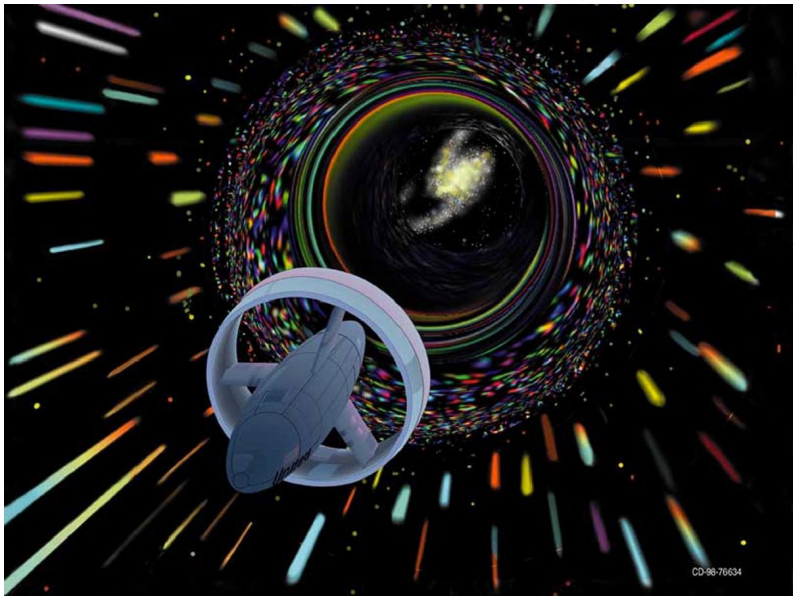
WORMHOLES

PROBLEM SET #7 ON WEBWORK – DUE MONDAY AT MIDNIGHT

FIRST MOVIE NIGHT TOMORROW!

Hypothetical spacecraft about to enter a hypothetical wormhole (Les Bossinas, Cortez III Service Group)



WORMHOLES

The nature of the mass-density singularity at the center of a black hole

Wormholes, and how to construct one using black holes

Wormhole maintenance: how a wormhole might work

Traversable wormholes not made from black holes

Wormhole time machines

IS DIRECT OBSERVATION OF THE MASS-DENSITY SINGULARITY POSSIBLE?

…While being able to communicate the observations back to others?

Penrose (1969): **No**. In a survey of analytical-mathematical solutions of the Einstein field equation for various collapsing objects, a horizon was always produced. He proposed, but could not yet prove, the converse of his horizon-singularity theorem, the **cosmic censorship conjecture**:

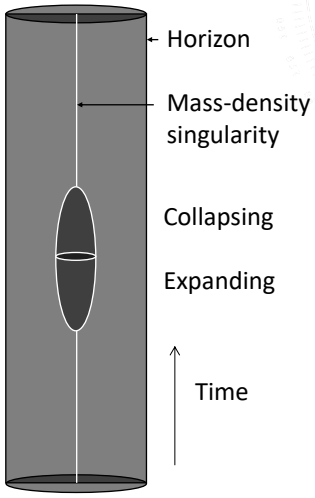
> Any solution to the Einstein field equation that involves the formation of a mass-density singularity also involves the formation of a black hole.

Teukolsky and Shapiro (1991): **Maybe**. In a survey of numerical computer solutions to the Einstein field equation for very lopsided collapsing star clusters, some **naked singularities** were produced, lacking horizons for a time. Whether they can exist in nature remains to be seen.

Choptuik (1997): **In a manner of speaking**. A numerical solution to the field equations for a collapsing spherical body, under some admittedly artificial initial conditions that probably would never be found in nature, produced a mass-density singularity before it produced a horizon.

EXPANDING AND COLLAPSING SINGULARITIES

- Some of the foam configurations might connect better to surrounding spacetime in which **expansion** takes place, as in the Big Bang (as we will see), rather than the contraction characteristic of black-hole formation.
  - Another way to look at this is that in expanding mode, **time flows *out* of the mass-density singularity** (like in the real Big Bang), rather than *in* (like in black hole formation).
- Therefore, it seems as though the mass-density singularity **might** switch back and forth between collapsing and expanding modes as it interacts with other masses and energies in the black hole's interior.



