Black hole remnants and topology changes

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The Black Hole Information Paradox

Two facts:

1. Given a state $|\Phi, t_0\rangle$ at time t_0, we can find the state at all other times via the Schrödinger equation (i.e. times either before or after our given states)

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2. Black holes emit Hawking radiation and evaporate in a finite time (Hawking 1975)

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Information is lost during black hole evaporation!

(Brief) Overview of entanglement

- If we partition system into subsystems, the total state of system is:

$$|\Phi\rangle = \sum_{i,j} a_{ij} \, |\alpha\rangle_i \, j \otimes |\beta\rangle_{ij}$$

  - This cannot always be factored as $|\Phi\rangle = |\phi\rangle_A \otimes |\phi\rangle_B$!

- All of the information is contained in the density matrix:

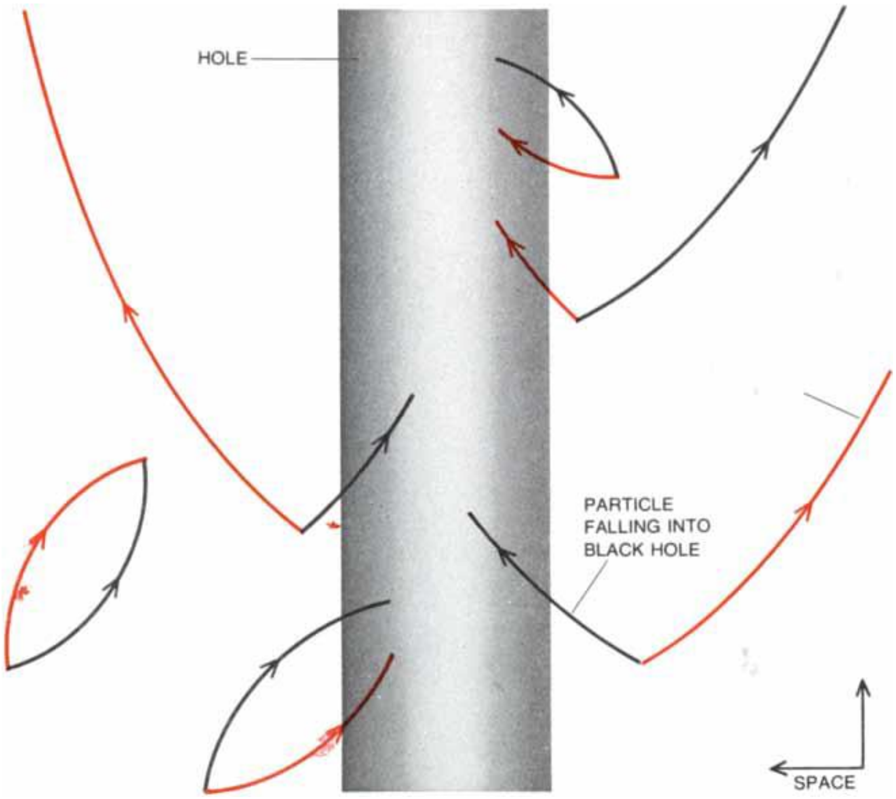
$$\rho = |\Phi\rangle \langle\Phi|$$

- In order to describe the subsystem A, we trace out the B part of the system

$$\rho_A = \mathrm{Tr}_B(|\Phi\rangle \langle\Phi|)$$

Black Holes and Hawking radiation

- Matter can gravitationally collapse into a black hole with a singularity at its center
- Hawking radiation causes black holes to evaporate over a long time scale
- Outgoing Hawking radiation is highly entangled with infalling matter

