Lecture Log
Phy1033C HIS 3931 IDH 3931
**Discovering Physics:** The Universe and Humanity's Place In It.
Fall 2016

**August 23**

1) Structure & goals of course, go over requirements & grading policy

See http://www.phys.ufl.edu/~pjh/teaching/phy1033/1033syllabus.html

Q: why are you taking this course?

Powers of 10 video
http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/index.html

Solar system simulator
http://janus.astro.umd.edu/SolarSystems/

John Mocko discusses HITT system.

**August 25**

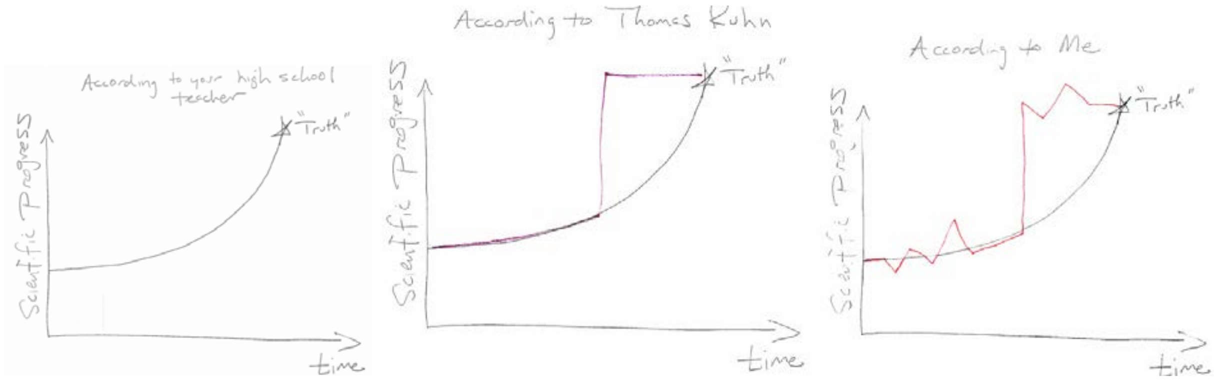
**Perspectives: history vs. physics**

1) Thomas Kuhn (*The Structure of Scientific Revolutions*): "Aritstotle wasn't a bad physicist; he was a good Greek philosopher"
2) Weinberg (*To Explain the World*): "What is most striking is not so much that Zeno and Parmenides were wrong, as that they did not bother …to explain how their theories about ultimate reality accounted for the appearance of things."
3) Kuhn notion of paradigms and scientific revolutions

    a) The recognition of novelty
    b) From novelty to anomaly
    c) The development of crisis
    d) Paradigm shift

    Not a logical process
    Resulting paradigm incomensurable with original
    Whither progress?
4) Revolution and scientific progress

Kuhn pointed out that progress in science wasn't gradual, but happened mostly during paradigm shifts. We can understand this visually:




Let's examine the colloquial notion of scientific progress, which suggests that scientists prove that something which was believed to be "right" was in fact, "wrong". When Copernicus states that the Earth goes around the sun, it is a revolutionary new perspective, with observable consequences. On the other hand, in terms of the *predicted positions of the planets*, even with Kepler's ellipses its predictions differ only by small amounts from that of the Ptolmaic (Earth-centered) model. Similarly, Einstein's theory of relativity replaces Newton's laws of motion. Quantum field theory is believed to incorporate, but be more fundamental than, the classical relativity theory Einstein propounded. Was Newton wrong? Was Einstein wrong? For essentially every experiment one can imagine with macroscopic objects (tennis balls, automobiles, planets), Newtonian theory provides answers which are so close to being correct that the difference with Einstein's laws of motion doesn't matter to us (not always: the very small corrections turn out to be important for allowing GPS satellites to function with the accuracy they do), and the corrections due to quantum physics are negligible too. Ask *different questions*, for example about what happens when things move at speeds close to the speed of light, the motion of atoms, etc. and the differences can become all-important. Thus revolutions in physics happen often at moments when a theory has "worked" – explained all observations – up to a point where very small discrepancies are discovered when experiments were done with new tools, in new situations, on new materials. Scientists have to be open to seeing these discrepancies and theories are *always* subject to refinement and, replacement if need be.

Finally, it's important to remember that science does not proceed linearly from point A to point B between "revolutions". There are many mistakes, many sidesteps, even many steps backwards. Scientists are humans whose studies are influenced by preconceptions, and sometimes really crazy ideas come to the fore; the only thing that saves the scientific enterprise is the insistence that every such theory be subject to the requirement that it explain all known observations. To illustrate how far backwards some of these steps can take us (in a way relevant to students in Florida) take the case of Cyrus Teed (physician and electrical researcher, 1839–1908), who believed that the earth was the *inner* surface of a hollow sphere, and the heavens were located inside it. Humans were held on the surface by centrifugal force, and all light and heat in the universe was generated by a giant electromagnetic battery. Teed founded a society called the Koreshians near Naples, Florida and funded a Geodetic Society with the stated purpose of proving via measurement that the Earth's surface curved upward at the horizon. You can still visit the Koreshan State Historic Site in Lee County.

**Ancient Greek Science:**

Overview: Facts that ancient Greeks knew and how it led to their worldview

a) The heavens turn round us once every 24 hours

b) We obviously live on the unmovable center of the cosmos

c) The earth is round, evident from shadow of earth in eclipse

d) The motion of the heavens is uniform

  1. Heavens move at uniform velocity

  2. Heavens move in perfect circles

e) The heavens, unlike earth, are unchanging.

  1. Heavens commence at the orb of the moon

  2. Above the moon there is only rational repetitive change of place (no generation or corruption

Current view: universe is probably infinite (powers of 10 video!), distances are so great that visible stars, while moving, appear fixed to us. Closer objects, like planets or comets, can be seen to move against the background of the "fixed" stars. The motion of celestial bodies is generally not uniform: e.g. planetary orbits are roughly ellipses perturbed by the gravitational influences of other celestial bodies.

Re: b) there were ancient Greeks who argued that the Earth rotated (Aristarchus of Samos, 3rd century BC). But the counterargument was telling, and it would reverberate for the next 200 years: When you're sitting on something spinning (e.g. carousel), you feel it. Were we living on a spinning Earth, there would be observable effects.

