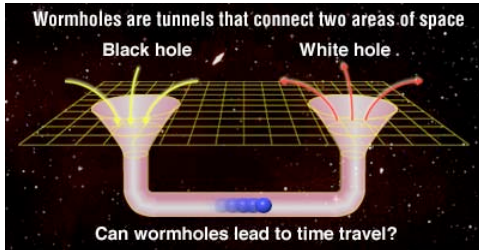


Astronomy 102.
November 29, 2005.



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Wormholes.

- Wormholes are solutions to the Einstein field equation that involve two 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, near and within a black hole horizon: a lot of space is contained therein, and if it weren't so strongly curved it could reach a long way.
 - 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 show better what we mean

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Construction and destruction of a wormhole.

- Start with two black holes that overlap in hyperspace, each in a configuration in which it is an expanding singularity (time flows out of the singularity).
 - According to our present (incomplete) understanding of quantum gravity, two such singularities may "unwarp" each other to produce a "tube" of continuous paths through hyperspace between the two black holes.
 - The "unwarping" may even eliminate the horizons!
 - This tube through hyperspace is the wormhole. It wouldn't look like a tube in physical space, though; each mouth would still look spherical from the outside.

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Construction and destruction of a wormhole.

Expanding singularities

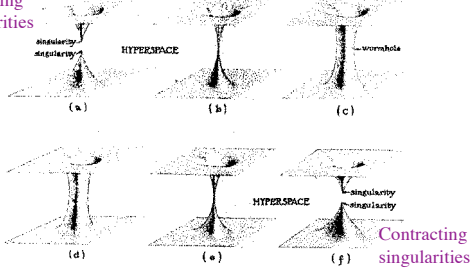


Figure from Thorne, *Black holes and time warps*.

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Construction and destruction of a wormhole.

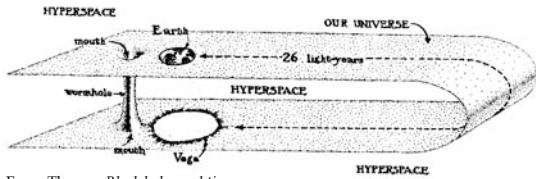
- Since the singularities are of the expanding type (time flows out in both hyperspace directions), the diameter of the wormhole initially expands with time.
 - Practical upshot: the paths through hyperspace become somewhat less strongly warped: there would be decreasing gravitational forces and tides 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, measured in "real" space-time.
 - Practical upshot: the wormhole can be a shortcut through space-time. (Of course, it could also be longer than the straight path through regular space-time...)

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A hyperspace shortcut via a wormhole.

- A **embedding diagram** of a wormhole with the properties described in Carl Sagan's novel *Contact*, that was used by the lead character, Ellie Arroway, to travel to the neighborhood of Vega and back in about eighteen hours.



From Thorne, *Black holes and time warps*

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Contact (1997).
Based on Carl Sagan's novel.



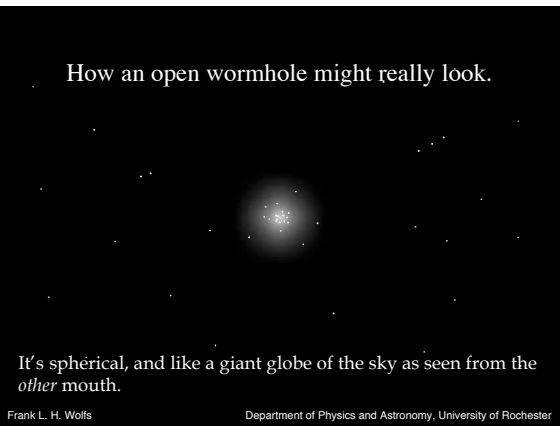
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Other methods of wormhole construction.

- Making wormholes from singularities ("quantum strategy"):
 - The quantum foam of a singularity contains many wormhole-like structures. Perhaps one could be expanded by throwing enough exotic matter into a black-hole singularity.
- Making wormholes without first making a singularity ("classical strategy"):
 - Severely warp and twist space-time. It is possible, according to the Einstein field equation, but extremely hard to picture, and impossible to do without distorting time as seen from all reference frames, in a manner that involves time reversal.

