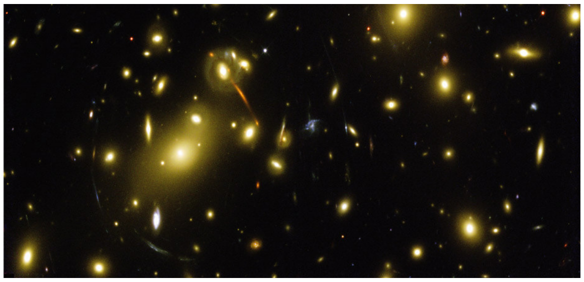
Chapter S3
Spacetime and Gravity



Agenda

- Announce:
  - Online Quizzes
  - Observations
  - Extra Credit Lecture
- Distinguishing Crackpot/Genuine Science
- Review of Special Relativity
- General Relativity

Distinguishing Crackpots

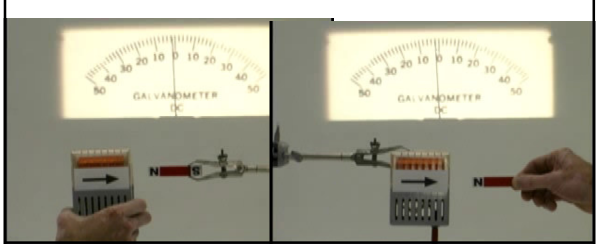
- Investigates failure of accepted theory
- Explains math used
- Tries to make specific prediction of testable effects
- May use esoteric jargon but provides references for where to learn about it

- Trashes all of "accepted theory"
- Avoids math or uses strange terminology w/ little explanation
- Tends to assert that theory explains all current data…no need to test
- Uses strange wording with no definitions…imprecise

Review of Special Relativity

- Two central tenets:
  - Speed of light
  - Equivalent laws in inertial frames
- Implications:
  - Time dilation
  - Length contraction
  - Electric field⇔Magnetic field
- Radical viewpoint, but experiments completely support (one of most tested theories):
  - Muon lifetimes hitting atmosphere
  - Flying atomic clocks
  - ALL of modern physics/chemistry

Equivalence of E & M



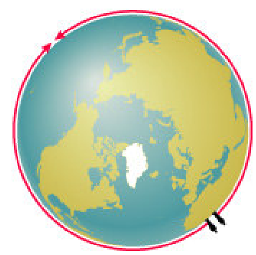
S3.1 Einstein's Revolution

- Our goals for learning
- What are the major ideas of general relativity?
- Is all motion relative?

Spacetime

- Special relativity showed that space and time are not absolute
- Instead they are inextricably linked in a four-dimensional combination called **spacetime**

Curved Space

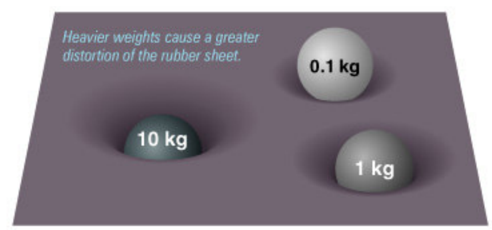


- Travelers going in opposite directions in straight lines will eventually meet
- Because they meet, the travelers know Earth's surface cannot be flat—it must be curved

Curved Spacetime

- Gravity can cause two space probes moving around Earth to meet
- General relativity says this happens because spacetime is curved

Rubber Sheet Analogy

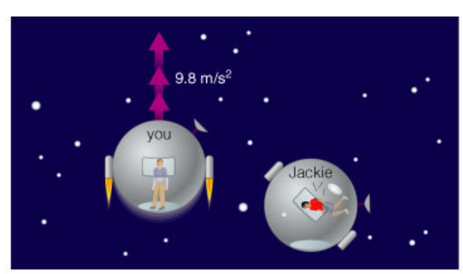


- Matter distorts spacetime in a manner analogous to how heavy weights distort a rubber sheet