> (Background) To see quantitatively how small the effect of the earth's rotation is on your weight, compare the gravitational acceleration $g=9.8\text{m/s}^2$ with the centripetal acceleration due to rotation, $a=\omega^2R$, where $\omega$ is the angular speed of the Earth's rotation, or $2\pi/T$, where T is the period of 24 hours. Calculate $\omega$ turns out to be $7.3 \times 10^{-5}\text{s}^{-1}$. The Earth's radius R is $6.4 \times 10^6$ meters, so the centripetal acceleration is $3 \times 10^{-2}\ \text{m/s}^2$, or 0.3% of g. You weigh 0.3% less than if the Earth were not rotating! All effects of your motion at the Earth's surface are of this order or smaller, nearly impossible to detect. Don't worry if you don't know where the equations come from!

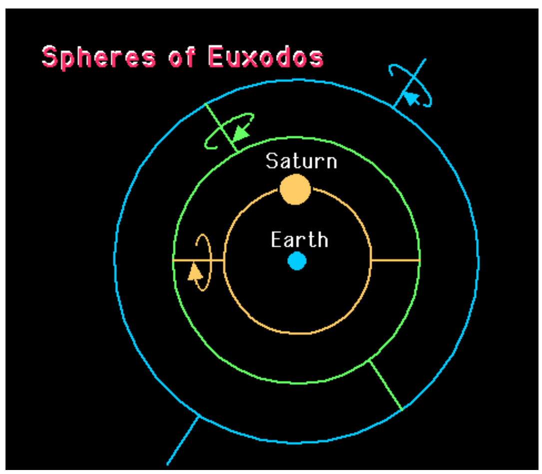
Demo: Centrifugal force bottles.

**Plato's challenge: how to save the phenomena**

Plato (424/423 – 348/347 B.C.) was largely responsible for institutionalizing the notion that the universe (celestial) was perfect.   For him the Earth and universe had been designed by a divine, perfect mind, and because of this it was explainable.    He recognized that there were some apparent exceptions to this celestial ``perfection", and posed a question to his students how to understand it.   There were 7 objects in the sky that were observed to move with respect to the fixed stars, and 5 of them (Mercury, Venus, Mars, Jupiter and Saturn) apparently did not move in uniform circular motion.   In fact, they experienced "retrograde motion", i.e. occasionally went backwards against the motion of the starry vault.

Simulations of retrograde planetary motion to help you visualize it:
http://astro.unl.edu/classaction/animations/renaissance/retrograde.html
http://astro.unl.edu/classaction/animations/coordsmotion/zodiac.html
http://astro.unl.edu/naap/ssm/animations/configurationsSimulator.html

They were called the  planets, which means "wanderers" in Greek.   Plato challenged his students to find a scheme by which this wandering could be reproduced with a geometrical model that used only *combinations* of circular motions at constant speed.  His student Eudoxus created a model that held the field for many years, namely assigning to each planet (and the sun & moon) so-called "crystalline spheres" that held the planets and rotated on a set of celestial gimbals, as it were.   Here's an example for 1 planet:




Each sphere is designed to rotate around its gimbals, producing the complicated motion of the planet as observed from Earth. It's interesting, and very important to note that no one worried about how one sphere was connected to the others, nor how they were constructed, nor what they were made out of (ok, it was crystal, but this just meant very pure and perfect material), nor what made them turn.

**August 30, 2016**

**Reminders for students:**  purchase text, lab book, clicker, calculator if not done already.
1st reading assignment (show in syllabus)
(There will be questions on HW and clicker relating to it on Thurs.)

**Aristotle**

We pay attention to A. because he was the towering intellectual figure of his age, whose dominated the physical sciences for 2000 years. Modern physics has rejected most of his notions about the nature and motion of objects, but he gave us part of what we now call the scientific method. It's important to try to understand why he was so influential.

**Life**

- born in 384 B.C. in near Macedonia studied at Plato's Academy
- tutor to King Philip of Macedonia's thirteen year old son Alexander (i.e. the great)
- Athens 335 B.C founds the Lyceum, own school
- studied at Plato's Academy, and stayed there twenty years until Plato's death in 348
- tutor to King Philip of Macedonia's thirteen year old son Alexander (i.e. the great)
- Athens 335 B.C founds the Lyceum, own school (French high schools are named lycee after Aristotle's establishment.)
- wrote extensively on all subjects: politics, metaphysics, ethics, poetry and drama, logic and science.

**Aristotle's Science**

Reminder: Kuhn quote: not bad science, good philosophy!

"first philosophy" - metaphysics and mathematics, the things Plato had worked on
"second philosophy": the world around us, from physics and mechanics to biology.

Lyceum was school of organized scientific inquiry on a scale far exceeding anything that had gone before. After Aristotle, there was no comparable professional science enterprise for over 2,000 years, and his work was of such quality that it was accepted by all, and had long been a part of the official orthodoxy of the Christian Church 2,000 years later.

A's Method propounded to his students included:
1. defining the subject matter
2. considering the difficulties involved by reviewing the generally accepted views on the subject, and suggestions of earlier writers
3. presenting his own arguments and solutions.

This is roughly the pattern modern research papers follow.

The arguments he used were of two types: dialectical, that is, based on logical deduction; and empirical, based on practical considerations.

**Aside: modern scientific empiricism would say that all theories of nature have to be confronted with observations of the natural world, and discarded if they do not agree. This notion does not appear to have been part of A's philosophy.**

**"Causes"**

In contrast to Plato, who felt the only worthwhile science to be the contemplation of abstract forms, Aristotle practiced detailed observation and dissection of plants and animals, to try to understand how each fitted into the grand scheme of nature, and the importance of the different organs of animals. Quote:

*For even in those kinds [of animals] that are not attractive to the senses, yet to the intellect the craftsmanship of nature provides extraordinary pleasures for those who can recognize the causes in things and who are naturally inclined to philosophy.*

His study of nature was a search for "causes." What, exactly are these "causes"? He gave some examples :

Any object (animal, plant, inanimate, whatever) has four attributes:

- matter
- form
- moving cause
- final cause

(e.g. table, the matter is wood, the form is the shape, the moving cause is the carpenter and the final cause is the reason the table was made in the first place, for a family to eat at, for example)

For man, he thought the matter was provided by the mother, the form was a rational two-legged animal, the moving cause was the father and the final cause was to become a fully grown human being.

