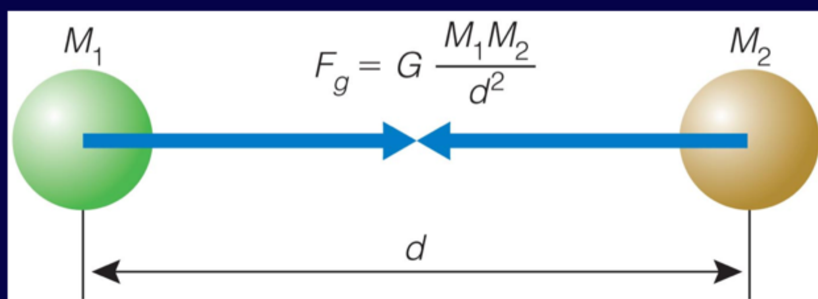
What determines the strength of gravity?

The **universal law of gravitation:**

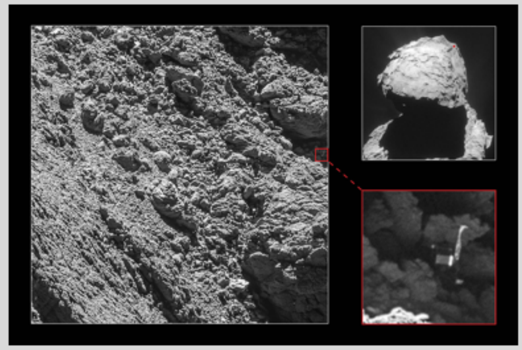
1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers.



You were here…

(Yester-)~~To~~day in science…

- Throwback Tuesday on the Rosetta Mission!
  - Rosetta = orbiter
  - Philae = lander



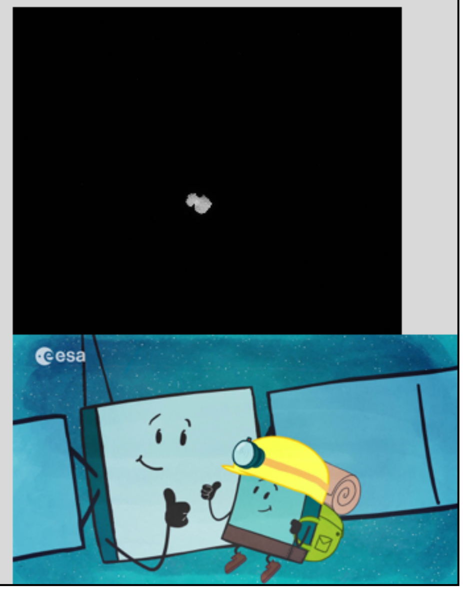
67P compared to Denver, I’m pretty sure
https://twitter.com/AntonioParis/status/1039274847719829504

67P/Churyumov-Gerasimenko is the full name of the comet

Why did Philae bounce?

- F_g!

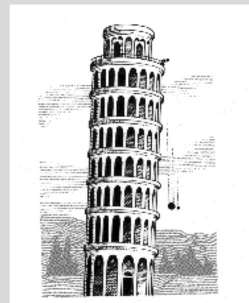
- A little math… what is acceleration due to gravity on the comet, and how does that compare to Earth?
  - $Fg = \frac{G\, M_{comet}\, M_{Philae}}{R_{comet}^2} = M_{Philae} * a$
  - $\frac{6.67\times10^{-11}\ m^3\ kg^{-1}\ s^{-2} * 10^{13} kg}{(4000m)^2} = a_{comet}$
  - $4.17\times10^{-5}\ m/s^2 = a_{comet}$ (compare to $9.8\ m/s^2$ on Earth!)



http://sci.esa.int/rosetta/14615-comet-67p/

Acceleration due to gravity

- According to legend, Galileo dropped weights from atop leaning tower of Pisa
  - Objects fall at the same rate, regardless their mass: they experience the same acceleration
  - Acceleration due to gravity on Earth will increase an object's speed by 9.8 m/s for every second the object is falling
  - Denoted as lower-case g
    - $g = 9.8 m/s^2$



(corrected units on g)

Why do all objects fall at the same rate?

- We can understand this using two laws Newton discovered.
- $F_g = \dfrac{G\, M_{Earth}\, M_{ball}}{R_{Earth}^{2}}$
- $F = m_{ball} a$
- Set them equal to each other…

$$\frac{G\, M_{Earth}\, \cancel{M_{ball}}}{R_{Earth}^{2}} = \cancel{m_{ball}}\, a$$

$$\ldots = g$$

You may remember me from such hits as… that half class on planetarium day, or, those 15 minutes the day Prof M left town

Recall: laws vs theories

- Law – a general rule to which many sets of data conform
- Theory – an in-depth scientific interpretation of a phenomenon, or a whole group of phenomena, that is capable of making correct predictions

- **While a law sounds better than a theory, it's not necessarily. Theories are more robust developments of ideas, while laws can be a single equation that describe a lot of data well.**

I'm going to back up a little bit to recap and refresh, it's been a while!

