(Information) Paradox Lost

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For Shelly at Joel's Conference
Rutgers, December 18, 2017

Black Holes

- As is well known, a black hole is a space-time structure that can form according the General Theory of Relativity.
- Every black hole has an event horizon: a surface that is like a one-way membrane. Whatever passes through the event horizon can never come back out. To do so, it would have to go faster than light.

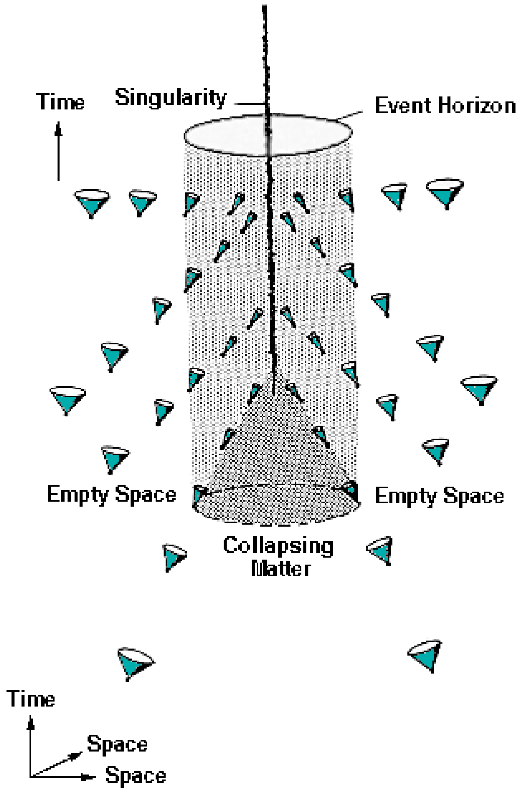
Classical Black Holes

- In pure (non-quantum-mechanical) General Relativity, then, if you throw a book into a black hole, the information in it will never come out again. The information is lost forever to the outside world.
- Is this somehow paradoxical?

Hawking

- Not according to Stephen Hawking:
- “This loss of information wasn’t a problem in the classical theory. A classical black hole would last forever and the information could be thought of as preserved inside it, but just not very accessible.“
- One might even recover the information in some cases by jumping into the black hole, although the result would be painful.

Space-Time Diagram of a Black Hole



Penrose Diagrams

- In order to help us understand the situation, we will use Penrose diagrams. The diagrams clearly indicate the light-cone structure of a space-time.
- According to the convention of the diagram, light always travels on line with a 45° slant.
- Here is a Penrose diagram of a classical eternal black hole.