Key Ideas of General Relativity

- Gravity arises from distortions of spacetime
- Time runs slowly in gravitational fields
- *Black holes* can exist in spacetime
- The universe may have no boundaries and no center but may still have finite volume
- Rapid changes in the motion of large masses can cause *gravitational waves*

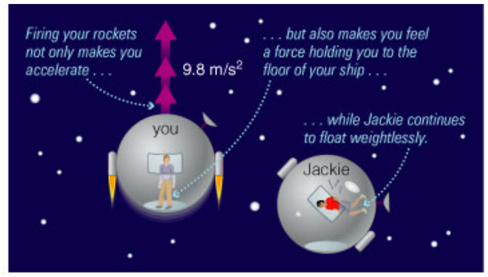
Is all motion relative?



Relativity and Acceleration

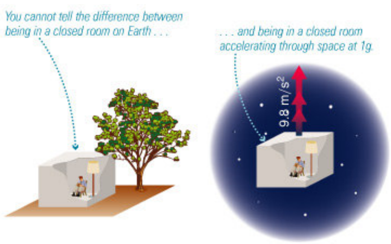
- Our thought experiments about special relativity involved spaceships moving at constant velocity
- Is all motion still relative when acceleration and gravity enter the picture?

Acceleration and Relative Motion



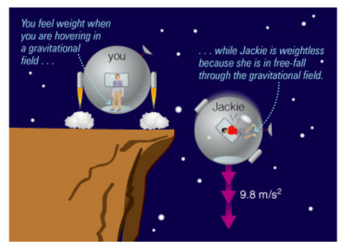
- How can your motion be relative if you're feeling a force causing acceleration?

The Equivalence Principle



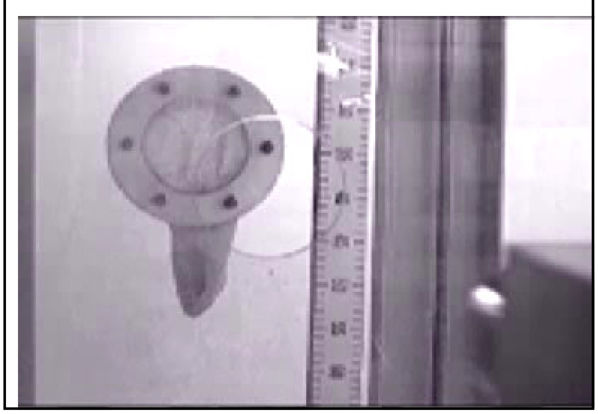
- Einstein preserved the idea that all motion is relative by pointing out that the effects of acceleration are exactly equivalent to those of gravity

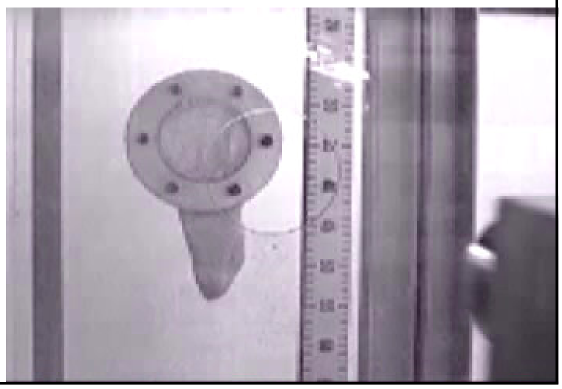
Gravity and Relative Motion



- Someone who feels a force may be hovering in a gravitational field
- Someone who feels weightless may be in free-fall

Classic Demonstration





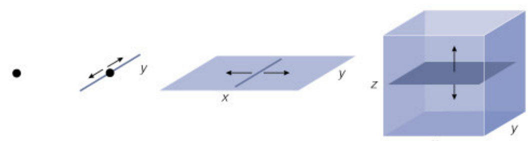
What have we learned?

