

Rethinking Hawking on black hole entropy



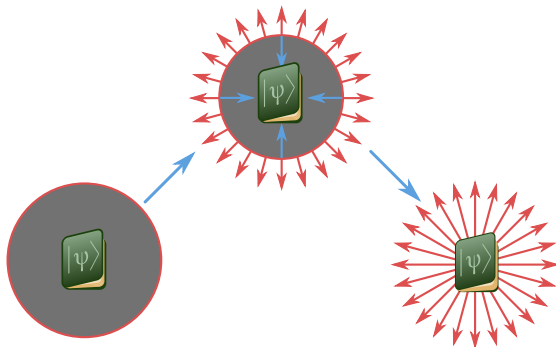
David Wakeham

PhD student @ Strings group, UBC

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Black holes can evaporate

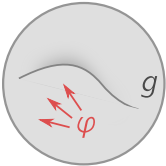
- ▶ Hawking discovered that black holes glow. This means they can **leak energy and evaporate**. Does this destroy information?



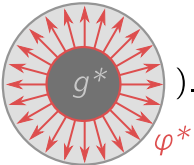
- ▶ If **evaporation is unitary**, BH starts and ends in a pure state with **quantum entropy $S = 0$** . Goal: find radiation entropy!

Hawking's answer

- ▶ Hawking calculated entropy from a **partition function**. This sums over metrics g (with a boundary circle) and matter φ :

$$Z[\beta] = \sum_{g, \varphi} \exp(-\beta \int \sqrt{-g} \mathcal{L}(g, \varphi) d^4x)$$


The diagram shows a light gray circular region representing a manifold. A wavy line inside the circle represents a metric g . Four red arrows point towards the center of the circle, labeled with the symbol φ .

$$\approx \exp(-\beta \int \sqrt{-g^*} \mathcal{L}(g^*, \varphi^*) d^4x)$$


The diagram shows a light gray circular region representing a manifold. A dark gray circle in the center represents a black hole metric g^* . Numerous red arrows point outwards from the dark gray circle towards the boundary of the light gray circle, labeled with the symbol φ^* .

- ▶ This sum is **dominated** by the black hole metric g^* and matter in a thermal state φ^* . So S seems to be big!
- ▶ Problem: this only gives quantum entropy for thermal states!

Replica wormholes

- ▶ More generally, we use the **replica trick**. This involves a partition function $Z_n[\beta]$ on n boundary circles, then $n \rightarrow 1$.
- ▶ Two options for sum over metrics: keep copies separate, or **connect with “replica wormholes”**. The second gives $S = 0$!

$$Z_3[\beta] = \left[\sum_{g, \varphi} \left(\text{Diagram 1} \right) \right]^3 \quad \text{vs.} \quad \sum_{g, \varphi} \left(\text{Diagram 2} \right)$$

The diagram on the left shows a single disk with a wavy line and four red arrows labeled φ . The diagram on the right shows three disks connected by three wormholes, with the bottom disk containing the wavy line and red arrows labeled φ . Both diagrams are labeled with g .

- ▶ We've **solved the information paradox**. This is awesome!
- ▶ But **many questions remain**. What are replica wormholes? Does **gravity = statistical averaging**? And is this unitary?

Thanks for listening!