For A, nature was not conscious, did not invoke a god/s; he believed this final cause to be somehow innate in a human being, and similarly in other organisms. This approach to studying nature fits very well with Christianity. The idea that every organism is beautifully crafted for a particular function - its "final cause" - in the grand scheme of nature certainly leads naturally to the thought that all this has been designed by somebody (who was not actively involved any more).

**Biology**
Aristotle's really great contribution to natural science was in biology. Living creatures and their parts provide far richer evidence of form, and of "final cause" in the sense of design for a particular purpose, than do inanimate objects. He wrote in detail about five hundred different animals in his works, including a hundred and twenty kinds of fish and sixty kinds of insect. He was the first to use dissection extensively.

**Elements**
All substances to be compounds of four elements: earth, water, air and fire, and each of these to be a combination of two of four opposites, hot and cold, and wet and dry. (Actually, the words he used for wet and dry also have the connotation of softness and hardness).

consistent with the way things present themselves to the senses, the way things really seem to be, as opposed to abstract geometric considerations (Plato)

Hot and cold, wet and dry are qualities immediately apparent to anyone, explains perhaps why idea had such staying power compared to "atomistic" theories.

He discussed the properties of real substances in terms of their "elemental" composition at great length, how they reacted to fire or water, how, for example, water evaporates on heating because it goes from cold and wet to hot and wet, becoming air.

**Aristotle's science continued**

**Physical science: motion, and causes of motion**
For A all motion all had a purpose. Took clue from biology: an animal moves to somewhere it would rather be, for some reason, so motion caused by the animal's will.

Motion was therefore **fulfilling the "nature" of the animal**, just as its natural growth fulfilled the"final cause" of the animal.   Remember not so many moving inanimate objects (falling rocks?) around, no cars, planes, etc.  so using behavior of living things to describe inanimate objects seemed like a good start.

Inanimate objects, such as a stone dropped from the hand: to be understood postulating that elements  to seek their natural place in the order of things, so earth moves downwards most strongly, water flows downwards too, but not so strongly, since a stone will fall through water. In contrast, air moves up (bubbles in water) and fire goes upwards most strongly of all, since it shoots upward through air.  Mixed materials: wood has both earth and air in it, since it does not sink in water.

**Natural Motion and Violent Motion: all motion has "mover"**

Of course, things also sometimes move because they are pushed. A stone's natural tendency, if left alone and unsupported, is to fall, but we can lift it, or even throw it through the air.  A. called such forced motion "violent" motion as opposed to natural motion, since some external force is applied to the body to cause the motion.  Crucial point: acc. to Aristotle, ***any*** **motion happening at any time requires a "mover".**  In case of falling rock, it is the rock's nature.  In the case of a thrown rock, it is the push (& effect of air, see below).  This influenced A's view of the Earth.  It must be at rest, because what mover could possibly move it?

Aside: from modern perspective, gravity would be perceived as outside force.  But until Newton,  the falling of a stone was thought of as natural motion that did not require any outside help.)

**Laws of Motion**

Aristotle was first one to really think quantitatively about the speeds involved in these movements. He made two *quantitative* assertions about how things fall (natural motion):

1. Heavier things fall faster, the speed being proportional to the weight (v ~  W)
2. The speed of fall of a given object depends inversely on the density of the medium it is falling through, so, for example, the same body will fall twice as fast through a medium of half the density (v ~  1/rho)

Obviously plausible and agree with some things we know about (falling stone, feather). Surprising, however, his observations in biology, he didn't check out these rules in any serious way. You say, he didn't have a vacuum system to remove air resistance, but he could easily have dropped a brick and half a brick, & would have seen a clear problem with his rule. Probably it was not something he felt was particularly important.

(From rule #2, by the way, A. concluded that a vacuum cannot exist, because if it did, all objects would fall through it at infinite speed, which is clearly nonsense. )

For violent motion, Aristotle stated that the speed of the moving object was in direct proportion to the applied force (v ~ F). This means first that if you stop pushing, the object stops moving (works for ox dragging a plow through a field).

> Modern view: object comes to a stop because the force of friction slows it down after the applied force is removed (see Galileo!)

**Projectile motion**

To explain projectile motion (i.e. arrows and cannonballs) Aristotle proposed a sort of reverse-air-resistance, where the air that the arrow is moving through passes over it and then closes in on the back of the arrow, pushing it forward, until it will eventually just stop. Once this reverse-air-resistance stops, the object will just drop straight to the ground.

## September 1

**Reminders for students:** purchase text, lab book, clicker, calculator if not done already.
1st reading assignment (show in syllabus)
(There will be questions on HW and clicker relating to it next wk.)

**Last time: Aristotle**

- founded Lyceum most famous ancient school

- foundations of Greek philosophy, science influenced educated thought for 2000 years
- approach to physical science distinctly *not* modern although he used some practical arguments, mostly dialectical in nature
- objects had natural place, sought to return there
- elements: earth, air fire and water
- objects fell with speed $\propto$ mass, inversely $\propto$ to resistance
- natural vs. violent motion. Stone's natural motion is to fall, to return to earth, its origin; can be endowed with violent motion by throwing it.
- planets natural motion (celestial realm) was to go in circles ($5^{th}$ elements: quintessence or "ether"

(modern) definition of ecliptic plane: plane in which planets, including Earth, move around the sun.