Eternal Black Hole

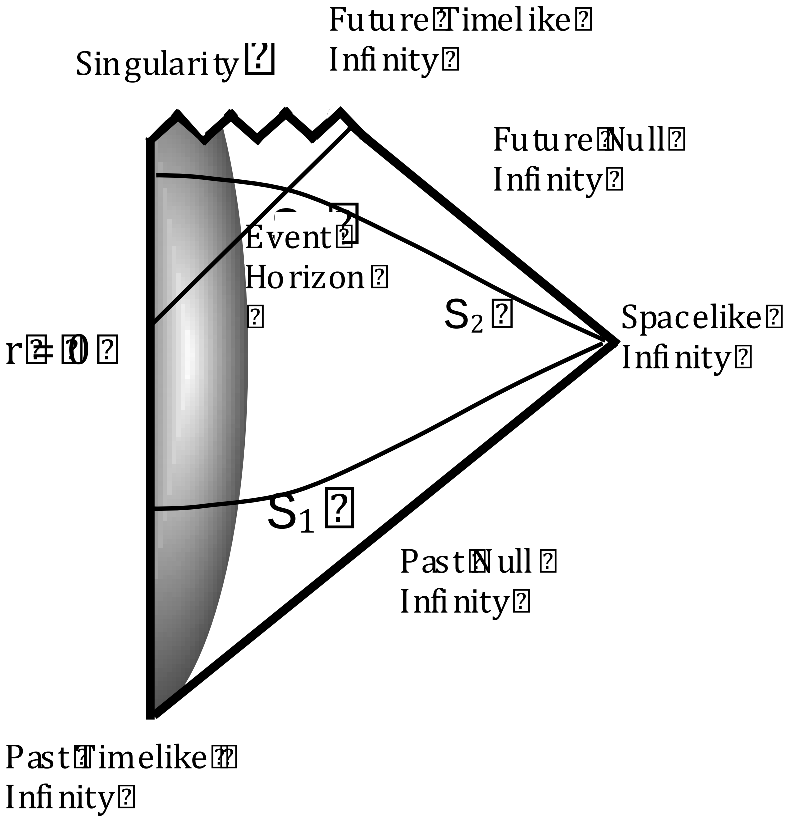
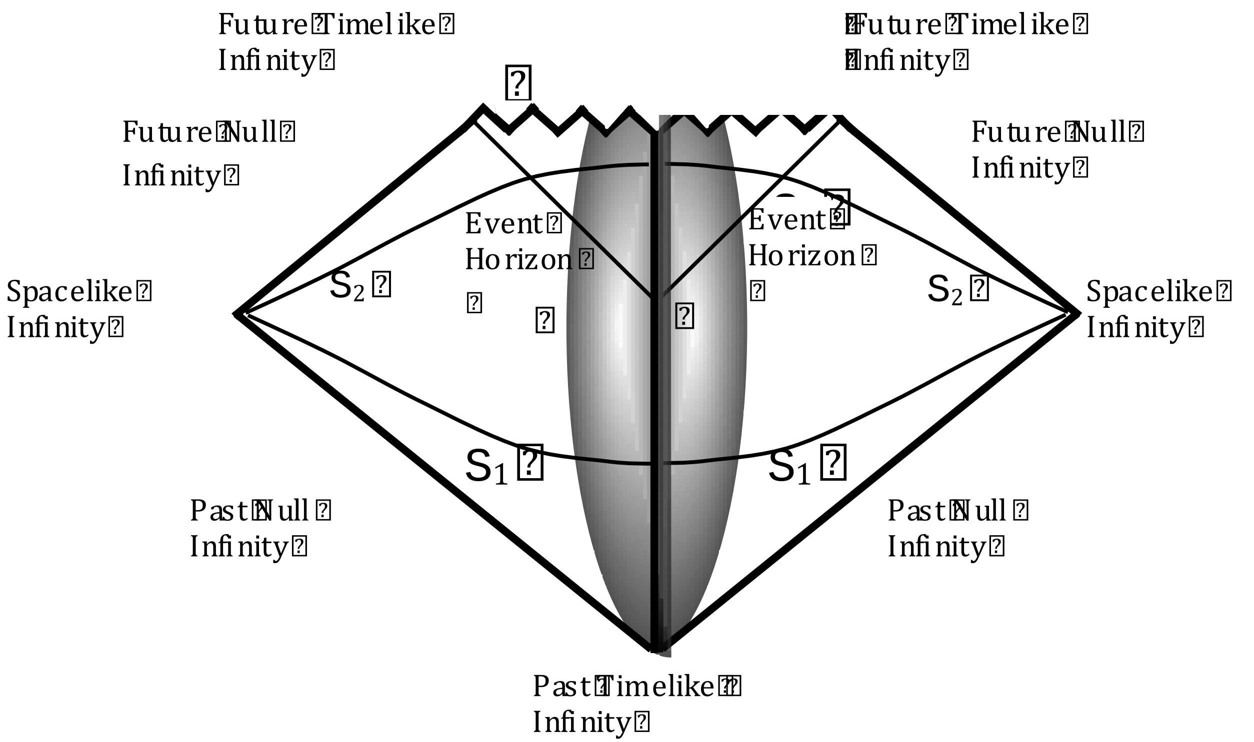


Diagram Unfolded



Hawking Radiation

- In 1975, Hawking made a calculation about how quantum fields would behave in the vicinity of the event horizon.
- Hawking discovered that the black hole would radiate. The radiation could be detected from arbitrarily far away.
- Hawking calculated the flux of energy that the radiation would carry away from the black hole.

Shrinkage

- Since energy is equivalent to mass by $E = MC^2$, Hawking concluded that the black hole must lose mass and shrink.
- He calculated that after a finite period of time, the black hole would shrink to nothing and disappear completely.
- In his paper, Hawking included a Penrose diagram

Hawking Again

- However, the situation changed when I discovered that quantum effects would cause a black hole to radiate at a steady rate. At least in the approximation I was using the radiation from the black hole would be completely thermal and would carry no information. So what would happen to all that information locked inside a black hole that evaporated away and disappeared completely?

