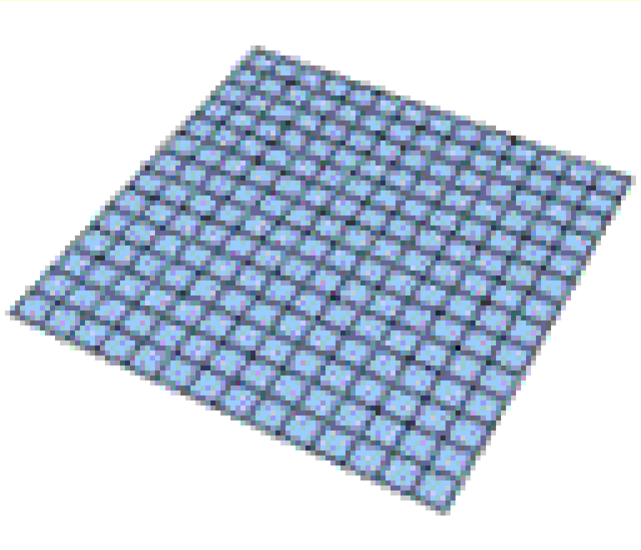
An Introduction to General Relativity

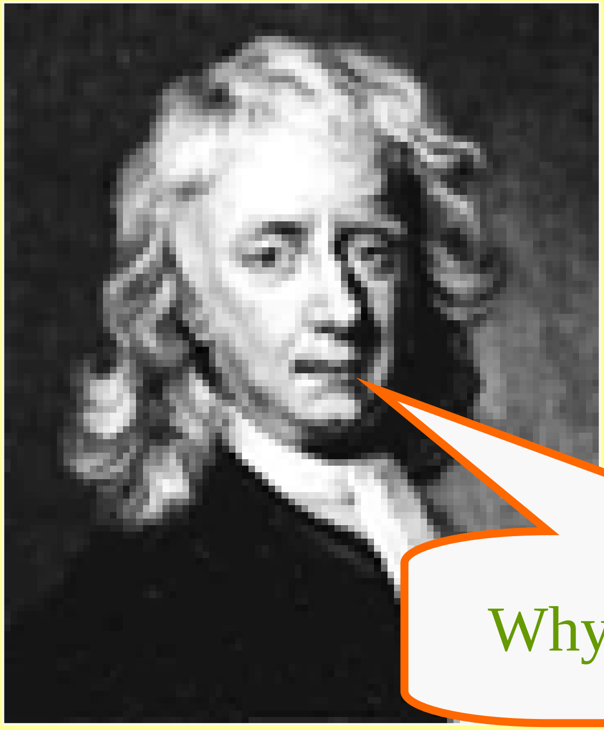


So Far, We Have…

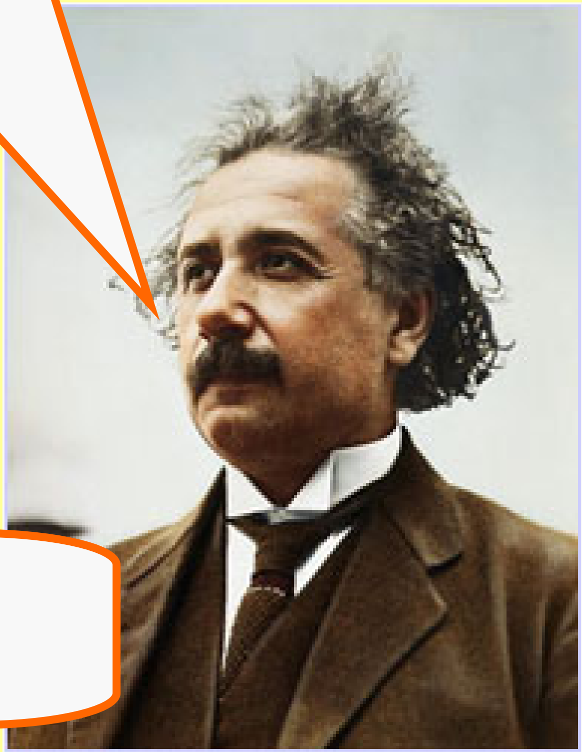
- Galileo's Concepts
  - Decided that constant velocity is the "natural" state of things
- Newton's Concepts
  - Devised a natural philosophy in which acceleration is the result of forces
  - Unified terrestrial and celestial mechanics & brought order to the Universe
- Einstein's Special Relativity
  - Decided that all inertial reference frames are equivalent

Frames of Reference

This is all fine, but moving with respect to *what*??



Why the Earth, of course!



Assumptions from the Past

- The Earth is at the center of the universe...
- The Earth is at the center of the solar system...
- The world is flat...
- The geometry of the Universe is flat...
- The surface of the Earth is the “natural” reference frame...
- Time and space are independent and absolute concepts

These assumptions have had a dramatic impact on our view of Nature

An Example: A Rotating Drum

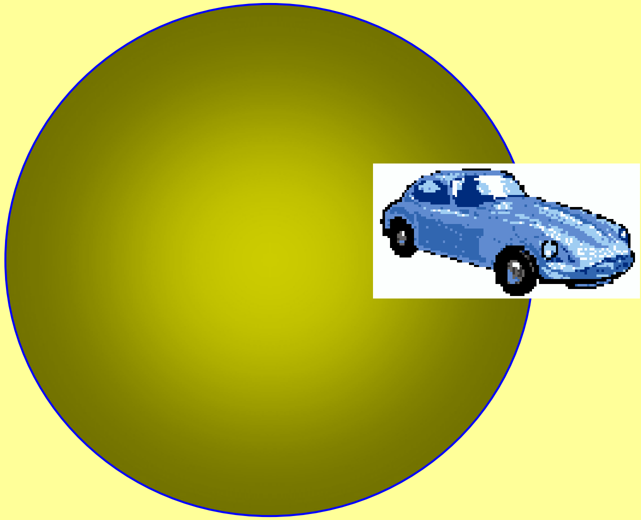
- An accelerating frame of reference can give the feel of gravity
- General Relativity considers “gravity” as an artifact of doing physics in a particular reference frame!

Gedankenexperiment (Thought Experiment) in a Car

- Windows are painted black
- Move the car to outer space
- Now imagine placing a few objects on the dashboard of this blacked-out car, still in outer space.
- If the car accelerates forward, what happens to these objects on the dashboard? (Why?)
- If you didn't know the car was accelerating, what would you infer about a "force" acting on the objects?
- How would that force depend on the masses of the objects?

Gravity vs. Acceleration

- Can you tell the difference between forward acceleration and gravity from a massive object being brought up behind the car?



