Black holes and quantum computers

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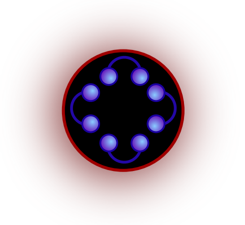

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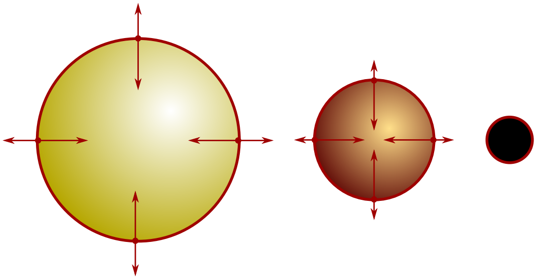
What are black holes?

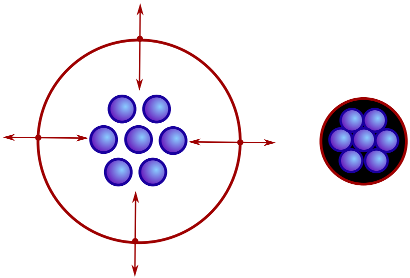
- Black holes form when stars collapse under their own weight. Pressure pushes outwards, but gravity wins.



- It's black because the collapsed star traps light. Nothing travels faster than light, so it traps everything else as well!

Black holes from qubits

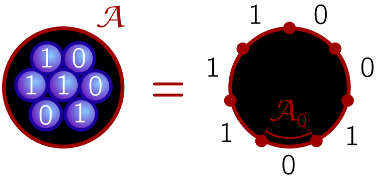
- We can make black holes by squishing N qubits together:



- If the qubits were in a pure state $|\psi\rangle$ before collapse, we assume they remain in a pure state.

Qubits and horizons

- In the 70s, Bekenstein and Hawking realized that black hole horizon area is proportional to number of qubits:



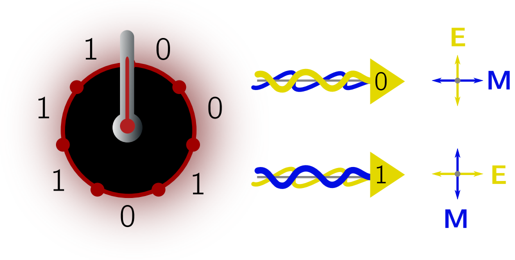
- Mathematically, if $\mathcal{A}$ is the horizon area, then

$$N = \frac{\mathcal{A}}{\mathcal{A}_0}, \quad \mathcal{A}_0 = 10^{-69}\ \mathrm{m}^2.$$

Each qubit gets a surface pixel of area $\mathcal{A}_0$.

Hawking radiation

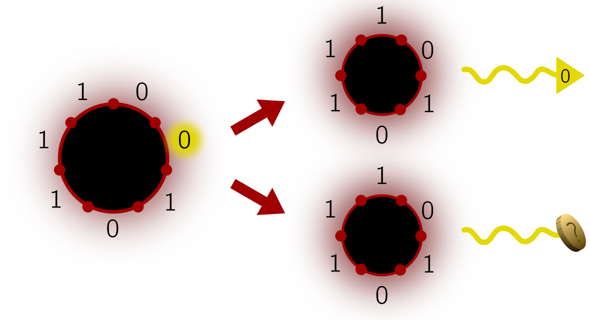
- Hawking discovered another amazing fact: black holes are hot, emitting a glow called Hawking radiation.
- Thus, over time, the black hole spits out photons.



- Photons have two independent polarizations, i.e. two ways the fields can wobble. This makes them qubits.

The evaporation enigma

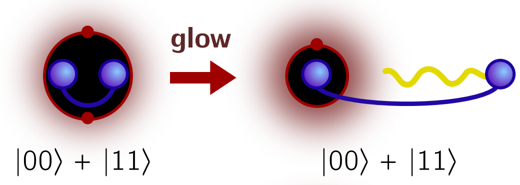
- Each photon emitted deletes the contents of a surface pixel. The question is: what happens to that qubit?



- The qubit could simply be encoded into the photon.
- This is not what Hawking found! Instead, his calculations showed it was replaced by a random coin flip.

Introducing entanglement (I)

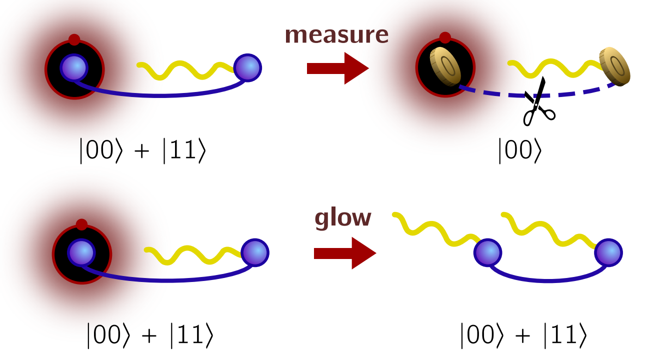
- Deleting qubits like this isn't allowed by quantum mechanics. So Hawking's argument is perplexing!
- But suppose our black hole is a single entangled pair. Entanglement is drawn as a blue line.



- When it glows, let's assume the photon carries off a qubit without affecting the entanglement.

Introducing entanglement (II)

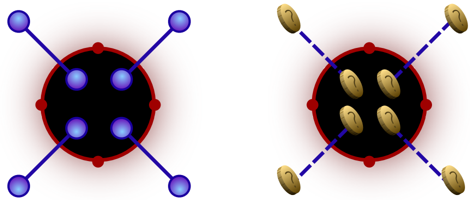
- If we now measure the state of the photon, we get a random outcome! This agrees with Hawking's result.