- What are the major ideas of general relativity?
  - Gravity arises from curvature of spacetime
  - Gravity slows passage of time
  - Black holes can exist; universe may be finite
- Is all motion relative?
  - Yes, because the effects of gravity are exactly equivalent to the effects of gravity (Einstein's *Equivalence Principle*)

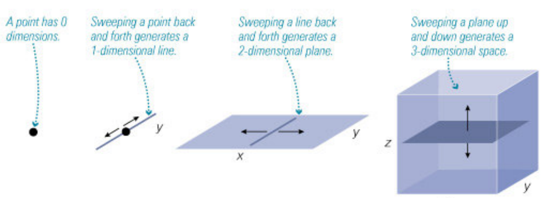
S3.2 Understanding Spacetime

- Our goals for learning
- What is spacetime?
- What is curved spacetime?

What is spacetime?



Dimensions of Space



- An object's number of dimensions is the number of independent directions in which movement is possible within the object

Dimensions of Spacetime

- We can move through three dimensions in space (*x,y,z*)
- We our motion through time is in one direction (*t*)
- Spacetime, the combination of space and time, has four dimensions (*x,y,x,t*)
- Need four numbers to specify out "address" in the Universe….hence 4D

Perspectives in Space

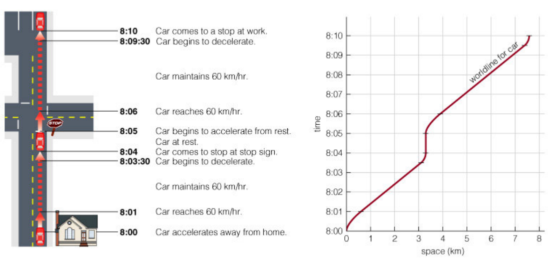
- A book has a definite three-dimensional shape
- But the book looks different in two-dimensional pictures of the book taken from different perspectives
- Similarly, space and time look different from different perspectives in spacetime

Perspectives in Spacetime

- Observers in relative motion do not share the same definitions of *x, y, z,* and *t*, taken individually

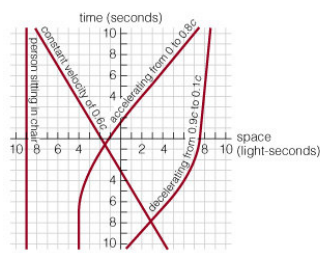
Space is different for different observers.
Time is different for different observers.
Spacetime is the same for everyone.

Spacetime Diagram of a Car



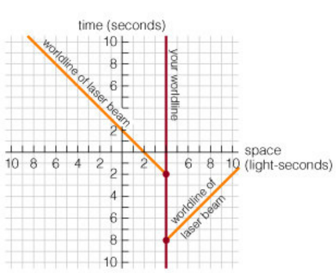
- A spacetime diagram plots an object's position in space at different moments in time

Worldlines



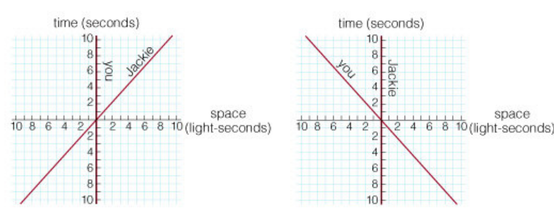
- A worldline shows an object's path through spacetime in a spacetime diagram
  - Vertical worldline: no motion
  - Diagonal worldline: constant-velocity motion
  - Curved worldline: accelerating motion

Worldlines for Light



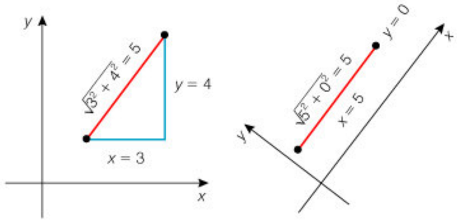
- Worldlines for light go at 45° angles in diagrams with light-seconds on one axis and seconds on the other

Worldlines and Relativity



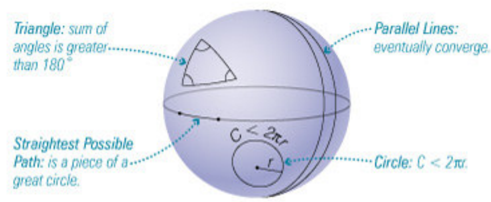
- Worldlines look different in different reference frames

Worldlines and Relativity

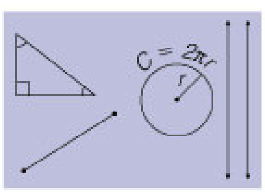


- But everyone will agree on the "distance" between two different events in spacetime: $x^2 + y^2 + z^2 - (ct)^2$

What is curved spacetime?