Can you tell the difference between

gravity

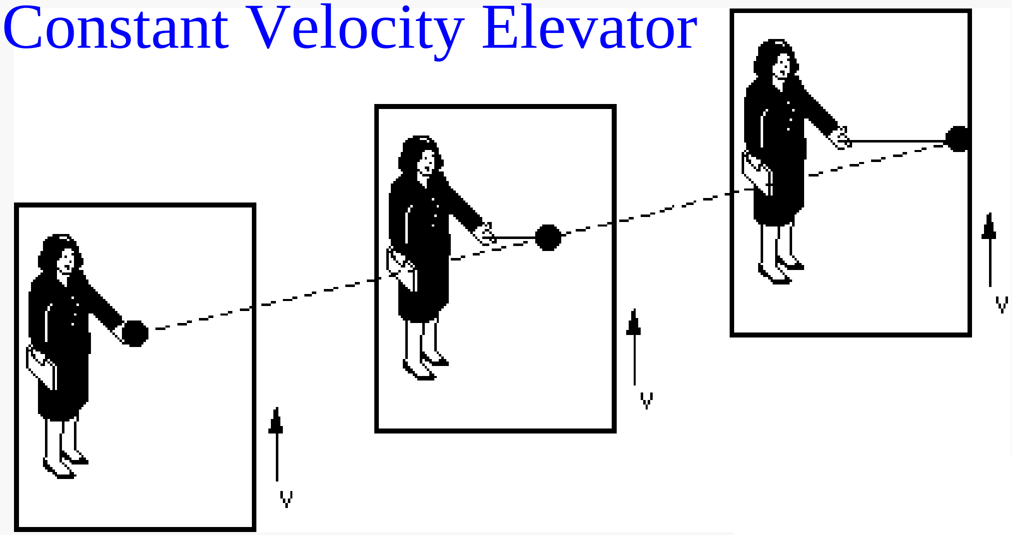
and

acceleration?

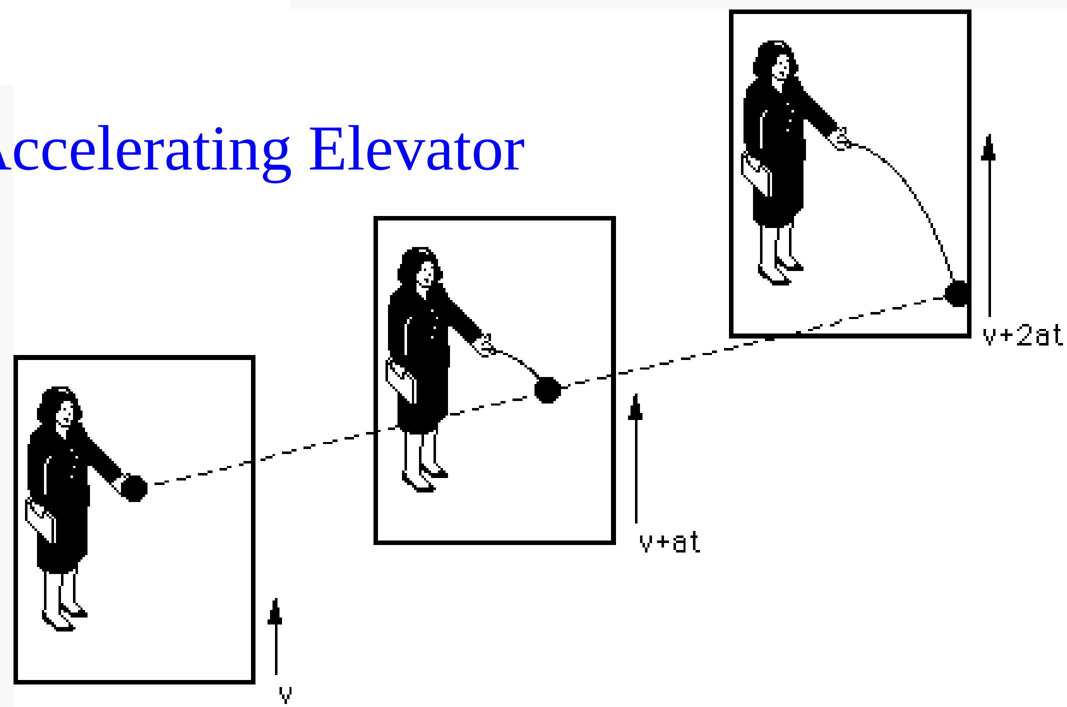
A ***Yes***

B ***No***

Constant Velocity Elevator



Accelerating Elevator



An Exercise – Changing Your Perspective

Close your eyes and imagine you're being accelerated upwards by the room around us

The "natural" (i.e. inertial) coordinate systems are falling past you at 9.8 m/s^2!

You are being accelerated upwards at 9.8 m/s^2 by the normal force of the seat you're in.

A Conclusion

Doing Newtonian mechanics in a particular frame of reference can force you to invoke "fictitious-forces", i.e., artifacts from doing physics in particular coordinate system.

Since these fictitious-forces are invoked to explain what is actually an acceleration of the entire reference frame, they are necessarily proportional to mass. Do you understand why?

Examples:

- "Centrifugal force" in rotating systems
- Gravity!

Einstein in an Elevator

View "elevator animation" film clip from Nova/PBS website
http://www.pbs.org/wgbh/nova/einstein/rela-i.html

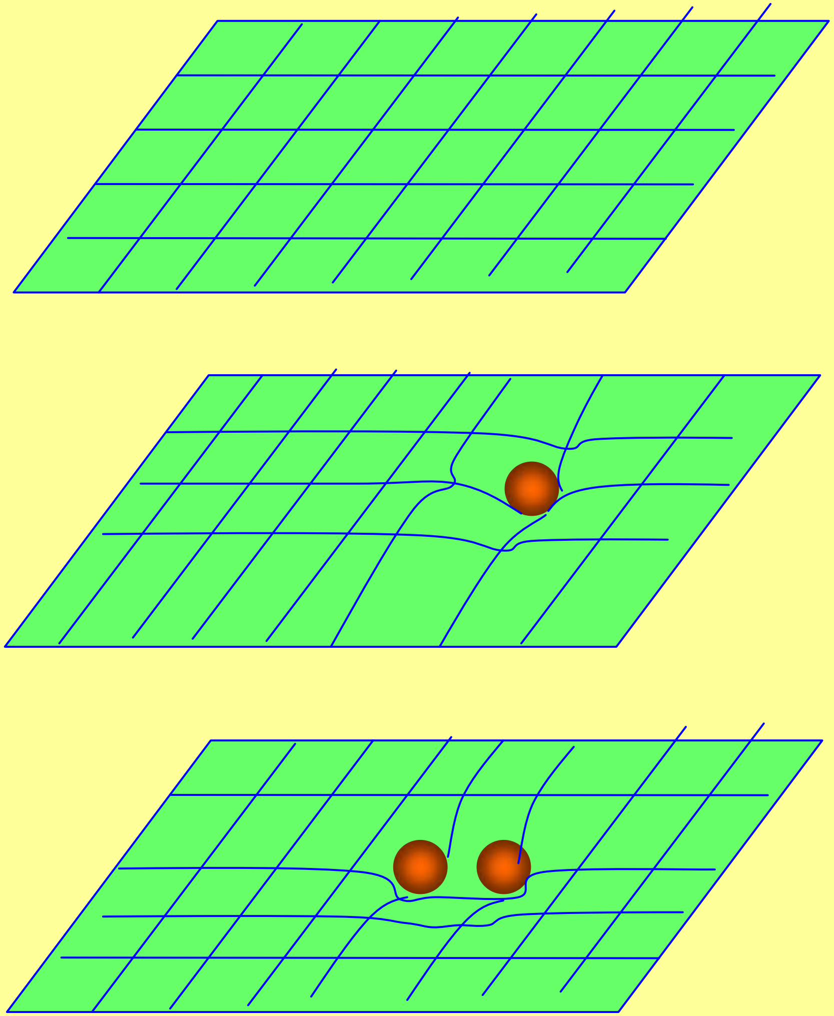
What’s next?!

