S3. Spacetime and Gravity

Nature conceals her secrets because she is sublime, not because she is a trickster.

Albert Einstein (1879 – 1955)
Swiss/American physicist

Agenda

- SOTU
- Flag Waving
- Speed of light
- Chapter S3 – Spacetime and Gravity
- Lab 2 Measurement
- Lab 3 discussion—Excel graphs

George Bush – SOTU 2/1/06

- I propose to **double** the Federal commitment to the most critical **basic research** programs in the physical sciences over the next ten years. This funding will support the work of America's most creative minds as they explore promising areas such as nanotechnology, supercomputing, and alternative energy sources.

http://www.redzero.demon.co.uk/moonhoax/Flag.htm

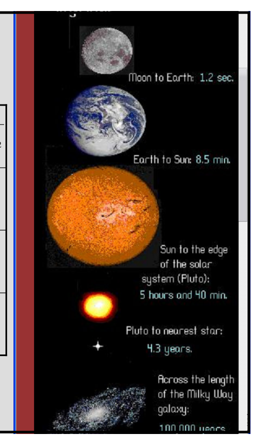
- Firstly the flag had a horizontal bar attached to it at the top. This was done so that the flag would stand out from the flagpole. NASA appreciated that there would be no wind on the moon, so any normal flag would just hang limply and unattractively down the pole. To make things look better they added a bar that stood out at 90 degrees from the pole. The flag was really hanging from this, rather than from the pole. The bar was also not quite the full width of the flag, so that it was slightly furled to give a 'wave look' to it.

- The moon's surface, once you get past the thin layer of dust, is very hard. So getting the flagpole to stick in was a tough job. The footage shows the astronaut twisting the pole back and forth in order to try and get it further into the ground. This movement made the attached bar and flag flutter.

- The flagpole itself was light aluminium that is quite springy. Even once the astronaut let go the pole would continue to vibrate. This in turn would shake the bar and flap the flag. Without any air to dampen this it would continue to do so for longer than you might expect.

Speed of Light

	Typical Speed	Fraction of c	$1/\sqrt{1-v^2/c^2}$
Racecar	200mph	0.0000003	1
Sound	700mph	0.000001	1
Muon in atmosphere	696 Million mph	0.994	9.14



Why did Einstein keep going?

- What was wrong that Einstein developed special relativity?
- So why did he work on general?

Why did Einstein keep going?

- What was wrong that Einstein developed special relativity?
  – Didn't like the idea of an ether no one could detect
  – Experimental results showing same speed of light always was hard to digest
- So why did he work on general?
  – Wanted to generalize to include acceleration
  – Bothered by "action at a distance" of gravity

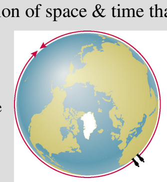
S3.1 Einstein's Second Revolution

Our goals for learning:

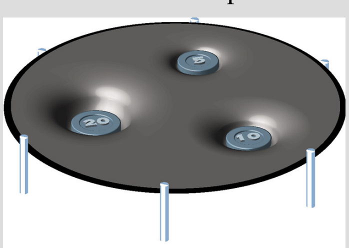
- What is the primary topic of the general theory of relativity?
- What is spacetime?

The Topic is 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.

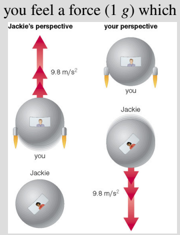
S3.2 The Equivalence Principle

Our goals for learning:

- What is the equivalence principle?
- How does general relativity allow for all motion to be relative?

Accelerated Motion

- The special theory of relativity states that all motion is relative…
  - for objects moving at a <u>constant</u> velocity with respect to each other
  - everyone (every reference frame) can claim to be stationary
- What if you fire your rockets and move away from Jackie?
  - your velocity increases 9.8 m/s every second…you are *accelerating*
  - you feel a force (1 *g*) which pushes you to the "floor" of your ship

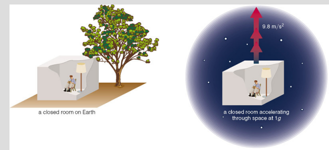


- Jackie sees you moving away from her stationary position.
  - you claim that Jackie is moving away
  - but she sees you pinned to the floor while she is still floating
  - this proves you must be accelerating
  - you are feeling a force; she is not
- Apparently we can distinguish between motion & non-motion.

The Equivalence Principle

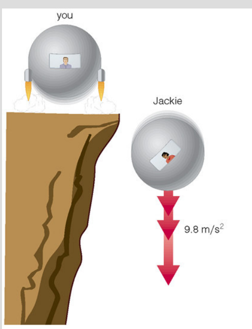
- This scenario bothered Einstein.
  - his intuition told him that <u>all</u> motion should be relative
  - until he had a revelation…the idea for the **equivalence principle**

The effects of gravity are exactly equivalent to the effects of acceleration.