Newton's laws

1. An object at rest will remain at rest unless acted upon by a force
2. F=ma
3. For any force, there is an equal and opposite force

http://www.cakeburger.com/comic/cat-physics/

Newton's Laws of Motion

1. In the absence of a net force, an object in motion or at rest remains in motion or at rest

- This probably seems somewhat obvious: a parked car on a flat surface isn't going to just roll away

Unless the parking brake is off, it's in neutral, and someone pushes it

Newton's Laws of Motion

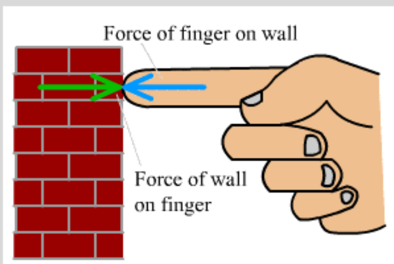
1. In the absence of a net force, an object in motion or at rest remains in motion or at rest
2. Force = mass $\times$ acceleration (F = ma)

- Possibly the most profound of all three laws; what it is saying is that *force* is the *rate of change of momentum.*

Recall that acceleration is the change in the velocity per unit time- if you regroup the terms in the equation, you get a change in momentum per time; that's what force is

Newton’s Laws of Motion

1. In the absence of a net force, an object in motion or at rest remains in motion or at rest
2. Force = mass × acceleration ($F = m \times a$)
3. For any action (applied force) there is an equal and opposite reaction (force)



Recall that acceleration is the change in the velocity per unit time- if you regroup the terms in the equation, you get a change in momentum per time; that’s what force is

Evolution of ideas

- Early observers collected the data later mathematicians and astrophysicists worked with later
- Kepler came up with the framework of *how*:
  - How do the planets move in the sky? On elliptical orbits, not circular!
- Newton came up with the *why*
  - Newton's laws, in combination with what we observe, give rise to what we call *conservation laws*
  - When a quantity is conserved, it means that over an entire system, the **net** amount of it stays the same

Conservation laws in astronomy: momentum

- Conservation of momentum
  - Linear momentum: $p = mv$ (units: kg * m/s)
  - Recall Newton's third law: for every force, there's an equal and opposite force
  - Recall also: a force is something that acts to change an object's momentum
  - Upon impact, momentum is transferred from one object to another

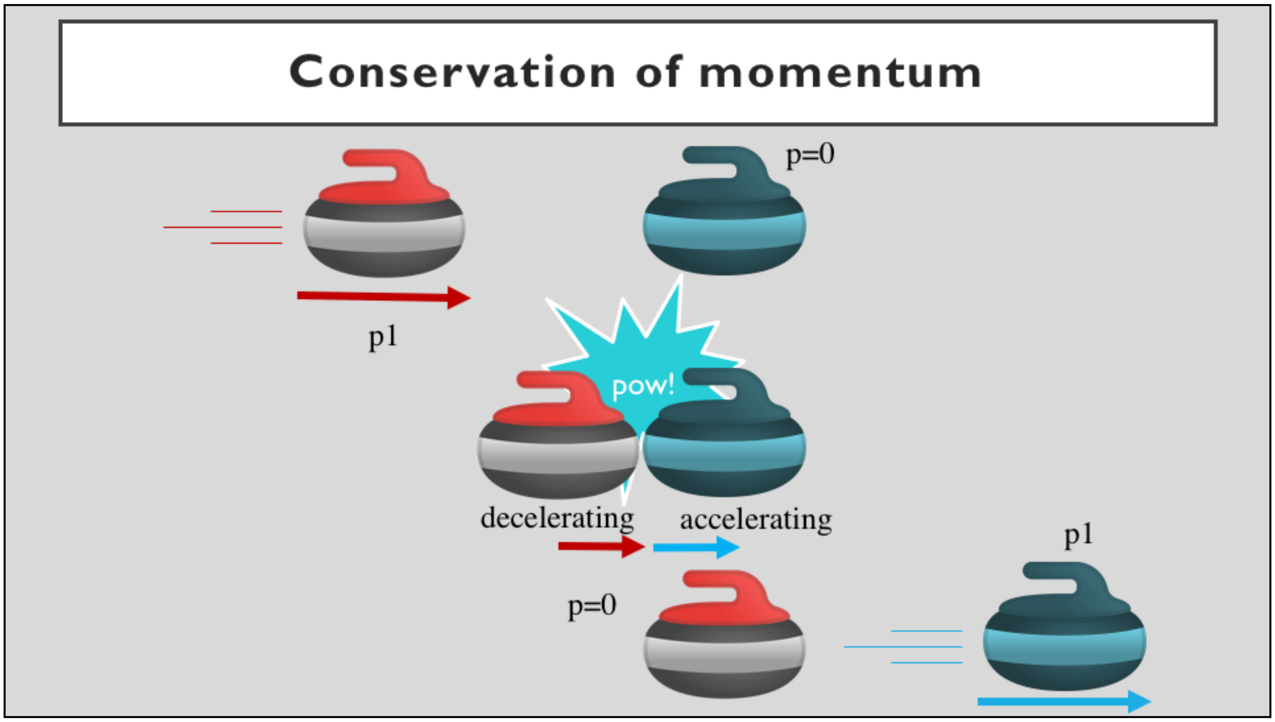
(Alicia: don't forget the demo)