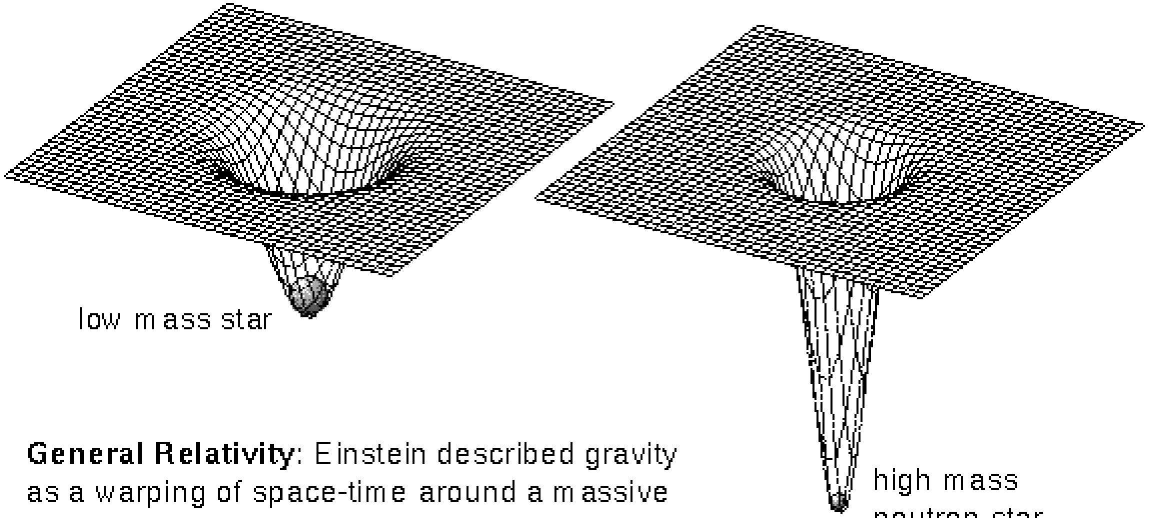
- If we blame gravity on our doing physics in a particular reference frame, is all of gravitational physics wiped out?
  - No!
- There is still an interaction there, just more subtle than Newton thought.....
  - Newton couldn’t explain what gravity *was*
  - Thought of it as instantaneous *action at a distance*

Mattress Example

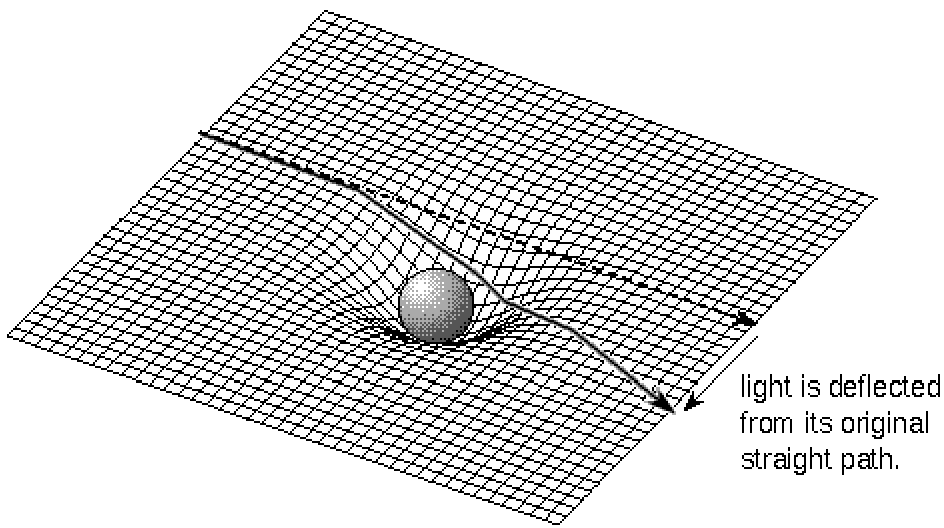
- Imagine 2 bowling balls on a mattress, ignore for the moment the “gravitational” interaction between them
- As they roll around on the mattress, they make dimples in its surface
- If they get close to each other, they sense these dimples and are “attracted” to each other

Bowling Balls on a Mattress



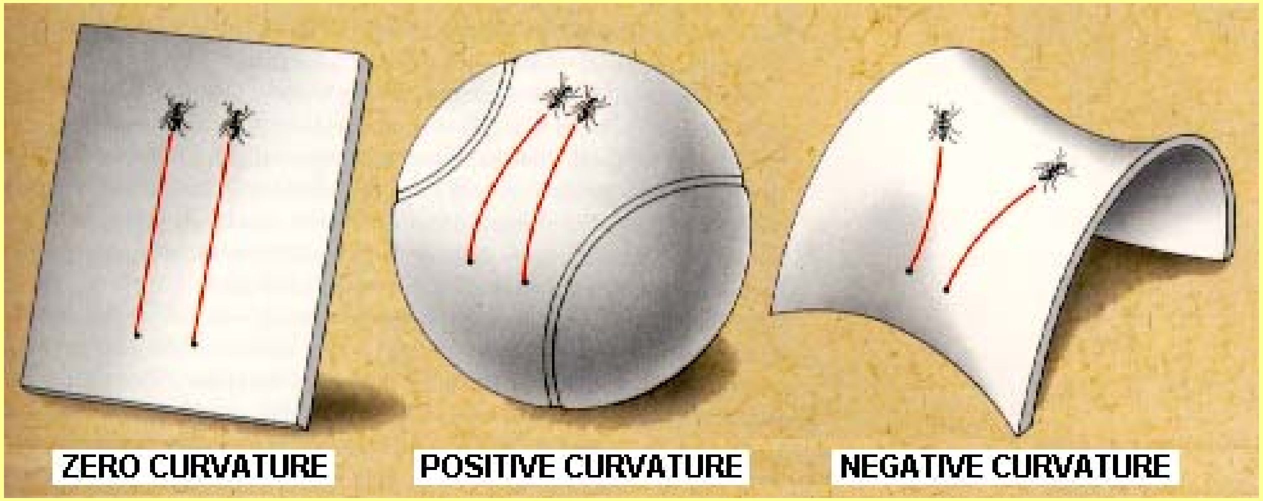


General Relativity: Einstein described gravity as a warping of space-time around a massive object. The stronger the gravity, the more space-time is warped.



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.