EXPANDING AND COLLAPSING SINGULARITIES

Implications:

- As it switches states, the mass-density singularity pushes and pulls the spacetime within the black hole's horizon. (Remember, spacetime *ends* at this singularity.)
  - If it really switches back *and* forth, it can create something resembling the "mixmaster" configuration of a black-hole interior.
- "Baby universes" may form inside the massive black holes. (This is the basis of many science-fiction stories…)
- Black holes with their mass-density singularities in expanding configuration provide a useful paradigm for the formation of a **wormhole**: a connection through hyperspace of two regions in spacetime that contain such singularities.

SWITCHING TO EXPANDING MODE

Which of these could most easily cause a mass-density singularity to spontaneously switch from black-hole (collapsing) type to big-bang (expanding) type?

A. Matter falling in from outside the horizon.
B. Light and/or gravitational waves falling in from outside the horizon.
C. Vacuum fluctuations very near the singularity, and their associated "Hawking radiation."
D. Disconnection in flow of time at singularity.

THE HAWKING-PRESKILL-THORNE BET

Mostly on the strength of the Choptuik result, and amid much fanfare and press coverage at Caltech, Stephen **Hawking** (1997) conceded the bet he had made with Kip **Thorne** and John **Preskill**. It cost him £100 and two T-shirts:

Whereas Stephen W. Hawking firmly believes that naked singularities are an anathema and should be prohibited by the laws of classical physics,

And whereas John Preskill and Kip Thorne regard naked singularities as quantum gravitational objects that might exist unclothed by horizons, for all to see.

Therefore Hawking offers, and Preskill/Thorne accept, a wager with odds of 100 pounds stirling to 50 pounds stirling, that when any form of classical matter or field that is incapable of becoming singular in flat spacetime is coupled to general relativity via the classical Einstein equations, the result can never be a singularity.

The loser will reward the winner with clothing to cover the winner's nakedness. The clothing is to be embroidered with a suitable concessionary message.

WORMHOLES

Wormholes are solutions to the Einstein field equation that involve two mass-density singularities. A wormhole can be thought of as a special combination of two black holes.

By special, we mean that the **interiors of the two black holes are connected** under some circumstances.

- Remember how strongly warped space is, both near and within a black hole horizon: a lot of space is contained within it, and if it were not so strongly curved, it could reach a long way – and, if it reaches inside another black hole…
- Or, if you prefer the hyperspace paradigm (as we do in this class): black holes that are distinct in physical space can **overlap in hyperspace**.

A concrete example may better show what we mean…

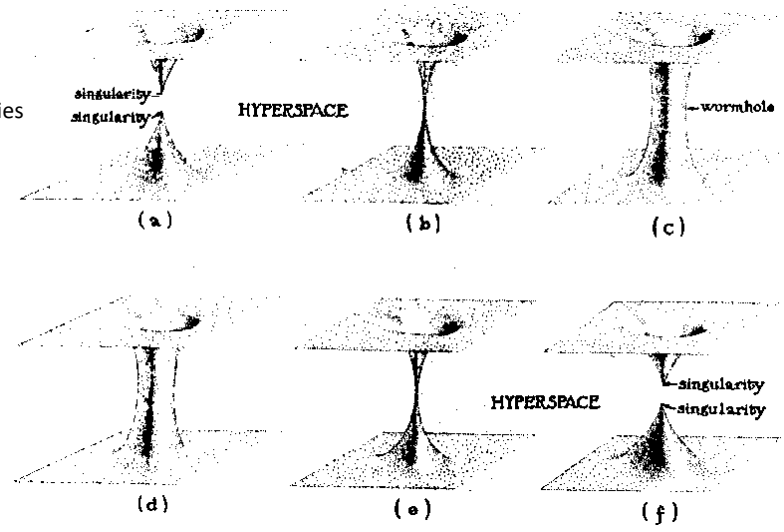
CONSTRUCTION & DESTRUCTION OF A WORMHOLE

Start with two black holes that overlap in hyperspace, each in a configuration in which the mass-density singularity is an expanding **singularity** (time flows out of the singularity; this is sometimes, but inconsistently, called a "white hole").

