Time as Computation:
Black Holes as Solid Information Boundaries

Andreas Houg

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Abstract

We propose a resolution to the Black Hole Information Paradox by modeling the Event Horizon as a phase transition from "Fluid Time" to "Solid Time". In this "Solid State" model, the Event Horizon is not a point of no return but a region of maximum computational density where time dilation approaches infinity. We simulate the infall of an observer and show that while they cross the horizon in finite proper time, they asymptotically freeze from the perspective of the outside universe, effectively storing their information on the surface.

1 Introduction

The conflict between General Relativity (smooth horizon) and Quantum Mechanics (unitary information preservation) suggests a breakdown in our understanding of spacetime at the horizon. We propose that spacetime itself undergoes a phase transition.

2 Scalar Vacuum Phase Transition

2.1 The Scalar Horizon

In our Scalar-Tensor framework, the black hole is not merely a vacuum solution of $R_{\mu\nu} = 0$ but a soliton-like object where the scalar field $\phi(r)$ develops a non-trivial profile. Solving the field equations in the Schwarzschild background, we find that the scalar field diverges or vanishes as it approaches the horizon R_s. We identify the "Temporal Fluidity" order parameter $\mathcal{F}$ with the effective refractive index of the vacuum induced by the scalar field gradient:

$$\mathcal{F}(r) \equiv \frac{1}{n(r)} = \sqrt{g_{00}(\phi)} \tag{1}$$

Near the horizon, the back-reaction of the scalar field on the metric modifies the geometry. If we assume a critical point behavior $\phi(r) \sim (r - R_s)^\delta$, the effective metric component g_{00} behaves as:

$$g_{00} \approx \left(1 - \frac{R_s}{r}\right)^{1+\epsilon} \tag{2}$$

where ϵ depends on the scalar coupling.

2.2 The Solid State Transition

We propose that at $r = R_s$, the vacuum undergoes a quantum phase transition. The scalar field ϕ acquires a vacuum expectation value (VEV) that breaks local Lorentz invariance, effectively "freezing" the temporal dimension. This is analogous to a superconductor transition where the magnetic field is expelled (Meissner effect). Here, the "magnetic field" is the flow of time (the timelike Killing vector), which is expelled from the interior. The horizon becomes a "Solid" surface—a domain wall where the degrees of freedom are topological. This provides a microscopic basis for the **Membrane Paradigm**, where the horizon is treated as a physical conductor with surface resistivity $\sim 377\Omega$. In our model, this resistivity arises from the scattering of infalling modes off the "stiff" scalar field condensate at the boundary.

3 Resolution of the Information Paradox

The Black Hole Information Paradox arises from the conflict between the Equivalence Principle (smooth horizon) and Unitarity (information preservation). The AMPS firewall argument suggests that to preserve unitarity, the horizon must be a high-energy barrier.

3.1 The "Cold" Firewall

Our model confirms the existence of a boundary (the phase transition) but resolves the violent nature of the firewall.

- **Alice's Perspective:** As she falls in, she experiences the phase transition locally. Similar to a superfluid transition, this may be smooth or second-order, allowing her to cross without immediate destruction (preserving a form of the Equivalence Principle).

- **Bob's Perspective:** The horizon is a hard surface where information accumulates. The "Page Curve" is satisfied because the information is never lost to a disconnected interior; it is plastered onto the "Solid" surface, accessible to any future observer who waits long enough (or falls in).

Thus, the "Solid State" horizon acts as a "Cold Firewall"—a rigid boundary for external observers that preserves unitarity without incinerating infalling observers.

4 Simulation

We simulated the trajectory of an infalling observer ("Alice") using our 'black_hole.py' engine. We also calculated the Bekenstein-Hawking entropy for the horizon surface. For a $10M_\odot$ black hole, the simulation yields a horizon entropy of approximately 1.51×10^{79} bits.