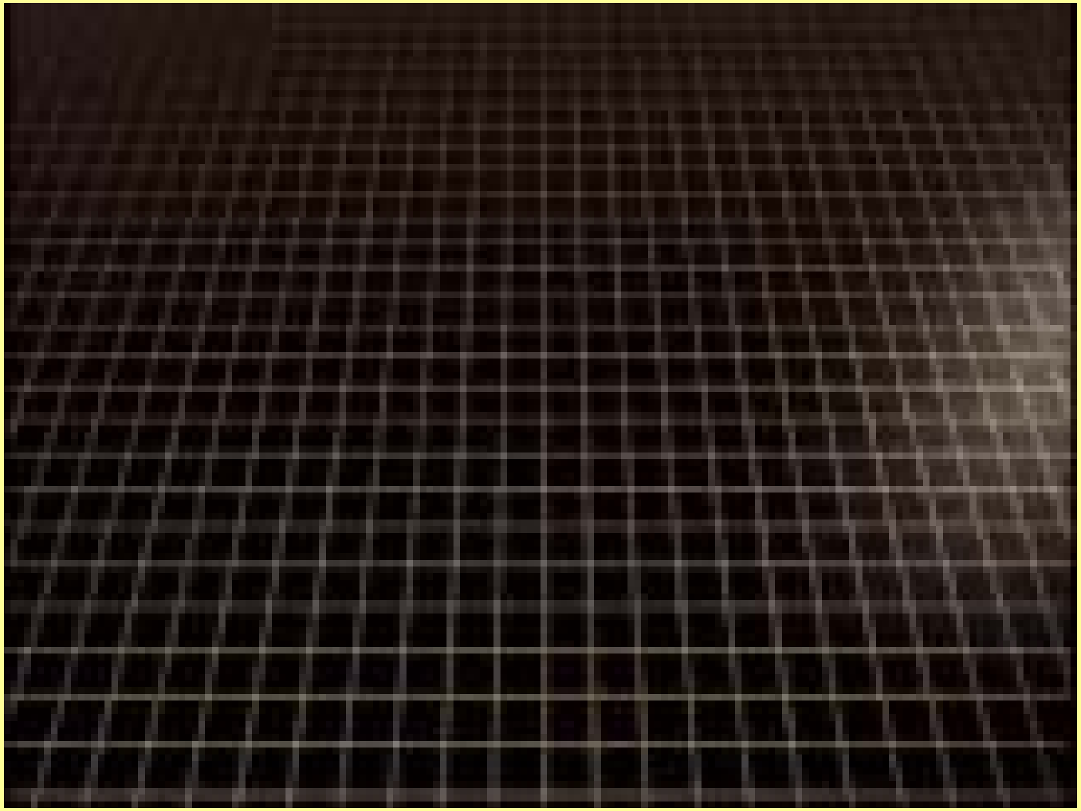
Think of ants *trying* to go straight on a surface



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.

- The representation of gravity as a curvature of space similar to a flexible rubber sheet was first expressed in
  - A Einstein's Special Theory of Relativity.
  - B Einstein's General Theory of Relativity.
  - C Newton's Laws of Motion.
  - D Newton's Law of Universal Gravitation.
  - E Heisenberg's Uncertainty Principle.

Gravity = Geometrical Distortions



View “space animation” film clip from Nova/PBS
http://www.pbs.org/wgbh/nova/einstein/rela-i.html

A Geometrical Approach

- Mass tells space-time how to curve
- Space tells mass how to move
- This naturally explains the Universality of Free Fall Acceleration – All objects move along the same geometrical distortions
  - Gravity is a property of the geometry of spacetime

Mass Tells Space-Time How to Curve

- The illustrations you've seen are what would occur if the world were 2-dimensional. This allows us to show the curvature in the 3rd dimension. In reality, gravity causes 3 spatial and 1 time dimensions to "curve", which is tough to visualize!

Space Tells Mass How to Move

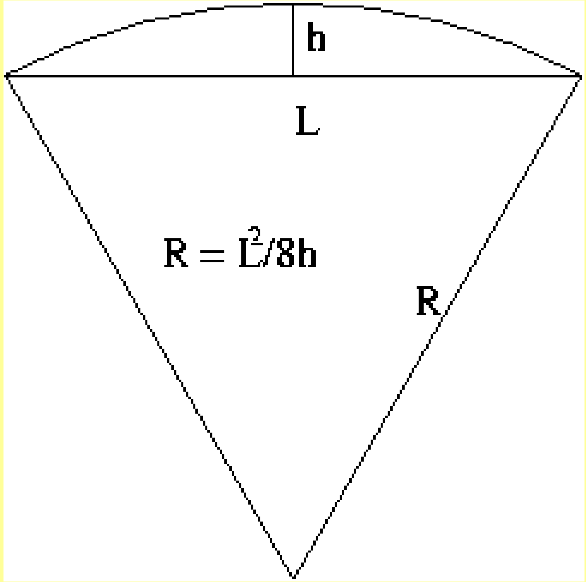
- Objects travel along straight lines in a curved spacetime.
- They don't "accelerate" due to gravity

Curvature in this room!

- Space (spacetime for that matter) *seems* flat to us
- Curvature is small
  - "Strength" of relativity in a room such as this one is given by $2GM/(Rc^2)$, roughly 1.4×10^{-9}
  - Near sun, this is about 10^{-6}
  - Actual radius of curvature on earth is about one light-year

Quantifying curvature

- Let's take a projectile traveling straight up
  - initial speed v (up) means "hang" time is $\Delta t = 2v/g$
  - height acquired is $h = \frac{1}{2} g(\Delta t/2)^2 = \frac{1}{2} v^2/g$
  - in this time, we "travel" $c\Delta t = 2vc/g$ meters through the time dimension
  - If we draw an arc of height h and length $2vc/g$, we would find that its radius was $R = c^2/g \approx 1$ light year
  - note that this is independent of initial velocity (could be a bullet or a superball)



A Contemporary View

- Curved Spacetime forms a stage upon which physics happens
- General Relativity (GR) is a very successful description of the interaction between spacetime and objects
- Einstein's Field Equation: (just for fun…)

Cosmological Constant: Einstein's Biggest Blunder (resurrected as dark energy)