Something we observe here on Earth: conservation of linear momentum; that is to say, momentum acting in a straight path

Note: Force = mass * acceleration. Acceleration is change in velocity per unit time (m/s /s). So force is mass * change in velocity / time, or kg * m/s /s. The kg* m/s part is momentum! Force is change in momentum over time.

Conservation of momentum

The book gives you an example of playing pool- curling is another good example, when the stones impact each other



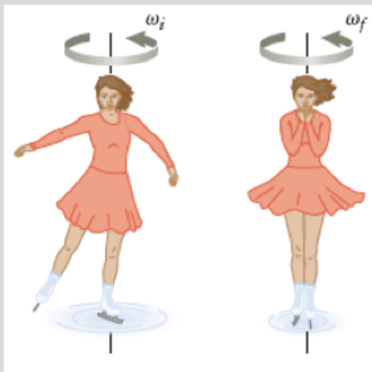
Let’s break down one of those impacts…

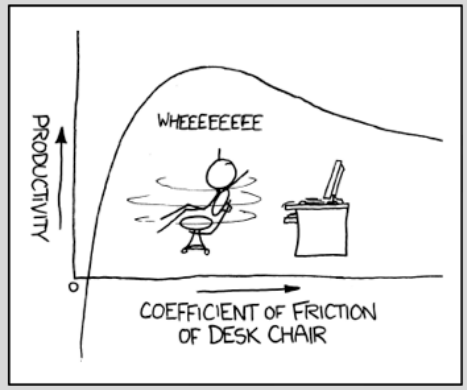
Conservation of momentum

The book gives you an example of playing pool- curling is another good example, when the stones impact each other

Conservation laws in astronomy: angular momentum

- Conservation of angular momentum (recall: ω = m * v * r)
  - Rotational



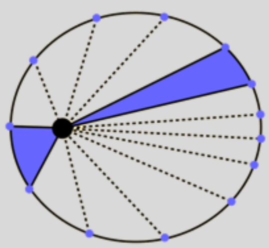


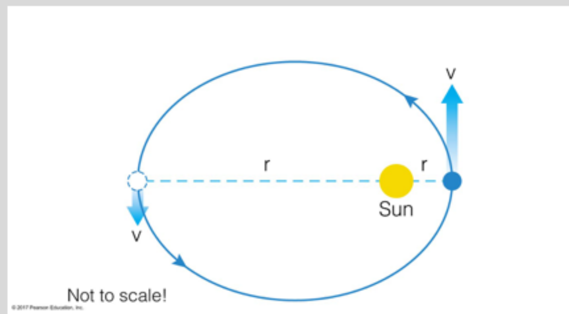
https://xkcd.com/815/

As figure skater's radius, r, decreases, to conserve angular momentum, her rotational velocity must increase

Conservation laws in astronomy: angular momentum

- Conservation of angular momentum (recall: ω = m * v * r)
  - Rotational
  - Orbital
- Newton's 1st law: if no force is acting on the orbiting planet, it will keep on orbiting
- Kepler saw orbital speeds changing, deduced elliptical orbits
  - ➢ its angular momentum is conserved





We see this in the observations Kepler's laws were built from

Kepler's second law: the path of the planet's orbit sweeps out equal areas for equal time

Energy

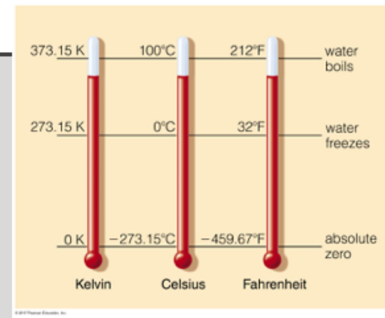
- Energy is a property that enables something to do work
- When a force acts to move an object a certain distance, it has done work
  - Work = force * distance
- For astronomy, important types of energy:
  - Kinetic
  - Radiative
  - Potential