Hawking's Diagram

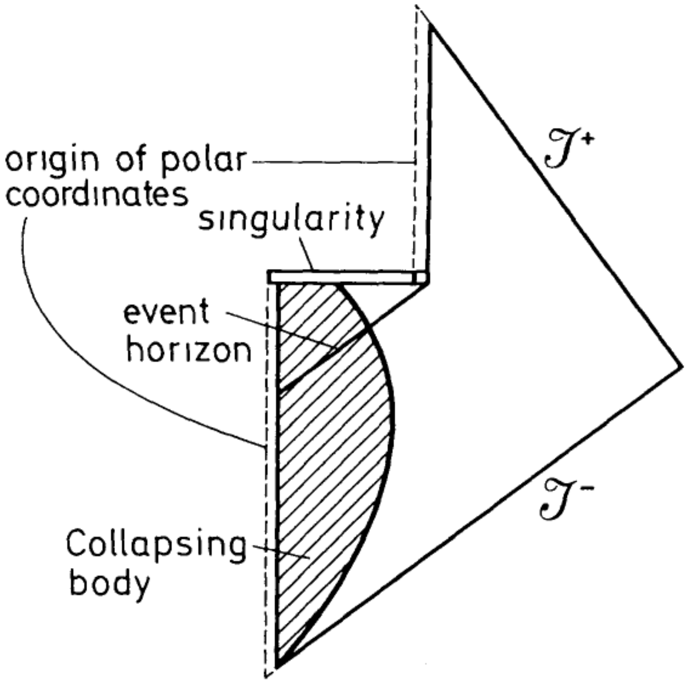
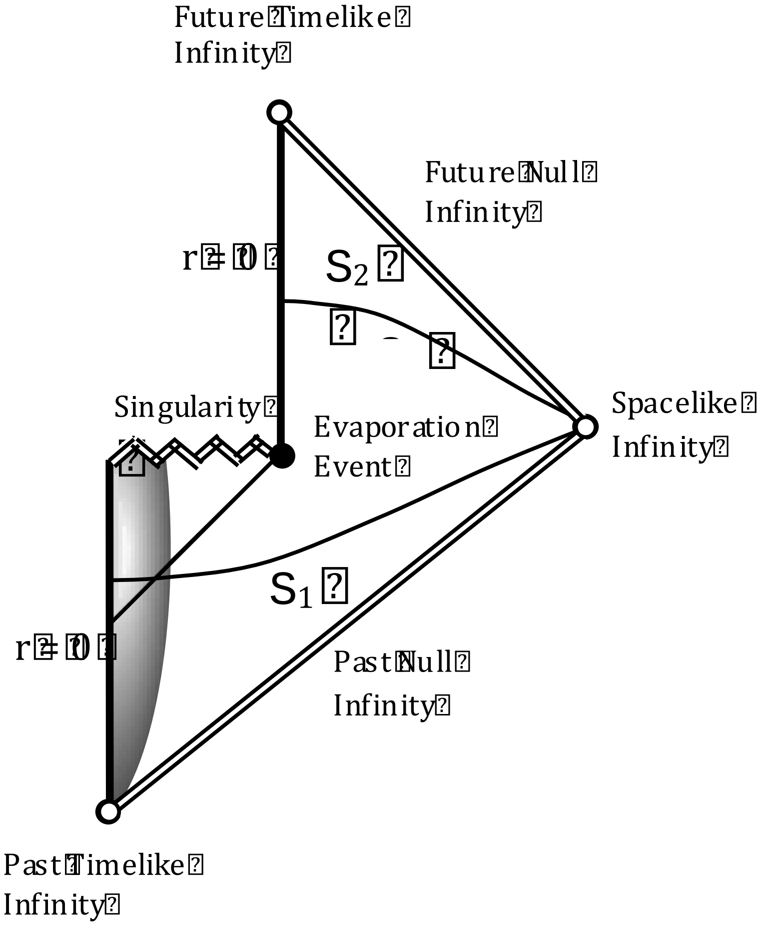


Fig. 5. The Penrose diagram for a gravitational collapse followed by the slow evaporation and eventual disappearance of the black hole, leaving empty space with no singularity at the origin

Diagram Clarified



Information and Determinism

- All the talk about information is really a way to talk about determinism.
- What is at issue is whether the state of the universe at an earlier time can be recovered—even in principle—from its state at a later time.
- Determinism in the backward time direction allows for perfect retrodiction.

Laplace

- We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes

Boscovich

- Now, if the law of forces were known, & the position, velocity & direction of all points at any given instant, it would be possible for a mind of this type to foresee all the necessary subsequent motions & states, & to predict all the phenomena that necessarily followed from them. It would be possible from a single arc described by any point in an interval of continuous time, no matter how small, which was sufficient for a mind to grasp, to determine the whole of the remainder of such a continuous curve, continued to infinity on either side.