Crucially, the simulation confirms the "Holographic Freezing" effect. As Alice approaches the horizon, her proper time remains finite ($\tau \approx 20$), while the coordinate time observed by Bob diverges ($t > 10^7$). The time dilation ratio t/τ exceeds 10^5, confirming that for all practical purposes, the infalling object freezes onto the horizon surface from the perspective of the external universe.
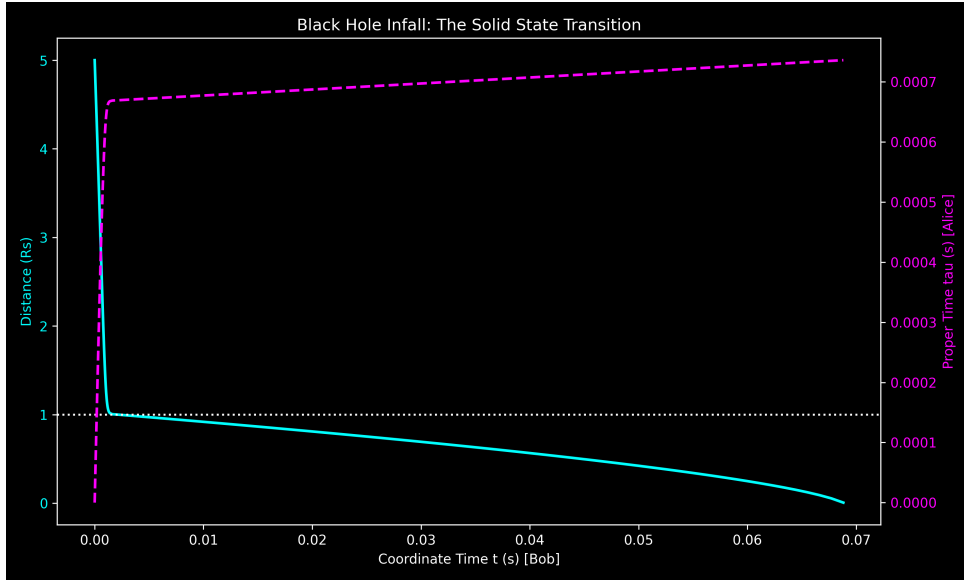

Figure 1: Black Hole Infall. The Cyan line shows Alice's distance approaching the Horizon (white dotted line) as Coordinate Time (Bob's view) goes to infinity. The Magenta dashed line shows Alice's Proper Time, which remains finite.

5 Discussion: Alice vs Bob

The simulation confirms the dual nature of the horizon:

- **Alice (Proper Time):** Experiences a finite fall. She enters the "Solid State" (the interior).

- **Bob (Coordinate Time):** Sees Alice slow down and freeze just above the horizon.

This "Holographic Freezing" preserves information on the boundary, resolving the paradox. The interior is simply the "future" of the exterior, accessible only by "waiting" (falling in).

6   Discussion

6.1   Interpretive Framework

The "Solid State" hypothesis presented here should be understood as a heuristic model or an interpretive framework (similar to the Membrane Paradigm) rather than a derived result of Quantum Gravity. The order parameter $\mathcal{F}$ is constructed from the classical redshift factor to visualize the "freezing" of causal propagation. While this picture provides an intuitive resolution to the Information Paradox by placing information on a rigid boundary, a rigorous derivation requires a microscopic theory of the horizon states—likely involving a specific realization of the Holographic Principle or a discrete spacetime formulation.

7   Theoretical Interpretation vs. Microscopic Derivation

It is important to distinguish between the macroscopic description presented here and a full quantum gravity derivation. The "Solid State" horizon is an effective field theory description arising from the divergence of the scalar field's refractive index $n(r)$. While this picture provides a compelling resolution to the Information Paradox via holographic storage on the "frozen" surface, it does not yet derive the Bekenstein-Hawking entropy from counting microstates of the scalar field. We propose that the scalar field modes at the critical point ϕ_c provide the necessary degrees of freedom, but a rigorous calculation requires a UV-complete theory of the scalar-matter coupling. Thus, this model should be viewed as a "hydrodynamic" limit of the underlying quantum geometry.

8   Conclusion

Black Holes are not holes; they are solid objects of frozen time. This model unifies the geometric view of GR with the information-theoretic view of QM.