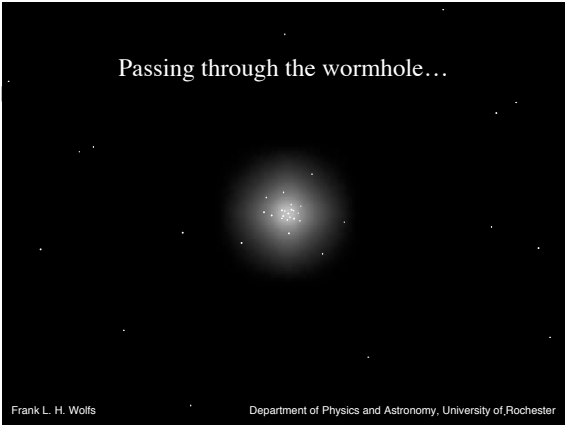
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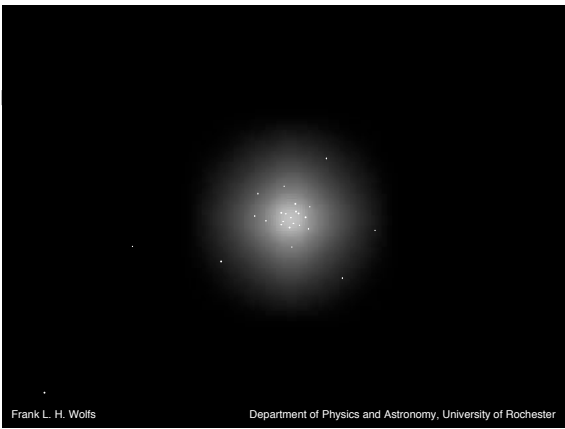
How an open wormhole might really look.

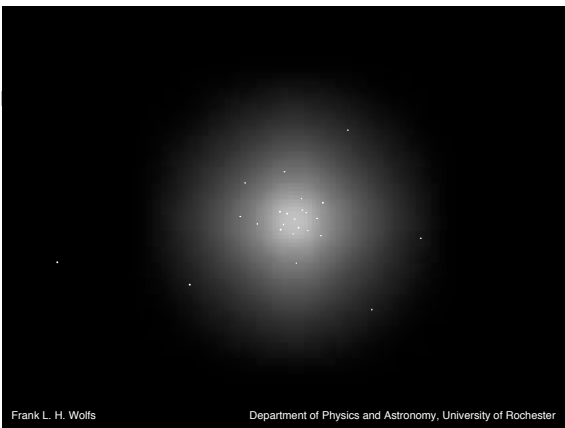


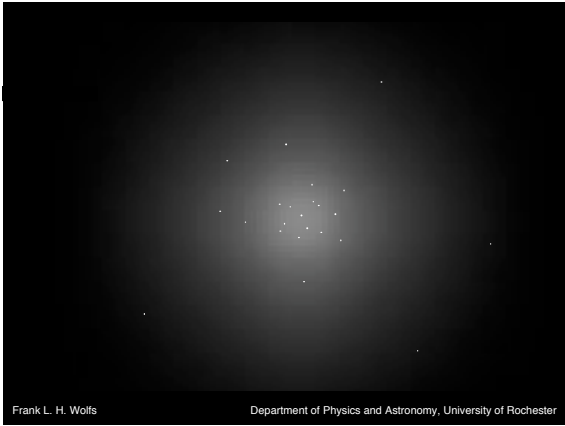
It's spherical, and like a giant globe of the sky as seen from the other mouth.

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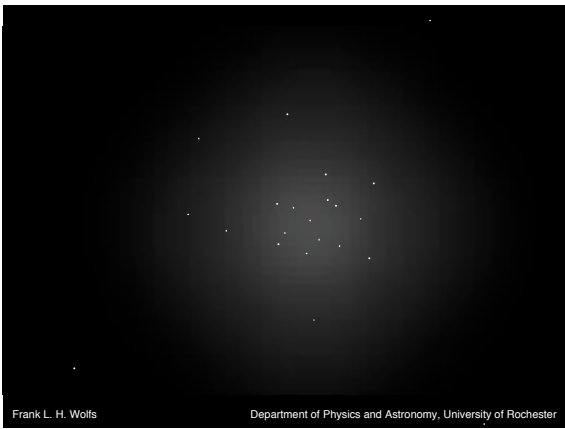






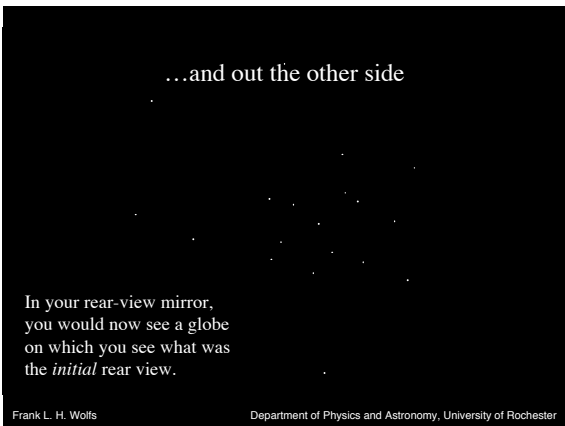
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Use and abuse of wormholes.