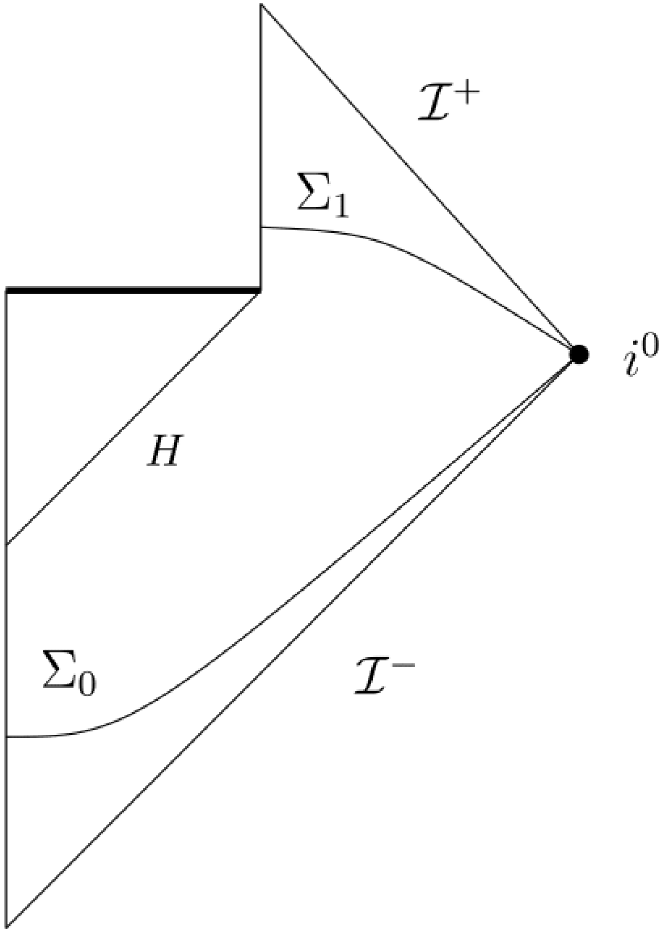


Hawking. " The Quantum Mechanics of Black Holes", Scientific American, vol. 236, Jan. 1977, p. 34-40.

Entanglement and Black Holes

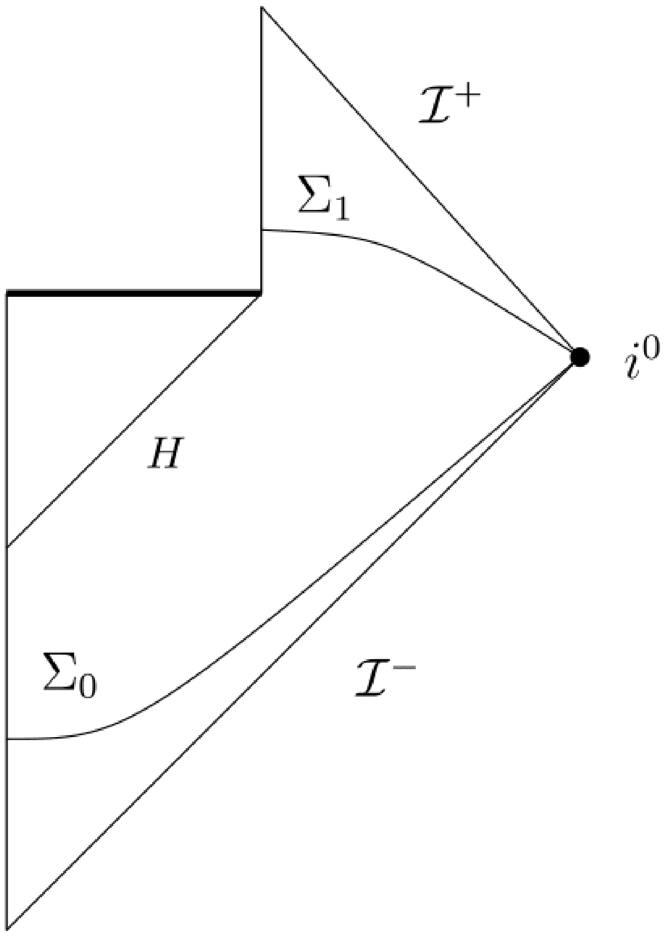
- As $t \to \infty$, matter is either far away ("future infinity") or is at the singularity. These are conformal boundaries.

- An observer at one boundary only has access to that boundary – must trace over subsystem at the other.



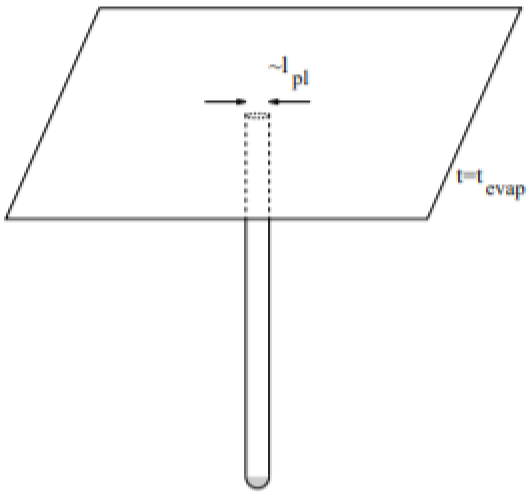
Information loss

- To an observer at $\mathcal{I}^+$, the final state looks mixed. Some information is trapped at the singularity.
- When the black hole evaporates, the second boundary (singularity) disappears. Where does there information go?
- This is non-unitary evolution – forbidden in QM!



Where does the information go?