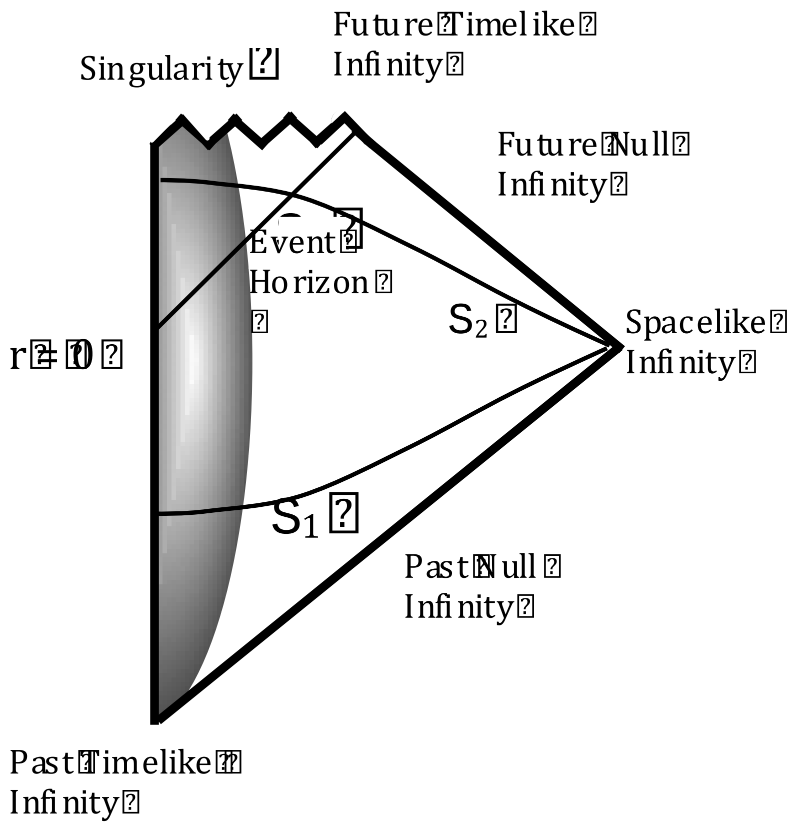
What is a "moment of time"

- Newton described a moment of time as follows:
- For we do not ascribe various durations to the different parts of space, but say that all endure together. The moment of duration is that same at Rome and at London, on the Earth and on the stars, and throughout all the heavens. And just as we understand any moment of duration to be diffused throughout all spaces….

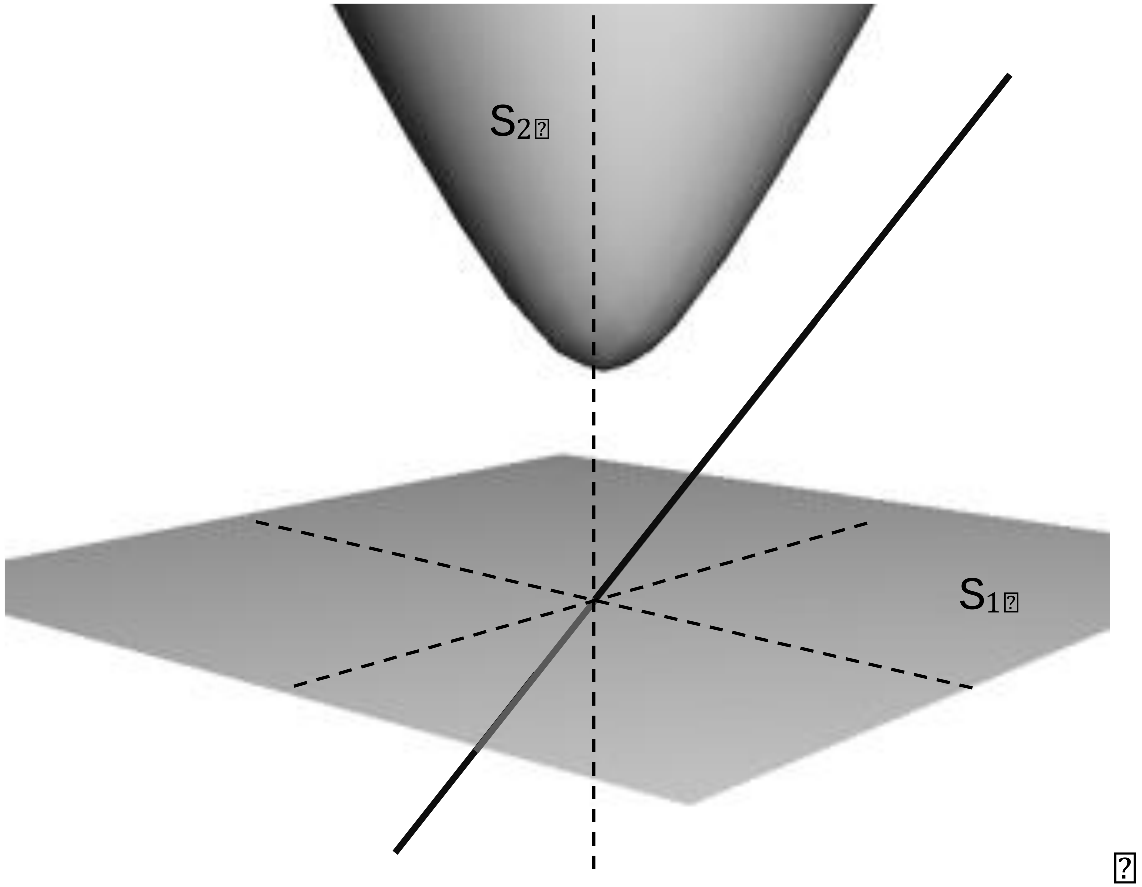
Cauchy Surfaces

- The closest analog to a moment of time that there is in Relativity is a Cauchy surface.
- A Cauchy surface is a collection of events that every inextensible timelike curve meets exactly once.

