Exam

Hour Exam 2: Wednesday, October 25th

- In-class, covering waves, electromagnetism, and relativity
- Twenty multiple-choice questions
- Will cover: Chapters 8, 9 10 and 11
  Lecture material
- You should bring
  - 1 page notes, written single sided
  - #2 Pencil and a Calculator
  - Review Monday October 23rd
  - Review test will be available online on Monday

From before

$$E = \gamma m_o c^2 = KE_{rel} + m_o c^2$$

$$E = \gamma m_o c^2, \quad or \quad E = mc^2$$

- The total energy of a particle is dependent on it's kinetic energy and its mass.
- Even when the particle is not moving it has energy.
- Mass is another form of energy
  - Moreover, energy can show up as mass.
  - The energy to put all the protons together in a nucleus gives the nucleus more mass!

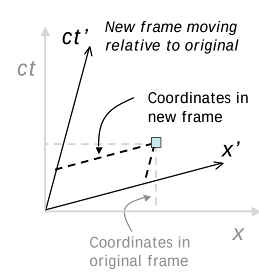
Space/Time - Energy/Momentum

- Relativity mixes up space and time - also energy and momentum
  - When converting from one inertial frame to another
  - In the time dilation and length contraction formulas time is in the length formula and length is in the time volume through the velocity (length/time)
  - In the total energy formula momentum(or kinetic energy) and mass energy are related
- There are combinations of space/time and energy/momentum that observers in any inertial frame will measure the as the same
  - For energy and momentum this invariant says that all observers can agree on mass an object has when it's at rest!

$$x^2 - c^2t^2 \qquad E^2 - c^2p^2 = (m_o c^2)^2$$

Observing from a new frame

- In relativity these events will look different in reference frame moving at some velocity
- The new reference frame can be represented as same events along different coordinate axes
- A graphical way of showing that length and time are contracted or expanded.



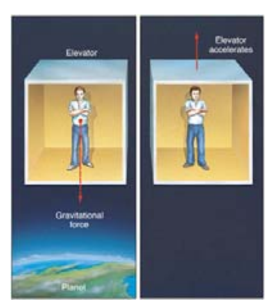
The Equivalence Principle

Clip from Einstein Nova special

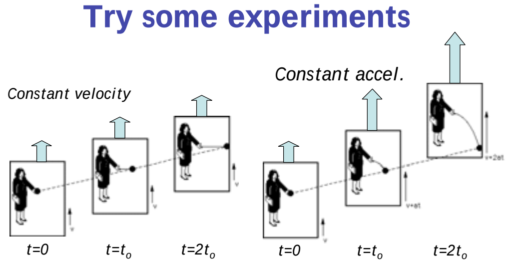
- Led Einstein to postulate the **Equivalence Principle**

Equivalence principle

Accelerating reference frames are **indistinguishable** from a gravitational force



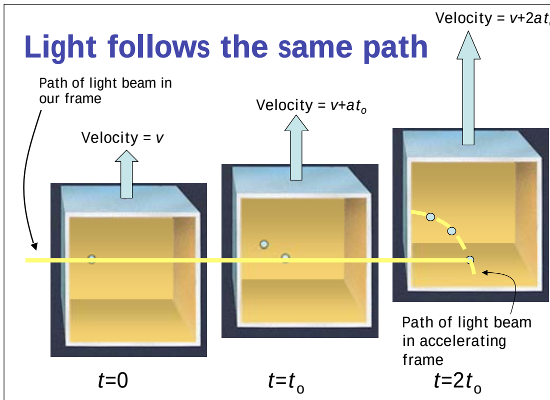
Try some experiments



Floor accelerates upward to meet ball

Cannot do any experiment to distinguish accelerating frame from gravitational field

Light follows the same path



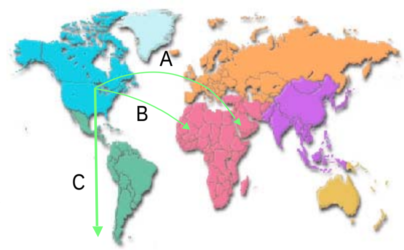
Is light bent by gravity?

- If we can't distinguish an accelerating reference frame from gravity…
- and light bends in an accelerating reference frame…
- then light must bend in a gravitational field

But light doesn't have any mass.
How can gravity affect light?

Maybe we are confused about what a straight line is

Which of these is a straight line?



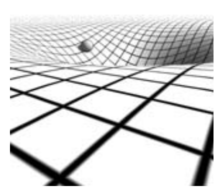
A. A
B. B
C. C
D. All of them

Straight is shortest distance

- They are the shortest distances determined by wrapping string around a globe. On a globe, they are called 'great circles'. In general, geodesics.
- This can be a general definition of straight, and is in fact an intuitive one on curved surfaces
- It is the one Einstein used for the path of all objects in curved space-time
- The confusion comes in when you don't know you are on a curved surface.