$$G_{\alpha\beta} = 8\pi T_{\alpha\beta} \quad + \Lambda$$

Curvature Tensor describing how spacetime is curved

"Stress-Energy" Tensor describing distribution of mass and energy

More than Meets the Eye

$$G_{\alpha\beta} = 8\pi T_{\alpha\beta}$$

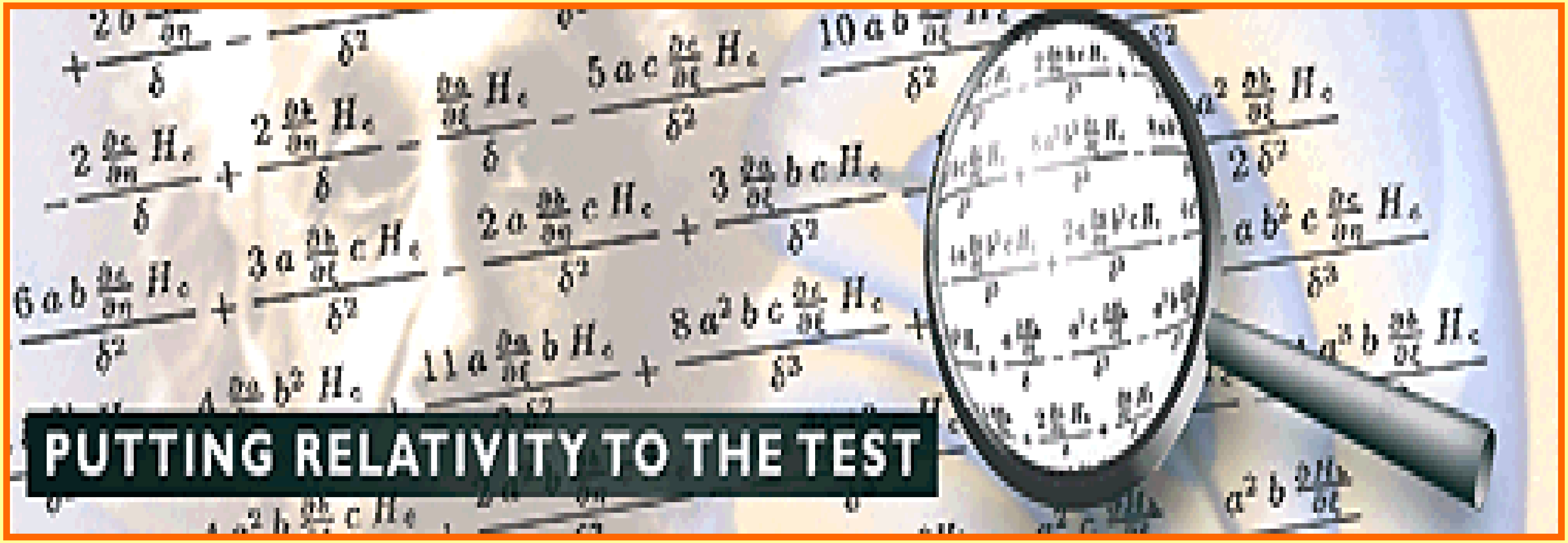
This is shorthand
for lots more

$$\begin{pmatrix} G_{11} & G_{12} & G_{13} & G_{14} \\ G_{21} & G_{22} & G_{23} & G_{24} \\ G_{31} & G_{32} & G_{33} & G_{34} \\ G_{41} & G_{42} & G_{43} & G_{44} \end{pmatrix} \qquad \begin{pmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \\ T_{41} & T_{42} & T_{43} & T_{44} \end{pmatrix}$$

Another Scientific Revolution

- The General Relativity view
  - Relegates "gravity" to the interaction between mass and spacetime
  - Abolishes the notion that the geometry of spacetime is *everywhere* flat
  - Mixes the concepts of space and time
- GR does <u>not</u> mean "everything is relative"!
  - The basic concept is that the equations/laws that describe physical systems should not depend on your reference frame.
  - "Coordinate Invariance" might be a better term.

- The Principle of Equivalence explains which of the following concepts?
  - A Weight and mass are the same thing.
  - B Equal masses have equal forces of gravity causing everything to fall at equal speeds.
  - C The force of gravity equals the force of matter.
  - D The force of gravity is equal on all masses.
  - E The force of gravity is greater on bodies with a greater mass causing all masses to fall to Earth with the same acceleration.


PUTTING RELATIVITY TO THE TEST

There are differences between the Newtonian and the Relativistic frameworks:

<u>Newtonian:</u>

Rigid flat geometry, universal clocks

Gravitational force between objects

"Magic" dependence on mass

<u>Relativistic:</u>

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?

A	Yes
B	No

- A-Yes, 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...

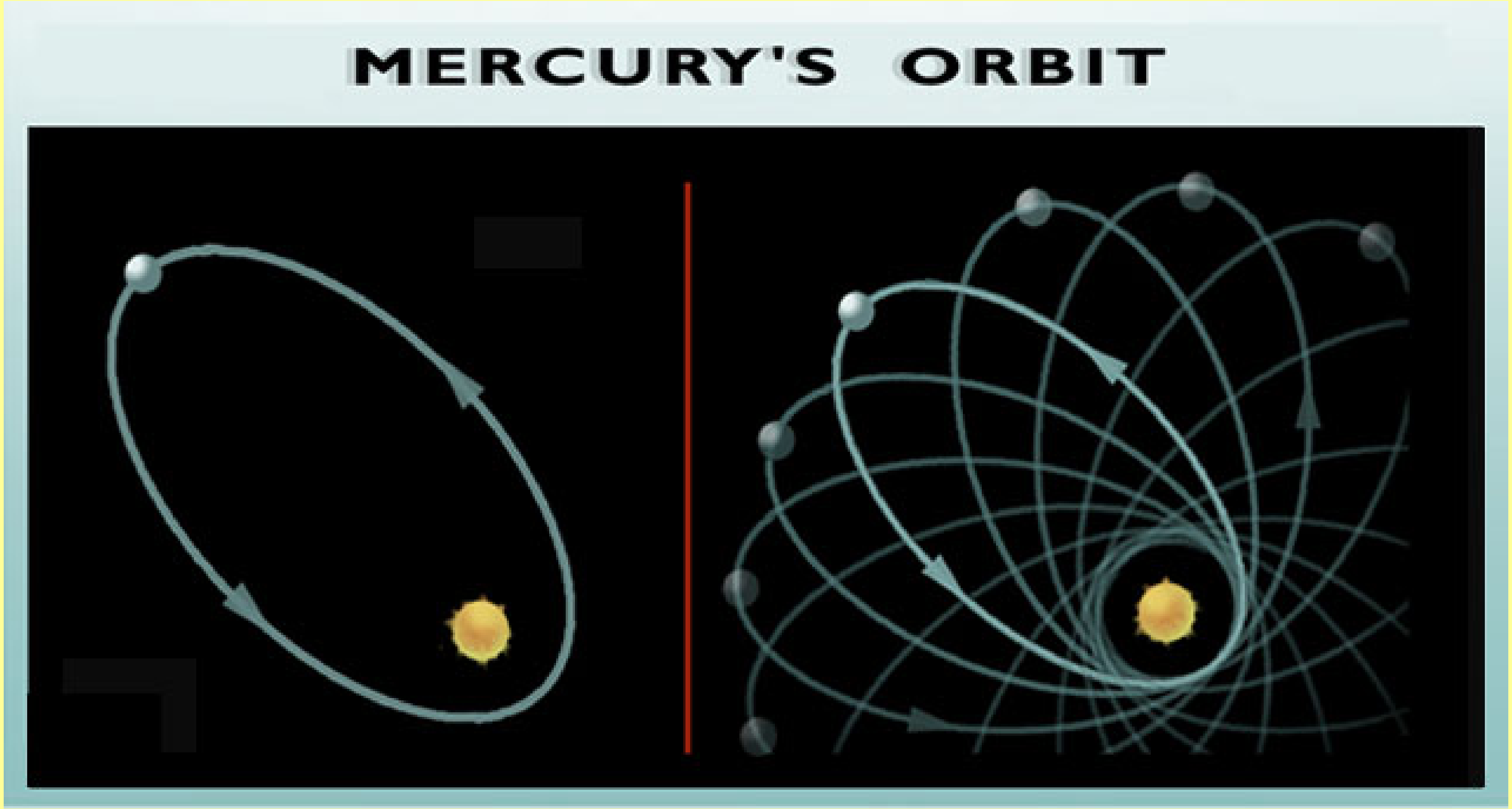
The Scientific Method at Work

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

The “Classic” Tests of General Relativity

- Precession of Mercury’s orbit
- Deflection of starlight (gravitational lensing)
- Gravitational Time Dilation
- Gravitational Red Shift