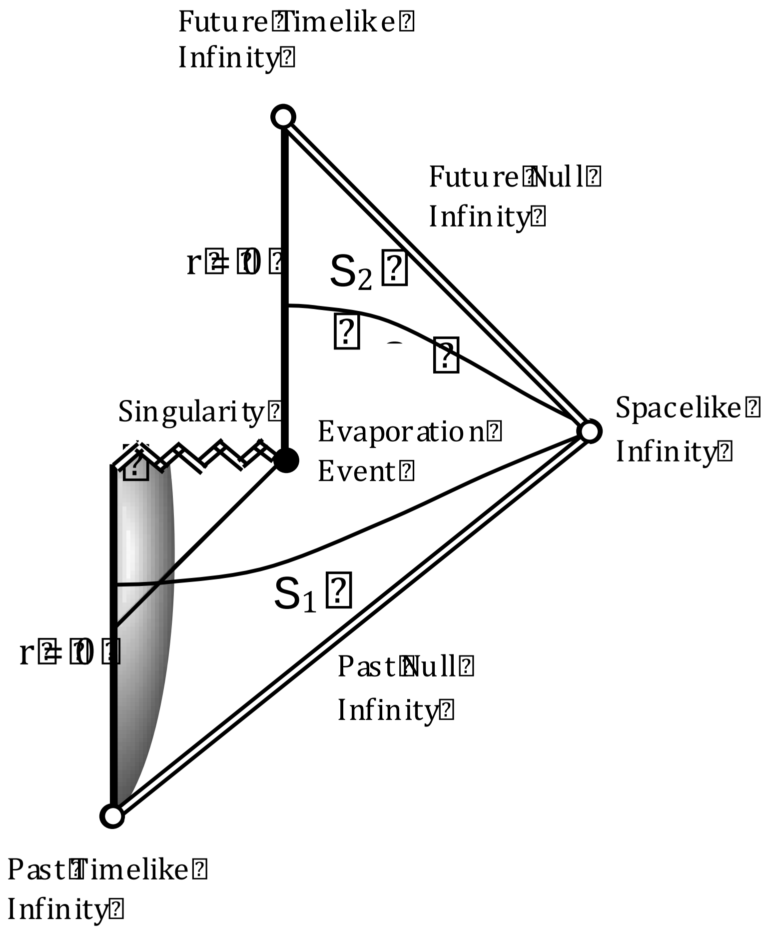
Eternal Black Hole Again



Determinism, Retrodiction and Cauchy Surfaces



Evaporating Black Hole Diagram



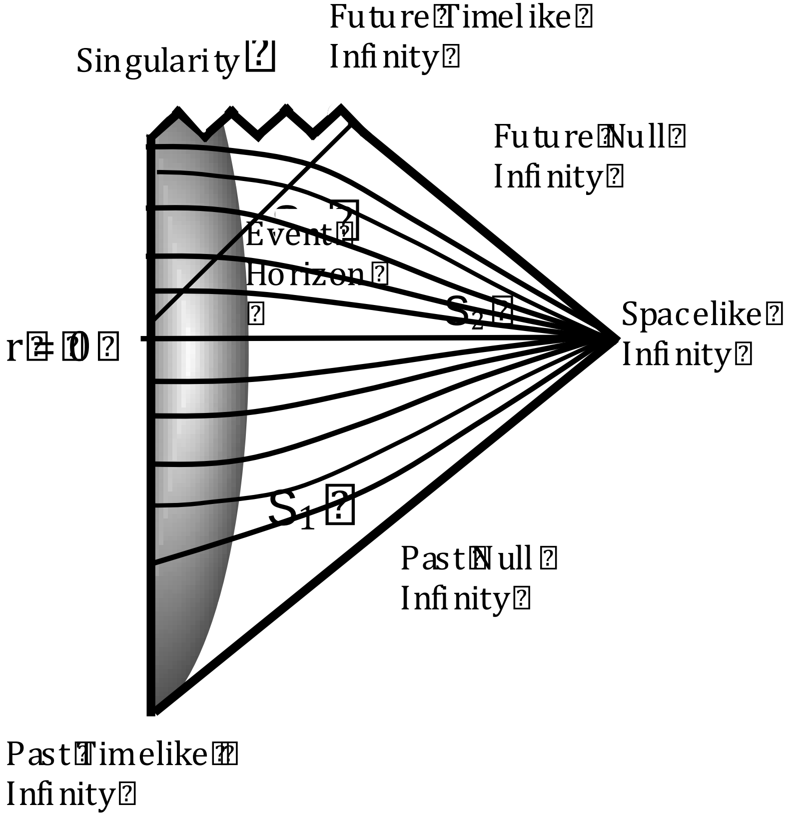
Two Theorems

- Robert Geroch proved two theorems about Cachy surfaces in a 4-dimensional manifold:
- 1) A space-time that admits of a Cauchy surface (these are called globally hyperbolic space-times) admits of a foliation into Cauchy surfaces.
