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Article

Modifying Horizon Backreaction Mechanisms: Scrambling, Error Correction, and the Page Curve

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Abstract

This work develops a microscopic perspective on black hole information dynamics consistent with the Page curve. Gravitational backreaction ensures that infalling matter immediately influences outgoing Hawking radiation, but chaotic horizon degrees of freedom render this influence highly mixed and inaccessible before the Page time. Incorporating fast scrambling and horizon-level quantum error correction shows how information gradually becomes recoverable in the radiation after the Page time, reconciling causal immediacy with the statistical evolution captured by the Page curve. The analysis is largely pedagogical, emphasizing conceptual clarity and the interplay between backreaction, scrambling, and charge-parity-time (CPT) conjugate encoding in preserving unitarity.

Keywords: blackhole; blackhole information paradox; backreaction mechanism

I. Introduction

It has been more than four decades since Hawking's groundbreaking discovery that black holes radiate thermally [1,2], and yet the fate of information falling into a black hole remains one of the deepest puzzles in modern physics. Initially, Hawking argued that the causal structure of classical black hole spacetimes implies that information entering the horizon cannot be recovered in the emitted radiation, resulting in a mixed final state even if the black hole began as a pure state [3]. This led to the formulation of the black hole information paradox [4]: the apparent tension between quantum unitarity and semiclassical gravity.

Over the years, several complementary ideas have been proposed to address this paradox, including black hole complementarity [5,6], the holographic principle, and the AdS/CFT correspondence [7,8], each suggesting that information is not destroyed but encoded in subtle correlations of the radiation. The holographic principle and its realization in string theory [9] have provided a strong theoretical scaffolding, suggesting that black holes are fundamentally consistent with quantum mechanics. The leading proposal of complementarity [5,6], however, faces the firewall problem. Almheiri, Marolf, Polchinski, and Sully (AMPS) [10,11] argued that the attempt to extract information by purifying the early Hawking radiation through maximal entanglement with the late Hawking radiation would result in a firewall [see also [12]], which would incinerate any observer attempting to cross the horizon.

A particularly sharp formulation of the information problem was given by Page [13,14,15], who computed the expected entanglement entropy of Hawking radiation under the assumption of unitary evolution, leading to the well-known Page curve. His result predicts that information begins to be released only after the black hole has radiated away roughly half of its entropy the "Page time". Building on this, Hayden and Preskill [16] introduced the perspective of black holes as fast scramblers, demonstrating that an old black hole, already entangled with its radiation, reflects newly infalling quantum information almost immediately after a scrambling time [see also [17]]. More recently, the island formula [18,19] has provided geometric interpretations for how information is encoded in the entanglement structure of spacetime. The island prescription, in particular, represents significant progress by combining classical gravity (through geometry) with quantum field theory (through

entanglement entropy) to describe how information is shared between the black hole interior and the emitted radiation.

Despite these advances, a crucial limitation remains: none of the existing proposals — whether complementarity, the Page curve, the firewall argument, AdS/CFT duality, or the island formula provide a true microscopic mechanism for how information leaks out of the black hole. These frameworks describe when and how much information must be released to preserve unitarity, but they do not specify the underlying physical processes by which microscopic degrees of freedom at the horizon encode and transfer information into Hawking radiation. Gerard 't Hooft made an early attempt in this direction by invoking gravitational backreaction effects near the horizon [20,21,22,23]. While his approach captured an essential physical ingredient, it faced serious difficulties: it failed to reproduce the Page curve, could not account for the characteristic rise and fall of entanglement entropy, and violated charge-parity-time (CPT) invariance in its strong form.

This gap underscores the pressing need for a physically plausible, microscopic mechanism that both preserves unitarity and explains the leakage of information at the level of fundamental dynamics. In this paper, we propose such a mechanism by building on 't Hooft's backreaction approach while extending his framework to include quantum error correction and the scrambling of information at the horizon. Our framework combines gravitational backreaction with horizon dynamics, ensuring that the evolution of information aligns with the Page curve and respects CPT invariance. With these enhancements, we present a model in which information gradually escapes from the black hole, encoded in subtle correlations resulting from scrambling, error correction, and energy-conserving processes at the horizon.

The aim of this letter is not to present a fully derived microscopic mechanism but rather to introduce a novel refinement of 't Hooft's scattering approach, motivated by recent insights on scrambling, error correction, and horizon encoding. A complete derivation will be provided in a forthcoming paper. The paper is organized as follows. Section II reviews 't Hooft's mechanism and sets the stage for our proposed framework by highlighting its limitations and identifying the necessary ingredients for improvement. Section III introduces our modified microscopic mechanism, developed through a Bob-and-Alice thought experiment, in which information is scrambled, error-corrected, and gradually released through horizon dynamics. Section IV concludes with a discussion of the implications of our model, its consistency with unitarity and the Page curve, and possible directions for future investigation.

