Einstein’s Theory of General Relativity
The Topic is Gravity

• Einstein stunned the scientific world in 1915…
  • with publication of his **general theory of relativity**
  • it is primarily a theory of **gravity**
• Isaac Newton saw gravity as a mysterious “force”. He could explain its actions, but not how it was transmitted through space

• Einstein theorized that the “force” of gravity arises from distortions of space (or **spacetime**) itself!
The Equivalence Principle

- Einstein’s intuition told him that all motion should be relative
- This led him to a revelation…the equivalence principle
  The effects of gravity are exactly equivalent to the effects of acceleration.

- Suppose you were in a closed room.
- Whether on Earth or accelerating through space at 9.8 m/s² you would never know the difference
- your weight would be the same
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- Suppose you were in a closed room.
- There is **no way** for you to know whether you are feeling gravity on earth or acceleration in space.
Rules of Geometry in Flat Space

- Straight line is the shortest distance between two points.
- Parallel lines stay the same distance apart.
- Angles of a triangle sum to 180°.
- Circumference of a 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 $< 180^\circ$
- Circumference of circle is $> 2\pi r$
Geometry of Spacetime

- Spacetime can have three possible geometries:
  - flat…the rules of Euclidean geometry apply
  - spherical…parallel lines eventually meet
  - saddle-shaped…parallel lines eventually diverge
- Spacetime may have different geometries in different places.
- If spacetime is curved, then no line can be perfectly straight.
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- An object in freefall does not feel acceleration
- Hence this must be equivalent to not feeling a force of gravity
- This is equivalent to motion with constant velocity (no force)
“Straight” lines in Spacetime

- According to **Equivalence Principle**, being in “free-fall” is equivalent to traveling at constant velocity (i.e. a straight line).
- Objects experiencing weightlessness (free fall) must be traveling along the straightest possible path in spacetime.
- Objects in orbit are in free fall (weightless).
- Thus their orbits are the straightest possible path in spacetime.
- Since this straightest possible path in spacetime is not a straight line, **spacetime is curved**.
- The shapes & speeds of the orbits can thus reveal the geometry of spacetime.
- Gravity thus appears due to the curvature of spacetime by massive objects.
Mass and Spacetime

- mass causes spacetime to curve
- the greater the mass, the greater the distortion of spacetime
- curvature of spacetime determines the paths of freely moving objects. This is what we call gravity.
Rubber Sheet Analogy

- Matter distorts spacetime in a manner analogous to how heavy weights distort a rubber sheet
  PBS animation
  http://www.pbs.org/wgbh/nova/einstein/rela-space-w-220.html
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

- Path of an orbiting object actually spirals through spacetime as it moves forward in time
Curvature near sun

- Mass of Sun curves spacetime
  - Free-falling objects near Sun follow curved paths
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*
Curvature near Black Hole

- Spacetime is so curved near a black hole that nothing can escape, not even light.
- The “point of no return” is called the *event horizon*.
- Event horizon is a three-dimensional surface.
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

• Current data indicates that the universe has a flat geometry
Gravitational Time Dilation

- You & Jackie in the ship have synchronized watches
  - the ship accelerates
  - the watches flash

- Moving away from Jackie, you see larger time intervals between her flashes.
  - time appears to be moving slower for her
- Moving towards you, Jackie sees shorter time intervals between your flashes.
  - time appears to be moving faster for you
  - you both agree
- So, using the equivalence principle, in a gravitational field…
  - time moves more slowly where the gravity is stronger
How do we test the predictions of general relativity?
Precession of Mercury

- The major axis of Mercury’s elliptical orbit precesses with time at a rate that disagrees with Newton’s laws.

- Newton’s law assumed that time was absolute & space was flat.
- but when Mercury is closest to the Sun, time runs more slowly & space is more curved.
- Predictions of general relativity matched the observations exactly.
Gravitational Lensing

- Curved spacetime alters the paths of light rays, shifting the apparent positions of objects in an effect called **gravitational lensing**

- During a Solar eclipse in 1919, two stars near the Sun…
  - were observed to have a smaller angular separation than… is usually measured for them at night at other times of the year
- This observation verified Einstein’s theory… making him an overnight celebrity
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)
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.
- This effect must be taken into account to make GPS devices function accurately!
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
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.
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 been directly detected for the first time in 2016!
  https://www.ligo.caltech.edu
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?
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