**Planetary Dynamics**

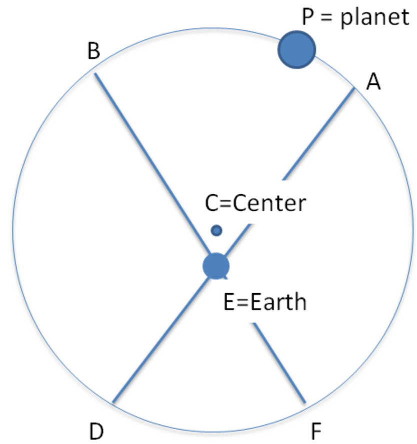
What is natural place of planets, which are going in circles (sort of)? Aristotle therefore postulated that the heavenly bodies were not made up of the four elements earth, water, air and fire, but of a fifth, different, element called quintessence, whose natural motion was circular. Slightly problematic: between here and the moon something has to change – no obvious boundary?

**Post-aristotelian ideas about planetary motion**

**Eccentric point**

- Apollonius of Perga (~20 -190 BCE) suggested moving the Earth away from the exact center of the circle of the planetary orbit, but preserving the circular character and the uniform motion. This model accounts for

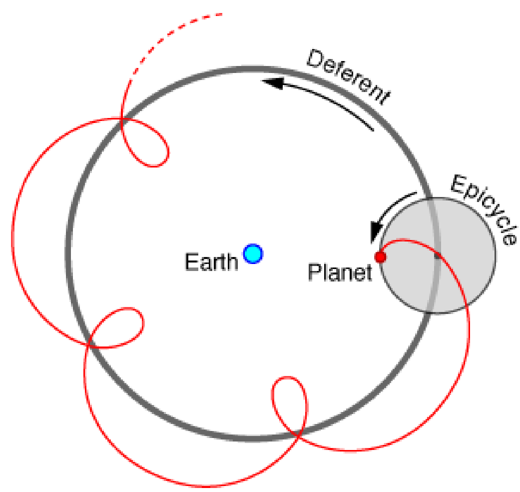
    1) variation in brightness of planets
    2) changes in angular speed



*The eccentric circle*

**Epicycles**

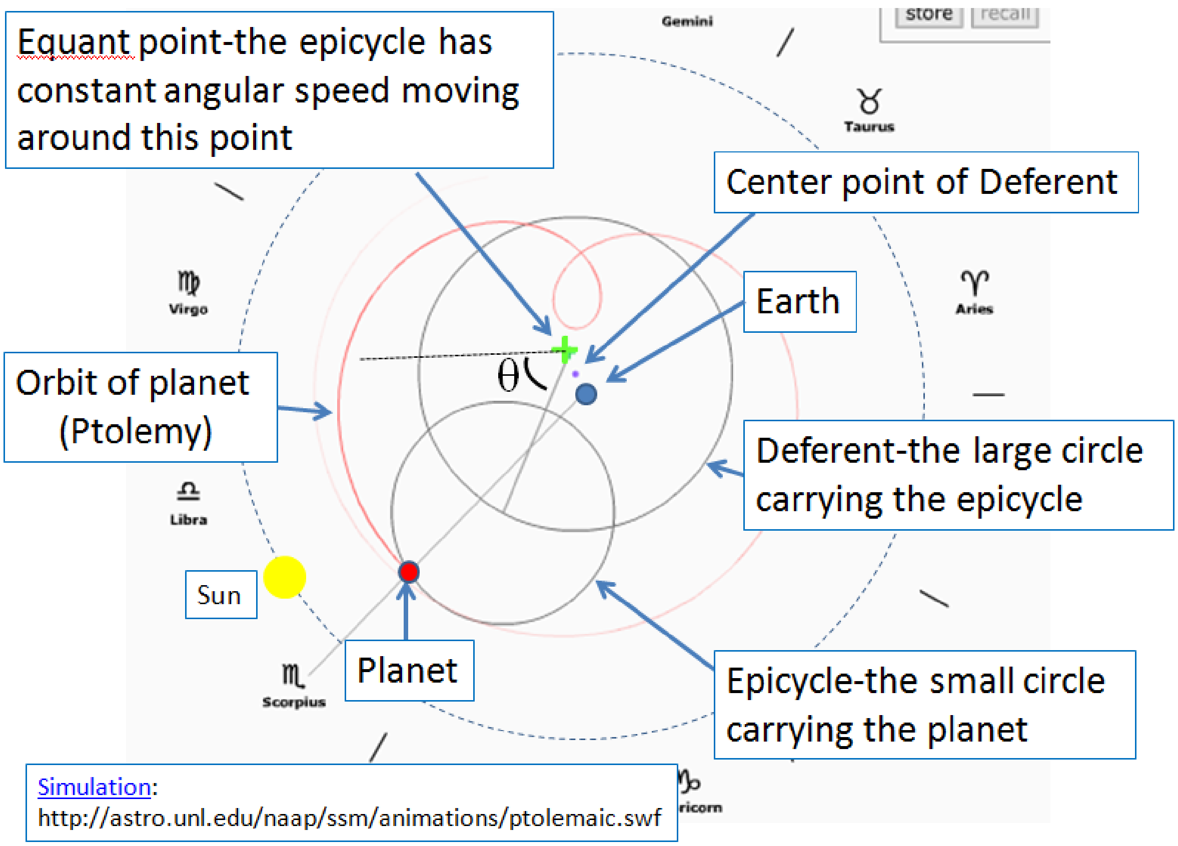
Although this concept is frequently associated with the Greek/Egyptian astronomer Ptolemy, it was discussed by others first and summarized in Ptolemy's famous Almagest. The idea




was to keep uniform circular motion but combine a circle rotating on another circle, both at different constant speeds. This idea was able to explain the retrograde motion of the planets, and was simpler than the homocentric spheres of Eudoxus.

**Claudius Ptolemy** (AD 100 – c. 170):
Greek/Egyptian mathematician and astronomer of Alexandria (currently Egypt). Author of *Almagest*, summarizing astronomical developments since Aristotle. It is through Ptolemy that we know about epicycles and eccentric orbit ideas proposed by earlier astronomers. *Almagest* considers critically questions about Geo- vs. Heliocentrism, reviewing arguments on both sides, but coming down in favor of the Earth not moving.

