"The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Hence-forth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality."

Hermann Minkowski, Russian-German mathematician (1864-1909)

"The whole fabric of the space-time continuum is not merely curved, it is in fact totally bent."

The Restaurant at the End of the Universe, Douglas Adams, British author (1952-2001)

Current Assignments ...

For today

- Read Sections 11.1 - 11.2

For Lecture 18

- Read Sections 11.2 - 11.7

Homework #3

- Late deadline 11:00 AM, Friday, March 15

Homework #4

- Posted March 7. Due 11:00 AM, Friday, March 22

Writing Assignment #2

- Posted Feb. 28. Due 11:00 AM, Thursday, April 4

Suggested Conceptual Exercises

- Ch. 11: 1,3,5,7,9,11,13,15,17,19,21,23,25,27,29,31, 33,35,37,39,41,43,45

Tutorial #8

Office hours: 3-4 Tuesdays & Thursdays

Review of Lecture 17

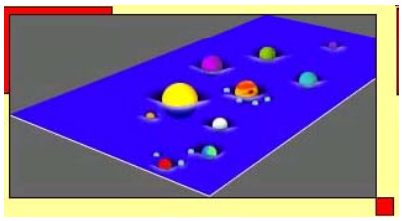
Textbook, Section 10.8

- Space-time diagrams and worldlines
- $E = mc^2$

Plan for Lecture 17

Textbook, Sections 11.1 - 11.2

- General relativity
- The big bang



http://www.pbs.org/wnet/hawking/strange/html/gravity.html

Chapter 11

- The General Theory of Relativity - *today*
- The Big Bang - *today*
- The Possible Geometries of the Universe
- The Shape of the Universe
- Dark Matter
- The Accelerating Universe and Dark Energy
- Cosmic Inflation and a Brief History of the Universe

General Theory of Relativity

- Recall that the Special Theory of Relativity states that the laws of physics are the same for all **unaccelerated** observers.
- The General Theory of Relativity applies to **accelerating** systems.
  - → It is one of the two most general physical theories known (the other is quantum field theory).
  - → It provides a unified description of gravity as a geometric property of space and time.
  - → Two key ideas: the equivalence principle and the bending of space-time. *Let's take a look...*

The Effects of Acceleration

- Imagine accelerating upward in an elevator.
  - → You feel squashed and heavier.
- If you are in a windowless elevator, is there any way to determine whether you are

(a) in space, accelerating at 10 m/s^2 ?

(b) on Earth, where the acceleration of gravity is 10 m/s^2 ?

Textbook Figure 11.1

Acceleration and Gravity

Textbook Figure 11.2

Acceleration and Gravity

Textbook Figure 11.3

http://www.phy.syr.edu/courses/modules/LIGHTCONE/anim/equ2-m.gif

The Equivalence Principle

- Einstein reasoned that it is not possible to tell the difference between gravity and acceleration.
- His Equivalence Principle is the foundation of General Relativity.

No experiment performed inside a closed room can tell you whether you are at rest in the presence of gravity or accelerating in the absence of gravity.

How does acceleration affect light?

Textbook Figure 11.4

http://www.phy.syr.edu/courses/modules/LIGHTCONE/anim/equv-m.gif

The light beam in the accelerating rocket appears to bend, so it must also appear to bend in a gravitational field.

Does a high-speed bullet's path bend more than a light beam bends as it passes near Earth?

(A) Yes, because the bullet moves slower than the light beam.

(B) Yes, because the light beam has a greater acceleration than the bullet.

(C) Yes, because the bullet is heavier than the light beam.

(D) No, because all falling objects accelerate at the same rate.

(E) No, because of Einstein's Equivalence Principle.

Gravity Bends Light

- Light beams are the definitions of straight lines; how can they bend?

Einstein's answer:

- Gravity warps space, so the light is still taking the shortest distance between two points.

