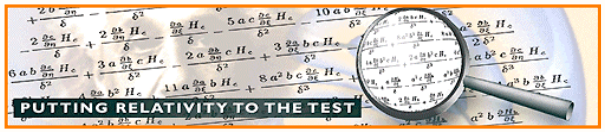


There is a big difference between the Newtonian and the Relativistic frameworks:

Newtonian:

Rigid flat geometry, universal clocks

Gravitational force between objects

"Magic" dependence on mass

Relativistic:

Objects interact with distorted spacetime

"Natural" reference frames are in free fall

Is There a *Real* (i.e. measurable) Distinction between General Relativity and the Newtonian Viewpoint?

- Absolutely!
- Discriminating among different contending theories is one of the tasks of experimental physics.
- Probing the basic foundations of gravity continues to be a forefront issue
- *Was Einstein Right* by Clifford Will is a nice reference for this topic...

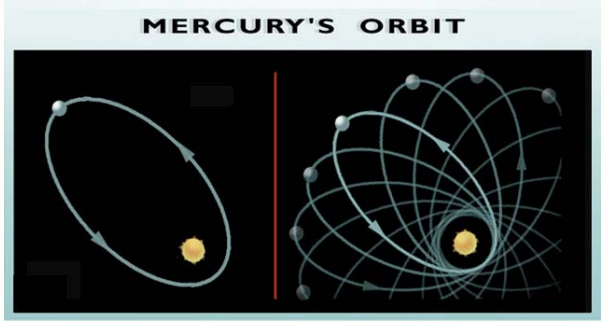
The Scientific Method at Work

- Newtonian world view was challenged by GR
- Both theories made concrete predictions for physical phenomena
- Nature is the final arbiter – carry out experiments

The 3 "Classic" Tests of General Relativity

- Precession of Mercury's orbit
- Deflection of starlight (gravitational lensing)
- Gravitational Redshift

Precession of Mercury's Orbit



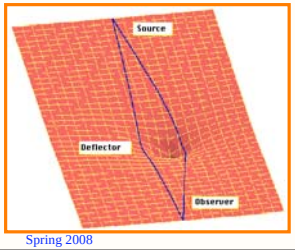
Newtonian General Relativity

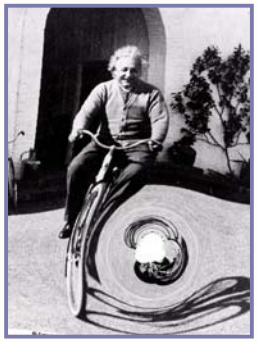
Mercury Precession

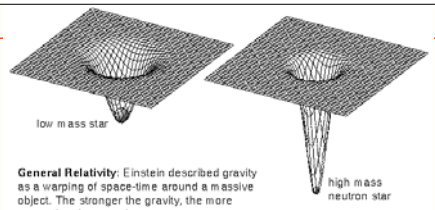
- Known since 1850's not to match Newtonian theory
  - Perihelion precessed by 43 arcseconds per century
    - Would take 30,000 years to go full-circle
- While putting finishing touches on GR in 1915, Einstein computed expected perihelion precession of Mercury
  - When he got out 43 arcsec/century, his heart fluttered!

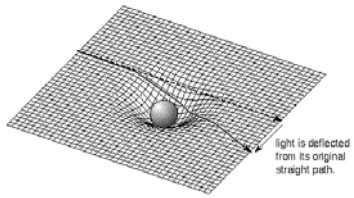
Deflection of Starlight

- Light is deflected by gravitational field
  - called "gravitational lensing"
- Much like ball deflected by divot



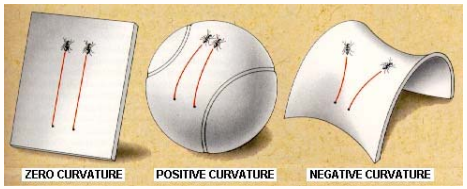






General Relativity: Light travels along the curved space taking the shortest path between two points. Therefore, light is deflected toward a massive object! The stronger the local gravity is, the greater the light path is bent.

Think of light as ants *trying* to go straight

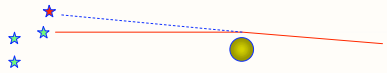


In each case, the ants do their best to pick out the straightest path they can. Unless space is flat, they don't stay on parallel lines forever, and either converge or diverge.

Deflection of Starlight

- During an eclipse, the sky around the sun is dark enough to see distant stars.
- Stars close to the sun have their light deflected and so appear at a shifted position (farther from sun)
- Comparing stellar locations with and without the presence of the sun along the line of sight allows for a measurement of the deflection of light rays.

