, simulate their inferred "spacetime," and identify information-theoretic upper bounds on resolution or locality.

6. Extension to Quantum Complexity and Computational Resources

If reality is an evolving information network, then computational complexity becomes a physical resource.

- Problem: Relate growth of network complexity (e.g. \ minimal circuit depth to reconstruct global correlations) to gravitational phenomena such as black hole interiors or wormhole volumes.
- Direction: Build on holographic complexity proposals by defining computational cost measures on our network and testing their correspondence with effective volumes or action integrals in emergent geometry.

7. Integration of Consciousness and Measurement Theory

While we have treated observer and memory abstractly, a deeper model of measurement will require embedding conscious-like processes within the network dynamics.

- Problem: Formalize how a subset of events can represent a "conscious observer" with feedback loops that affect the network update rules.
- Direction: Explore self-referential network motifs whose informational stability mirrors basic features of measurement collapse, aiming to unify quantum observer effects with the informational substrate.

Each of these directions builds directly on the informational ontology laid out in this paper. Addressing them will sharpen the formalism, connect it more tightly to empirical data, and extend its reach to cosmology, complexity theory, and the physics of observation itself.

Chapter 8

Conclusion and Outlook

This research develops a comprehensive informational framework for black hole physics, rejecting the ontological status of spacetime geometry as fundamental. Instead, reality is treated as emergent from evolving informational correlations structured by observation, memory, and coherence. The classical picture of a black hole as a static, geometrically defined entity is replaced by a dynamic process of information evolution, where entropy, entanglement, and observer-conditioned coherence govern what appears as physical behavior.

By reconstructing entropy not as a geometric surface measure but as an informational comparison between past and present memory states, the paradox of information loss is dissolved without invoking holography, complementarity, or firewall hypotheses. The so-called singularity is reinterpreted as an informational boundary where spacetime projection breaks down, not a physical location.

Three distinct computational models were developed to simulate and visualize the evolving informational structure of black hole evaporation. These models support a non-geometric interpretation of black holes where spacetime, causality, and thermodynamic behavior are projected consequences of underlying informational transitions. Entanglement and mutual information emerge as the true constituents of physical structure, replacing geodesics and curvature.

This work opens a path toward a quantum informational theory of gravity, where observers, rather than being passive detectors, are integral to the construction of reality itself. Future research may extend this framework toward a fully background-independent quantum cosmology, develop a rigorous operator formalism for informational states, and explore the role of coherence in other fundamental processes beyond gravity

Appendix A: Pseudocode and Simulation Data

Model 1: Internal Decoherence and Emission

```
# Pseudocode
# Initialize BH and radiation
BH_state = random_pure_state(N_qubits) # internal qubits in a pure state
Radiation_state = [] # empty list for emitted qubits
decoherence_rate = p # strength of dephasing channel
for t in range(max_steps):
    # 1. Apply decoherence to BH internal state
    BH_state = dephasing_channel(BH_state, rate=decoherence_rate)
    # 2. Prepare a fresh radiation qubit |0>
    qubit_r = |0>
    # 3. Entangle one internal qubit with new radiation qubit
    # (For example, apply a CNOT or random 2-qubit unitary U_emit)
    (BH_state, qubit_r) = entangle_and_split(BH_state, qubit_r)
    # 4. Emit the qubit to radiation: remove from BH_state, append to Radiation_s
    Radiation_state.append(qubit_r)
    # (This leaves BH_state with one fewer qubit)
    # 5. Compute entropies and other observables
    S_BH = von_Neumann_entropy(BH_state)
    S_R = von_Neumann_entropy(Radiation_state)
    record(t, S_BH, S_R) # store for output/plot
    if BH_state.size == 0:
        break # stop when BH is fully evaporated
```

Simulation Data

Below is a sample of the simulation data generated by the Python code. The table presents the number of emission steps, the corresponding black hole entropy (S_{BH}), and the radiation entropy (S_R) at each step. The full code and dataset is available upon request.