Precession of Mercury's Orbit



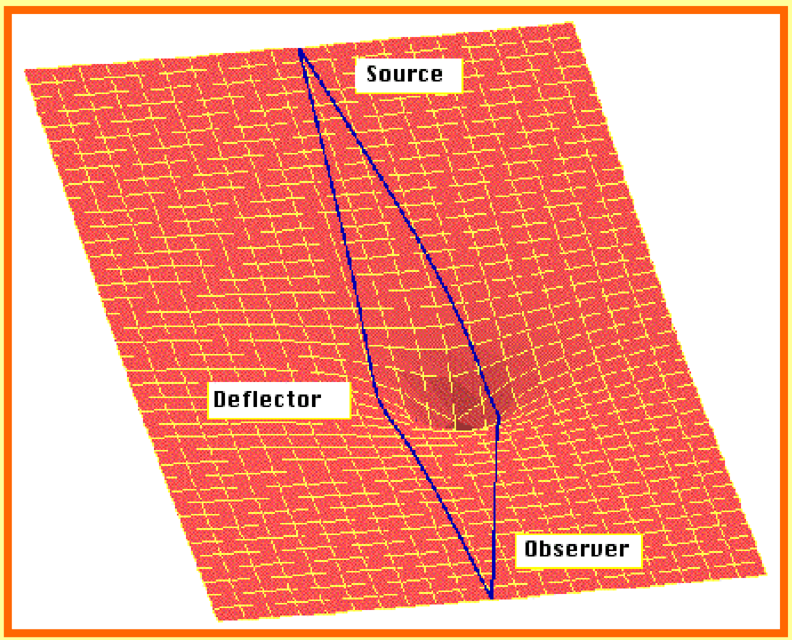
Newtonian General Relativity

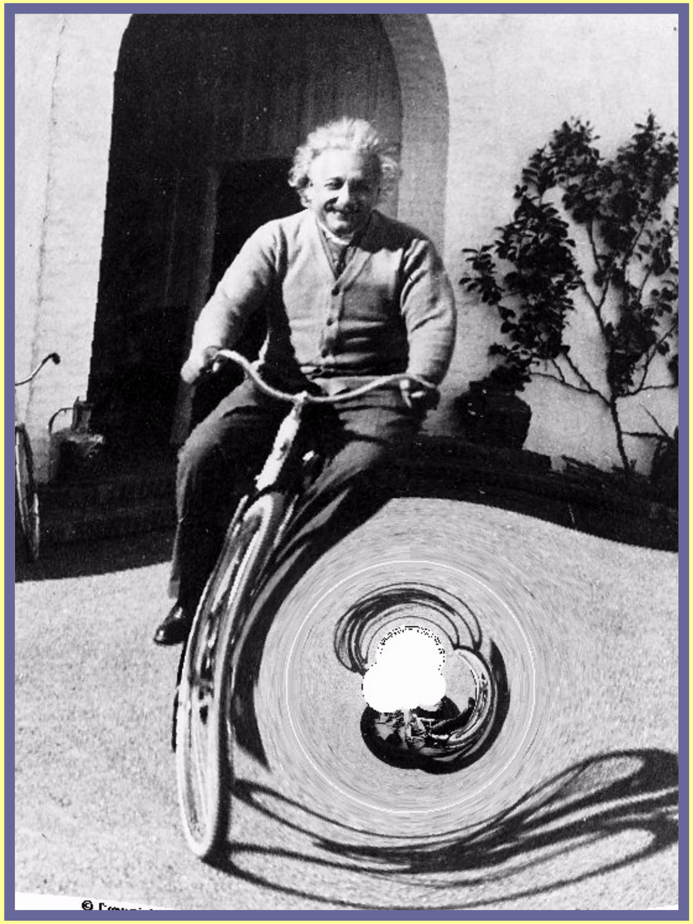
Mercury Precession

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

Deflection of Starlight

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

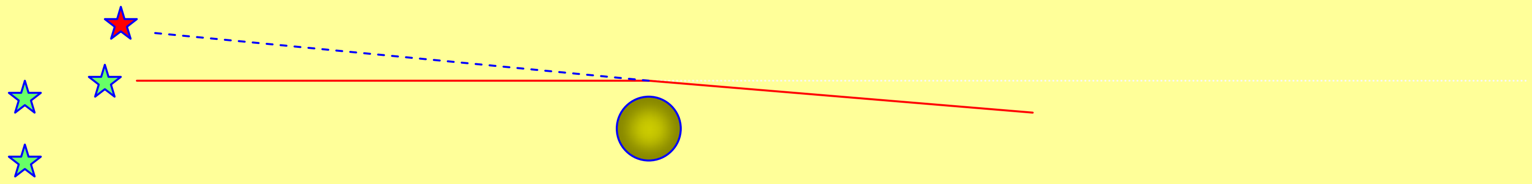




Deflection of Starlight

- 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



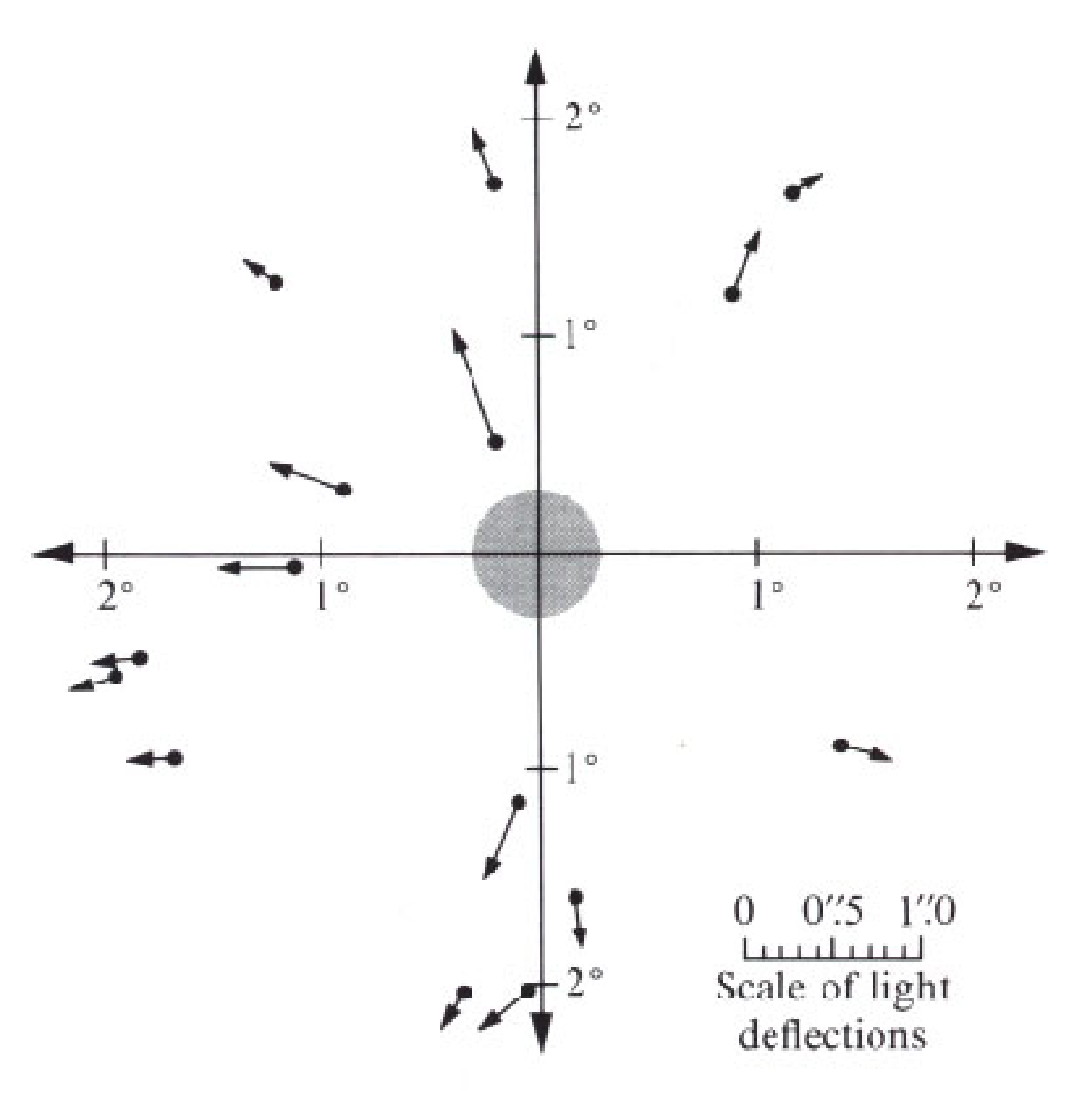
If deflection = 1.74 arcseconds	General Relativity Supported
If deflection = 0.0 arcseconds	Newton Rules