II. Setting the Stage: Revisiting 't Hooft's Blackhole Mechanism

One of the earliest systematic attempts to identify a microscopic mechanism for information conservation in black holes was advanced by 't Hooft through the study of gravitational backreaction at the horizon [24]. In his approach, the essential idea is that infalling matter produces a shockwave that shifts the trajectories of outgoing Hawking particles. This shift imprints information about the ingoing state on the outgoing modes, providing the seed of a horizon S-matrix. Physically, particles going in interact with the outgoing Hawking quanta, modifying their quantum states while leaving the thermodynamical distribution essentially unaffected [24,25]. This effect cannot be achieved by Standard Model interactions alone, but near the horizon, gravitational interactions dominate, leading to a unitary relation between ingoing and outgoing states.

The first formulation of this idea begins with describing the in-going and out-going excitations in terms of distributions on the horizon two-sphere. Let $p_{\text{in}}(\Omega)$ denote the momentum distribution of matter falling into the black hole, and $p_{\text{out}}(\Omega)$ the distribution of outgoing Hawking quanta, where $\Omega = (\theta, \phi)$ labels angular position on the horizon [25,26,27]. The canonically conjugate position operators are $u_{\text{in}}(\Omega)$ and $u_{\text{out}}(\Omega)$, which together obey the local commutation relations

$$[u_{\text{in}}(\Omega), p_{\text{in}}(\Omega')] = i\delta^2(\Omega - \Omega'), \quad [u_{\text{out}}(\Omega), p_{\text{out}}(\Omega')] = i\delta^2(\Omega - \Omega'). \quad (1)$$

These relations establish that each point on the horizon carries canonical degrees of freedom analogous to a field theory defined on the two-sphere.

The effect of gravitational backreaction, derived in the Rindler limit by Dray and 't Hooft, is to produce a displacement of the outgoing positions proportional to the momentum of ingoing matter [25,27]. Explicitly, the operator $u_{\text{out}}(\Omega)$ is shifted according to

$$u_{\text{out}}(\Omega) \rightarrow u_{\text{out}}(\Omega) + 8\pi GR^2 \int d\Omega' f(\Omega, \Omega') p_{\text{in}}(\Omega'), \quad (2)$$

where $R = 2GM$ is the horizon radius and $f(\Omega, \Omega')$ is the Green's function on the unit two-sphere, defined by $\Delta_{\Omega} f(\Omega, \Omega') = -\delta^2(\Omega - \Omega')$ with Δ_{Ω} the Laplacian on S^2 . Physically, this equation means that an ingoing shell of matter generates a shockwave that shifts the outgoing geodesics by an angle-dependent amount, directly encoding the incoming momentum into the outgoing position variable. The dynamics is unitary.

To make this algebra tractable, one expands the horizon variables into spherical harmonics:[26,27]

$$p(\Omega) = \sum_{\ell, m} p_{\ell m} Y_{\ell m}(\Omega), \quad u(\Omega) = \sum_{\ell, m} u_{\ell m} Y_{\ell m}(\Omega), \quad (3)$$

so that the canonical commutator (1) reduces to mode-by-mode relations

$$[u_{\ell m}, p_{\ell' m'}] = i\delta_{\ell\ell'}\delta_{mm'}. \quad (4)$$

In this basis, the backreaction simplifies dramatically: for each mode one finds a proportionality between an outgoing position and the ingoing momentum,

$$u_{\ell m}^{\text{out}} = \frac{8\pi GR^2}{\ell(\ell+1)+1} p_{\ell m}^{\text{in}} \quad (5)$$

with analogous relations for the conjugate variables [26,27]. Each (ℓ, m) thus behaves as an independent quantum mechanical system, allowing the horizon to be represented as a direct product of such mode algebras.

A crucial feature of this construction is the necessity of a cutoff in angular momentum. Without restriction, the number of independent modes would diverge, leading to an infinite-dimensional Hilbert space. 't Hooft proposed a natural cutoff $\ell_{\text{max}} \sim R/\ell_P$, which ensures that the total number of horizon degrees of freedom scales as

$$N \sim \sum_{\ell \leq \ell_{\text{max}}} (2\ell+1) \sim \ell_{\text{max}}^2 \sim \frac{R^2}{\ell_P^2} \sim \frac{A}{\ell_P^2}, \quad (6)$$

reproducing the Bekenstein–Hawking entropy law $S_{\text{BH}} = A/4G$ up to constants. Thus the backreaction algebra not only encodes information transfer but also provides a microstate counting consistent with black hole thermodynamics.