- 2) The topology of the Cauchy surfaces in such a foliation cannot change.

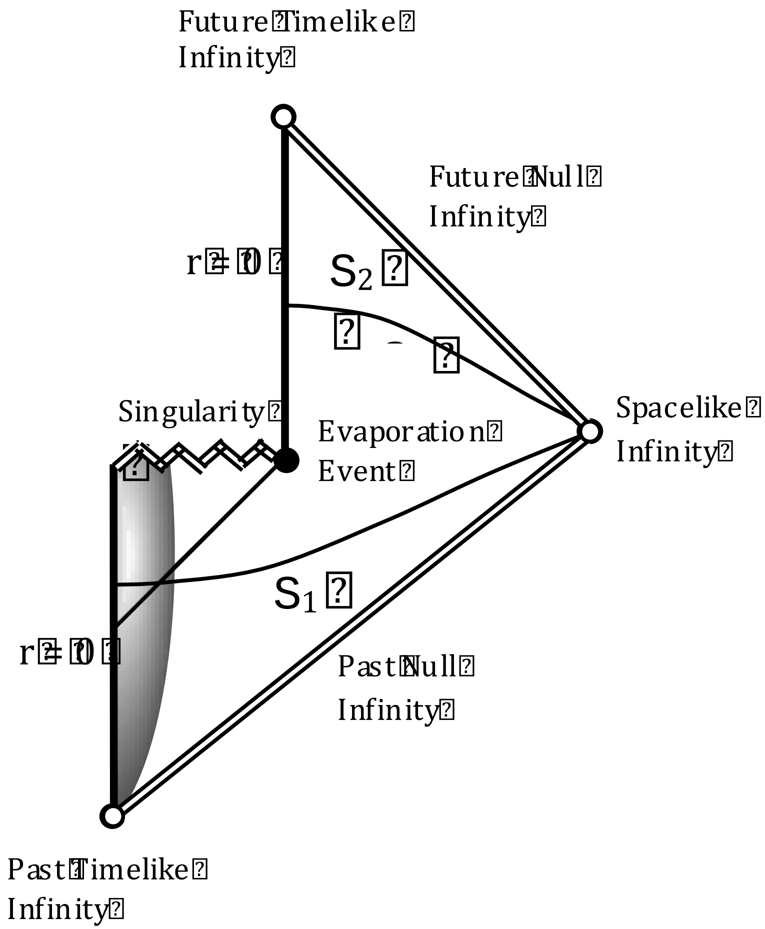
Foliations and Time

- A foliation into Cauchy surfaces can be used to define a global time function. Just parameterize the leaves of the foliation using the real numbers, such that the numerical order of the parameters respects the time order of the leaves.

