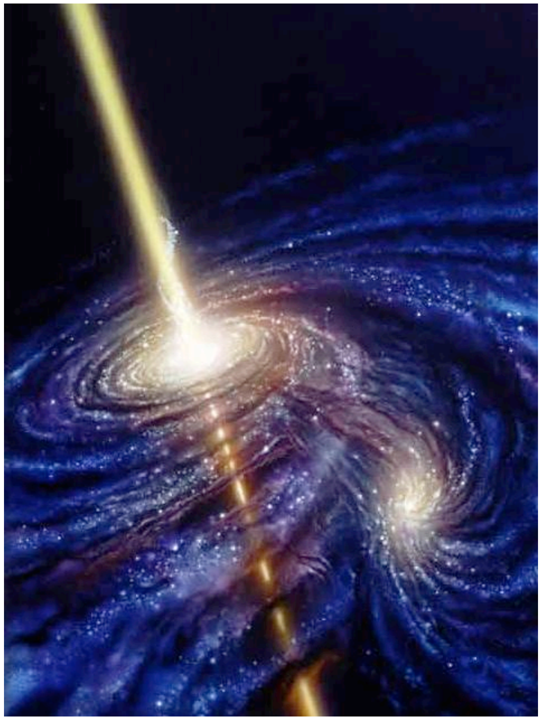
Black Holes, Entropy, and Information



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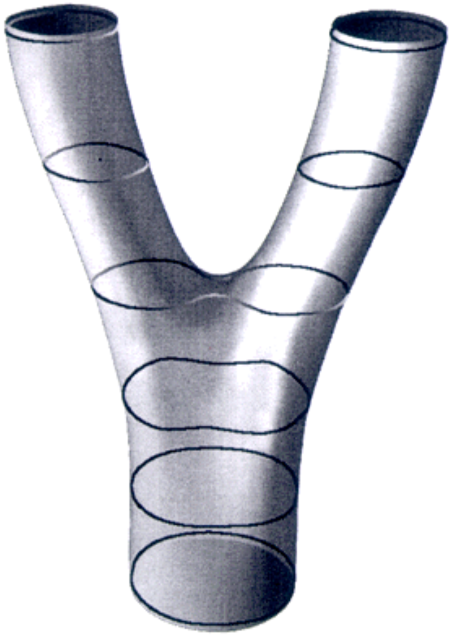


Outline

- Classical black holes:

  Review of basic properties
- Semi-classical black holes:

  Deep puzzles arise
- Quantum black holes:

  Puzzles answered, but some questions remain

Laws of black hole mechanics

(Carter, Bardeen, Hawking, 1973)

0) For stationary black holes, the surface gravity is constant on the horizon

1) Under a small perturbation: $dM = \frac{\kappa}{8\pi G} dA + \Omega dJ$

2) The area of the event horizon always increases

Laws of thermodynamics

If κ is like a temperature, and A is like an entropy, then there is a close analogy:

0) Temperature of an object in thermal equilibrium is constant

1) $dE = TdS - PdV$

2) Entropy always increases

Semiclassical black holes

Hawking coupled quantum matter fields to a classical black hole, and showed that they emit black body radiation with a temperature

$$T = \frac{\hbar\kappa}{2\pi}$$

This implies black holes have an entropy

$$S_{BH} = \frac{A}{4\hbar G}$$

For a solar mass black hole, the temperature is very low ($T \sim 10^{-7}$ K) so it is astrophysically negligible. But $T \sim 1/M$ so if a black hole starts evaporating, it gets hotter and eventually explodes.

The entropy is enormous ($S \sim 10^{77}$). This is much greater than the entropy of the matter that collapsed to form it: A ball of thermal radiation has $M \sim T^4 R^3$, $S \sim T^3 R^3$.

When it forms a black hole $R \sim M$, so $T \sim M^{-1/2}$ and hence $S \sim M^{3/2}$. But $S_{BH} \sim M^2$.

Fundamental questions

- What is the origin of black hole entropy?
- Does black hole evaporation lose information? Does it violate quantum mechanics? Hawking argued for three decades that it did.