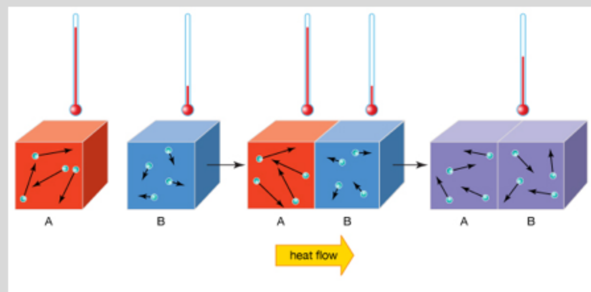
- Affiliated conservation law: energy is not created or destroyed

We'll talk a lot about radiative energy in chapter 5

Kinetic energy

- The energy of a moving object: $\frac{1}{2} mv^2$
- Important form of kinetic energy for us: thermal energy
  - Kinetic energy of atoms or molecules in a substance
- Temperature: measures the *average* kinetic energy
- Temperature tells us which way energy will move when two systems come into contact
- Rate of energy flow depends on density
- Absolute zero (Kelvin): thermal energy is 0

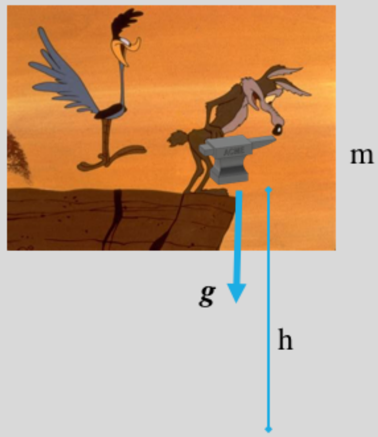




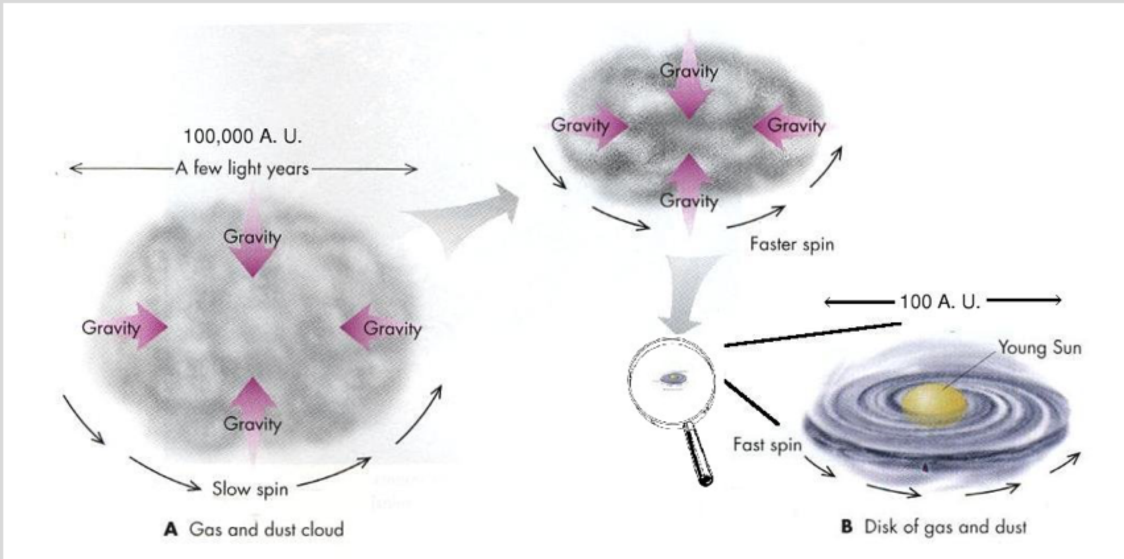
The book gives a good example of a boiling pot of water vs an oven. The oven may be hotter, meaning the particles have higher average kinetic energy, but there are fewer of them than say, in a pot of boiling water.