- Suppose you were in a closed room.
  - whether on Earth or accelerating through space at 9.8 m/s²
  - you would never know the difference
  - your weight would be the same

Accelerated Motion or Standing Still?



- Now…back to Jackie!
  - because you are feeling a force, she claims that you are accelerating
  - she is the stationary one
- But the equivalence principle of general relativity tells us that…
  - you can legitimately consider this force to be the weight of gravity
  - you are firing your rockets in order to remain stationary (to hover)
  - the weightless Jackie is in free-fall
- General relativity makes all motion relative again!

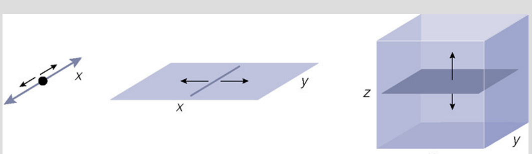
S3.3 Understanding Spacetime

Our goals for learning:

- What do we mean by dimensions?
- Does spacetime differ for different observers?
- How are spacetime diagrams useful?
- What are the three possible geometries of spacetime?
- Are there straight lines in curved spacetime?

Dimensions

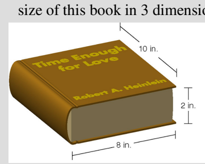
dimension… an <u>independent</u> direction of possible motion



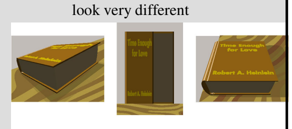
- A point (0–D) moved in one direction creates a line (1–D).
- A line moved in a direction 90º to itself creates a plane (2–D).
- A plane moved in a direction 90º to itself creates a space (3–D).
- A space moved in a direction 90º to itself creates a 4–D space.
  - we can not perceive this **hyperspace**…any space > 3–D

Spacetime for All

- The reality of spacetime is the same in all reference frames.
  - we can not visualize the 4–D spacetime since we can't see through time
  - we perceive a 3–D projection (view) of spacetime
  - while spacetime is the same for all observers, their 3–D perceptions of it (e.g. space & time) can be very different
- By analogy…
  - we can all agree on the shape & size of this book in 3 dimensions

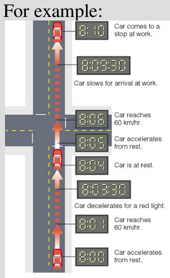


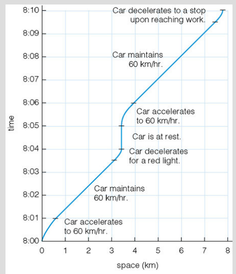
- But…
  - the following 2–D projections (views) of the same book all look very different



Spacetime Diagrams

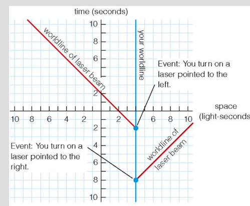
- To gain some sort of perception of motion through spacetime…
  - we draw a **spacetime diagram** by plotting…
  - one dimension of space on the x-axis & time on the y-axis
- For example:

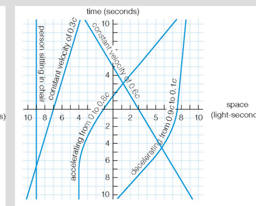




Spacetime Diagrams

- An object's motion through spacetime is called its **worldline**.
- The worldline for an object…
  - at rest is vertical
  - moving at constant velocity is straight and slanted
  - which is accelerating is curved (towards vertical if a < 0, horizontal if a > 0)
  - is never horizontal

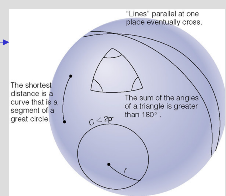


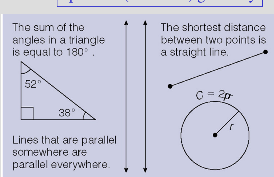


The Rules of Geometry

- The geometry you know is valid when drawn on a flat surface.
- The rules change if the surface is not flat.