- According to our present (incomplete) understanding of quantum gravity, two such singularities may "unwrap" each other to produce a "tube" of continuous paths through hyperspace between the two black holes.
- **The "unwrapping" may even eliminate the horizons!**
- This tube through hyperspace is the wormhole. It would not look like a tube in *physical* space, though; each mouth would still look spherical from the outside.

CONSTRUCTION & DESTRUCTION OF A WORMHOLE

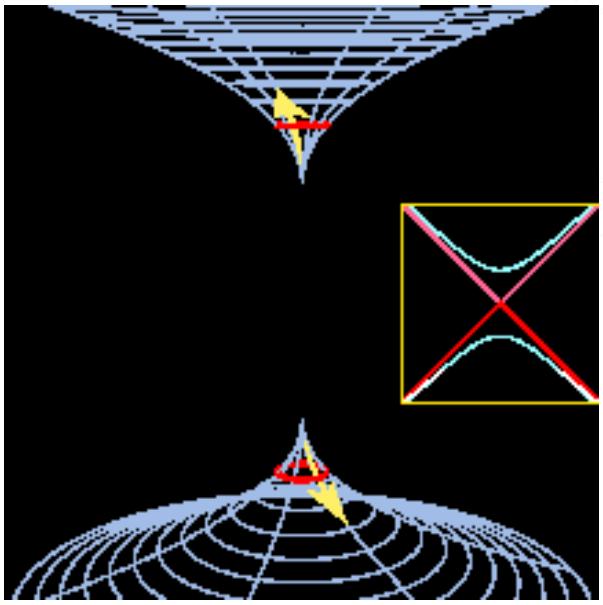
Expanding mass-density singularities



Contracting mass-density singularities

CONSTRUCTION & DESTRUCTION OF A WORMHOLE

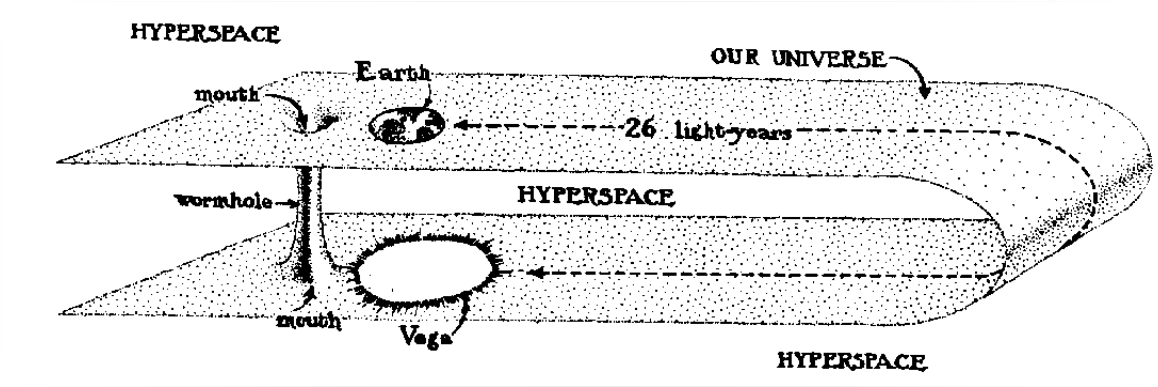
Expansion and contraction of the mass-density singularities (Andew Hamilton)



CONSTRUCTION & DESTRUCTION OF A WORMHOLE

- Since the mass-density singularities were of the expanding type (time flows out in both hyperspace directions), the diameter of the wormhole initially expands with time.
  - **Practical upshot**: The paths through hyperspace become somewhat less strongly warped; there would be decreasing gravitational forces and tides on bodies that found themselves there, while it expands.