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

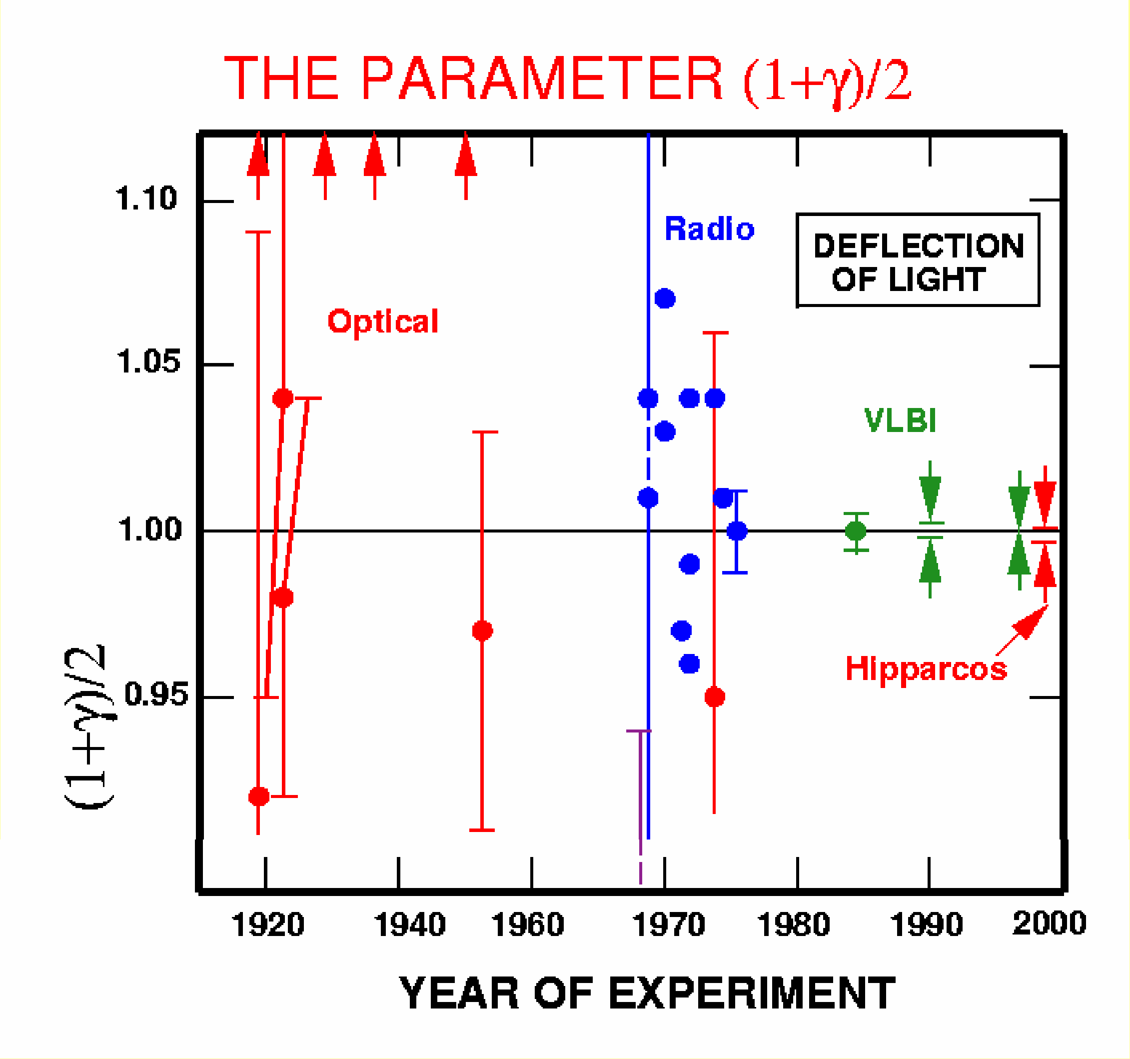
Eddington's Eclipse Expedition in 1919

- Eddington was a British astronomer
- Eddington decided to go to Principe Island in the Gulf of Guinea for the eclipse
- After months of drought, it was pouring rain on the day of the eclipse
- The clouds parted just in time for the team to take photographic plates showing the location of stars around the limb of the sun
- Analysis of the photographs produced a deflection in agreement with the GR prediction
- Gravitational Lensing is now a powerful tool in astrophysics