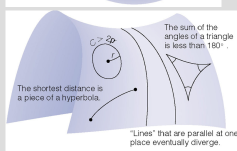
spherical (curved-in) geometry





flat (Euclidean) geometry

saddle-shaped (curved-out) geometry



Geometry of Spacetime

- Spacetime can have three possible geometries:
  - flat…the rules of Euclidean geometry apply
  - spherical…parallel lines eventually meet
  - saddle-shaped…parallel lines eventually diverge
- Spacetime may have different geometries in different places.
- If spacetime is curved, then no line can be perfectly straight.
- Since being in "free-fall" is equivalent to traveling at constant velocity (i.e. a straight line)…
  - objects experiencing weightlessness must be traveling along the straightest possible worldline in spacetime
- Objects in orbit are weightless.
  - the shapes & speeds of their orbits can reveal the geometry of spacetime
  - these same orbits are determined by *gravity*

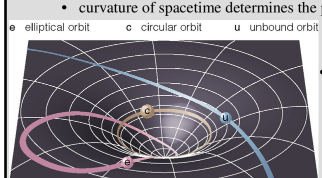
S3.4 A New View of Gravity

Our goals for learning:

- How does mass affect spacetime?
- How would an ordinary star, a white dwarf, and a black hole of the same mass differ in spacetime?
- According to general relativity, how does gravity affect time?

Mass and Spacetime

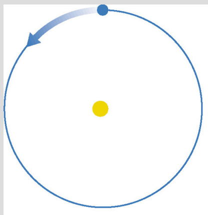
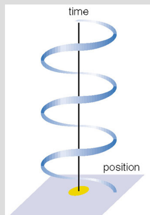
- According to Newton, all bodies with mass exert a gravitational force on each other.
  - even Newton had problems accepting this concept of "action at a distance"
- General relativity removes this concept.
  - mass causes spacetime to curve
  - the greater the mass, the greater the distortion of spacetime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



- Orbits can now be explained in a new way.
  - an object will travel on as straight a path as possible through spacetime

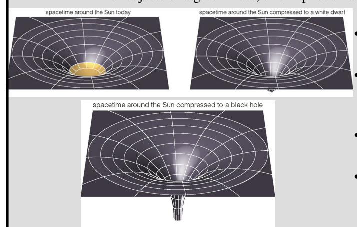
Orbits in Spacetime

- 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 not return to the same position in spacetime each year
  - Earth must also move forward in time

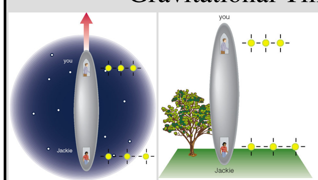
The Strength of Gravity

- 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.

Gravitational Time Dilation



- We use the equivalence principle to study the effect of gravity on time.
- You & Jackie in the ship have synchronized watches
  - the ship accelerates
  - the watches flash
- Moving away from Jackie, you see larger time intervals between her flashes.
  - time appears to be moving slower for her
- Moving towards you, Jackie sees shorter time intervals between your flashes.
  - time appears to be moving faster for you
  - you both agree
- So, in the equivalent gravitational field…
  - time moves more slowly where the gravity is stronger

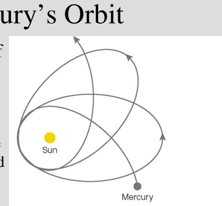
S3.5 Is it True?

Our goals for learning:

- How have experiments and observations verified the predictions of the general theory of relativity?
- What are gravitational waves, and do they really exist?

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

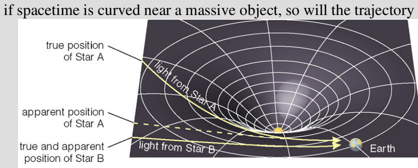


Note: The amount of precession with each orbit is highly exaggerated in this picture.

- 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

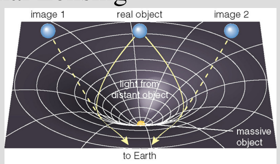
- Light will always travel at a constant velocity.
  - therefore, it will follow the straightest possible path through spacetime
  - if spacetime is curved near a massive object, so will the trajectory of light

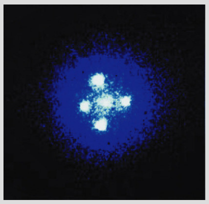


- During a Solar eclipse in 1919, two stars near the Sun…
  - were observed to have a smaller angular separation than…
  - is usually measured for them at night at other times of the year
- This observation verified Einstein's theory…
  - making him a celebrity

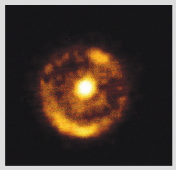
Gravitational Lensing

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





Einstein's Cross



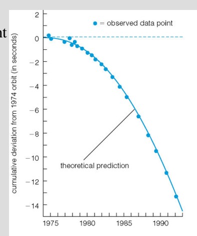
an Einstein ring
galaxy directly behind a galaxy

Gravitational Redshift

- 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.

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



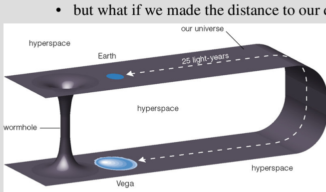
S3.6 Hyperspace, Wormholes, & Warp Drive

Our goals for learning:

- What is a wormhole?
- Is it really possible to travel through hyperspace or wormholes, or to use warp drive to circumvent the limitation on speeds greater than the speed of light?