Acc. to Ptolemy, it is not exactly in the center, however.  Ptolemy wanted to preserve some vestige of rational celestial motion, but all the ideas of Aristotle and those who came later were still not able to account for the accumulating astronomical data on the 5 known planets, moon and Sun.  He proposed a variation which proved helpful to improve the agreement, a new point called the Equant point, as far from the center of a planet's orbit as the Earth was in Appolonius' eccentric model, and along a line containing all three points




In Ptolemy's model, the center of the planet's epicycle maintains a constant angular speed with respect to the Equant point (the angle changing is called θ in the picture), not with respect to the center point or the Earth.  This means that when the planet is closer to the Earth, it has a longer distance to go in the same amount of time (angle swept out), so it is actually going faster (this is in fact the case, and is accounted for in the modern picture by the gravitational force being larger when the planet is closer).

Note that Ptolemy's model was designed only to give the angular positions of the planets as seen in the sky relative to the zodiac.  Because of uncertainty about the location of a planet's epicycle, the order of the planets (relative distance from Earth)  could not be confidently determined.

Ptolemy's model was flexible enough to explain the data up until that time, and for another 1000 years.  In the 16th century Copernicus would be driven to create his heliocentric universe in part because of accumulating errors beyond Ptolemy's model's ability to describe, but also because the asymmetry of the Equant point bothered him so much. What was created by the crisis of confronting simple Platonic/Aristotelian ideas of uniform circular motion with observational data was an increasing tension, as the framework of ideas was stretched further and further, with deviations of observation and theory requiring more and more elaborate ornamentation, until someone finally raised the question of whether "rational" behavior (assumption of circular, uniform motion) was in fact, correct. Only then could the fundamental hypothesis of geocentrism become the focus of attention again. This is in fact one of Kuhn's paradigm shifts.

## September 6

**Last time: Appolius of Perga, Ptolemy, post-Aristotelian ideas about the solar system**

- Appolonius of Perga (~20 -190 BCE) : proposed: 1) eccentric orbits (planet goes in circular orbit at const. speed, but E moved off center; 2) epicycles (planet moves on its own circle [epicycle] around a point that travels in circle [deferent] around E. Model explained
    - variation in brightness of planets
    - changes in angular speed
- Ptolemy (AD 100 – c. 170): his *Almagest* summarized ideas about solar system. He himself proposed "equant point": eccentric point about which planet moved with *constant angular speed.* Not true uniform circular motion, so "irrational" from pt. of view of ancient thinkers. Nevertheless it explained the data better, in particular associated an increase in angular speed with proximity of planet to Earth.

  (Note that Ptolemy's model was designed only to give the angular positions of the planets as seen in the sky relative to the zodiac. Relative order of orbits could not be determined)

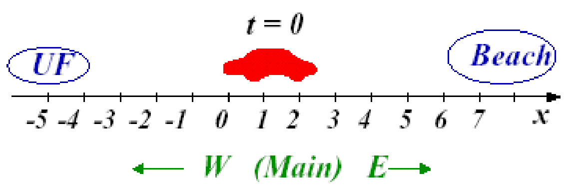
## Post-Aristotelean physics of motion

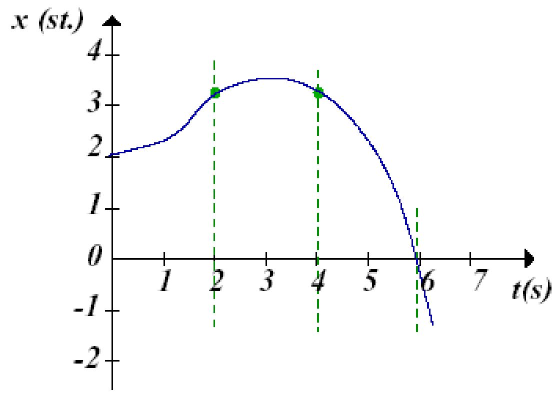
The early middle ages in Europe was a period where Aristotle's philosophy was rediscovered, in many cases through the medium of Arab scholars who had preserved the ancient Greek texts during the period of intellectual decline in Europe after the fall of the Roman empire. But it was also a period where Aristotle's ideas were criticized, generalized, and modified. The first type of criticism came from the church, who found in A. discrepancy with established doctrine. Examples: for A. Earth was eternal, church insists on creation at one moment by God. A. says no vacuum possible; church says God could do it if he tried!

We will focus on natural philosophical critiques of Aristotle instead.  1st, a review of modern physics.

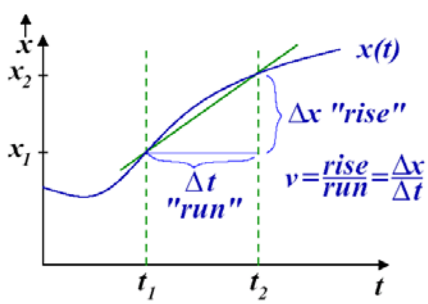
First: intro to ideas of position, velocity and acceleration

Definitions: x(t) = position of object at time t.  Example: position of car along University Ave.




Average velocity v = Δx/Δt == change of position/change in time
Instantaneous velocity v(t) == slope of tangent line to x vs. t curve




Average acceleration a = Δv/Δt == change of velocity/change in time
Instantaneous acceleration a == slope of tangent line to v vs. t curve

See slides from class kinematics_Sept8.pptx
at http://www.phys.ufl.edu/~pjh/teaching/phy1033/1033notes.html

**Reminder of Aristotle's tenets:**

· **Up or down?** Recall according to Aristotle, some things rose (away from Earth center; their natural place was inner surface of lunar sphere) because they consisted of light elements (fire,air) –; and some fell (towards center of E) because they consisted of heavy ones (earth,water) .

· **Motion after violent action.** Aristotle attributed motive force after arrow left bowstring to air (note for A and other ancients motive force had to be in const. physical contact with the body: if arrow was moving, something must be in contact with it pushing – hence air).

· **How fast?** $v \propto F/R$ For falling body F is weight, so object with twice as much weight falls twice as fast through some medium, and if medium is more resistive, bodies fall proportionally slower.

· **Acceleration.** Aristotle knew things fell faster each second when they fell, but didn't see to feel the need to explain this. He makes clear in some of his writings that the proportionality of velocity to weight describes some kind of average, or relative speed.