- We would like to retain unitary evolution, so how can we resolve this?
- One proposal: The issues only arise when the second boundary disappears. Maybe it doesn't!
- Instead of complete evaporation, there is a long lived black hole remnant, that stores all of the information.
    - Final state is still pure if we consider the whole system.



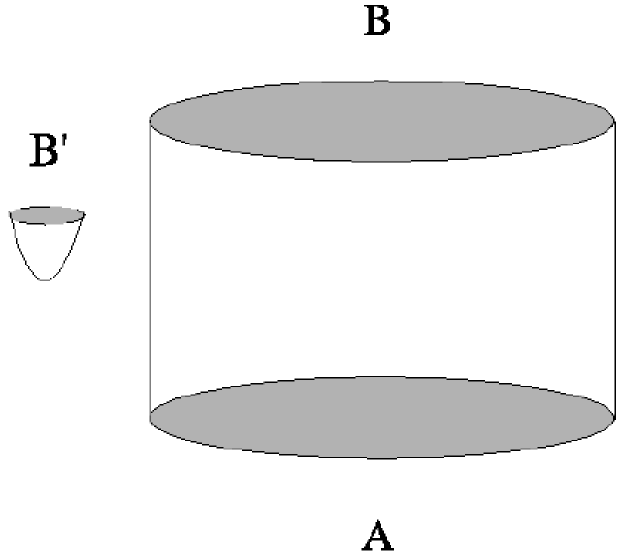
https://arxiv.org/pdf/hep-th/9412159.pdf

Complications

- One possible remnant for every possible initial state. This implies there are arbitrarily many remnant microstates.
- Thermodynamically, we would expect remnants to be produced at an infinite rate through pair production. A lack of observational evidence makes this unlikely.
- Are remnants useless?

A possible fix

- Multiple authors suggest that remnants take the form of large, topologically disconnected regions in spacetime.
- The result is an internally large, disconnected "pocket" of information that doesn't interact with the parent universe
  - Since it doesn't interact, the thermodynamic problems are resolved.
  - Still big enough to hold information



Hsu arXiv:hep-th/0608175

My thesis

- My thesis explores what the effects of topology change are on entanglement between disconnected regions.

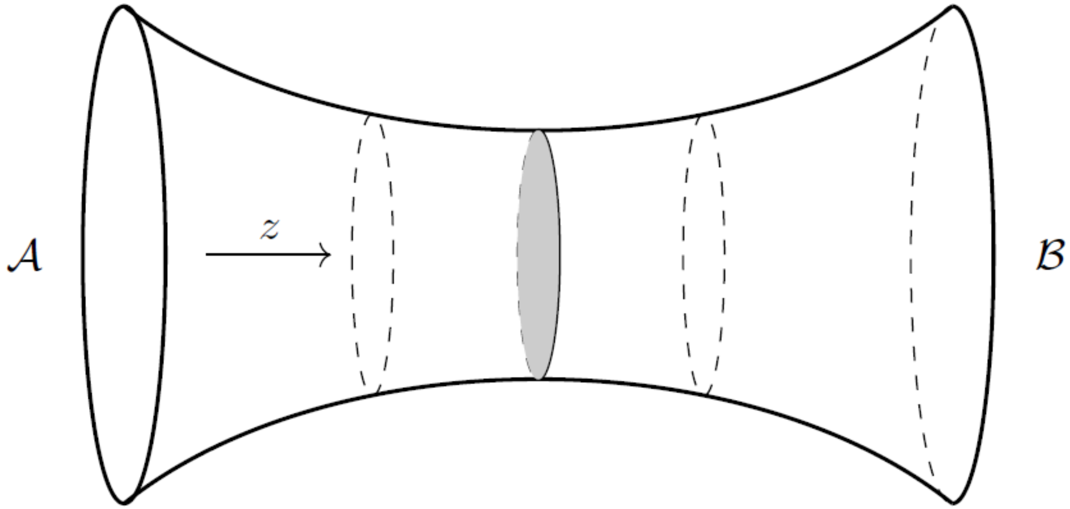
- Want to use some results from the AdS/CFT correspondence that relate entanglement to spacetime geometry.

- First, we need a spacetime that:
  1. Is asymptotically AdS, so that the above results can be applied
  2. Shares important features with spacetimes that have remnants

Criteria for our spacetime

- We want a spacetime with two asymptotic regions with boundaries, and some type of entanglement between the boundaries.

- We would also like these regions to be separated by horizons, and for there to be some entanglement across the horizons.