This original formulation still contained a duplication problem: the maximally extended Schwarzschild geometry contains two exterior regions, suggesting a doubling of the Hilbert space. 't Hooft later resolved this by proposing an antipodal identification [27]. In this approach, each point on the horizon is mapped to its antipode, such that

$$(u_{\text{in}}^+, u_{\text{out}}) \longleftrightarrow (u_{\text{in}}^+, u_{\text{out}})_{\text{antipode}}. \quad (7)$$

Physically, this means that the wavefunctions in region II correspond to the same black hole as in region I, but with the time direction effectively reversed in the Penrose diagram. Classical particles entering region II do not represent independent degrees of freedom—they appear as the negative energy counterparts of region I particles, or equivalently, as annihilated modes.

For quantum mechanics, this identification is crucial. Wavefunctions have support across both regions, so in-going or outgoing waves in region I extend into region II. The antipodal mapping ensures that both signs of the position operators for the in-going and out-going shells of matter are included, which is necessary for unitarity. Importantly, the two antipodal points never come close together, preventing any singularities from forming. This construction effectively eliminates the black hole interior as an independent region and enforces global unitarity by correlating opposite points on the horizon.

More recently, in *Quantum Clones inside Black Holes* [28], 't Hooft refined the proposal by introducing the notion of quantum clones. Rather than treating region II as identical to region I under antipodal mapping, it is treated as its CPT conjugate. Explicitly, the wavefunctions in region II are constrained to be exact complex conjugates of those in region I,

$$\Psi_{\text{II}}(u) = \Psi_{\text{I}}^*(u), \quad (8)$$

so that no independent duplication of degrees of freedom arises. This construction preserves CPT invariance and maintains a one-to-one correspondence with Bekenstein–Hawking entropy, but at the cost of introducing a nonstandard interpretation of quantum mechanics, since it resembles a form of “quantum cloning” normally forbidden in standard frameworks. The Hamiltonian in this formulation is imaginary and antisymmetric, allowing all physical wavefunctions to be taken real, and hence ensuring unitary evolution.

Taken together, these developments constitute one of the earliest and most concrete attempts to formulate a microscopic mechanism for information conservation in black holes. 't Hooft's approach demonstrates explicitly how gravitational backreaction couples infalling matter with outgoing Hawking quanta, providing a unitary mapping at the horizon and offering a first step toward a horizon-based S-matrix formulation. The construction reproduces the correct scaling of black hole entropy and addresses duplication issues through antipodal identification and quantum cloning.

However, despite these successes, the framework requires significant modifications. The original formulation does not reproduce the Page curve, as information appears to be reflected almost immediately rather than being gradually released, violating expectations from semiclassical Hawking emission. Moreover, the quantum clone interpretation introduces nonstandard elements that challenge CPT invariance in conventional quantum mechanics. The approach is also highly sensitive to trans-Planckian modes and lacks a built-in mechanism for microscopic scrambling or quantum error correction. These limitations highlight that, while pioneering, 't Hooft's mechanism remains an incomplete model, pointing toward the need for extensions that reconcile horizon-level scattering with the full semiclassical and entropic dynamics of black hole evaporation.

III. Modifying Horizon Backreaction: Towards a Page Curve-Consistent Mechanism

While 't Hooft's scattering approach represents one of the earliest microscopic mechanisms for black hole unitarity [21,22,23], it faces several limitations when compared to modern expectations and does not reproduce the Page curve, which is now regarded as a hallmark of unitary black hole evaporation [14]. Here, I extend this idea by incorporating the scrambling of information at the external horizon degrees of freedom, where information injected into the black hole takes time to become randomly distributed across the horizon. In 't Hooft's framework, ingoing matter influences outgoing Hawking radiation via gravitational backreaction. Denoting the momentum distribution of ingoing matter by $p_{\text{in}}(\Omega)$ and the outgoing horizon position operators by $u_{\text{out}}(\Omega)$, the backreaction shifts the outgoing positions as (2)

$$u_{\text{out}}(\Omega) \rightarrow u_{\text{out}}(\Omega) + 8\pi GR^2 \int d\Omega' f(\Omega, \Omega') p_{\text{in}}(\Omega'), \quad (1)$$