**Projectile motion.** To explain projectile motion (i.e. arrows and cannonballs) Aristotle proposed a sort of reverse-air-resistance, where the air that the arrow is moving through passes over it and then closes in on the back of the arrow, pushing it forward, until it will eventually just stop. Once this reverse-air-resistance stops, the object will just drop straight to the ground.

**Arisotle's critics**

· **John Philoponus** $6^{th}$ cent. A.D. Greek. Rejected air as external push for arrow: suggested a force "impressed" into the arrow by the bowstring

· **Averroes (Ibn Rushd), Avempace (Ibn Bajja)** $12^{th}$ century Spanish moors criticize A's laws of motion applied to planets: A's law that 2 similar bodies can move with different velocities because they move through different media. But planets move with different velocities, through same medium with no resistance (aether) acc. to A. Conclude: **resistive medium not necessary for motion, but sole function was to retard it!**

**Avicenna (Ibn Sina) –** $11^{th}$ century Persian physician, philosopher,…:

A body capable of receiving *impressed force* ("*mail*") in proportion to its weight.

· **Possibility of vacuum**, or finite motion without resistive medium begins to occupy philosophers. Suppose a vacuum exists:

- o Would real body rise or fall in vacuum with natural motion?
- o If hurled violently, could it move with continuous motion?

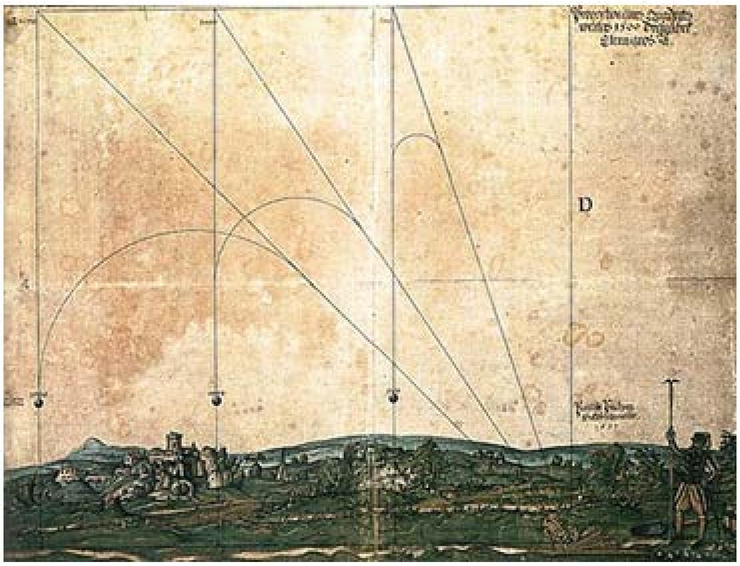
· **Natural motion of mixed bodies**. Aristotle had said that if you had mixed body, like wood (earth and air), dominant element would determine if it rose or fell. Medieval critics start to question: maybe mixture (ratio) is important for how fast it rises or falls. Falling body: heaviness conceived as motive force, lightness as "internal resistance"; rising body – opposite.

**But now you can solve problem of a vacuum:** in the absence of a resistive medium, a real body has an internal resistive force that keeps its velocity finite. Fine, except this implies that if you have a pure body, there is no resistance, so still infinite speed. Still paradoxical, oh well.

However**, implication**: two bodies of same substance but different size & weight might fall in a vacuum at same rate, proposed by Thomas Bradwardine – 14$^{th}$ cent. English cleric. Wow! Each piece of the homogeneous body has the same ratio of heavy to light therefore falls at the same rate; if you have more of those pieces, it doesn't matter! Clearly contradicts Aristotle's notion of natural fall.

**Violent motion revisited.** Nobody was very happy with Aristotle's theory of the air pushing the arrow. Philopponus pointed out that had it been correct, you should be able to shoot an arrow by agitating the air behind it. Instead, he thought of an "impressed force", imparted to the arrow by the bowstring at the beginning of flight. Air acts only as resistance. Avicenna (Ibn Sina), great Persian physician and polymath of came up with similar idea, calling his impressed force *mail.* Acc. to him, body was capable of receiving impressed mail in proportion to its weight. Stated that the mail would persist in a body forever, object would continue to move, in the absence of external resistance (void). Starts to sound just a bit like Galileo or Newton, no?

· **Jean Buridan (Paris, 1300s).** Jean Buridan (1300s) had similar idea to Avicenna, called his impressed force impetus, and said clearly that impetus only diminishes if there is a resistance (modern counterpart of Newton's 2$^{nd}$ law if *impetus* is interpreted as *momentum*. If you could remove the resistance (i.e. in vacuum), you would get infinite rectilinear motion. He is thus credited with the idea of *inertia*. By the way, this is the same Buridan who conceived the philosophical paradox of an ass placed equally far between two equal bales of hay, saying he would starve since there was no way to make the decision.




Projectile motion acc. to Buridan (curved trajectories) and Aristotle (straight ones)

## September 8

### Last time

- Review of position, velocity from modern perspective (see slides on web)
- Development of medieval scientific thought: attempt to reconcile a rediscovered Aristotle with church teachings.
- Medieval critiques of Aristotle's theories of motion: idea of "impressed force" to keep an arrow moving after it has left the bow. Jean Buridan—moving object has "impetus".
- Possibility of "infinitite rectilinear motion" if one can remove resistance understood

in 1300s.

**Acceleration.** Modern viewpoint: acceleration is rate of change of velocity. Define average acceleration the same way we defined average velocity, over a particular time interval $\Delta t=t_f-t_i$: average acceleration $a = \Delta v/\Delta t$ . Examples: putting foot on gas pedal, you accelerate your car forward: a=+. Can also apply brakes: this is also acceleration, but with – sign. The period when velocity is changing is *not uniform*.

Late medieval notions of acceleration of falling bodies. Buridan explains acceleration by saying that the heaviness of body not only initiates downward fall, but also produces successive and cumultative increments of impetus:

- At end of time $\Delta t$, W produces an original velocity v. Simultaneously it makes a quantity of impetus I.
- During 2nd interval $\Delta t$, both original W and I operate, so v is proportional to W+I, making speed of fall $v+\Delta v$
- During 2nd interval, more I was generated, so motive force is now W+2I, so during 3rd interval v is $v+2\Delta v$.