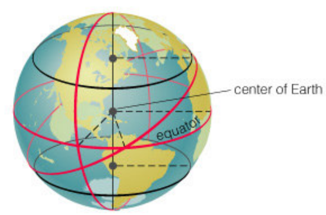


Rules of Geometry in Flat Space



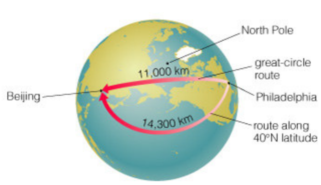
- Straight line is shortest distance between two points
- Parallel lines stay same distance apart
- Angles of a triangle sum to 180°
- Circumference of circle is $2\pi r$

Geometry on a Curved Surface



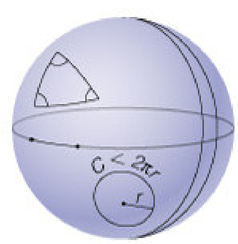
- The straightest lines on a sphere are *great circles* sharing the same center as the sphere
- Great circles intersect, unlike parallel lines in flat space

Geometry on a Curved Surface



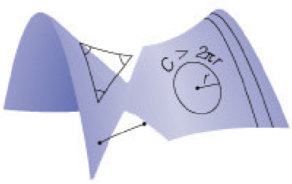
- Straight lines are shortest paths between two points in flat space
- Great circles are the shortest paths between two points on a sphere

Rules of Spherical Geometry



- Great circle is shortest distance between two points
- Parallel lines eventually converge
- Angles of a triangle sum to > 180°
- Circumference of circle is $< 2\pi r$

Rules of Saddle-Shaped Geometry



- Piece of hyperbola is shortest distance between two points
- Parallel lines diverge
- Angles of a triangle sum to < 180°
- Circumference of circle is > $2\pi r$

Geometry of the Universe

- Universe may be either flat, spherical, or saddle-shaped depending on how much matter (and energy) it contains
  - Flat and saddle-shaped universe are infinite in extent
  - Spherical universe is finite in extent
  - No center and no edge to the universe is necessary in any of these cases

"Straight" lines in Spacetime

- According to Equivalence Principle:
  - If you are floating freely, then your worldline is following the *straightest possible path* through spacetime
  - If you feel weight, then you are not on the straightest possible path

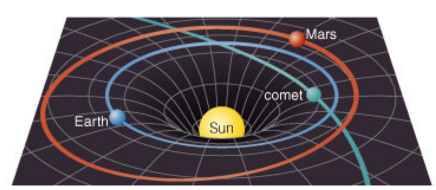
What have we learned?

- What is spacetime?
  - Spacetime is the four-dimensional combination of space and time that forms the "fabric" of our universe
- What is curved spacetime?
  - Spacetime can be curved just as a piece of paper can be curved
  - The three possible geometries for spacetime are flat, spherical, and saddle-shaped
  - The rules of geometry differ among these cases

S3.3 A New View of Gravity

- Our goals for learning
- What is gravity?
- What is a black hole?
- How does gravity affect time?

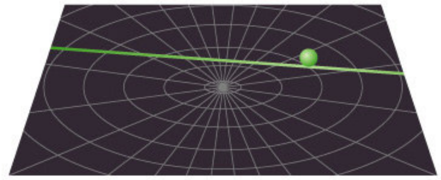
What is gravity?