Constructing the 'toy' spacetime

- This is constructed by quotienting AdS_3 by a subgroup of its isometry group (essentially identifying certain points with each other). For us, the topology is given by $\mathrm{AdS}_3/\mathbb{Z}$

- This spacetime is isometric to the extended BTZ black hole with metric:

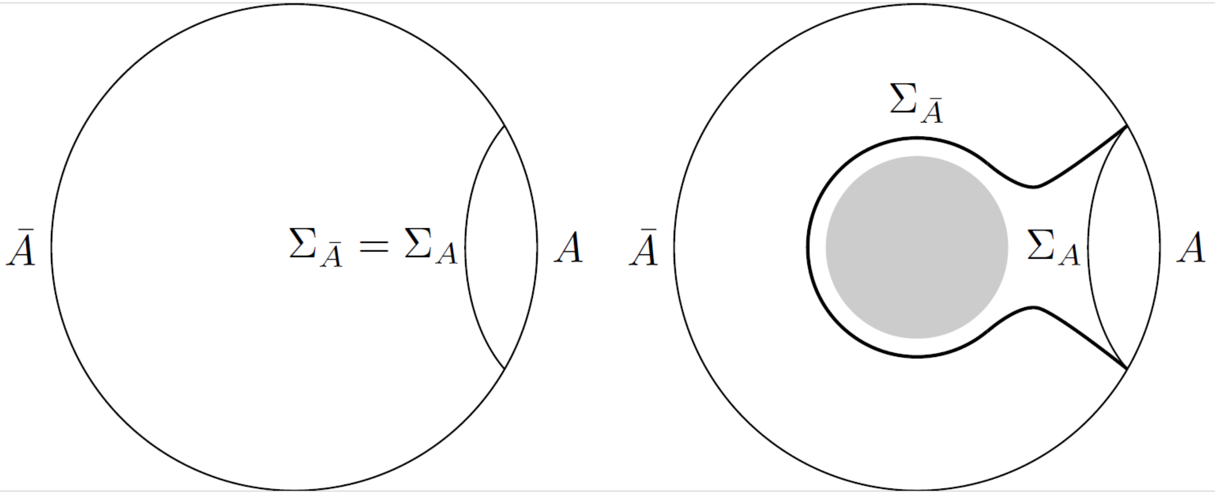
$$ds^2 = \frac{1}{z^2}\left(dz^2 - \left(1 - \frac{M}{4}z^2\right)^2 dt^2 + \left(1 + \frac{M}{4}z^2\right)^2 d\phi^2\right)$$

- The dual CFT to this spacetime is an entangled pair of thermal CFTs living on each boundary:

$$|\Phi\rangle = \frac{1}{\sqrt{Z(\beta)}} \sum_n e^{-\beta E_n/2} |E_n\rangle_{\mathcal{A}} \otimes |E_n\rangle_{\mathcal{B}}$$

Entanglement and Connectivity

- We can consider the entanglement entropy of the CFT living on boundary A with the CFT living on boundary B.
- The Ryu-Takayanagi formula relates the entanglement entropy of a subsystem A of the boundary with the area of a certain surface in the bulk



$$S_A = \frac{\text{Area}(\Sigma_A)}{4G_3}$$

Implications for remnants

- We take the above spacetime to be an AdS analog for the previously discussed remnant spacetimes. We can apply Ryu-Takayanagi, where the subsystem we consider is the whole boundary $\mathcal{A}$. The result is:

$$S_{\mathcal{A}} = \frac{H}{4G_3}$$

- We conjecture that the disconnection process corresponds to taking the limit $H \to 0$

- As the two regions disconnect, the entanglement of the dual CFTs is destroyed

Implications for remnants, con't

- We further conjecture that this extends to all types of entanglement, not just between the dual CFTs (i.e. between Hawking radiation on one boundary and infalling matter on the other)

- Disconnection destroys entanglement → disconnected remnants have the same problems has black hole firewalls. They are no longer clearly a viable solution to the information paradox.

- Entanglement is a sufficient condition for connectedness.

Conclusions

- $\mathrm{AdS}_3/\mathrm{CFT}_2$ wormholes with 2 disconnected regions are appropriate analogs to certain black hole remnant scenarios.
- Disconnecting two regions of spacetime destroys the entanglement between those regions.
- Disconnected black hole remnants suffer from the same problems as black hole firewalls, and therefore are not a clear solution to the paradox.
- Future work: further justifying these conjectures, as well as constructing other spacetimes with 'better' features

Further Reading

[1] William G. Unruh and Robert M. Wald, "Information Loss", arXiv:1703.02140 [hep-th]

[2] S. D. H. Hsu. Spacetime topology change and black hole information. Physics Letters B, 644:67-71, Jan. 2007. arXiv:hep-th/0608175

[3] M. van Raamsdonk. Building up spacetime with quantum entanglement. General Relativity and Gravitation, 42:2323 - 2329, Oct. 2010. arXiv:1005.3035