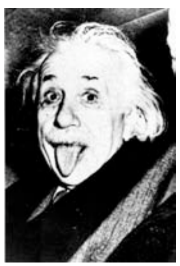
Important Announcement!

- MID-TERM ON OCTOBER 26!
  - Instead of October 19
  - 40 Multiple Choices from the review questions handed out today. Multiple Choices only.
  - Pick your copy!
- Homework#4 has been canceled due to the date change of mid-term.

Station #3, "Einstein's World"

Lecture 13: Space, Time, and Gravity (Chapter S2,S3)

Lecture 14: The Bizzarre Stellar Graveyard (Chapter 18)



Lecture 13
Space, Time, and Gravity

Reading: S2 and S3

Relativity & Astrophysics

- Newton's laws of Motion and Gravity are not sufficient to describe many astrophysical phenomena.
  - It's not like Newton's theory was wrong – his theory was not sufficient in some circumstances.
  - Slow motion, weak gravity: Newton
  - Fast motion, strong gravity: Einstein
- Einstein has **extended** Newton's theory.
  - **Relativity**

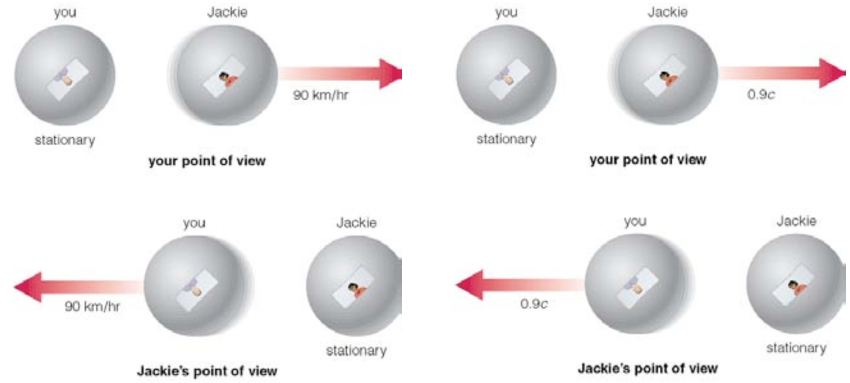
The Theory of Relativity

- Albert Einstein surprised the world in 1905 when…
  - he theorized that time and distance can not be measured absolutely
  - they only have meaning when they are measured relative to *something*
- Einstein published his theory in two steps:
  - **special theory of relativity** (1905)…how space & time are interwoven
  - **general theory of relativity** (1915)…effects of gravity on space & time
- What is "relative" in relativity?
  - motion…all motion is relative
  - measurements of motion (and space & time) make no sense unless we are told what they are being measured relative to
- What is absolute in relativity?
  - the laws of nature are the same for everyone
  - the speed of light (in a vacuum), c, is the same for everyone

"Relative" Motion

Low Speed

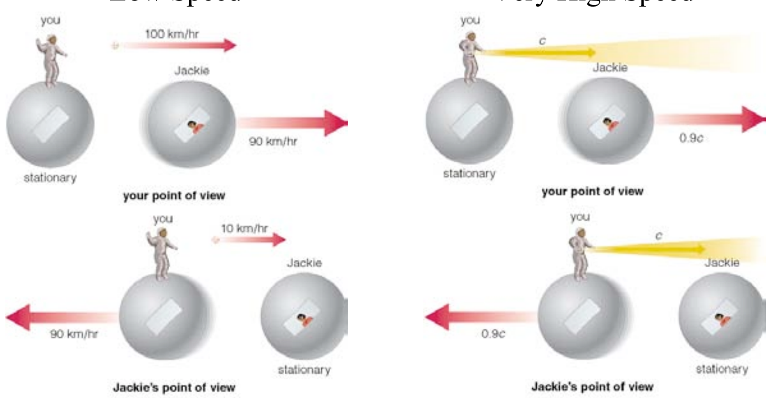
Very High Speed



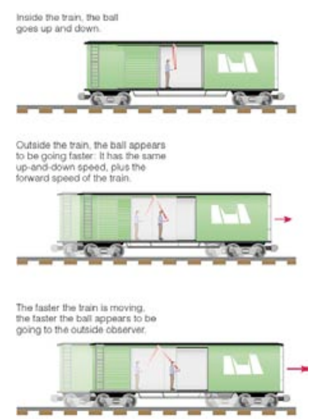
Speed of Light is Absolute! (not Relative!)