Potential energy

- Potential energy is the capacity of something to do work
  - Example: if Wile E. Coyote is holding an anvil over a cliff, about to drop it, its potential energy depends on
    - The mass of the anvil
    - The acceleration due to gravity
    - The height of the cliff
      - PE = m*g*h



Gravitational potential energy



Gravitational potential energy decreases the smaller the protostellar cloud gets

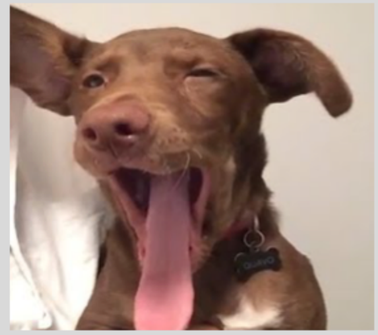
Thermal energy increases because density is increasing; the star forms in the middle, getting heated up from conversion of potential to kinetic energy

Due to conservation of angular momentum, we think material speeds up as it collapses

http://faculty.virginia.edu/skrutskie/ASTR1210/notes/ssrecip.html

Conservation of energy

- Energy is not created or destroyed, it simply changes form
- Example: you raise your hand to stifle a yawn
  - Your muscles exerted energy to perform the mechanical action of raising your hand
  - The energy your muscles used came from what you ate for breakfast
  - What you ate for breakfast got its energy from sunlight, one way or another
  - The sun is radiating energy in the form of light that came from fusing H atoms at its core, converting mass into energy
  - H atoms came from the big bang, which was a conversion of energy into mass



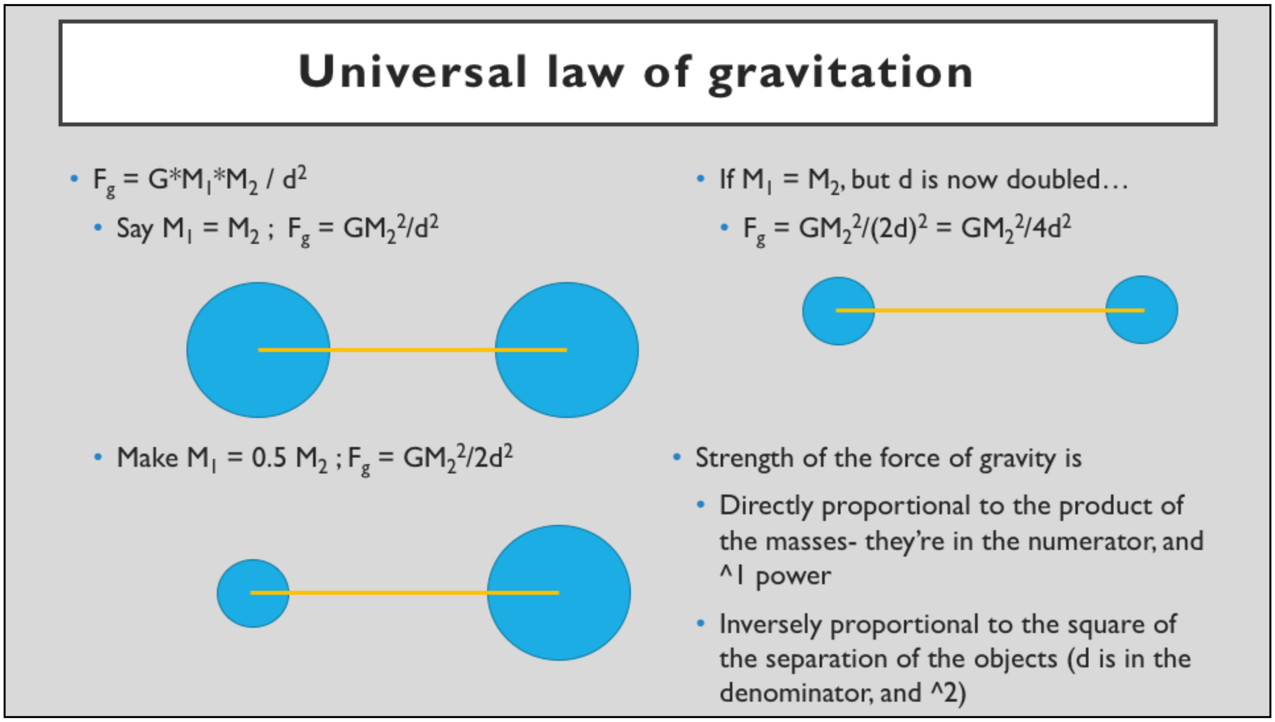
Universal law of gravitation

- Newton, not content to stop at laws of motion, calculus, optics, etc… carried on to develop a framework for understanding gravity

1. Every mass attracts every other mass through a force called gravity
2. the strength of the force of gravity is *directly proportional* to the product of those two masses
3. the strength of the force of gravity decreases as the square of the distance between the two masses' centers

$F_g = G*M_1*M_2 / d^2$

Note the big G- this is a universal constant, not to be confused with the little g for acceleration due to gravity on earth



Examples of what would happen to the force of gravity between two objects if their masses or separation changed