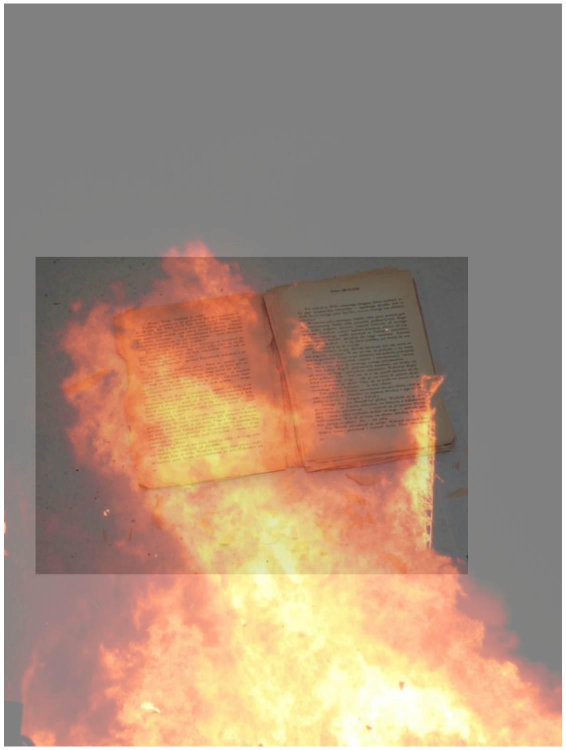
Hawking’s argument

A black hole can be formed in many ways (throw in books, computers, etc.). After it settles down, spacetime outside is described by only M, J.

The radiation it emits is essentially thermal. It can’t depend on the information inside without violating causality or locality.

When the black hole evaporates, M and J are recovered, but the detailed information that was thrown in is lost. Pure states → mixed states.

Hawking argued that this is very different from burning a book:



All the information in the book can in principle be recovered from the ashes and emitted radiation.

Introduction to string theory

All particles are excitations of a one dimensional string with tension $1/l_s^2$.

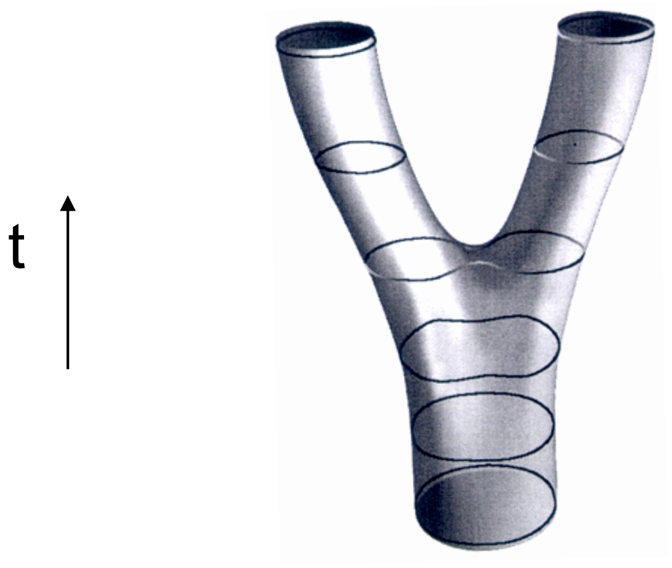
Quantizing a string in flat space yields a few massless states: graviton, dilaton …

And an infinite tower of massive modes with

$$M^2 = N/l_s^2$$

Number of states with mass M is ~ $\exp(M\, l_s)$

Assume the simplest interaction with strength g



This reproduces the perturbative expansion of general relativity with $G \sim g^2 l_s^2$

Quantizing the string in curved space reproduces Einstein's equation provided the curvature is less than $1/l_s^2$.

When the curvature is of order $1/l_s^2$, the metric is no longer well defined due to quantum fluctuations.

Quantizing a string also leads to extra spatial dimensions.

The idea that spacetime may have more than four dimensions was first proposed in the 1920's by Kaluza and Klein.

We don't see the extra dimensions since they are curled up into a small ball. A theory of pure gravity in five dimensions is equivalent to gravity + electromagnetism in four dimensions.