Science Fact or Fiction?

- Do the theories of relativity prohibit interstellar travel?
  - we can not travel faster than the speed of light
  - but what if we made the distance to our destination shorter?



- We might tunnel through hyperspace in a **wormhole**.
- A wormhole connects two distant points in the Universe.
- Or perhaps we could warp spacetime so that two locations of our choosing could touch momentarily.

- None of these ideas is prohibited by our current understanding of physics.
- Most scientists are pessimistic about the possibilities.
  - wormholes would also make time travel possible, with its severe paradoxes
- For the moment, the Universe is safe for science fiction writers!

S3.7 The Last Word

Death signifies nothing…the distinction between past, present, and future is only a stubbornly persistent illusion.

Albert Einstein, April 18, 1955

What have we learned?

- What is the primary topic of the general theory of relativity?
  - The general theory of relativity is primarily a theory of gravity, stating that the force of gravity arises from distortions of spacetime.
- What is spacetime?
  - Spacetime is the four-dimensional combination of space and time that forms the "fabric" of our universe.

What have we learned?

- What is the equivalence principle?
  - The effects of gravity are exactly equivalent to the effects of acceleration.
- How does general relativity allow for all motion to be relative?
  - Special relativity shows that motion at constant velocity is always relative, but the fact that an accelerating object feels a force makes it seem as if accelerated motion can be distinguished from nonmotion. By telling us that the effects of gravity and acceleration are equivalent, general relativity makes all motion relative: An object that is feeling a force can be explained equally as well as a moving object undergoing acceleration or as a stationary object feeling effects of gravity.

What have we learned?

- What do we mean by dimensions?
  - Each dimension represents an independent direction of possible motion. In three-dimensional space, the three dimensions of length, width, height are perpendicular to one another. A four-dimensional space has a fourth dimension perpendicular to all three of the others. We cannot visualize this, but it can still exist.
- Does spacetime differ for different observers?
  - No. Both time and space differ for observers in different reference frames, but the combination of spacetime is the same for everyone.
- How are spacetime diagrams useful?
  - Spacetime diagrams can clarify the relativity of time and space. Objects with vertical worldlines are stationary. Objects with slanted worldlines are moving at constant velocity (relative to the person making the space-time diagram). Objects with curved worldlines are accelerating.

What have we learned?

- What are the three possible geometries of spacetime?
  - The three possible geometries are a flat geometry, in which the ordinary laws of flat (Euclidean) geometry apply; a spherical geometry, in which lines that start out parallel tend to converge; and a saddle-shaped geometry, in which lines that start out parallel tend to diverge. Spacetime may have different geometries in different places.
- Are there straight lines in curved spacetime?
  - If spacetime is curved, then no line can be perfectly straight. However, and worldline that follows the *straightest possible* path is a worldline on which an object or person would feel weightless.

What have we learned?

- How does mass affect spacetime?
  - Mass causes spacetime to curve, and the curvature of spacetime determines the paths of freely moving masses.
- How would an ordinary star, a white dwarf, and a black hole of the same mass differ in spacetime?
  - Because all three objects have the same mass, far from their surfaces they would affect spacetime in precisely the same way. Up close, however, the white dwarf would distort spacetime much more than the ordinary star, and the black hole would distort spacetime so much that it essentially would form a bottomless pit—a true hole in the universe.
- According to general relativity, how does gravity affect time?
  - Time runs slower in places where gravity is stronger.

What have we learned?

- How have experiments and observations verified the predictions of the general theory of relativity?
  - Observations of the precession of Mercury's orbit match the precession predicted by Einstein's theory. Observations of stars during eclipses and photos of gravitational lensing provide spectacular confirmation of the idea that light can travel curved paths through space. Gravitational redshifts observed in the light of objects with strong gravity confirm the slowing of time predicted by general relativity.
- What are gravitational waves, and do they really exist?
  - General relativity predicts that accelerating masses produce gravitational waves that travel at the speed of light. Observations of binary neutron stars provide solid indirect evidence that gravitational waves really exist.

What have we learned?

- What is a wormhole?
  - A wormhole is a theoretical construct that connects two remote parts of the universe with a “tunnel” through spacetime.
- Is it really possible to travel through hyperspace or wormholes, or to use warp drive to circumvent the limitation on speeds greater than the speed of light?
  - No one knows. No known physical laws prevent these possibilities from being reality. However, if any one of them proves to be real, then cause and effect might not be absolute, a proposition troubling many scientists.