Mass vs weight

- **Mass** is a fundamental measure of the amount of matter in an object
  - Mass is measured with a balance
  - Unit of mass: g (in US system, our unit of mass is called a slug)
- **Weight** is the downward force exerted by an object of a particular mass under acceleration due to gravity
  - Weight is measured with a scale
  - Unit of weight: newtons (lbs, in our daily lives)

Free-fall and weightlessness

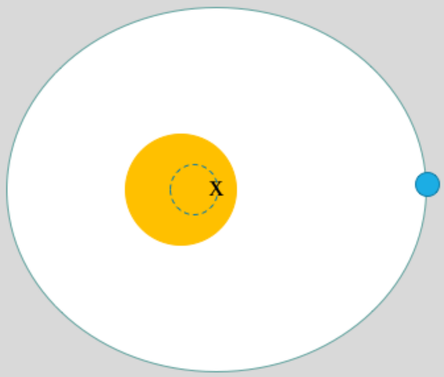
- Free fall happens when there is nothing to *prevent* you from falling- no force acting against your downward motion
  - Good example: you go sky diving, voluntarily, because you wanted to*
  - Scary example from the book: you're in an elevator and the cable snaps*

  - *note: there isn't an absence of forces when you're skydiving.. Air resistance is a big one, but it's not stopping you from falling, just slowing you down a little
  - *note: elevators are really really safe and this basically never happens

*

Kepler's laws and Newton's laws

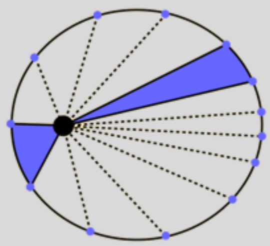
- Kepler found the how, Newton found the why
  1. Planets travel in elliptical orbits around the Sun
     - This is a natural consequence of Newton's law of gravitation: both bodies are orbiting the center of mass of the Sun+planet system

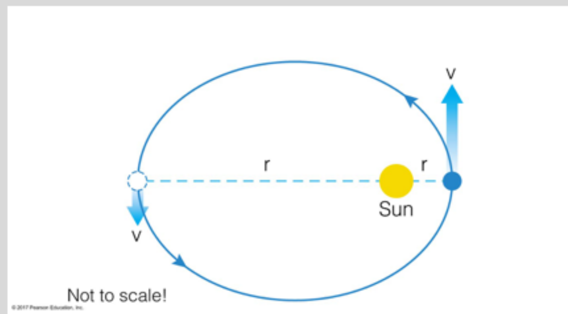


Exaggerated for effect…

Kepler's laws and Newton's laws

- Kepler found the how, Newton found the why
  1. Planets travel in elliptical orbits around the Sun
  2. Planets cover equal areas in equal time along their orbits
     - Conservation of angular momentum



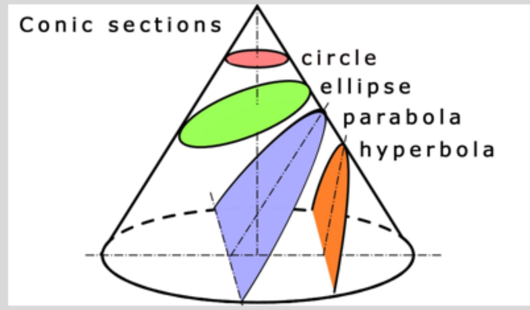


Kepler's laws and Newton's laws

- Kepler found the how, Newton found the why
  1. Planets travel in elliptical orbits around the Sun
  2. Planets cover equal areas in equal time along their orbits
  3. Planets' orbital periods and semimajor axis radii are related as $p^2 = a^3$
     - Planets experience less force due to gravity farther away from the Sun, and they move more slowly ($F_g \sim 1/d^2$)

Beyond Kepler's laws

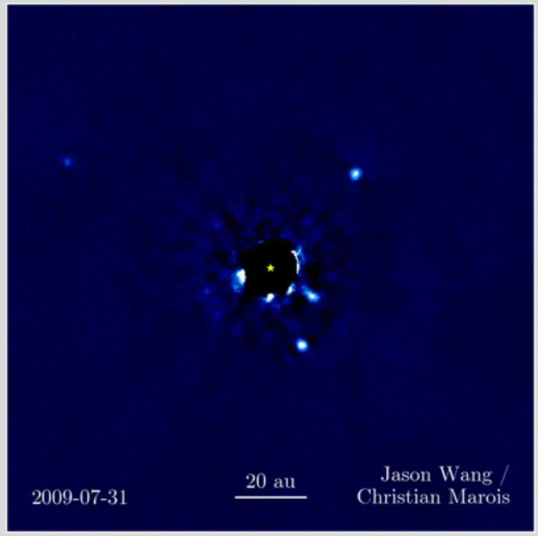
- Planets aren't the only bodies that travel in elliptical orbits
  - So do moons
  - And asteroids
- Ellipses aren't the only kinds of orbits
  - Unbound parabolic orbits
  - Unbound hyperbolic orbits
- Knowing orbital parameters, we can now calculate masses of orbiting bodies using the universal law of gravitation



