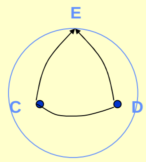
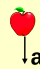
Lect. 17 General Relativity - Curved Space-Time.

General Relativity - Curved Space-time

Gravity waves





Accelerated motion caused by "Force of Gravity" or inertial motion in curved space-time

Announcements

- Schedule:
  - Today: Continue General Relativity
    - March (Ch 12, p. 130- 140) "Did God have any choice?" (Rest of Chapter 12 about the universe covered later.)
  - Next Time: Review before Exam 2
    - March (Ch 6- 12, p. 140)
- Homework 7: Due Monday.
- Exam II: Wed. Nov. 5

Introduction

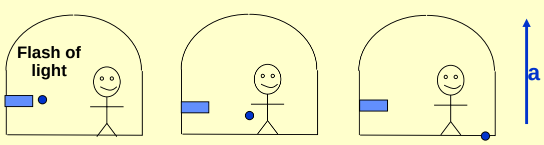
- Last time: General Relativity
  - Gravitational mass and inertial mass
  - Equivalence Principle: the basis of General Relativity
  - No need for gravitational forces!
  - Examples:
    - Bending of light in gravitational field
    - Gravitational red shift
- Today: General Relativity - continued
  - The consequence- Curved space time
  - Examples:
    - Free fall according to Galileo and Newton
    - Free fall according to Einstein
  - Success for Einstein's theory of Gravity - Unification of theory of space, time, energy, mass, gravity!
  - But no one been able to extend this kind of theory to other forces ! Still active area of research in physics!

Status at this point for Einstein (and us)

- Einstein's Equivalence Principle proposes gravity and acceleration are equivalent
  - Cleverly explains why gravitational mass = inertial mass
  - It follows immediately that all bodies fall with same acceleration
  - Important predictions such as "gravitational red shift", bending of light in gravitational field
- Now what to do about Newton's laws:
  - What replaces Newton's Laws:
    1. Inertia: Objects move in straight lines if there are no forces
    2. F= Ma
    3. Action/Reaction (Conservation of Momentum)
  - What replaces forces (e.g., force of gravity)
  - How to get around Newton's problem of gravity as "action at a distance"

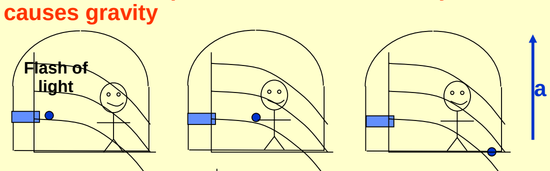
Einstein's Solution: Curved Space-time

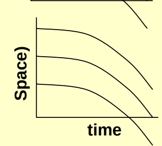
- Einstein: "No experiment performed in one place can distinguish a gravitational field from an accelerated reference frame"
- "Accelerated" means motion that changes with time, i.e., curved!
- Example: Light must bend in a gravitational field just as in an accelerating reference frame
  - Figure from last time: Path of light seen by astronaut in an accelerating rocket. Light appears to accelerate toward bottom of rocket just like anything else!



Einstein's Solution: Curved Space-time

- From point of view of the astronaut, space-time itself is curved!
- The same whether he/she is in an accelerated rocket or in the presence of a massive object that causes gravity

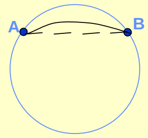




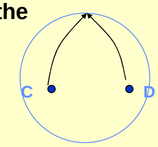
Lect. 17 General Relativity - Curved Space-Time.

Curved Space-time

- One analogy: Shortest distance on the curved (spherical) earth is a "geodesic" curved line



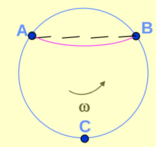
- Two people starting at the equator and each heading due north. Meet at the north pole. Is this due to some mysterious force of attraction?



Curved Space-time

- We now move to Einstein's formulation of the theory in terms of curved (non-Euclidean) spacetime.

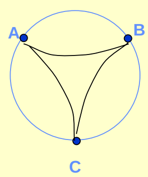
• **Example:** imagine you were on a merry-go-round which was rotating at a fast speed. If you were asked to find the shortest distance between points A and B in the diagram, you would pick the "curved" line rather than the dashed line. **Why?**

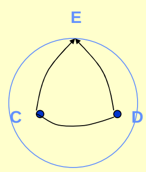


• Your meter sticks would shrink less at a smaller radius, therefore you would need fewer of them on the "curved" path!
• Similarly, you would find "curved paths" to be the shortest routes between A & C and B & C. Therefore the sum of your angles in the triangle ABC would be < 180°! You would measure your space to be curved!
• Applying the equivalence principle once again, we are led to the conclusion that what we call a gravitational field can be viewed as just the "physical manifestation" of curved space-time!

Curved Space-time

- Curved (non-Euclidean) space-time.
- Example from previous slides: Space can be curved in either positive or negative directions





Sum of angles less than 180°

Sum of angles greater than 180°

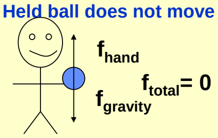
- "Inertial motion" in a curved space is defined to be motion along the shortest path - generalizes the idea of a "straight line" in flat space

No Need for "Force" of Gravity!