Deflection of Starlight During an Eclipse



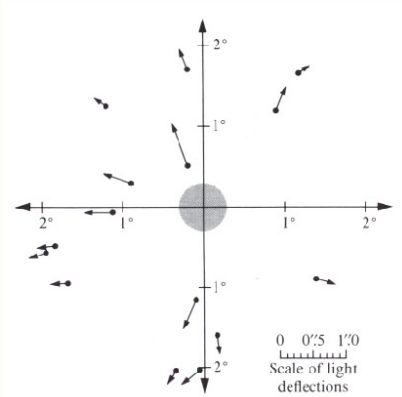
If deflection = 1.74 arcseconds	General Relativity Prediction
If deflection = 0.87 arcseconds	Newtonian Prediction
If deflection = 0.0 arcseconds	Both wrong!!

Seen at a distance of 4 km, a quarter (25 cents) spans about an arcsecond of angle

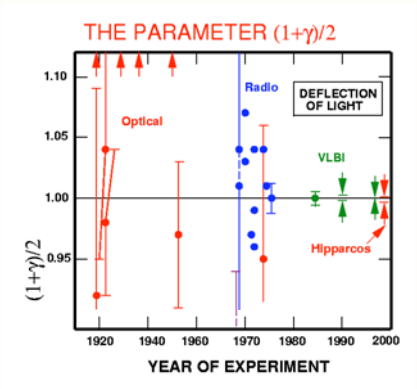
Eddington's Eclipse Expedition Experience, 1919

- Eddington was a British astronomer (and arrogant!)
- Decided to go to Principe Island in the Gulf of Guinea
- 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 around the limb of the sun
- Analysis of the photographs back in the UK produced a deflection in agreement with the GR prediction
- Gravitational Lensing is now a powerful tool in astrophysics

As GR predicts, starlight is deflected



Improvements over Time



Gravitational Redshift

- Clocks that are deeper in a gravitational potential well (spacetime divot) run more slowly!
  - A clock on earth's surface runs 20 milliseconds slow over the course of a year compared to a clock in space
- Tested in the 1970's by putting a precision atomic clock on an airplane at high altitude, flying around for a while, and then comparing its elapsed time with that of a clock that was kept on the ground.
  - Difference of a few hundred nanoseconds after 50 hour flight: agreed with GR prediction
- GPS would be *useless* without redshift correction!

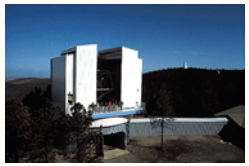
Lunar Laser Ranging

- Can test Equivalence Principle (universality of free-fall) by pinging moon with laser pulse
- GR relies completely on this principle: accelerations independent of mass→gravity can be "fictitious" force
- Test Earth and Moon in free fall toward (around) Sun

Lunar Laser Ranging, continued

- Precisely time round-trip light time to moon (2.5 s)
- Previous experiments got 2–3 cm accuracy
- APOLLO gets 1 mm accuracy
- Carefully measure orbit and look for distortions or displacements not consistent with GR
- One part in 10^{14} precision!

Apollo 11 reflector array



Apache Point Observatory 3.5 m telescope (NM)

Other Consequences of GR

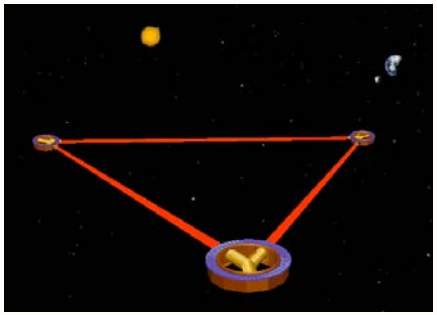
- Gravitational Radiation!
  - Laser Interferometric Gravitational Observatory (LIGO)
    - One in Washington state, and one in Louisiana
  - LISA: space-based gravitational wave interferometer
- Black Holes
- Expanding Universe (although Einstein missed the chance to predict it!)

LIGO

LIGO is a pair of L-shaped laser interferometers (4 km vacuum pipe legs!), with one station in Hanford WA, and the other in Livingston LA.
Could be the first to detect grav. waves as black holes inspiral and merge.

http://www.ligo.caltech.edu/

LISA: A space-based grav. wave observatory



LISA is like a LIGO in space, with three legs, 5 million km long.
Will see gravity waves full time, from many sources (a symphony of waves).
Joint European/US project not yet fully funded

Is GR the last word on gravity?

- Probably not: GR and Quantum Mechanics need to be merged
- Possible hints from observation: Accelerating expansion of the Universe
- Possible hints from theory: additional dimensions/string theory

References and Assignments

- *Was Einstein Right?* by Clifford Will
- Websites
  - http://en.wikipedia.org/wiki/Tests_of_general_relativity
  - http://physics.ucsd.edu/~tmurphy/apollo/
- Assignments
  - Read Hewitt Chapter 22
  - HW5 due 5/16: 9.R.13, 9.E.9, 9.E.14, 9.E.43, 9.P.7, 10.E.16, 35.R.27, 35.E.6, 35.E.19, 35.E.20, 35.E.37, 35.P.3, 35.P.10, 36.R.7, 36.E.2, 36.E.6