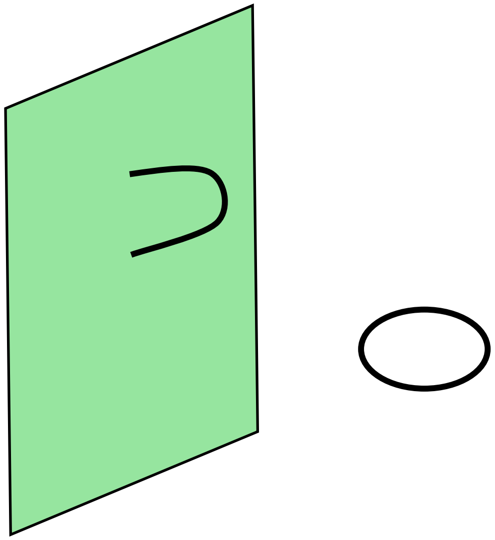
String theory has supersymmetry

Supersymmetric theories have a bound on the mass of all states given by their charge (BPS bound): $M \geq Q$.

States which saturate this bound are called BPS. They have the special property that the mass does not receive any quantum corrections.

String theory is not just a theory of strings.

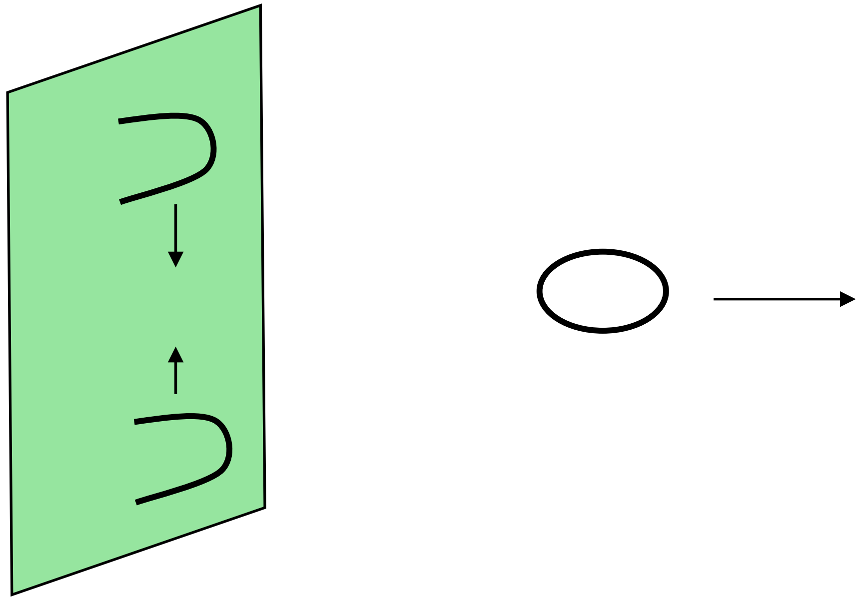
There are other extended objects: D-branes



They are nonperturbative objects with mass M~1/g. But GM ~ g. At weak coupling they are described by surfaces on which open strings can end.

D-branes exist in various dimensions and carry a charge. With no open strings attached, they are BPS states.

Excited D-branes (with open strings) lose energy when two strings combine to form a closed string which can leave the brane:



Return to black holes

Recall our fundamental questions:

- What is the origin of black hole entropy?
- Does black hole evaporation lose information? Does it violate quantum mechanics?

Microstates of black holes

Breakthough came in 1996 in a paper by Strominger and Vafa. They considered a charged black hole.

Charged black holes are not interesting astrophysically, but they are interesting theoretically since they satisfy a bound $M \geq Q$.

Black holes with $M = Q$ are called extremal and have zero Hawking temperature. They are stable, even quantum mechanically.

In string theory, extremal black holes are strong coupling analogs of BPS states. One can now do the following calculation:

Start with an extremal black hole and compute its entropy S_{BH}. Imagine reducing the string coupling g. One obtains a weakly coupled system of strings and branes with the same charge.