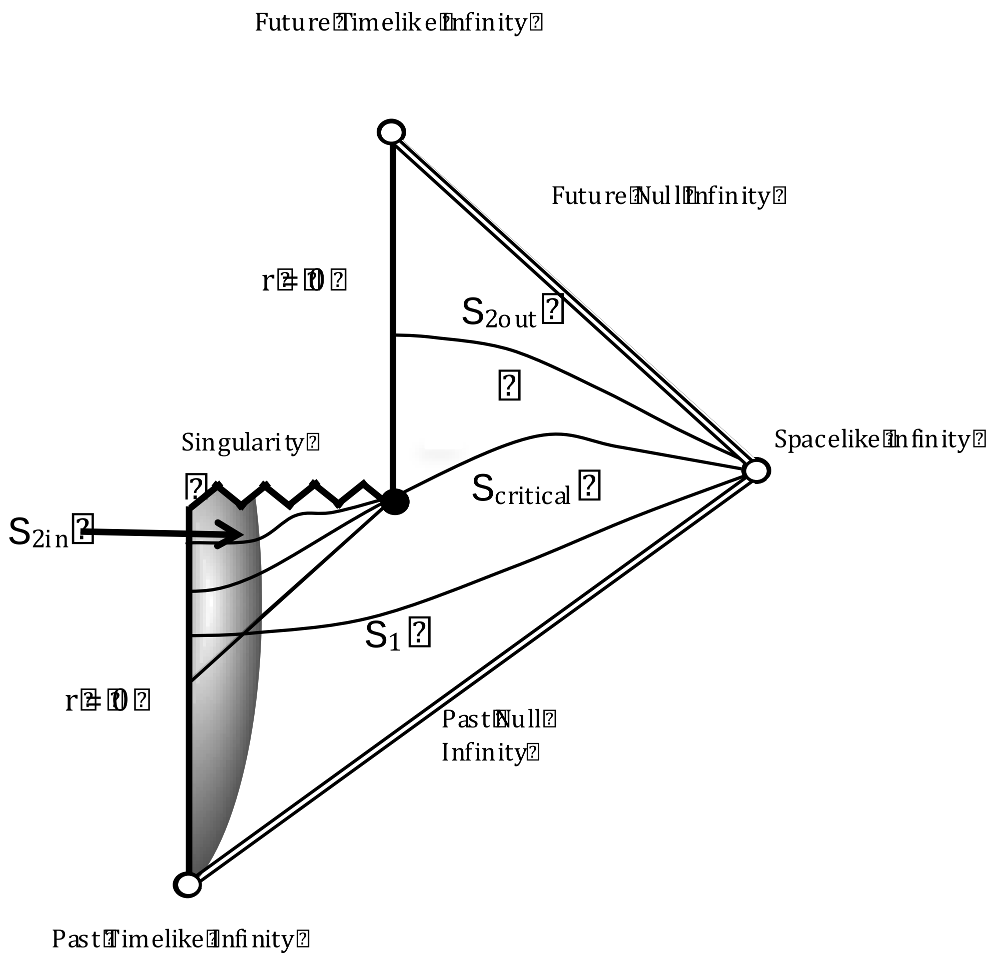
Eternal Black Hole Foliated



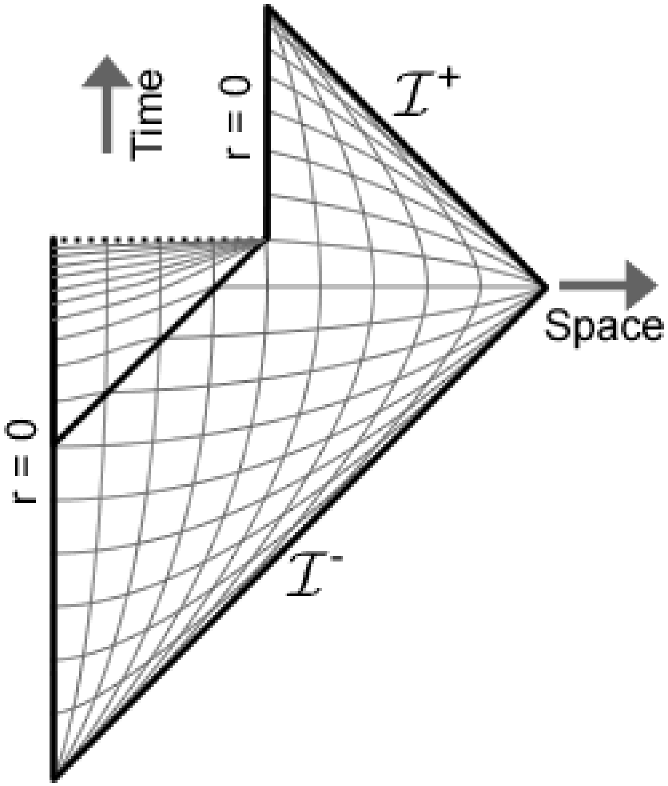
Evaporating Black Hole Diagram



Foliating the Evaporating Black Hole



The Foliation in Action



Gif by Christi Stoica

Where Did the Information Go?

- Relative to Σ_2, the black hole has evaporated: it is gone.
- So where did the information about what fell in go?
- Recall Hawking: "So what would happen to all that information locked inside a black hole that evaporated away and disappeared completely?"

Answer

- It is still in the interior of the black hole.