Gravity, Newton, and Einstein

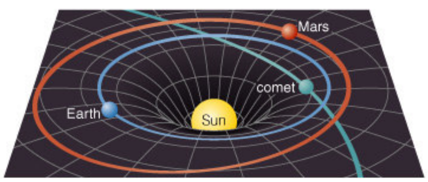
- Newton viewed gravity as a mysterious "action at a distance"
- Einstein removed the mystery by showing that what we perceive as gravity arises from curvature of spacetime

Rubber Sheet Analogy



- On a flat rubber sheet
  - Free-falling objects move in straight lines
  - Circles all have circumference $2\pi r$

Rubber Sheet Analogy

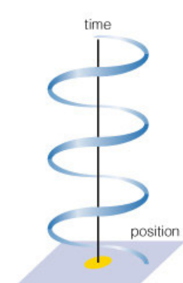


- Mass of Sun curves spacetime
  - Free-falling objects near Sun follow curved paths
  - Circles near Sun have circumference < $2\pi r$

Limitations of the Analogy

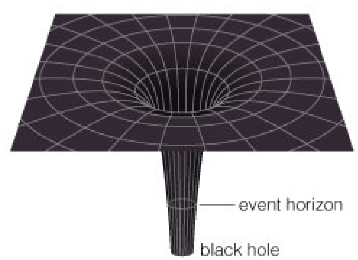
- Masses do not rest "upon" the spacetime like they rest on a rubber sheet
- Rubber sheet shows only two dimensions of space

Limitations of the Analogy

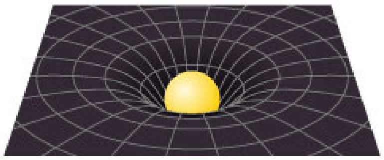


- Rubber sheet shows only two dimensions of space
- Path of an orbiting object actually spirals through spacetime as it moves forward in time

What is a black hole?

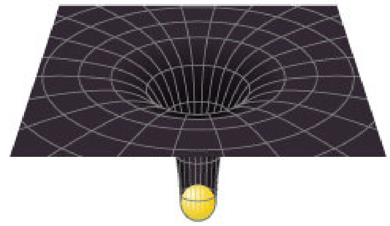


Curvature near Sun



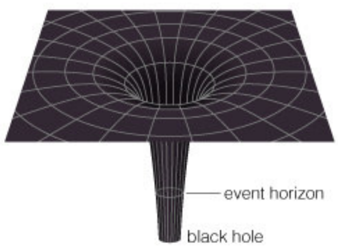
- Sun's mass curves spacetime near its surface

Curvature near Sun



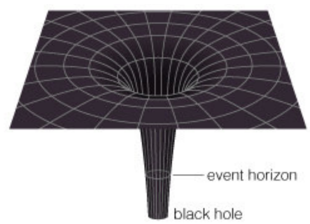
- If we could shrink the Sun without changing its mass, curvature of spacetime would become greater near its surface, as would strength of gravity

Curvature near Black Hole



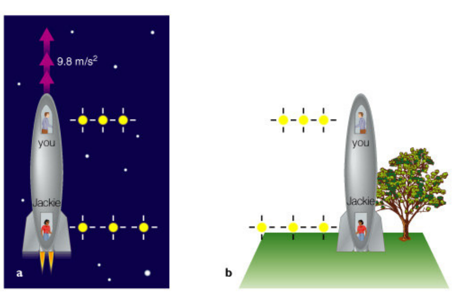
- Continued shrinkage of Sun would eventually make curvature so great that it would be like a bottomless pit in spacetime: a *black hole*

Limitations of the Analogy

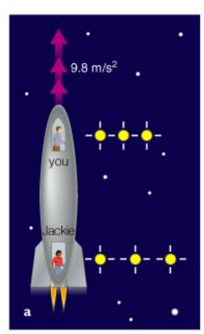


- Spacetime is so curved near a black hole that nothing can escape
- The "point of no return" is called the *event horizon*
- Event horizon is a three-dimensional surface

How does gravity affect time?