Low Speed

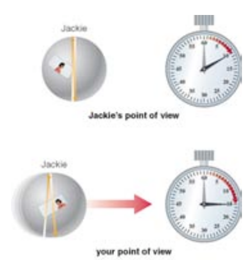
Very High Speed



Time Dilation



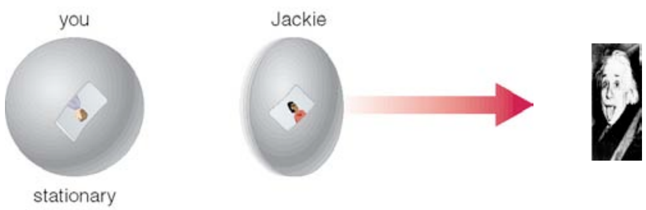
- To an observer outside the train, the ball appears to move faster.
  - makes *common sense*
- Now lets consider Jackie moving by at close to the speed of light .
  - she bounces light instead of a ball



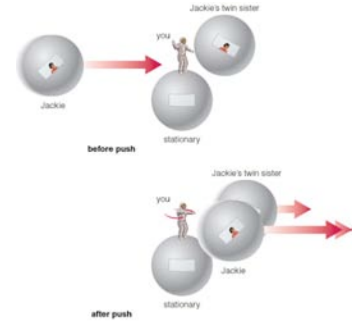
- The outside observer can **not** see the light moving faster than c.
  - yet the light <u>does</u> travel a longer distance as seen by the observer
  - so time <u>must</u> run more slowly for Jackie!

Length Contraction

- As Jackie moves past you at high velocity…
  - she tries to measure the diameter of your ship
  - but time moves more slowly for her
  - so she measures a shorter length than you do (distance = velocity x time)
- Objects appear shorter to you in the direction which they are moving.



Mass Increase



- As Jackie moves by at high speed, you give both her & her identical sister a push.
  - time runs more slowly for Jackie, so she feels the push for a shorter time
  - Jackie accelerates less than her sister does
  - Newton's 2^{nd} Law ($F = ma$) says if F is same, Jackie's mass must be greater
- Objects moving by you have a greater mass than when at rest.

Is it true?

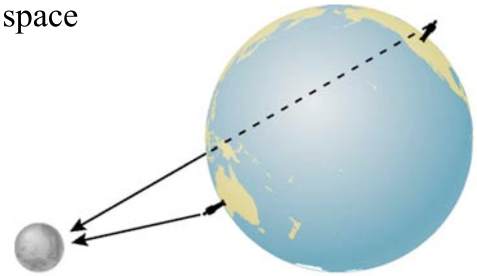
- Some tests of the special theory of relativity:
  - Constancy of speed of light verified in 1887.
  - subatomic particles have been accelerated to speeds of 0.9999 c
  - no matter how much energy we put in, they never reach c
  - the π^+ meson particle decays in 18 nsec when at rest
  - at high velocities, it lasts longer…proving time dilation
  - the equation $E = mc^2$, exemplified by nuclear reactors and bombs, is a direct consequence of special relativity

New Common Sense…It's All Relative!

- As Jackie moves by you at close to the speed of light…
  - you will see her time run slower, her length contract, and her mass increase
- But what does Jackie see?
  - she is stationary; she sees *you* moving by at high speed
  - since the laws of nature are the same for everyone
  - she sees *your* time run slower, *your* length contract, and *your* mass increase

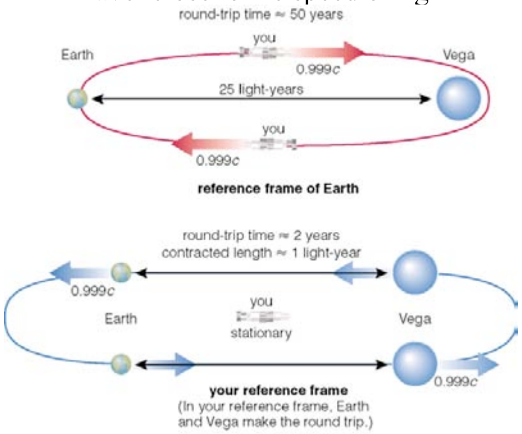
New Common Sense…It's All Relative!