As GR predicts, starlight is deflected

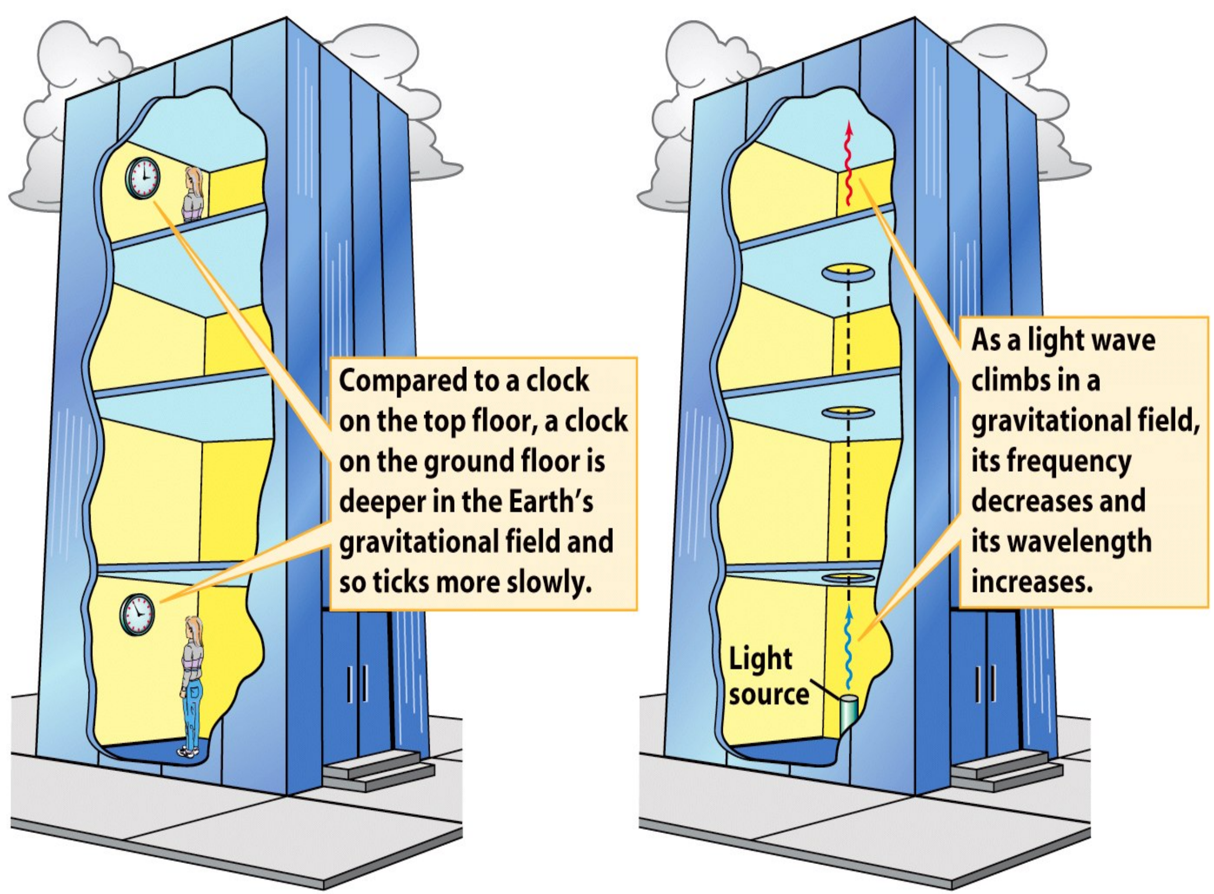


Improvements over Time



Gravitational Time Dilation and Gravitational Redshift

- Clocks that are deeper in a gravitational potential well (spacetime hanging chad) 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
- GPS would be *useless* without considering GR correction!



(a) The gravitational slowing of time (b) The gravitational redshift

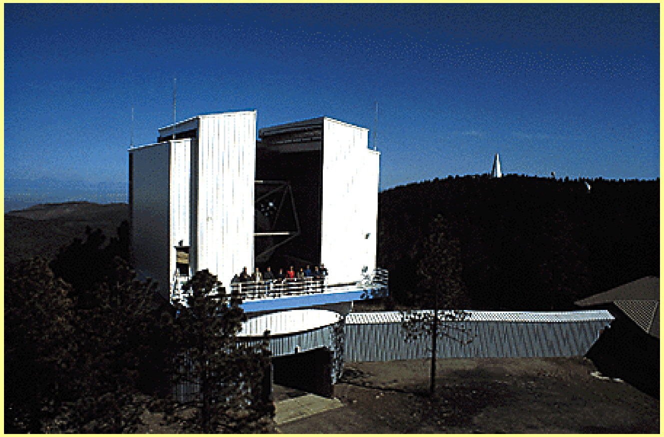
Lunar Laser Ranging

- 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)
- Currently get 2-3 cm accuracy
- APOLLO will get 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)

iClicker Question

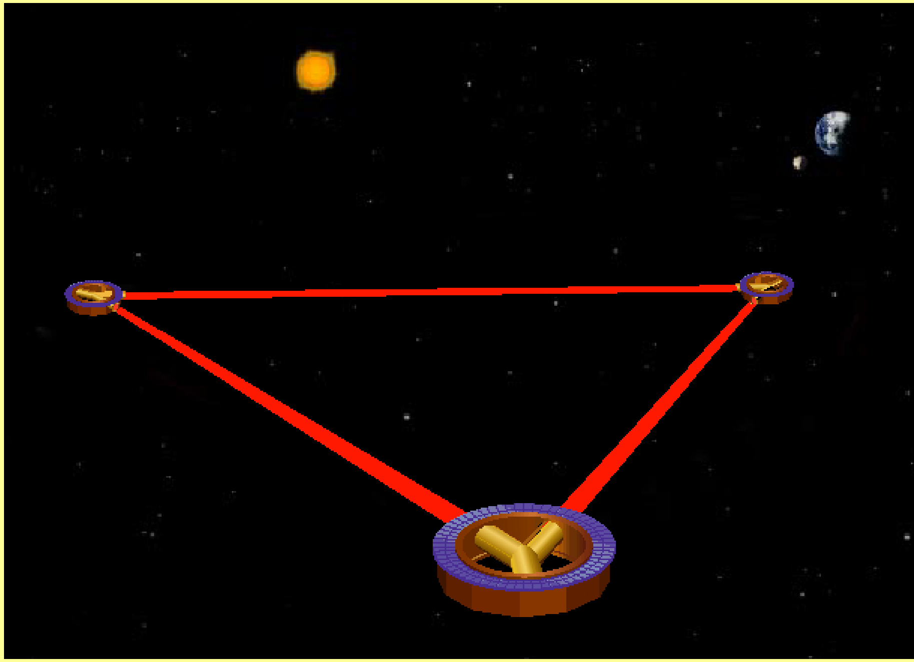
- Which of the following is a test of Einstein's General Theory of Relativity?
  - A Gravitational Lensing Effect
  - B Gravitational Redshift
  - C Gravitational Time Dilation
  - D All of the above
  - E None of the Above

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

LISA: A space-based gravitational wave observatory



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

- *Was Einstein Right?* by Clifford Will
- *Relativity Visualized*, by L. C. Epstein
    - great intuitive development, low math (low PC also)
- Websites
    - http://physics.ucsd.edu/~tmurphy/apollo/
    - http://www.dmoz.org/Science/Physics/Relativity/
        - especially links titled "General Relativity"