This is the cone Neil deGrasse Tyson was talking about in the video last week

Beyond Kepler's laws

- Newton applied law of gravitation universally



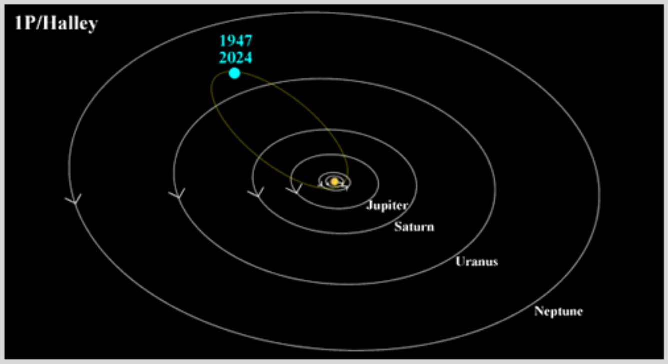
https://www.forbes.com/sites/startswithabang/2017/01/30/watch-four-gas-giants-in-orbit-around-another-star-for-the-first-time/

Orbital energy & gravitational encounters

- A body's total orbital energy is the sum of its kinetic energy (energy of motion, related to speed) and gravitational potential energy (dependent upon distance)
- These components vary throughout the planet's orbit, but the total energy is conserved

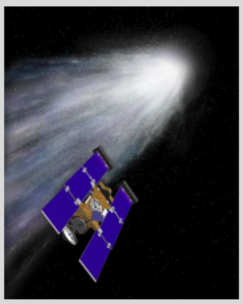
- A close pass between a planet and a body (a comet, a satellite, another planet) can exchange orbital energy
- The change in energy is almost negligible for the larger body

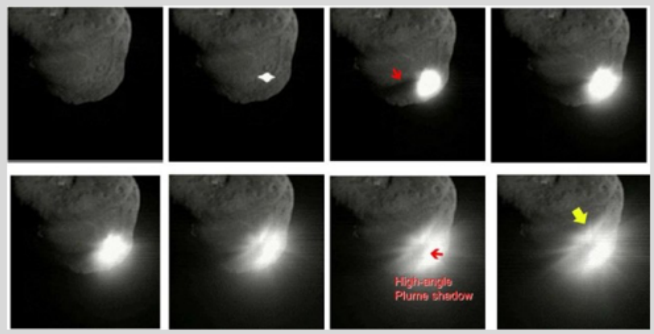
Orbital energy & gravitational encounters



Comet shenanigans

- Stardust mission
  - Flew into coma of comet Wild 2 to collect material comet was outgassing
- Deep Impact
  - Dropped a refrigerator-sized impactor onto comet Tempel 1 to see what would come out





https://arstechnica.com/science/2013/09/deep-impact-probe-down-and-out-ice-back-for-maybe-more/

Atmospheric drag & escape velocity

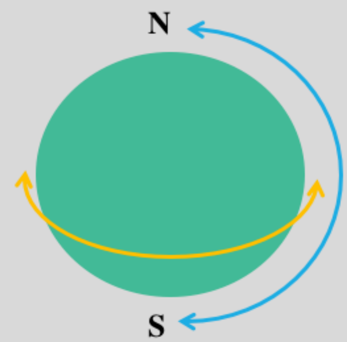
- Back to orbital energy considerations…
- Orbital energy will be conserved, unless a force acts to change it
  - Atmospheric drag can reduce orbital energy, causing satellites' trajectories to change
    - This could be bad: satellites we launch need to overcome/get far enough away to be safe
    - This could be good/interesting: planets in the outer solar system may have captured a lot of moons this way

- As you increase its orbital energy, body will get farther and farther away
  - At some velocity, body can entirely leave its bound orbit: *escape* velocity

Tidal effects

- The Earth's rotation makes it an oblate spheroid shape
  - Centrifugal forces push outward, most at the equator
    - From N->S poles, Earth's diameter is 12,713 km
    - Around Equator, Earth's diameter is 12,756 km!