One can now count the number of BPS states in this system at weak coupling and find…

$$N_{BPS} = \exp S_{BH}$$

This is a microscopic explanation of black hole entropy!

Unlike previous attempts to explain S_{BH}, one counts states in flat spacetime where there is no horizon. One obtains a number which remarkably is related to the area of the black hole which forms at strong coupling.

After the initial breakthrough, this was quickly extended:

1) Entropy agrees for extremal charged black holes with rotation.
2) Entropy agrees for near extremal black holes with nonzero temperature.
3) Total rate of radiation from black hole agrees with radiation from D-branes.
4) Slight deviations from black body spectrum also agree!

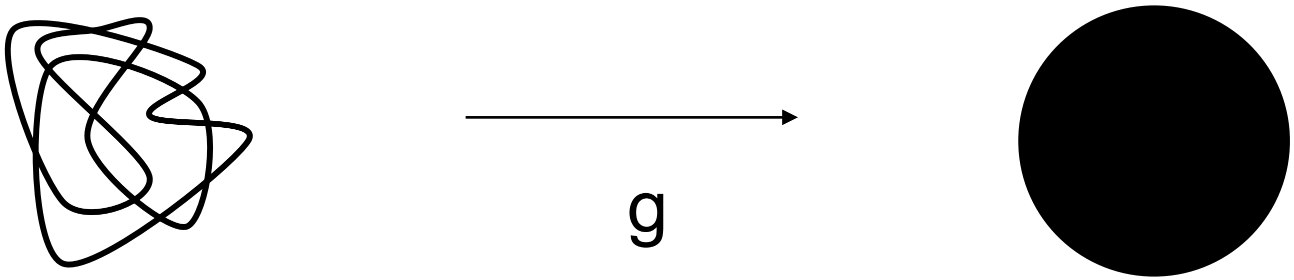
A small black hole has an entropy which is not exactly equal to A/4. There are subleading corrections.

Recently, it has been shown that for certain extremal black holes the counting of microstates reproduces the black hole entropy including these subleading corrections.

(Dabholkar, …)

What about neutral black holes?

Susskind (1993) suggested that there should be a 1-1 correspondence between ordinary excited string states and black holes. (Recall $G = g^2 l_s^2$)



But there is an obvious problem:

$$S_s \sim M_s, \quad \text{but} \quad S_{BH} \sim M_{BH}^2$$

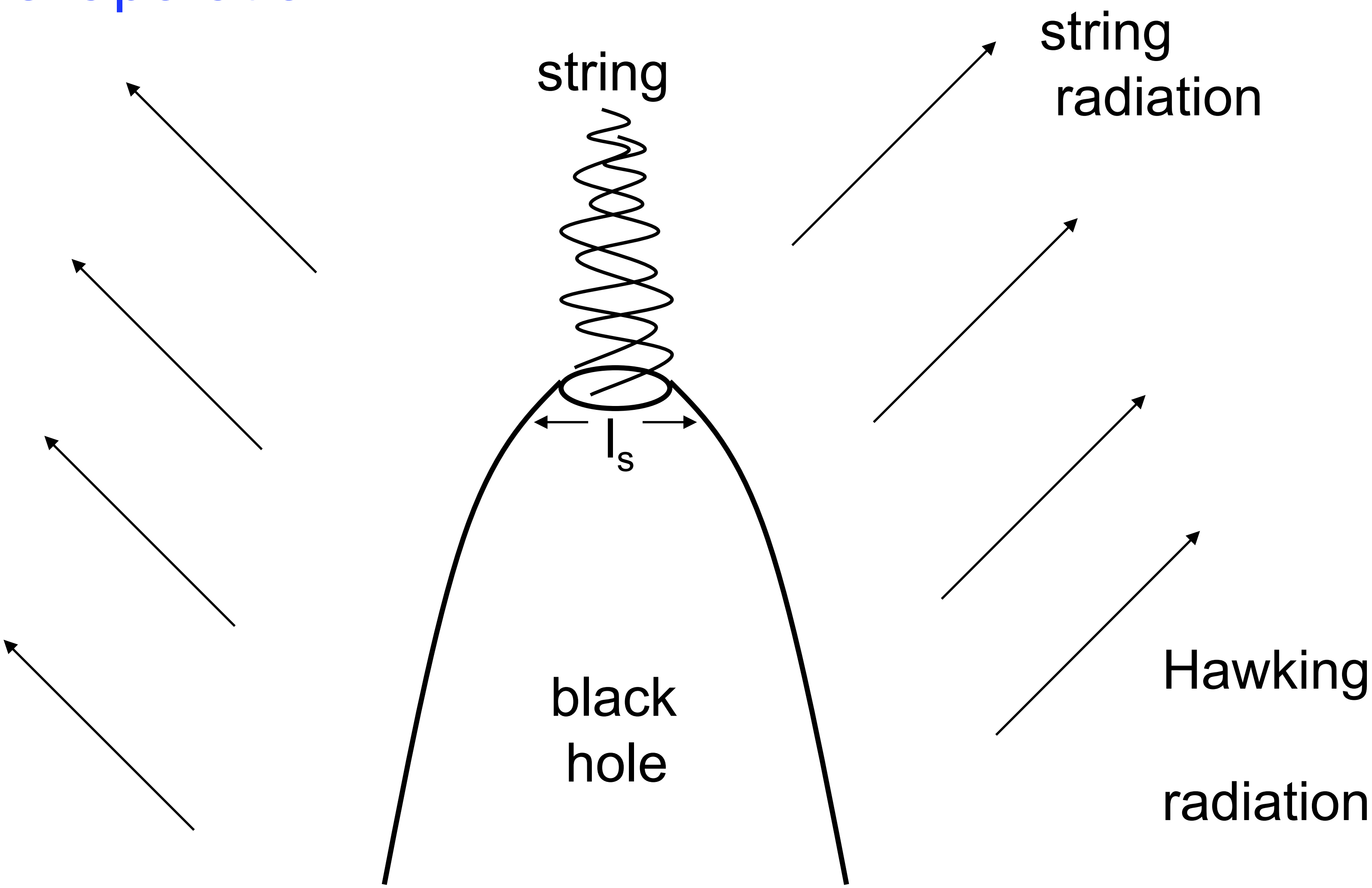
Resolution (J. Polchinski and GH, 1997):

M_s/M_{BH} depends on g. Expect the transition when the curvature at the horizon of the black hole reaches the string scale.

Setting $M_s \sim M_{BH}$ at the value of g corresponding to this transition, find $S_s \sim S_{BH}$:

$$S_{BH} \sim r_0\, M_{BH} \sim l_s\, M_s \sim S_s$$

This leads to a simple picture of black hole evaporation:



This shows that strings have enough states to reproduce the entropy of all black holes, but this argument does not reproduce the entropy exactly.

Recently a precise calculation of the entropy of a neutral black hole in string theory was achieved (Emparan and GH, 2006).

This was not for a four dimensional black hole, but a rotating five dimensional black hole in Kaluza-Klein theory. In a certain limit, it approaches an extremal Kerr solution.

Do black holes lose information?

For near extremal black holes, the weak coupling description provides a quantum mechanical description of a system with the same entropy and radiation.

This was a good indication that black hole evaporation would not violate quantum mechanics. The case soon became much stronger…

Gravity/gauge correspondence

(Maldacena,1997)

Under certain boundary conditions, string theory (which includes gravity) is completely equivalent to a (nongravitational) gauge theory “living at infinity”.

There is now considerable evidence to support this remarkable statement. When string theory is weakly coupled, gauge theory is strongly coupled, and vice versa.

Immediate consequence: The formation and evaporation of small black holes can be described by ordinary Hamiltonian evolution in the gauge theory. It does not violate quantum mechanics.

After thirty years, Hawking finally conceded this point in 2004.

Open questions

1) Can we count the entropy of Schwarzschild black holes precisely?
2) How does the information get out of the black hole? What is wrong with Hawking's original argument?

What is the origin of spacetime?

How is it reconstructed from the gauge theory?

How does a black hole horizon know to adjust itself to have area $A = 4G\,S$?