Not so different from our idea of acceleration v=at, but note that we used $v \propto W$ in each time interval!

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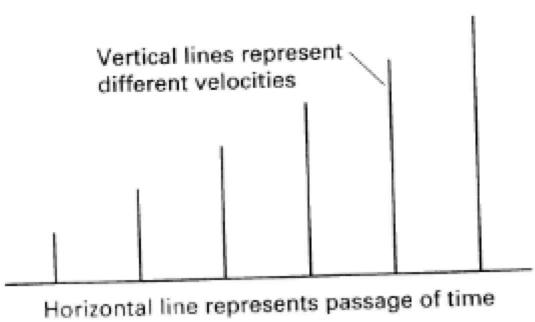
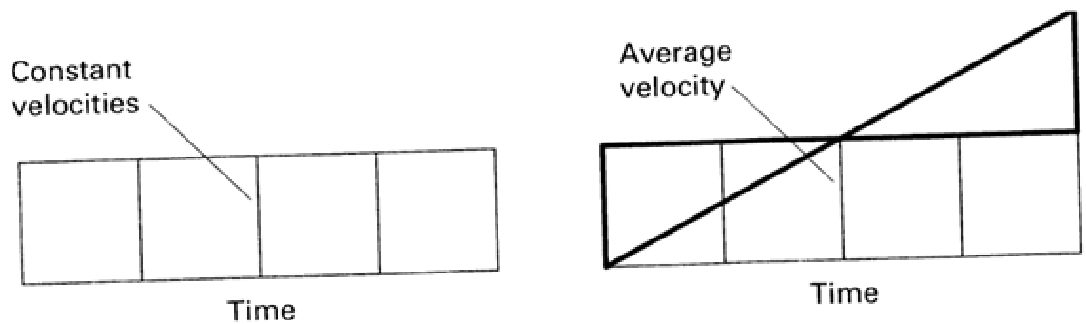
**Mertonian scholars (Oxford 1300s).** Mathematical representation of new parameters of motion. They conceived of velocities as vertical lines and plotted them vs. time:




Use of Horizontal and Vertical Lines to Show Acceleration

Then (Nichole Oresme) proved the "average velocity theorem" by comparing the distance gone in a trip at constant velocity (left), with one gone at contant acceleration (right). He showed geometrically that the average velocity (if you start from zero) is the same in both cases, by defining the distance travelled as the area of the construction. This is obvious on the left, requires a bit of a leap on the right, but of course, it is correct!




**European knowledge of the globe**

The world according to Ptolemy's *Geography* : Used lower figure (Posidonius) for earth's circumference. Note not centered on Jerusalem – something of a shock when discovered by medieval cartographers. Referred to "Terra Australis" unknown land in south that was felt necessary to "balance" land mass in N.

Knowledge of the East

- Traders reports
- Marco Polo (Venetian 1254-1324) journey to China ~ 1270 AD. Stayed 25 years, met Kublai Khan, wrote account of his travels and stay that captivated Europe. Inspires Columbus.

**Exploration quickens in 1400s –why?**

- New navigational techniques quickened pace of exploration
  - Ancient techniques – landmarks on coasts (e.g. lighthouse at Alexandria)
  - Open ocean – find latitude by measuring angle of Polaris from horizon
    - "running along the parallel"
  - New tools for higher accuracy --finding latitude at noon with *cross staff*
    - (requires tables with latitude – angle correspondence at different times of year)
  - Magnetic compass: sail along a bearing. Use object on knotted rope cast over side to determine speed → hence "knots" as measure of nautical speed.
- New royal funding to challenge monopoly of trade with East

Gold – Africa
Converts & crusades
Spice trade – to liven up bland European diet. Land caravan route to India through Ottoman empire, who extracted high taxes, journey difficult.

**September 13**

**Exploration of Africa –** much funded by Prince Henry of Portugal (1394-1460)
Motivation: search for Prester John. (Prester John = mysterious figure under Nestorian Christians, thought to rule over an empire, 1st in India then in Ethiopia. Jesus statement in Gospel acc. to John: "If he were not to die before I come again, what is that to you?" taken by some to mean that John was still alive. One of purposes of expeditions was to find him)
Batholomeu Dias, 1487`
Overland expeditions: Northeast coast of Africa reached from India
Treaty of Tordesillas 1494 (in wake of Columbus) N-S line 360 leagues W of Cape Verde Islands to E $\rightarrow$ Portugal; to W $\rightarrow$ Spain. Note at the time almost nothing W of line!
Vasco da Gamma, 1497
Columbus, 1492 et seq consults Ptolemy, assumed China went much further to E than most people thought. Imagined he had in fact reached China and Spice Islands by going W. Went to Portugal, no go, went to Spain. Navigated by dead reckoning.

Columbus as "greatest politician of all time" (joke):

- When he left, he didn't know where he was going
- When he arrived, he didn't know where he was
- He messed up the lives of everyone he encountered
- Did it all on someone else's money

Underreported distances he had calculated by dead reckoning to crew.

Amerigo Vespucci believes was a "new world", makes several visits. Makes new map, map of Waldseemüller, 1507
Magellan's voyage, 1519-1522 – 1st circumnavigation
The elusive pass
Death in the Philippines, 1521
The world after Magellan. Scientific advantage of explorations:

**Extraterrestrial life**
(See Power Point slides under Notes on Course Homepage)
Lucretius (99-55 BCE) Nature results from random collision of atoms. Highly

Unlikely that our earth the only one to have creatures.
Aquinas (1225-1274) Aristotelian idea of natural place says we are center
And life doesn't exist elsewhere. Still, God could have made life elsewhere
Misunderstood by Church to have said God could not make other worlds.
Idea that God could not make other worlds condemned in 1277. This
Put Church on record to say that other worlds were possible, reversing
The position of Christian theologians up to that time.
Nicholas of Cusa Supposes that God, who is center and circumference of
has peopled it everywhere beings, possibly nobler than us.
Question of redemption sharpened the issue: was Christ's sacrifice sufficient
for peoples elsewhere. Asked by Wm Vorilong (1463d)
In ensuing history the issue is debated, with some opposed to life elsewhere
(e.g., Melanchthon, Kepler) and many open to it (e.g. Descartes, Newton).