- But if we wait until both qubits are emitted without measuring, we recover the entangled pair!

Horizons revisited

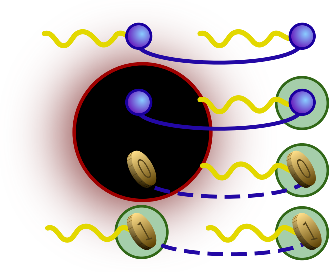
- This gives us a new way to think about horizons.
- Suppose blue lines have a thickness $\mathcal{A}_0$. Then the horizon is big enough to let each qubit entangle with one outside.



- The horizon is a sort of entanglement bottleneck.
- They don't need to pair up, but they can if they want.

Entanglement entropy

- It's useful to keep track of how many photons are entangled, and how many are random.
- We call their sum the entanglement entropy S. It measures uncertainty of the quantum state of photons.

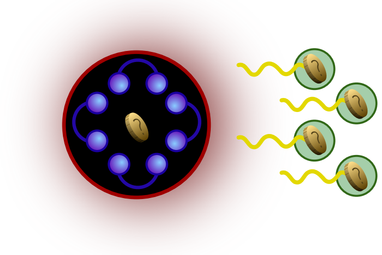


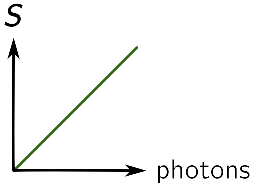
$S = 4$

- Note that if you measure only one end of an entangled pair, you effectively turn it into a coin.

The Hawking curve

- Using S, we can probe the evaporation enigma.
- Hawking argued that each photon was a random coin flip. Thus, entanglement entropy increases linearly.

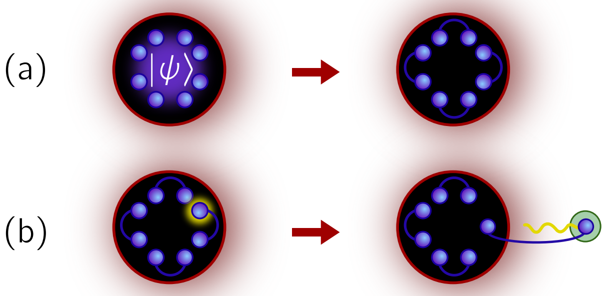




- We call this the Hawking curve. It's as if the black hole itself measures any departing qubits.

Evaporating pairs

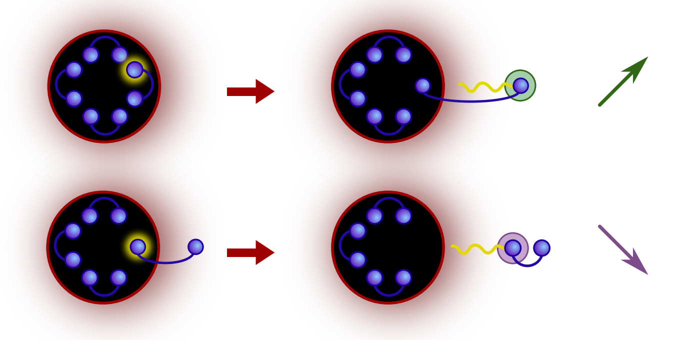
- What if the black hole doesn't measure the qubits?
- We assume the black hole (a) quickly evolves into a set of entangled pairs; (b) emits internal qubits at random.



- Note that there are no coins in this model!

Ups and downs

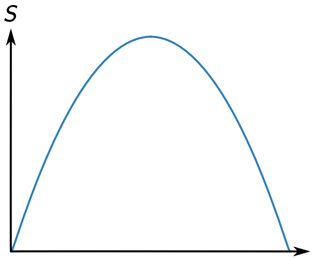
- Let's think more about how S changes with time!
- When the first partner of a pair is emitted, S increases. More blue lines cross the horizon.

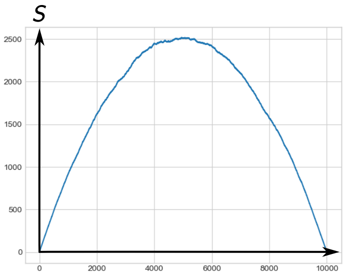


- When the second partner of a "half pair" is emitted, S decreases. Fewer lines cross the horizon.

The Page curve

- At first, all emitted qubits are first partners, so S grows.
- As half pairs grow, it becomes more likely to emit a second partner. S should slow and then decrease.

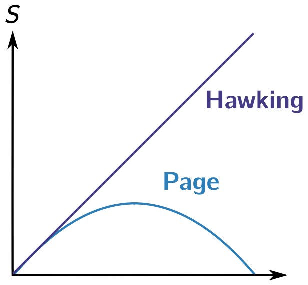




- Our guess (left) matches simulations (right). We call this up-and-down behaviour the Page curve.

Hawking vs Page

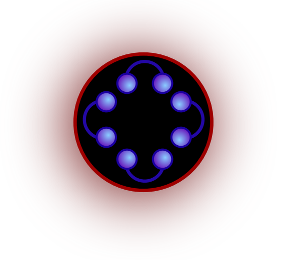
- The Page curve is consistent with quantum mechanics.
- Hawking's curve follows from a beautiful gravitational calculation. Which one is correct?



- It comes down to the following question: how should we calculate entanglement entropy from gravity?

Conclusion

- In the last two years, we've found fine-grained ways to calculate entanglement entropy in gravity theories.
- They involve insights from string theory, gravity, and quantum information science. The result: gravity obeys the Page curve after all! Quantum mechanics is saved.
- It's a fun time to study black hole quantum computers.



Thanks for listening! Questions?