- How can both perceptions be correct?
  - just as an Australian can see the Moon "up" in the sky while simultaneously an American does not
  - a correct definition of "up" will resolve the dispute
  - the dispute between Jackie's and your perceptions of each other can be resolved with more adequate definitions of time & space



Ticket to the Stars

- Although we can not travel faster than the speed of light…
  - special relativity will make the journey seem shorter <u>if</u> we can travel close to the speed of light

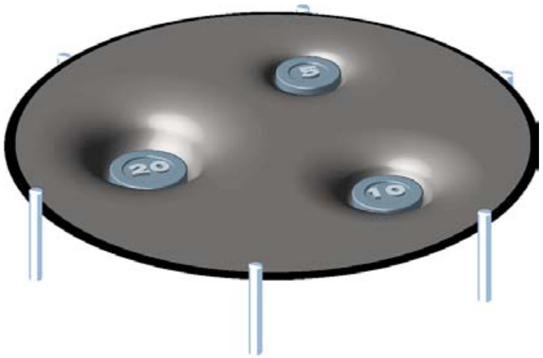


- Time moves more slowly for the space traveler.
- The distance to be covered is contracted.
- Space travelers can reach distant stars in their lifetimes.
- Their friends and family will not be there to greet them when they return home to Earth.

General Relativity: Gravity

- Albert Einstein stunned the scientific world again in 1915…
  - with publication of his **general theory of relativity**
  - it is primarily a theory of *gravity*
- Isaac Newton saw gravity as a mysterious "force."
  - he could explain its actions, but not how it was transmitted through space
  - Einstein theorized that the "force" of gravity arises from distortions of space (or **spacetime**) itself!
- spacetime…the 4-dimensional combination of space & time that forms the very fabric of the Universe
- matter shapes and distorts spacetime
  - space(time) itself can be curved
  - you may think you are traveling a straight line
  - but your motion is actually curved

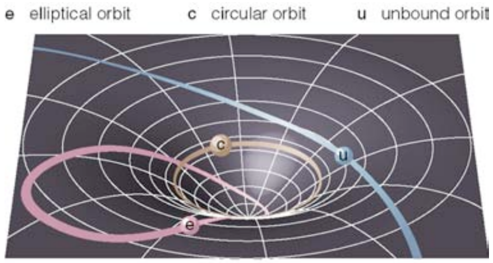
Matter Distorts Spacetime



- Matter distorts spacetime like weights on a taut rubber sheet.
- The greater the mass, the greater the distortion of spacetime.

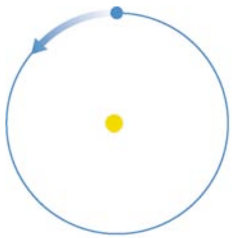
Mass and Spacetime

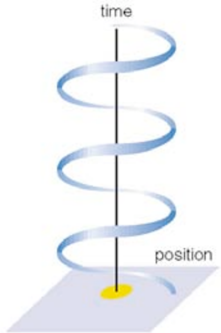
- According to Newton, all bodies with mass exert a gravitational force on each other.
  - even Newton had problems accepting this concept of "action at a distance"
- General relativity removes this concept.
  - mass causes spacetime to curve
  - the greater the mass, the greater the distortion of spacetime
  - curvature of spacetime determines the paths of freely moving objects



Orbits in Spacetime

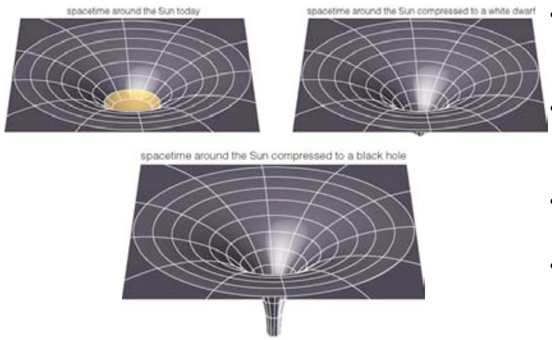
- The "rubber mat" analogy shows only an object's position in two dimensions of space.
  - Earth returns to the same position in space (*w.r.t.* the Sun) each year
  - Earth does <u>not</u> return to the same position in spacetime each year
  - Earth must also move forward in time





The Strength of Gravity

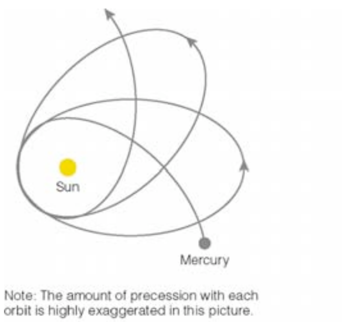
- The more that spacetime curves, the stronger gravity becomes.
- Two basic ways to increase gravity/curvature of spacetime:
  - increased mass results in greater curvature at distances away from it
  - curvature is greater near the object's surface for denser objects
    - for objects of a given mass, this implies smaller objects



- All three objects impose the same curvature at a distance.
- White dwarf imposes steeper curvature at Sun's former position.
- Black hole punches a hole in the fabric of spacetime.
- Nothing can escape from within the event horizon.