- The down side: 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 view of distant observers.
 - Your mass eventually becomes large enough, halfway through the wormhole, that your own gravity warps space-time, collapsing the wormhole onto you.
 - As your gravity “pinches off” the wormhole, singularities form again - but this time, they’re of the black hole type. Your energy is added to the black holes, and the wormhole is destroyed.

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Use and abuse of wormholes.

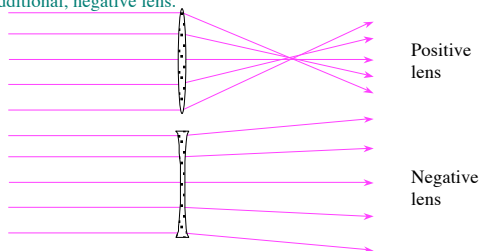
- How could we prevent the collapse of the wormhole under your gravitational influence, so you could make it through unscratched?
 - By putting exotic matter into it. Exotic matter, with its negative energy density, would be “anti-gravity”; it would warp space-time in senses opposite to the way normal matter warps it.
 - In particular, adding exotic matter to a wormhole would tend to expand the diameter of its effective “hyperspace tunnel.”
- Recall the calculation of the effect on gravitational deflection of light by the (exotic) vacuum fluctuations near a black hole’s event horizon.

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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.



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If a wormhole is stable, it must contain exotic matter.

- Photons that enter the wormhole travelling radially inward leave it travelling 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 focussed them to a point before they could diverge, as a positive lens would.

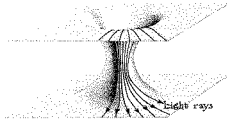


Figure from Thorne, *Black holes and time warps*.

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Mid-Lecture Break.

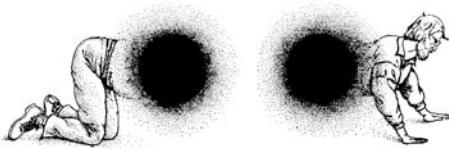
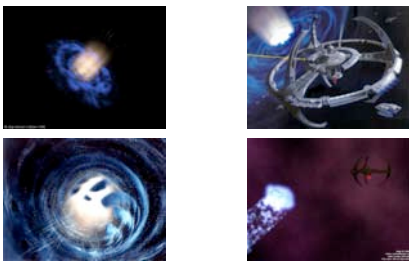


Image: Kip Thorne crawling through a wormhole. From *Black holes and time warps*.

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Star Trek: Deep Space 9. Paramount Pictures.



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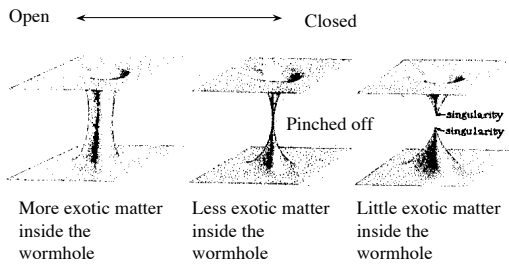
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Wormhole maintenance: how the Star Trek wormhole might work.

- 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 couldn't be made completely of exotic matter, since they are intelligent. It is hard to imagine something as orderly as intelligence arising from random vacuum fluctuations.

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Wormhole maintenance: how the Star Trek wormhole might work.



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Wormhole maintenance: how the Star Trek wormhole might work.

- How does the wormhole appear when it's closed? The same as a black hole, from both mouths.
- What does the wormhole look like from the outside, when it's open? Like a faint, spherically symmetric source of light; it transmits all the light incident upon the other mouth. Look into it to see a view of the sky on the other side.
- It certainly would not look anything like this (The ST-DS9 Wormhole; Paramount Studios).



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Wormhole maintenance: how the Star Trek wormhole might work.

- What does the wormhole look like from the inside, when it's closed? Like the neighborhood of a singularity: space-time very strongly warped, time ceasing 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's open? Like a spherically symmetrical 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.

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Wormhole maintenance: how the Star Trek wormhole might work.

- Is energy required to move through the wormhole? No; gravity accelerates you and pulls you through. It would take a great deal of thrust to hold still inside the wormhole, contrary to what's shown on the TV show.
- How does one open the wormhole from the outside? By sending a prearranged signal or beam of particles down the mouth; this arrives (highly accelerated or blue shifted) 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's closed. When it is closed, it has two, one at each mouth.
- Is there a limit to how much matter can be moved through the wormhole at once? Yes; if there's much more normal matter than exotic matter inside, the wormhole will collapse.

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Wormholes as time machines.