- Gravitational forces between the Earth and the Moon also add to Earth's bulge (~1m in water, ~30cm in rock) as do gravitational forces between the Earth and the Sun (about half as much as the Moon's effect)



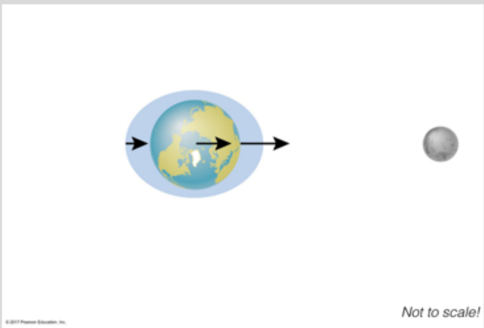
http://www.slate.com/blogs/bad_astronomy/2008/09/08/ten_things_you_dont_know_about_the_earth.html

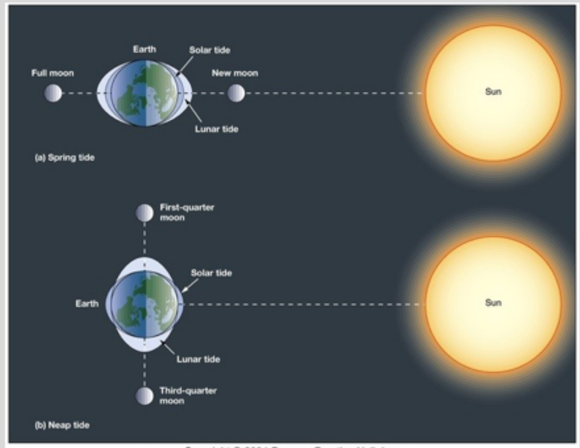
Also

http://www.slate.com/blogs/bad_astronomy/2006/08/30/when_i_say_centrifugal_i_mean_centrifugal.html

Tidal effects

- Amount of bulge depends on distance (it's a gravitational effect!)

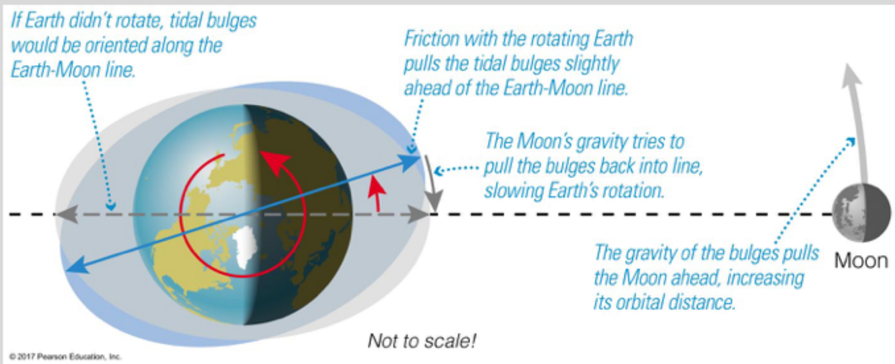




- Sun and Moon can work together or against each other, depending on where Earth, and Moon are in orbits

Tidal friction

- Gravitational force between Earth and Moon has raised a bulge on Earth
- Earth is rotating, so a tug-of-war begins as bulge starts to outpace the Moon



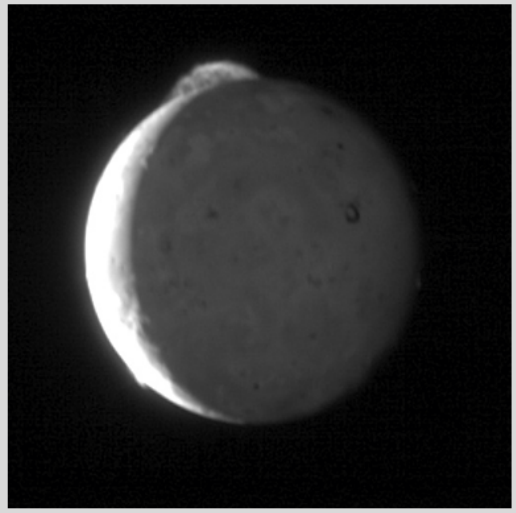
The moon's synchronous rotation

- As the Moon is creating tidal effects on Earth, so the Earth has also done to the Moon
  - Moon gains orbital angular momentum from the Earth as it slows earth down
  - Moon's distance from Earth starts to grow (conservation of angular momentum)
- The Moon used to be a lot closer to us than it is now
- It also likely rotated faster
- 2014: Scientists were able to measure a "lunar body tide," a 20 inch bulge in the Moon's surface due to Earth's gravitational pull

https://www.space.com/26246-lunar-tide-seen-from-space.html

Tidal effects on other worlds

- Synchronous rotation of moons is common
- Tidal bulging also common on other moons
  - the more massive the planet, the stronger the force
  - Jupiter's moon Io is volcanically active from being squeezed by Jupiter, Ganymede, and Europa (numerous tidal bulges!)



Video from New Horizons spacecraft while flying by