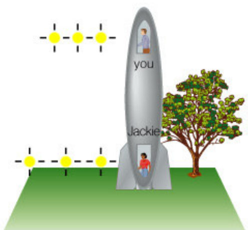


Time in an Accelerating Spaceship



- Light pulse travel more quickly from front to back of an accelerating spaceship than in other direction
- Everyone on ship agrees that time runs faster in front than in back

Time in an Gravitational Field

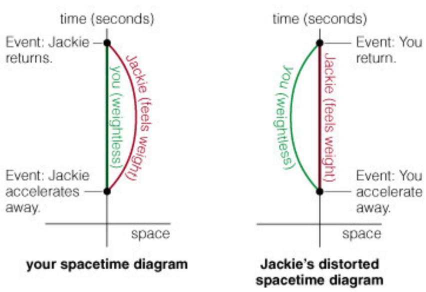


- Effects of gravity are exactly equivalent to those of acceleration
- Time must run more quickly at higher altitudes in a gravitational field than at lower altitudes

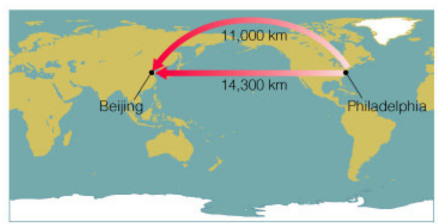
Special Topic: The Twin Paradox

- If one twin takes a high-speed round trip to a distant star, that twin will have aged less than the other that remains on Earth
- But doesn't time on Earth appear to run slower from the perspective of the twin on the high-speed trip?
- Solution: The twin on the trip is accelerating

Special Topic: The Twin Paradox



Special Topic: The Twin Paradox



- The shortest path may look curved from some perspectives, but more time always passes for the twin following the shorter path through spacetime

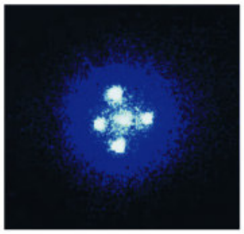
What have we learned?

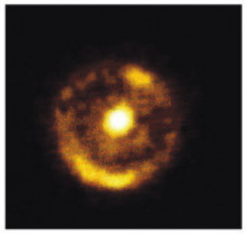
- What is gravity?
  - Gravity arises from curvature of spacetime
- What is a black hole?
  - Spacetime becomes very highly curved around a large mass compressed into a tiny space
  - Around a black hole, spacetime becomes so curved that nothing can escape
- How does gravity affect time?
  - Time runs more slowly at lower altitudes in a gravitational field

S3.4 Testing General Relativity

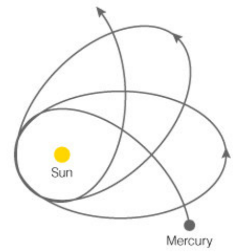
- Our goals for learning
- How do we test the predictions of the general theory of relativity?
- What are gravitational waves?

How do we test the predictions of general relativity?





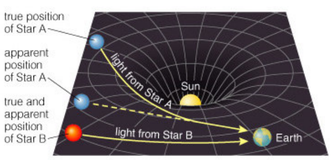
Precession of Mercury



Note: The amount of precession with each orbit is highly exaggerated in this picture.

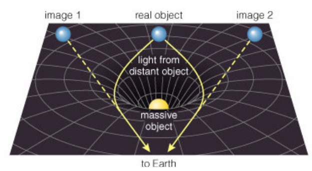
- The major axis of Mercury’s elliptical orbit precesses with time at a rate that disagrees with Newton’s laws
- General relativity precisely accounts for Mercury’s precession

Gravitational Lensing



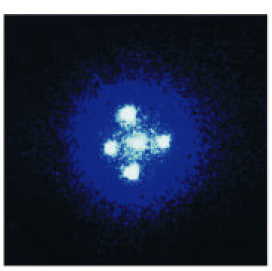
- Curved spacetime alters the paths of light rays, shifting the apparent positions of objects in an effect called *gravitational lensing*
- Observed shifts precisely agree with general relativity

Gravitational Lensing



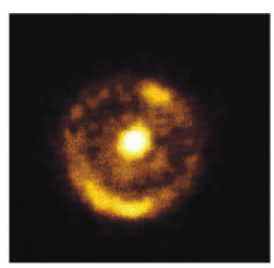
- Gravitational lensing can distort the images of objects
- Lensing can even make one object appear to be at two or more points in the sky

