Black Hole Interior Reconstruction and the Information Loss Paradox

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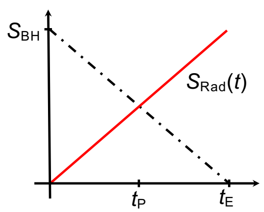
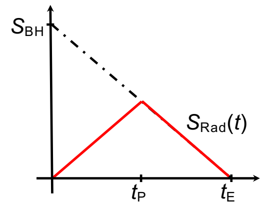
Abstract

Our project's objective is to evaluate the validity of recent attempts [1], [2] to resolve the infamous Black Hole Information Loss Paradox at a conceptual level. In broad terms, this paradox describes two contradicting theories about whether the evaporation of a black hole can be described as a unitary process. The resolution is based on a duality relation between a region *B* on the boundary of the spacetime external to a black hole, and a corresponding region in the black hole's interior, called the "entanglement wedge" of *B*. This duality relation allows information encoded in physical systems inside the black hole to be extracted from information encoded in physical systems located in its exterior. The basis for these claims centers around to what extent can quantum entanglement describe black hole evaporation, and how different notions of entropy both question the assumptions of quantum entanglement and give an alternative explanation to the black hole evaporation phenomena. Thus, our goals for the project will be to provide a comprehensive analysis of the Black Hole Information Loss Paradox, generate a conceptual map of the entanglement wedge reconstruction resolution, and evaluate how different notions of entropy relate to both the paradox and the resolution.

Information Loss Paradox[3]

How does the entanglement entropy of Hawking radiation behave?





***Hawking**: Info loss!* versus ***Page**: No info loss!*

"Info loss"?

$S_{Rad}(0) = 0 \Rightarrow$ pure initial state

$S_{Rad}(t_E) \neq 0 \Rightarrow$ mixed finial state

(Pure to mixed) ⇒ non-unitary, info loss!

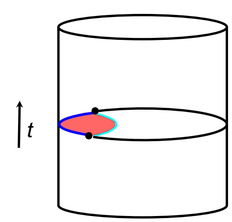
Entropy

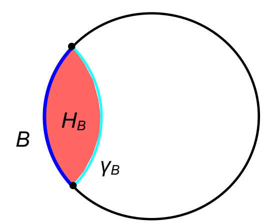
Entropy	
Thermodynamical $S_{TD}(\sigma) = \int \delta Q/T$	Ratio of heat to temperature of a physical system during a reversible process.
Statistical Mechanical $S_{Gibbs}(\rho_{mc}) = \ln\Omega(E)$	Number of possible states of a physical system with constant energy *E*.
Black Hole S_{BH} = Area(horizon)/4*G*	Area of event horizon of a black hole.
Entanglement $S_B = -\mathrm{Tr}(\rho_B \ln \rho_B)$	Degree to which the state of a subsystem of a composite system in an entangled state is mixed.

Entanglement Wedge Reconstruction [1], [2]

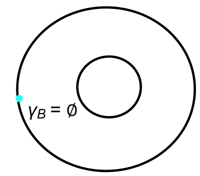
How to Calculate $S_{Rad}(t)$

RT Formula: $S_B = \mathrm{Area}(\gamma_B)/4G + S_{H_B}$



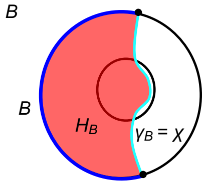


Two RT Surfaces for Evap. Black Hole [1], [2]



- RT surface ∅ (the empty surface) for an evaporting black hole for $0 < t < t_P$.
- $S_B(\emptyset)$ increases linearly from 0 to S_{BH}.

Radiation lives on *B*



- RT surface χ for an evaporating black hole for $t_P < t < t_E$.
- $S_B(\chi)$ decreases linearly from S_{BH} to 0.

Questions to Guide Future Work

(i) The RT formula and entanglement wedge resolution requires AdS/CFT: Is this applicable to the general case of an evaporating black hole?

(ii) In what sense is entanglement (as measured by mixedness) encoded in spacetime geometry (as measured by a minimal area surface)?

(iii) In what senses can black hole entropy be associated with thermodynamical and statistical mechanical entropy? In what sense can the latter be associated with entanglement entropy?

Works Cited

[1] Penington, G. (2020) 'Entanglement Wedge Reconstruction and the Information Paradox', *JHEP 09*, 002.

[2] Almheiri, A., *et al.* (2021) 'The Entropy of Hawking Radiation', *Rev Mod Phys 93*, 035002.

[3] Wallace, D. (2020) 'Why Black Hole Information Loss is Paradoxical', in Huggett, N., K. Matsubara, C. Wüthrich (eds.) *Beyond Spacetime: The Foundations of Quantum Gravity*, Cambridge Univ. Press, 209-236.

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