Mass and curvature

- General relativity says that any mass will give space-time a curvature
- Motion of objects in space-time is determined by that curvature
- Similar distortions to those we saw when we drew graphs in special relativity



Idea behind geometric theory

- Matter bends space and time.
- Bending on a two-dimensional surface is characterized by the radius of curvature: r
- Einstein deduced that $1/r^2$ is proportional to the the local energy and momentum density
- The proportionality constant is

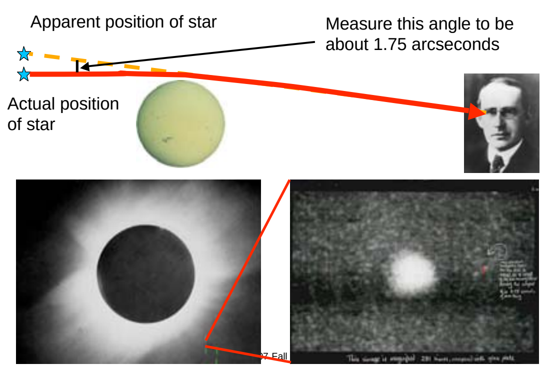
$$\frac{8\pi G}{c^2}$$

- where G is Newton's constant

A test of General Relativity

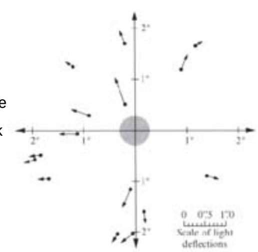
- Can test to see if the path of light appears curved to us
- Local massive object is the sun
- Can observe apparent position of stars with and without the sun
- But need to block glare from sun

Eddington and the Total Eclipse of 1919



Eddington's Eclipse Expedition 1919

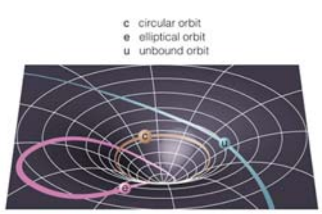
- Eddington, British astronomer, went to Principe Island in the Gulf of Guinea to observe solar eclipse.
- After months of drought, it was pouring rain on the day of the eclipse
- Clouds parted just in time, they took photographic plates showing the location of stars near the sun.
- Analysis of the photographs back in the UK produced a deflection in agreement with the GR prediction



Space is Curved

- Einstein said to picture gravity as a warp in space

- Kepler's Laws can all be explained by movement around these "puckers"
- Everything moving is affected, regardless of mass



Other Consequences of GR

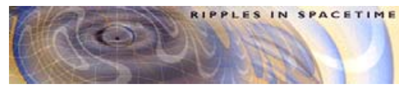
- Time dilation from gravity effects
- Gravitational Radiation!
  - Created when big gravity sources are moved around quickly
  - Similar to the electromagnetic waves that were caused by moving electron charges quickly
- Black Holes
- Expanding Universe (although Einstein missed the chance to predict it!)

Gravitational time dilation

- Gravity warps both space and time!
- At 10,000 km above the Earth's surface, a clock should run 4.5 parts in 10^{10} faster than one on the Earth
- Comparing timing pulses from atomic oscillator clocks confirms the gravitational time dilation in 1976 to within 0.01%.
- Corrections are now standard in the synchronizing satellites
- This correction needed in addition to the special relativity correction for GPS

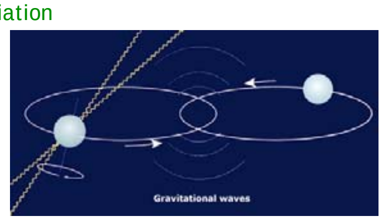
Gravitational radiation

- When a mass is moved, the curvature of space-time changes
- If a mass is oscillated, ripples of space-time curvature carry the signal
- Gravitational radiation carries energy and momentum and wiggles mass in its path



Evidence for gravity waves

- In 1974, Joseph Taylor and his student Russell Hulse discovered a binary neutron star system losing energy as expected from gravitational radiation



Direct detection of gravity waves

LIGO is a collection of large laser interferometers searching for gravity waves generated by exploding stars or colliding black holes

The big bang

- In 1929 Observation of nearby and far away galaxies indicate that everything is receding from us.
  - Key physics needed to understand this is the simple Doppler shift of light waves. Waves from sources moving away from us are stretched out or lower frequency.
- Extrapolating backwards indicates that all the galaxies originated from the same source 14 billion years ago.
- In 1964 radiation from the early stages of that explosion was detected.
  - Again the Doppler shift was the key since the waves were shifted to low frequency - microwave

This Years Nobel Prize

- For the universe to start small and expand space and time must be thing that can expand(or contract)
  - General relativity was key physics needed to understand that process
- However, a simple model of that would predict such a universe would not have clumps of matter(stars, galaxies)
- Unless those clumpings were present very early on
- This years Nobel prize was given to the people who designed the COBE experiment which was sensitive enough to see those clumpings in the CMB