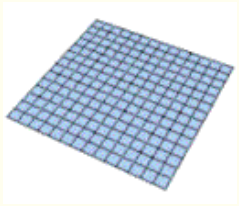
General Relativity
Einstein Upsets the Applecart

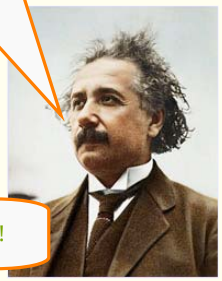


So Far, We Have…

- Decided that constant velocity is the "natural" state of things
- Devised a natural philosophy in which acceleration is the result of forces
- Unified terrestrial and celestial mechanics & brought order to the Universe

Frames of Reference

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



Why the Earth, of course!

Science is Fraught with Assumptions

- 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 concepts

These assumptions can have a dramatic impact on our views of Nature

Recall the Rotating Drum Example

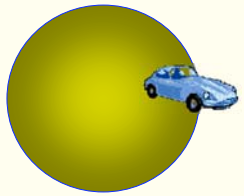
- An accelerating frame of reference feels a lot like gravity
  - In fact, it feels *exactly* like gravity
- The essence of General Relativity is the recognition that "gravitational force" is an artifact of doing physics in a particular reference frame!

Imagine Being 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 star being brought up behind the car?



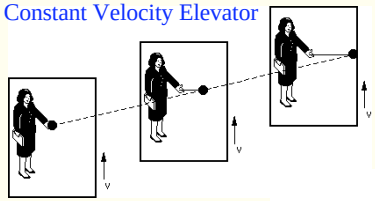
Can you tell the difference between

gravity

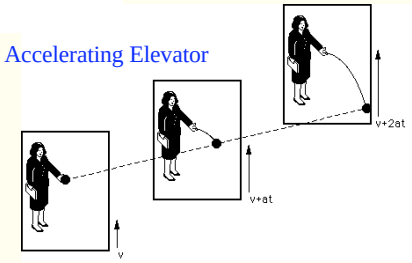
and

acceleration?

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 non-inertial frame of reference can force you to invoke "fictitious-forces", really just *unexpected* forces, i.e., artifacts from doing physics in that frame.

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
  - Actually an example of gravity in the theory of General Relativity
- Gravity!

Einstein in an Elevator

Film clip from Nova/PBS
http://www.pbs.org/wgbh/nova/einstein/rela-i.html

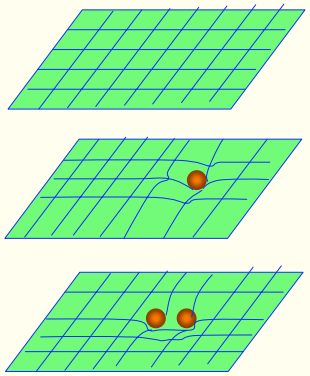
What's left?!

- If we blame gravity on our doing physics in the wrong 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*
    - *What's wrong with action at a distance?*

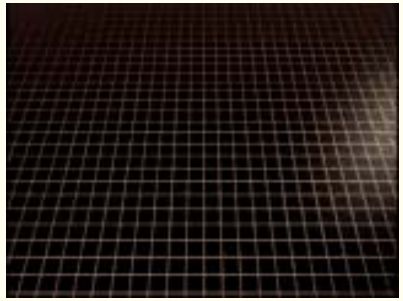
Mattress Example

- Imagine 2 bowling balls on a mattress, on earth
- As they roll around on the mattress, they make dimples in its surface
- If they get close to each other, they roll into each other's dimples
  - they are "attracted" to each other

Bowling Balls on a Mattress



Gravity = Geometrical Distortions



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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

How fast are you moving?

- If time is a dimension like space, then how many meters long is one second:
  - Answer: 300,000,000 meters: c = 300,000,000 m/s
- Then in each second, we're traveling 300,000 km through the *time* dimension!
  - We're all going at the speed of light!
- If we accelerate ourselves to a substantial speed through space, we give up some of our speed in the time dimension:
  - our clock runs slower compared to a stationary observer
  - our total speed through *spacetime* is always c

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

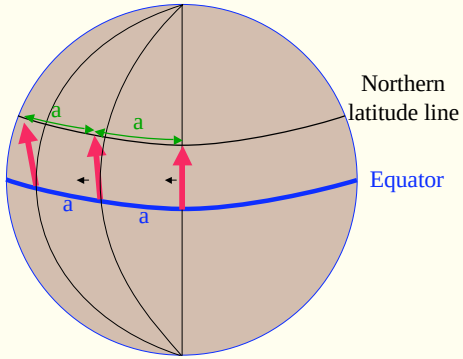
- Objects travel along straight lines in a curved spacetime.
- They don't "accelerate" due to gravity

Curvature in this room!

- Space (spacetime for that matter) *seems* flat to us
- Curvature is small
  - "Strength" of relativity in this room 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
- Is there some way to measure curved space?
  - Yes! Orbiting satellites with gyroscopes

The Curvature of Space is Real

- It has been measured: GR is right!
- How?

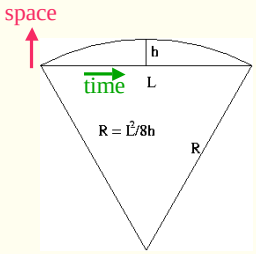


Curved Space is Real (Part Deux)

- Orbiting gyroscope (Gravity probe B, and others)
- Tips because space is curved, just like the arrow before

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 drew 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 this is independent of initial velocity (could be a bullet or a superball)



A Contemporary View

- Curved Spacetime forms a stage on which other physics happens
- General Relativity (GR) is a very successful description of the interaction between spacetime and objects
  - GPS wouldn't work without it
- Einstein's Field Equation: (just for fun…)

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

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

Einstein Tensor describing how spacetime is curved

Stress-Energy Tensor describing distribution of mass and energy

A Genuine Scientific Revolution

- The General Relativity view
  - Relegated "gravity" to the interaction between mass and spacetime
  - Abolished the notion that the geometry of spacetime is *everywhere* flat
  - Mixed the concepts of space and time
- GR does not 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" would be a better term...
  - Einstein wanted to call it "The Theory of Invariants"

References and Assignments

- References
  - dmoz.org/Science/Physics/Relativity/Overviews/
    - especially links titled "General Relativity"
  - *Relativity Visualized*, by L. C. Epstein
    - great intuitive development, low math (low PC also)
- Assignments
  - Read Hewitt Chapters 35 and 36
  - HW5: 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