- It is possible for the path through hyperspace to be short while the distance between the singularities is very large as measured in “real” spacetime.
  - **Practical upshot**: The wormhole can be a shortcut through spacetime. (Of course, it could also be longer than the straight path through regular spacetime…)



A HYPERSPACE SHORTCUT VIA A WORMHOLE

An **embedding diagram** of a wormhole with the ability to travel between Vega and Earth in about eighteen hours.

OTHER METHODS OF WORMHOLE CONSTRUCTION

Making wormholes from mass-density singularities (“quantum strategy”):

- The quantum foam of a mass-density singularity contains many wormhole-like structures. Perhaps one could be expanded by throwing enough exotic matter into a black-hole mass-density singularity.

Making wormholes without first making a singularity (“classical strategy”):

- Severely warp and twist spacetime. According to the Einstein field equation, it is possible (but extremely difficult to imagine or illustrate, and impossible to do without distorting time as seen from all reference frames) in a manner that involves time reversal.

HOW AN OPEN WORMHOLE MIGHT LOOK

It is spherical, like a giant globe of the sky as seen from the *other* mouth.

Pablo A. Cano

USE & ABUSE OF WORMHOLES

The downside: What happens if you try to enter the wormhole to employ the shortcut?

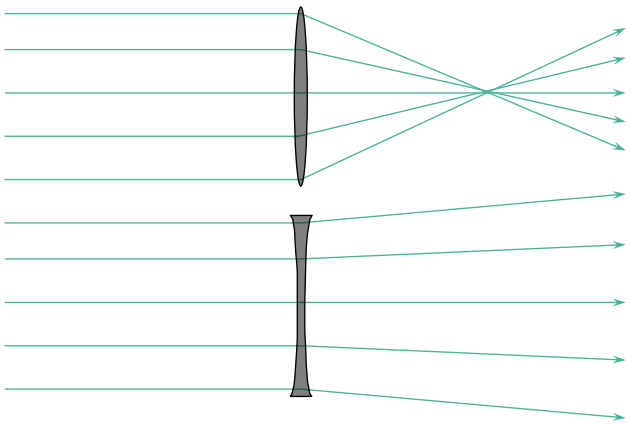
- You are accelerated to relativistic speeds on your way through. As a result, your energy (and mass) increase dramatically in the rest frame of the wormhole.
- Halfway through the wormhole, your mass eventually becomes large enough that your own gravity warps spacetime, collapsing the wormhole onto you.
- As your gravity "pinches off" the wormhole, singularities form again – but this time, they are of the black-hole type. Your energy is added to the black holes, and the wormhole is destroyed (and you are, too).

USE & ABUSE OF WORMHOLES

How could we prevent the collapse of the wormhole under your gravitational influence so that you could make it through unscathed?

- By putting exotic matter into it. Exotic matter, with its negative energy density, would be "anti-gravity:" it would warp spacetime opposite to the way normal matter warps it.
- In particular, adding exotic matter to a wormhole would tend to expand the diameter of its effective "hyperspace tunnel."

Recall our discussion of the effect on gravitational deflection of light by the (exotic) vacuum fluctuations near a black hole's event horizon.

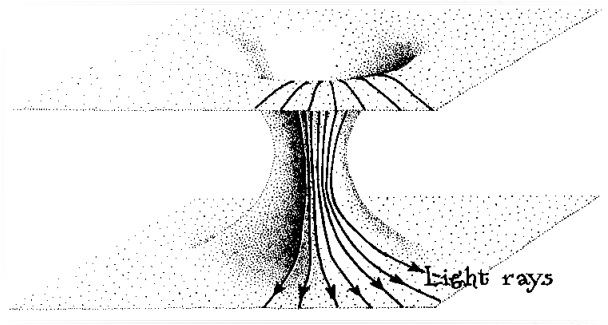


EXOTIC MATTER IN WORMHOLES

In the sense of gravitational deflection of light, a black hole acts as a positive lens and the surrounding vacuum fluctuations act as an additional, negative lens.