Precession of Mercury's Orbit

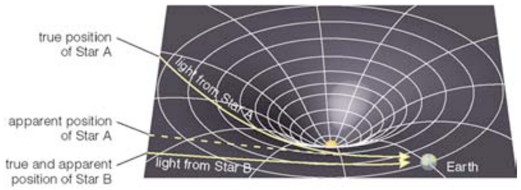
- Newton's law predicted that the orbit of Mercury should precess.
  - due to gravitational influence of the planets
  - this precession was measured in the 1800s
  - **but** Newton's law could not account for the exact precession period which was observed
  - the discrepancy between observation and theoretical prediction was real



- Einstein knew of this discrepancy and used general relativity to explain it.
  - Newton's law assumed that time was absolute & space was flat
  - but when Mercury is closest to the Sun, time runs more slowly & space is more curved
- Predictions of general relativity matched the observations exactly!

Gravitational Lensing

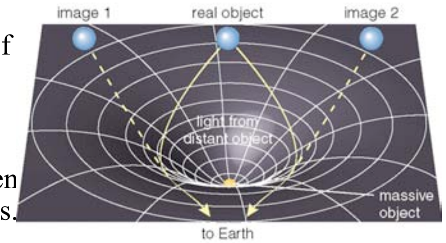
- Light will always travel at a constant velocity.
  - therefore, it will follow the straightest possible path through spacetime
  - if spacetime is curved near a massive object, so will the trajectory of light

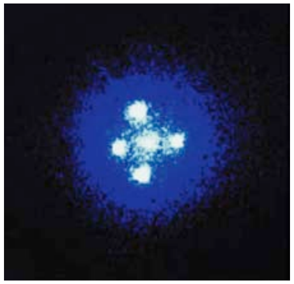


- During a Solar eclipse in 1919, two stars near the Sun…
  - were observed to have a smaller angular separation than…
  - is usually measured for them at night at other times of the year
- This observation verified Einstein's theory…
  - making him a celebrity

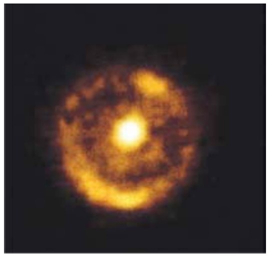
Gravitational Lensing

- Since that time, more examples of **gravitational lensing** have been seen.
- They usually involve light paths from quasars & galaxies being ben by intervening galaxies & clusters.





Einstein's Cross



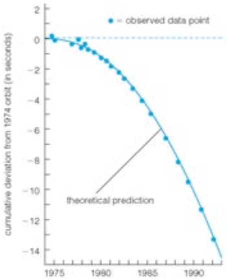
an Einstein ring
galaxy directly behind a galaxy

Gravitational Redshift

- General Relativity predicts that time runs more slowly when gravity is stronger.
- If time runs more slowly on the surface of stars than on Earth…
  - spectral lines emitted or absorbed on the surfaces of stars
  - will appear at a lower frequency (cycles/s) than measured on Earth
  - the length of 1 second is longer on the star's surface than on Earth
- This **gravitational redshift** has been observed.
- It takes infinite amount of time to get out of a blackhole.

Gravitational Waves

- General relativity also predicts that…
  - rapidly accelerating masses should send ripples of curvature through spacetime
  - Einstein called these ripples **gravitational waves**
  - similar to light waves, but far weaker
  - they have no mass and travel at the speed of light
- They have not yet been directly observed.
  - but the loss of energy from binary neutron stars
  - the "Hulse-Taylor" binary
  - is consistent with the energy being emitted as gravitational waves



Next Lecture: "The Bizarre Stellar Graveyard"

- Reading: 18

- Please turn in your homework#3 before the class begins!
  - Type your homework.
  - Staple it together.