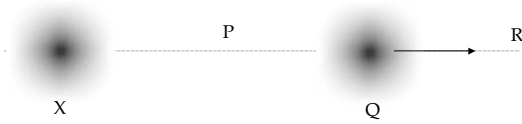
- How does time hook up inside a wormhole? Imagine a wormhole with **constant length in hyperspace**, but with the **two mouths moving with respect to each other in physical space**, with one of them experiencing acceleration.
 - Time dilation: clocks just outside the two mouths would appear to a distant observer to run at different speeds; the rates of time flow are different.
 - From the inside, though, the mouths appear at rest with respect to each other; the rates of time flow are the same.
 - This effect, the difference in time flows at the two mouths and the joining in the middle, could enable the use of a wormhole as a time machine, as follows.....

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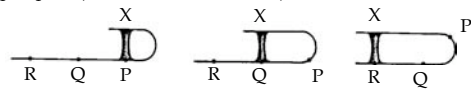
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Wormholes as time machines.

Wormhole "mouths" in physical space at one instant of time



Hyperspace (at three instants of time)



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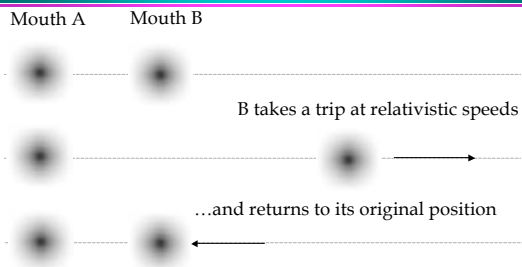
How to build a wormhole time machine.

- Start with a wormhole whose two mouths (called mouths A and B) are close together in space. Fix things up so that they stay the same distance apart in hyperspace.
- In Thorne's description in the book, this is illustrated by two people reaching into each mouth to hold hands.
- Take mouth B on a trip at high speeds (approaching light speed), out a great distance, and then back to its former spot, without ever changing the distance between the two mouths in hyperspace.

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How to build a wormhole time machine.



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How to build a wormhole time machine.

- Because of time dilation, the trip will take a short time according to an observer travelling with mouth B, and a much longer time according to an observer who stays with the “stationary” mouth A.
- While B is gone, the observer at A can travel into the future (to the time when B returns) by passing through mouth A.
- After B returns, an observer at B can travel into the past (to the time when B left) by passing through mouth B.
- The length of time travel is thus the time lag between clocks fixed to A and B during B’s trip, and is thus adjustable by adjusting the details of the trip.
- Travel between arbitrary times is not provided!

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Odd features of time travel.

- Paradoxes such as the “matricide paradox” come up! One could use a time machine, for example, for travelling back through time before one’s birthday and killing one’s mother.
- Does physics prevent one from being born and travelling back through time in the first place?
 - Maybe. How is it that one can start with laws of physics like the Einstein field equation, that have cause and effect built in, and derive from them violations of cause and effect?
 - Maybe not. What about quantum mechanics? Vacuum fluctuations, for instance, have no “cause.” If quantum behavior (associated with singularities) is inherent in the wormhole, one could still exist after committing paradoxical matricide.

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Alas, it may be impossible to build a stable wormhole time machine.

- Geroch, Wald, and Hawking on self-destruction of wormhole time machines:
 - Light leaving the origin during B’s trip, and entering mouth B as it is returning, can travel backwards in time, emerge from A, and meet itself in the act of leaving.
 - It can do this as many times as it likes, even an infinite number of times.
 - Since light can interfere constructively (all the peaks and troughs of the light wave lining up), a large positive energy density could be generated in the wormhole, which would collapse it.
 - This process could take as little as 10⁻⁹⁵ seconds in the frame of reference of mouth A.

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A recipe for wormhole time-machine destruction.

A (past) B (future)

Light emerging from mouth A

Mirror

Laser

Aim a laser at mouth B; orient mirror so that light emerging from mouth A joins up with the beam aimed at mouth B.

Immediately a huge number of photons emerges from mouth A, and the vast increase of energy inside it collapses the wormhole.

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Alas, it may be impossible to build a stable wormhole time machine.

- It's also possible for this to happen with light created by vacuum fluctuations!
- Since light has wave properties too, the probability that virtual photons from near A to travel to B and re-emerge from A pointed again at B is not zero, even if there is nothing to aim the photons that way.
- The interference may not be constructive, though, because the wormhole tends to defocus the light in the manner of a negative lens; therefore we do not know whether this is a fatal objection.

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The end (at least for today)!

- See you on Thursday when we start discussing the origin of the Universe.

Inside the Eagle Nebula. Credit & Copyright: T. A. Rector & B. A. Wolpa, NOAO, AURA, NSF

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