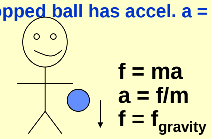
- **Einstein's theory:** The mass in a region determines the curvature of space-time.
- **Newton's Theory:** Force determines motion. For example, the gravitational attraction between the Sun and a planet determines the curved orbit of the planet about the Sun.
- **Einstein:** It is not necessary to "solve" for the motion. All motion is along "straight lines" (geodesics) in a curved spacetime! The notion of gravitational "force" then has essentially been eliminated.
- "Matter tells space how to curve and space tells matter how to move". **All is geometry!**

Motion in Curved Space-time

- Newton's Description
  - Held ball does not move

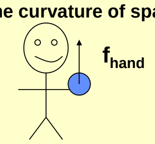


Dropped ball has accel. a = g

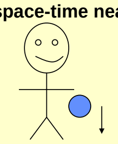


•Einstein's Description: No "force of gravity"

•Held ball does not move
Force of hand balances the curvature of space-time

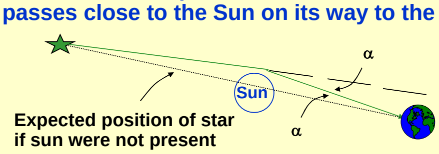


Dropped ball has accel. a = g
Inertial motion in curved space-time near earth

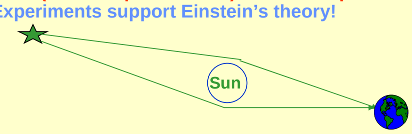


Path of light near sun

- Measurement of positions of stars whose light passes close to the Sun on its way to the Earth.



Is this due to a "force" causing light to bend - or to "straight-line motion (shortest path motion) in curved space-time near sun? Experiments support Einstein's theory!



Parallel lines can converge to a point in curved space time!

Lect. 17 General Relativity - Curved Space-Time.

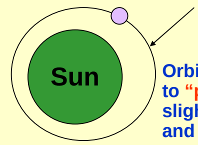
No Need for "Force" of Gravity - Continued

- Recall from last time:
- Einstein's theory is very mathematical and difficult to actually use.
- Because Newton's Theory is still very accurate for small gravitational fields, and it is MUCH easier to use, it is used for "everyday" problems"
  - Falling Bodies, Projectiles, . . .
  - Moon going around the Earth
  - Planetary motion EXCEPT that very accurate descriptions require Einstein's theory of General Relativity (orbit of Mercury)
- General Relativity VERY important to understand the universe!
  - Black Holes, Big Bang, ...
  - More about this later in course!

Evidence for General Relativity

- Careful tests
  - The gravitational red shift observed in the laboratory
  - Seen in light from massive stars
  - The orbit of Mercury
  - ......

Slightly elliptical orbit of Mercury



Orbit of Mercury predicted to "precess" around sun slightly differently in Newton and Einstein Theories

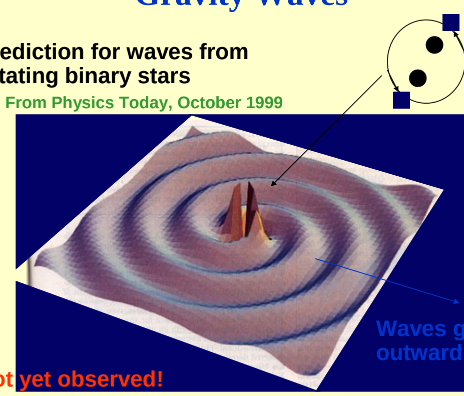
Experiment support Einstein!

The Speed of Gravity???

- What about the problem of "action at a distance" in Newton's Theory of Gravity
  - Not plausible even in Newton's time
  - Not allowed by special relativity - nothing can travel faster than light!
- Einstein's theory predicts gravitation waves
  - Analogous to electromagnetic waves
- Recall a wave is a moving pattern
- A gravitational wave is a moving pattern of the curvature of space-time!

Gravity Waves

- Prediction for waves from rotating binary stars
  - From Physics Today, October 1999

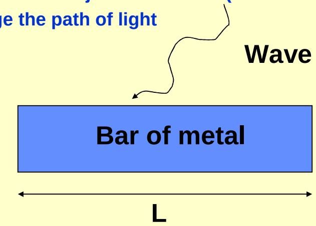


Waves going outward

- Not yet observed!

Can Gravity Waves be detected?

- VERY Difficult!
  - Easy to detect electromagnet waves
  - But recall gravity is MUCH, MUCH weaker!
- What would a gravity wave do?
  - Distort material just like a force (or acceleration)
  - Change the path of light



Searches for Gravity Waves

- Experiments over large distances
  - Coordinated measurements across the US

(from Physics Today, October 1999)

- Very large (4 km !) Michelson interferometer to measure changes in the path of light VERY accurately

4 km vacuum pipes in the desert in Eastern Washington

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Where To From Here?

- Einstein's general relativity is STILL our current theory of gravitation. It provides the framework for all current work.
  - Example: Cosmology is understood in terms of the general theory. The expansion of the universe from an initial "big bang" around 14 billion years ago is a solution to Einstein's equations for the evolution of the universe.
  - Example: Stellar evolution in terms of gravitational collapse.
- But what about other "forces"?
- Attempts at "Grand Unification Theories" but none complete up to now
  - Much Progress - see later - but unsolved!
  - The major scientific goal of Einstein during the last half of his life was the search for the grand unification
  - He "failed" -- but he pointed the way for future work!

Summary

- Matter causes space-time to be curved!
  - Matter moves along "geodesic lines" (shortest paths) in curved space-time.
  - "Matter tells space how to curve and space tells matter how to move". All is geometry!
  - No need for forces!
- General Relativity essential to understand the universe
  - Predicts Black Holes, Big band , … (later)
  - Experimentally tested
  - Resolves problem - "no action at a distance"
- Newton's laws still work for "everyday problems"
  - Einstein's theory very mathematical and very difficult
- The theory is unfinished!
  - One of the goals of current physics research: to describe other "forces" (like electrical forces) in a unified way.