STABLE WORMHOLES MUST CONTAIN EXOTIC MATTER

Photons that enter the wormhole traveling radially inward leave it traveling radially outward without their paths crossing, like a negative lens would do; this gravitational defocusing of light can only be accomplished with negative energy-density material, since a positive energy density would have focused them to a point before they could diverge, as a positive lens would.



THE STAR TREK DS9 WORMHOLE

The most extensively-described fictional wormhole is almost definitely the one in *Star Trek: Deep Space Nine*.

HOW THE STAR TREK DS9 WORMHOLE MIGHT WORK

In *Star Trek: Deep Space Nine*, a stable wormhole provides a hyperspace shortcut from the "alpha" quadrant to the "gamma" quadrant of the Milky Way galaxy. In the story, it is inhabited by strange Epicurean beings who permit travelers to pass through by opening and closing the wormhole.

- ***How do they open and close the wormhole?***

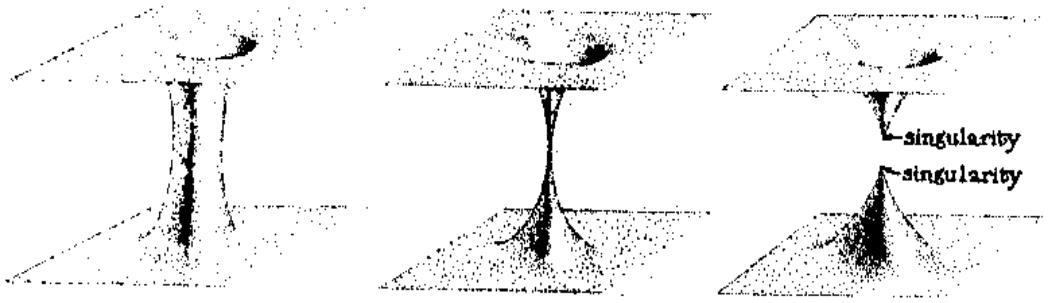
  By rearranging large amounts of exotic matter within the wormhole.

- ***Are the beings themselves made of exotic matter?***

  They are intelligent. Something as orderly as intelligence cannot arise from random vacuum fluctuations, so if the beings themselves are exotic, then there must be other forms of exotic matter besides vacuum fluctuations in strong gravity.

HOW THE STAR TREK DS9 WORMHOLE MIGHT WORK

Open ⟷ Closed



More exotic matter inside the wormhole

Less exotic matter inside the wormhole

Little exotic matter inside the wormhole

HOW THE STAR TREK DS9 WORMHOLE MIGHT WORK

- ***What does the wormhole look like from the inside when it is closed?***

  Like the neighborhood of a mass-density singularity: spacetime is very strongly warped, time ceases to exist at the center, etc. The non-existence of time at the center of the closed wormhole presumably gives the wormhole beings their peculiar view of time as something that can run forward, backward, stop, transpire out of sequence, and so forth.

- ***What does the wormhole look like from the inside when it is open?***

  Like a spherically symmetric space where everything is converging toward a center, gradually changing to a spherically-symmetric divergence from a center. It does not look like a tube in physical space, only in hyperspace.

TRAVELING THROUGH A WORMHOLE

If you proceeded to enter a wormhole in your spaceship, would you need to use your engines to move through the wormhole?

A. Yes – Even though space and time are strongly warped in the region, we still need to throw mass backwards to move forwards.