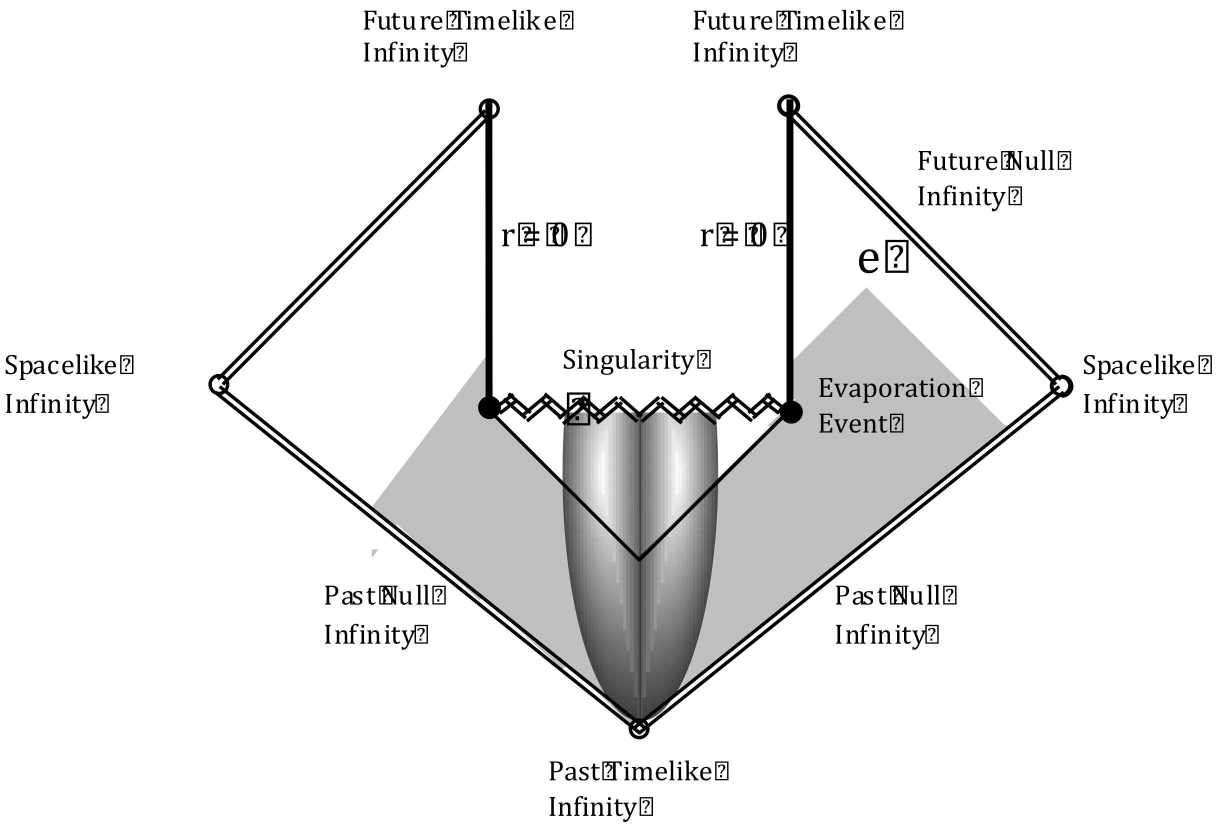
The Meaning of Is, Was, and Will Be

- In Relativity, temporal locutions have to be handled with some care.
- What does it mean to say, relative to a certain event, “X no longer exists”?
- It means: “The entirety of X lies in my past light-cone”.
- Similarly, “X has yet to exist” means “The entirety of X lies in my future light cone.”
- What about “X still exists”?

X Still Exists

- If the only choices are "X no longer exists", "X has yet to exist" and "X exists now", then "X exists now" *must* mean "Some part of X is neither in my past light-cone nor in my future light cone".
- Given this, the right thing to say is that even though the *event horizon* of the black hole no longer exists, the *interior* of the event horizon does exist.

The Past of an Event



Black Holes Are Not Like Spherical Bodies

- It is tempting to think of a black hole on analogy with a bronze sphere, or a balloon, with the event horizon as its spherical surface.
- But if you were to watch a balloon shrink and disappear, when the disappearance event is in your past, so too is the whole interior of the balloon.
- The event horizon can be in your past, and no longer exist, even though the interior of the event horizon is not in your past, and still exists.

Geroch's Second Theorem

- The fact that Σ_2 U Σ_{2in} is a Cauchy surface in our foliation is a surprise: it is disconnected and Gerloch's theorem stays that the leaves of a foliation cannot change topology.
- What went wrong?

Not a Manifold

- Geroch's theorems both presuppose that the space-time is a 4-domensional manifold. But the evaporating black hole space-time is not a manifold. The manifold structure fails exactly and only at the Evaporation Event.

- Although Geroch's first theorem still holds the second does not. That may be why this solution was overlooked.

In Sum

- Evaporating black holes are unusual spatio-temporal objects.
- By analogizing them inappropriately to spherical bodies it is easy to come to false conclusions about their structure.
- In particular, the event horizon around a black hole can evaporate and no longer exist even though the interior still exists.
- It is in this interior that the relevant information is kept. Paradox solved.