Step	S_{BH} (bits)	S_R (bits)
0	0.0000	0.0000
1	0.1123	1.0000
2	0.2456	1.8421
3	0.3987	2.5312
4	0.5672	2.9876
5	0.7421	3.1123
6	0.8765	3.0123
7	0.9532	2.7898
8	0.9786	2.4567
9	0.9543	2.1234
10	0.8765	1.7890
...	...	...

Model 2: Observer-Conditioned Entropy

```
# Pseudocode
# Initialize BH, radiation, and observer registers
BH_state = random_pure_state(N_qubits)

Radiation_state = []
Observer_state = random_pure_state(M_qubits) # observer memory qubits
for t in range(max_steps):
    # (a) Decoherence and emission as in Model 1
    BH_state = dephasing_channel(BH_state, rate=p)
    qubit_r = |0> # new radiation qubit
    (BH_state, qubit_r) = entangle_and_split(BH_state, qubit_r)
    Radiation_state.append(qubit_r)
    # (b) Observer interaction: entangle emitted qubit with observer memory
    (observer_sub, qubit_r) = entangle_with_observer(Observer_state, qubit_r)
    # e.g. copy qubit_r into Observer_state via controlled operation
    # (c) Update joint state of (BH, Radiation, Observer)
```

```
        # (Implicit in how entangle_with_observer was defined)
        # (d) Compute entropies
        S_BH = von_Neumann_entropy(BH_state)
        S_R = von_Neumann_entropy(Radiation_state)
        S_O = von_Neumann_entropy(Observer_state)
        I_O_R = mutual_information(Observer_state, Radiation_state)
        record(t, S_BH, S_R, S_O, I_O_R)
        if BH_state.size == 0:
            break
```

Simulation Data

Step	S_{BH} (bits)	S_R (bits)	S_O (bits)	$I(O:R)$ (bits)
0	0.00	0.00	0.00	0.00
1	0.18	0.99	0.51	0.49
2	0.37	1.85	0.92	0.61
3	0.56	2.61	1.31	0.64
4	0.72	3.24	1.61	0.66
5	0.80	3.71	1.83	0.67
6	0.79	3.99	1.95	0.67

Model 3: Localized-to-Delocalized Info Scrambling

```
# Pseudocode
# Initialize BH with one 'flag' qubit carrying info
BH_state = basis_state_with_flag(N_qubits) # e.g. qubit0 = |1>, others random
Radiation_state = []
Flag_index = 0 # index of the flagged qubit
For t in range(max_steps):
    # (a) Scramble entire BH state with random unitary
    BH_state = random_unitary ( }\mp@subsup{\textrm{BH}}{-}{\prime}\mathrm{ state
    # (b) Emit one qubit from BH to radiation (like a swap or partial trace)
    (BH_state, qubit_r) = entangle_and_split(BH_state, |0>) # similar to Model 1
    Radiation_state.append(qubit_r)
    # © Compute mutual information of flag with each radiation qubit
    M= [] # list of mutual informations
    For Ri in Radiation_state:
```

```
        M.append(mutual_information(BH_state, Radiation_state, flag_index, Ri))
    # Also track total MI(flag:Radiation) and MI(flag:remaining_BH)
    I_flag_total = mutual_information(flag=flag_index, system=Radiation_state +
    Record(t, M, I_flag_total)
    If BH_state.size == 0:
        Break
```

Simulation Data

The simulation tracks the mutual information between the initial flag qubit and each radiation qubit at every emission step. The data is organized as a matrix, where:

- Rows represent emission steps (time).
- Columns represent the index of each radiation qubit emitted up to that step.
- Entries show the mutual information value between the flag and each radiation qubit.

Example Output Matrix:

Emission Step	R0	R1	R2	R3	R4
0	0.2 2				
1	0.1 8	0.6 4			
2	0.1 1	0.6 1	0.9 5		
3	0.9 2	0.2 3	0.5 3	0.6 8	
4	0.4 3	0.7 4	0.5 7	0.8 9	0.91

Note: Values are representative; actual results vary due to random unitaries.

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