where R is the horizon radius and $f(\Omega, \Omega')$ is the Green's function on the unit two-sphere. This effect is instantaneous, meaning that information carried by Alice's qubit modifies the outgoing radiation immediately [also see [17] for Bob and Alice thought experiment]. However, because the black hole possesses an enormous number of horizon degrees of freedom, the information is rapidly scrambled; the black hole acts as a fast scrambler with scrambling time [16,17]

$$t_{\text{scr}} \sim \frac{\beta}{2\pi} \ln S_h \sim R \ln \frac{R}{\ell_p}, \quad (9)$$

where β is the inverse Hawking temperature and S_h is the black hole entropy. In this framework, I assume that the scrambling occurs at the horizon degrees of freedom, and the scrambling time is identical to the thermalization time derived by Preskill for internal black hole degrees of freedom [17]. This assumption is justified by a wide range of research indicating that the black hole horizon effectively encodes the information of the interior. Holographic principles suggest that all information about the bulk spacetime can be represented on the boundary [29,30], and the horizon naturally serves as this storage surface. Moreover, following ideas analogous to 't Hooft's horizon cloning [27,28] and recent discussions by Neil Turok on black mirrors[31], the interior degrees of freedom can be viewed as the CPT conjugate of the horizon degrees of freedom. Consequently, information is redundantly encoded at the horizon, allowing it to be both scrambled and preserved, in agreement with unitarity and the fast-scrambling behavior expected of black holes.

Let us consider a black hole of semiclassical entropy S_h and surrounding radiation with thermodynamic entropy S_r . The black hole Hilbert space has dimension $n \sim e^{S_h}$ and the radiation Hilbert space dimension $m \sim e^{S_r}$. Assuming that the combined system (black hole + radiation) is in a pure state $|\Psi\rangle$ with density matrix $\rho_{rh} = |\Psi\rangle\langle\Psi|$, the reduced density matrices for the subsystems are $\rho_r = \text{Tr}_h(\rho_{rh})$ and $\rho_h = \text{Tr}_r(\rho_{rh})$, with von Neumann entropies $S_r = -\text{Tr}(\rho_r \ln \rho_r)$ and $S_h = -\text{Tr}(\rho_h \ln \rho_h)$. The information content in the radiation is defined as the deviation from maximal entropy: $I_r = \ln m - S_r \approx S_r - S_r^{\text{ent}}$, $I_h = \ln n - S_h$.

Due to fast scrambling, the information is initially spread randomly across all exterior degrees of freedom, making the outgoing radiation appear nearly thermal. Even though Alice's qubit has influenced the outgoing radiation through backreaction, Bob cannot decode the information because it is highly mixed and distributed across an enormous Hilbert space. Only after the radiation subsystem becomes comparable in size to the black hole, i.e., after the Page time, does the information begin to accumulate in the radiation in a measurable way. Denoting the horizon Hilbert space as H_{horizon} with dimension $N \sim e^{S_{\text{BH}}}$, the information initially localized in some state $|\psi_{\text{in}}\rangle$ becomes encoded in a highly mixed state on the horizon:

$$|\psi_{\text{horizon}}\rangle = U_{\text{scr}}|\psi_{\text{in}}\rangle, \quad (10)$$

where U_{scr} is a fast-scrambling unitary acting on the horizon degrees of freedom. The interior Hilbert space is the CPT conjugate of the exterior, $H_{\text{int}} \simeq H_{\text{ext}}^*$, so the horizon effectively encodes all information from the interior. The reduced density matrix for the outgoing radiation is then

$$\rho_{\text{out}}(t) = \text{Tr}_{\text{Horizon}} \left[U_{\text{scr}}(t) |\psi_{\text{horizon}}\rangle \langle \psi_{\text{horizon}}| U_{\text{scr}}^\dagger(t) \right], \quad (11)$$

and the information is initially inaccessible. Bob observes only a nearly thermal state, and decoding Alice's information requires access to correlations spread across nearly the entire horizon Hilbert space. After the Page time t_{Page} , when a sufficient fraction of horizon degrees of freedom have been radiated away, the outgoing radiation becomes sufficiently purified, and the information becomes accessible:

$$I_{\text{Bob}}(t) \approx \begin{cases} 0, & t < t_{\text{Page}}, \\ I_{\text{Alice}}, & t \geq t_{\text{Page}}. \end{cases} \quad (12)$$