Gravitational Lensing



- Gravity of foreground galaxy (center) bends light from an object almost directly behind it
- Four images of that object appear in the sky (Einstein’s Cross)

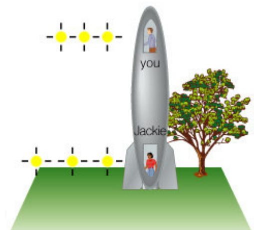
Gravitational Lensing



- Gravity of foreground galaxy (center) bends light from an object directly behind it
- A ring of light from the background object appears in the sky (Einstein Ring)

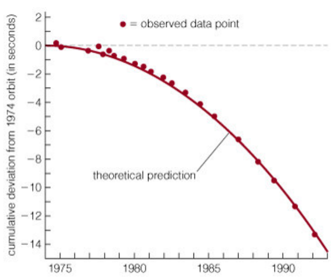
Demonstration of Grav. Lensing

Gravitational Time Dilation



- Passage of time has been measured at different altitudes has been precisely measured
- Time indeed passes more slowly at lower altitudes in precise agreement with general relativity

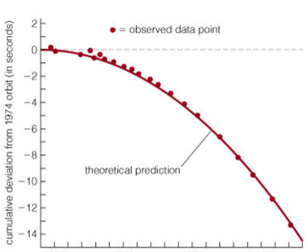
What are gravitational waves?



Gravitational Waves

- General relativity predicts that movements of a massive object can produce gravitational waves just as movements of a charged particle produce light waves
- Gravitational waves have not yet been directly detected

Indirect Detection of Waves



- Observed changes in orbit of a binary system consisting of two neutron stars agree precisely with predictions of general relativity
- Orbital energy is being carried away by gravitational waves

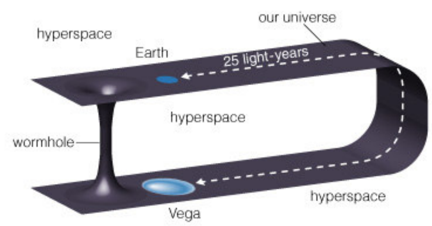
What have we learned?

- How do we test the predictions of the general theory of relativity?
  - Precession of Mercury
  - Gravitational Lensing
  - Gravitational Time Dilation
- What are gravitational waves?
  - Movements of massive objects produce wavelike disturbances in spacetime called gravitational waves

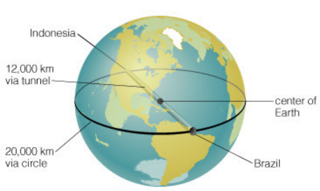
S3.5 Hyperspace, Wormholes, and Warp Drive

- Our goals for learning
- Where does science end and science fiction begin?

Where does science end and science fiction begin?

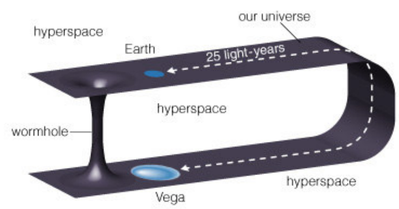


Shortcuts through Space



- If we could somehow build a tunnel through the center of Earth, the trip from Indonesia to Brazil would be much shorter
- Could there be analogous tunnels through spacetime?

Shortcut through Spacetime



- Some mathematical solutions of the equations of general relativity allow for shortcuts called *wormholes* that are tunnels through *hyperspace*

Are Wormholes Really Possible?

- Wormholes are not explicitly prohibited by known laws of physics but there is no known way to make one
- If wormholes exist, then they can be used for time travel
- Time travel leads to paradoxes that some scientists believe should rule out the possibility of wormholes

What have we learned?

- Where does science end and science fiction begin?
  - No known laws of physics prohibit the shortcuts through spacetime known as wormholes
  - However, wormholes would enable time travel, leading to paradoxes that some believe rule out the possibility of wormholes