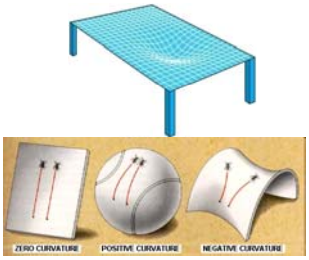
Evidence:

- Stars behind the sun can be seen during a solar eclipse.

Textbook Figure 11.5

Visualizing Warped Space

- This is hard to do for 3D space!
- Here are some 2D examples.



Textbook Figure 11.9

http://www.phy.syr.edu/courses/modules/LIGHTCONE/einstein-gr.html
originally from Wheeler (A Journey into Spacetime)

Spacetime

- Special Relativity showed us that space and time are closely connected.
- Thus warping of space also warps time.
  - → Time goes slower in strong gravitational fields.
- Space and time are bent by masses.
  - → There is a bending in the three space dimensions plus in the time dimension.
- Spacetime = these four dimensions.
- *"Spacetime tells matter how to move; matter tells spacetime how to curve."* John Wheeler

Textbook Figure 11.11

Concept Check 2

The equator is the "straightest possible" line on the surface of the globe. Are the other east-west circles of latitude also "straightest possible" lines"?

(A) Yes

(B) No, they curve more than the equator's curvature.

(C) No, they curve less than the equator's curvature.

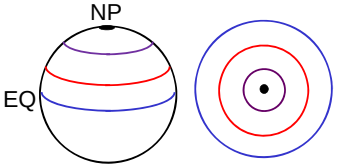
(D) No, despite the fact that their curvature is the same as the equator's curvature.

Concept Check 2 – Explanation

The equator is the "straightest possible" line on the surface of the globe. Are the other east-west circles of latitude also "straightest possible" lines"?

(B) No, they curve more than the equator's curvature.

By "straightest possible" line on the surface of the globe, we mean the line with the least curvature, NOT the shortest distance between any two points.



This is the view looking down on the North Pole (black dot). The equator (blue line) is the least curved = straightest possible east-west latitude circle because it is at the widest part of the sphere.

Gravity as Curved Spacetime

Gravity in Newton's Universe

- http://einstein.stanford.edu/Media/Newtons_Universe_Anima-Flash.html

Gravity in Einstein's Universe

- http://einstein.stanford.edu/Media/Einsteins_Universe_Anima-Flash.html

All-Sky Milky Way Panorama - 3000 CCD images

http://home.arcor-online.de/axel.mellinger/

Animation of the Big Bang. Credit: NASA/LBL/SNAP Team

http://snap.lbl.gov/multimedia/animations/BigBangAni.mov

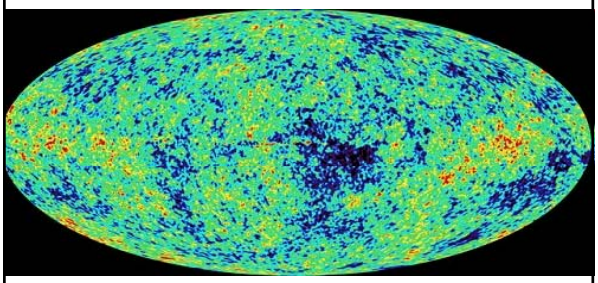
Cosmology

- Cosmology is the study of the origin, structure, and evolution of the universe.
- General relativity and cosmology predict that the universe started about 14 billion years ago in a single event called the big bang.
  - → Created matter and energy, time and space.
  - → Made the universe expand dramatically.

Evidence for the Big Bang

1. In 1929 it was discovered that the universe was expanding; extrapolating backwards led to the big bang.
2. The cosmic microwave background (CMB), left over from the big bang, has been observed and agrees with theoretical predictions.
3. The CMB has been mapped in great detail; its small variations are just as they should be to create galaxies as we see them today.
4. Theory predicts just which elements, and in what ratios, should be produced in the big bang; these agree well with observations.

The Oldest Light in the Universe



NASA's Wilkinson Microwave Anisotropy Probe (WMAP)

http://science.nasa.gov/headlines/y2003/11feb_map.htm

Credit: NASA/WMAP Science Team