Explicitly, modeling the scrambling as a random unitary $U_{\text{scr}} \in U(N)$, for k qubits of Alice's information, the reduced density matrix of the outgoing radiation after the Page time is approximately

$$\rho_{\text{out}}(k) \approx \frac{1}{2^k} \sum_{i=1}^{2^k} |i\rangle\langle i| + \epsilon, \quad (13)$$

where ϵ represents small corrections due to entanglement with the remaining horizon degrees of freedom. The information flux then evolves as

$$\frac{dI_{\text{out}}}{dt} \sim \frac{k}{t_{\text{Page}}}, \quad t \gtrsim t_{\text{Page}}, \quad (14)$$

reproducing the Page curve while preserving the instantaneous imprint of 't Hooft backreaction. This approach demonstrates that although information enters the horizon and affects outgoing radiation immediately, fast scrambling and CPT mirror encoding hide it in a highly mixed state, and only after sufficient radiation has been emitted does it become observable. In this way, we reconcile 't Hooft's microscopic backreaction with unitarity and quantum information theory.

IV. Discussion and Conclusions

In this work, we have revisited and extended 't Hooft's pioneering framework of horizon backreaction to provide a microscopic mechanism for black hole information recovery that is consistent with the Page curve and modern insights from quantum information theory. A central feature of 't Hooft's original proposal is the instantaneous imprinting of information: infalling matter modifies the outgoing Hawking radiation immediately through gravitational backreaction. While this establishes a direct coupling between ingoing and outgoing degrees of freedom, the mechanism alone does not explain the gradual recovery of information observed in unitary black hole evaporation, as encoded by the Page curve.

By incorporating the scrambling of information across the horizon degrees of freedom, our framework addresses this limitation. Although information is initially imprinted on the outgoing modes, the enormous number of horizon degrees of freedom ensures that this information becomes highly mixed almost immediately. The horizon behaves as a fast scrambler, with a characteristic scrambling time $t_{\text{scr}} \sim (\beta/2\pi) \ln S_h \sim R \ln(R/\ell_p)$, during which the information spreads pseudo-randomly over the horizon Hilbert space. As a result, the outgoing radiation appears nearly thermal to an external observer prior to the Page time, even though the underlying microscopic dynamics preserves unitarity. This duality of instant imprinting and chaotic mixing captures both the causal immediacy of 't Hooft's backreaction and the statistical concealment of information until a sufficient fraction of the black hole has evaporated.

Our approach aligns with several modern developments in black hole physics while providing a more explicit microscopic mechanism. In contrast to the Page curve and island formula frameworks, which predict when and how information emerges but remain agnostic about the detailed dynamics, our model offers a concrete unitary mapping between ingoing matter and outgoing radiation, mediated by horizon degrees of freedom and fast-scrambling unitaries. Compared to Hayden-Preskill's description of black holes as fast scramblers, our work grounds the scrambling process in the physically motivated backreaction and CPT-conjugate horizon mapping, extending their idealized quantum information considerations to a horizon-specific dynamical mechanism. Furthermore, by incorporating aspects of quantum error correction, the framework accounts for redundancy and robust information encoding, which enhances the reliability of information retrieval without requiring fine-tuned assumptions about the nature of emitted radiation.

It is important to emphasize that the aim of this paper is largely pedagogical. Our goal is to present a self-consistent, conceptually transparent extension of 't Hooft's ideas, clarifying how horizon-level interactions, scrambling, and CPT-conjugate encoding jointly lead to a Page curve-consistent evolution of information. While a fully derived microscopic Hamiltonian and explicit dynamical

construction remain open problems, the current model demonstrates the principles and constraints that any successful microscopic mechanism must satisfy: (i) unitarity of black hole evaporation, (ii) fast but incomplete mixing prior to the Page time, (iii) gradual information recovery consistent with the Page curve, and (iv) preservation of CPT invariance. By situating the analysis in this pedagogical context, we aim to bridge conceptual gaps between semiclassical gravity, quantum information theory, and horizon-based scattering frameworks, making these ideas accessible for further exploration and refinement.

In conclusion, our refined horizon backreaction mechanism demonstrates how microscopic dynamics at the black hole horizon can reconcile the instantaneous imprinting of information with the apparent thermalization of Hawking radiation, producing an evolution consistent with the Page curve. This approach not only provides a clearer picture of information retention and release in evaporating black holes but also highlights the interplay between gravitational backreaction, horizon chaos, fast scrambling, and quantum error-correcting structures. While further work is required to construct an explicit Hamiltonian and explore computational feasibility for information decoding, the framework presented here constitutes a conceptually coherent, pedagogically valuable, and quantitatively suggestive model for understanding black hole unitarity and the microscopic foundations of the Page curve.

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