B. No – The warped spacetime of the wormhole will exert a force on us and pull us through!

HOW THE STAR TREK DS9 WORMHOLE MIGHT WORK

- ***How do you open the wormhole from the outside?***

  By sending a prearranged signal or beam of particles down the mouth; this arrives (highly accelerated or blueshifted) at the singularity, where the wormhole beings live, and when they detect it, they proceed to rearrange the exotic matter.

- ***Does the wormhole have a horizon?***

  Only when it is closed. (Then it has two, one at each mouth.)

- ***Is there a limit on how much matter can be moved through the wormhole at once?***

  Yes; if there is much more normal matter than exotic matter inside, the wormhole will collapse.

TRAVERSABLE, CONSTRUCTIBLE WORMHOLES

Advising Carl Sagan in the writing of *Contact* got Kip Thorne and his graduate student Mike Morris interested in how an advanced civilization might build wormholes for transportation. They wrote a set of instructions based on the following principles:

- For simplicity, the wormhole's geometry is taken to be spherical and static.
- It must represent a solution to the Einstein field equations (of course), and one stable against small perturbations.
- It must have a throat that connects two regions of flat spacetime, so that it can be used to connect places in our Universe. Thus, its equatorial-plane embedding diagram looks like the classic "hyperspace tunnel."
- There should be no horizon. (Wormholes do not have horizons while open!)
- The tidal forces and accelerations experienced by a traveler must be bearably small; they took < 1 Earth g.

TRAVERSABLE, CONSTRUCTIBLE WORMHOLES

- A traveler must be able to cross the wormhole in a finite amount of time in both the traveler's frame and in the frame of reference at rest with respect to the wormhole's mouths; they took < 1 year.
- The matter and fields that generate the wormhole's spacetime curvature must be physically reasonable.
- It should be possible to assemble the wormhole: it should require energy much less than the mass of the Universe times c^2, and take time much less than the age of the Universe.

The most difficult constraints turn out to be on the material that generates the curvature:

- It must be able to withstand enormous tension: the pressure represented by this tension turns out to be approximately

$$P = \left(\begin{matrix}\text{pressure at the center of the} \\ \text{most massive neutron stars}\end{matrix}\right) \times \left(\frac{20\ \text{km}}{\text{circumference of throat}}\right)^2$$

- This tension must exceed the material's mass density, and there is no such material known.

TRAVERSABLE, CONSTRUCTIBLE WORMHOLES

- In fact, if it were to have this property and be part of the structure, it would appear in the viewpoint of a distant observer to have negative energy density: **exotic matter**.
- So, there does not seem to be any way to avoid exotic matter in the construction of a traversable wormhole. All they could do was consider ways to minimize the amount.

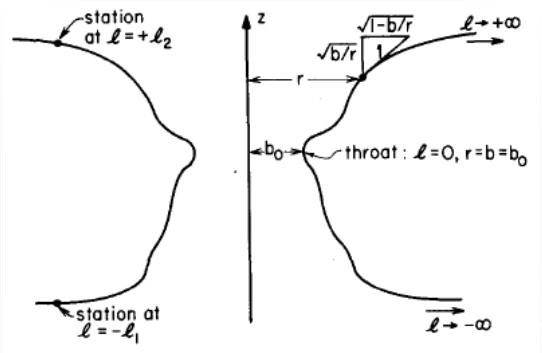


Fig. 2. Embedding diagram for a general wormhole, as seen in profile. (The diagram must be rotated about the vertical z axis to make it complete; cf. Fig. 1.).

Morris & Thorne (1988)

TRAVERSABLE, CONSTRUCTIBLE WORMHOLES

Properties of the minimum-exotic-matter solution:

- Exotic matter provided as a spherical shell slightly larger than the throat of the wormhole. All the other matter is non-exotic.
- Characteristic size of the mouths is rather large (600 times the size of the Solar System) in order to keep the accelerations modest.
- Accelerations no greater than one Earth *g*, small tidal forces, so traversing it would be perfectly comfortable.
- It would take 200 days to traverse the wormhole.
- How long it is in physical space determines the total mass.

So all we need is the exotic matter!