**Ancient references to possible motion of the earth**

Heraclides (390-310 BCE) rotation of the earth
Aristarchus (310-230 BCE) earth revolves around a "central fire"
Archimedes (287-212 BCE) Aristarchus said earth revolves around the Sun
Aristarchus calculates relative distance of Sun to be 19x that of moon –
his answer 20x too small due to inaccurate measure of angle.
Ptolemy ($2^{nd}$ cen CE) rejected arguments in favor of the earth's motion

**Medieval references to earth's motion**

Jean Buridan (1300-~1358) Can't decide if earth is still or rotates astronomically
Can decide the question physically (arrow argument)
Nicole Oresme (~1320-1382) Rejected Burdian's reasoning.
Atmosphere could be carried with moving earth. But earth doesn't
Move because the Psalmist has God decree "the earth shall not be moved"
Nicholas of Cusa (1401-1464) Concludes earth's motion for theological reasons
God is "Absolute Maximum," creation is "contracted maximum"
Creation "unfolds from God," so all nature is "enfolded" in Abs Max
Humans know by measuring, but can only measure finite things
Hence humans cannot know God, who is utterly unknowable
Still we try to understand the implications of this, which is "learned ignor"
As circumference of a circle increases it approaches a line in *imagination*
This is an example of "coincidence of opposites", gives us a glimpse of God
As coincidence of opposites, God is the center and the circum of the universe
Earth therefore not fixed in place, but moves, nothing natural is utterly at rest
If we went to another planet, it would seem to be center

## September 15

### Who was Copernicus?

What we tell students in high school/even college physics: he "discovered" that the earth went around the sun.   Here's the real story

### The state of astronomy on the eve of Copernicus (1473-1543)

### Why Ptolemaic astronomical systems were in crisis

- Ancient observations of the planets woefully out of date

  - Fit between theory and observation way off:

Make your theory with N epicycles and velocities, then you have a *prediction* for where planet will be found forever after. If there is a small error, and you run the system for a few hundred year, the actual positions of the planets are way off.
Astronomical clock of Prague 1410 http://en.wikipedia.org/wiki/Prague_astronomical_clock

  - All attempts to adjust Ptolemy's system failed to improve fit sufficiently to account for actual observations.

- External pressures

  - From the church (need for calendar reform)

Julius Caesar: year is 365 ¼ days long; every year add extra day. True solar year is 11 minute longer than this; each year you miss 11 minutes; over hundreds of years, summer solstice and all other solar-calendar tied events were occurring at the wrong time! In Copernicus' time 10 extra days had accumulated: vernal equinox occurred on March 11! Easter is *defined* to occur 1st full moon after vernal equinox; church was worried it would miss by a month eventually!

  - From the maritime sector (star charts not accurate)

Longitude problem: navigator needs to the time at a fixed reference point (e.g. Greenwich), then can measure the apparent local time (e.g. noon when sun is highest in the sky); this gives the the ship's longitudinal position relative to the fixed location. Say the difference was 4 hours; this corresponds to 1/6 of an Earth's rotation and so 60 degrees of longitude or 1/6 of the Earth's circumference, about 4000 miles. Clearly this has to be very accurate however if you want to avoid some rocks on a chart. Problem was how to determine the time at a distant reference point –" absolute time"-- while on a ship. If you knew exactly when Jupiter was supposed to be at a certain point in Libra, you could in principle determine your time. But the models were much too inaccurate.

· Theoretical problems

Equant – off center circle with effective nonuniform motion – violated notion of rationality

**Reminder: which questions were *not* being asked?**

Solar system visualize: http://janus.astro.umd.edu/SolarSystems/

· *Why* do the planets move the way they do?

(*Natural* circular motion of heavenly bodies still assumed; no real questions about *cause; except assumption that God moves the fixed stars, which drive everything else*)

· Is there any relationship between the motion of planets and the motion of bodies on earth?

(No: separation of earthly and celestial realms still assumed)

**Reminder: what assumptions are still being made?**

· All motions had to consist of uniform circular ones; epicycles for example.

· All still assuming that Earth must be in center

**Some remarks on the mathematics of circular motion**

· velocity direction changes although speed (magnitude of velocity) is constant

· change of direction is instantaneously towards center of circle

· so-called centripetal (center-seeking) acceleration has magnitude $a=v^2/r$

**Copernicus' great work**

*On the Revolutions of the Heavenly Orbs (1543) [De Revolutionibus Orbium Coelestium]*

· Early versions - the Commentariolous: circulated privately in 1514

· Osiander's Preface (Gregory previous lecture) Copernican heliocentric system a tool with which to calculate better; doesn't represent the truth.

· The dedication (to the Pope) Copernicus

o acknowledges that having sun at center violates common sense & will seem absurd to astronomers, and that he has waited a long time to present them to pope & world. Does not back away from belief that sun is in fact at the center.

- outlines his arguments that Ptolemaic system is inharmonious
- reviews ancients' arguments that earth stands still (e.g. ball thrown straight up doesn't fall to side) & refutes them (e.g. air moves with the earth [NOT CORRECT ACC TO MODERN PERSPECTIVE)

·

**Traditional aspects of the De Rev**

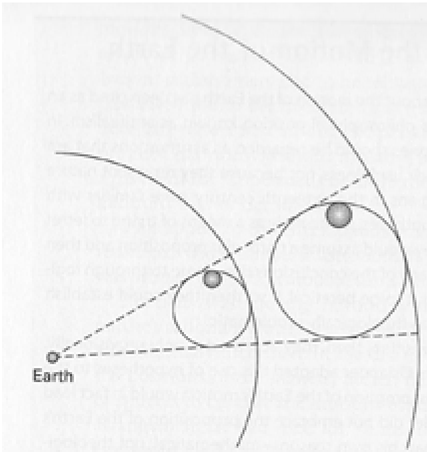
- Platonic assumptions regarding circles and uniform motion
- Use of Ptolemaic techniques (perfect circles and uniform motion)
- Aristotle's physics of motion?

· **Novel aspects of the De Rev**

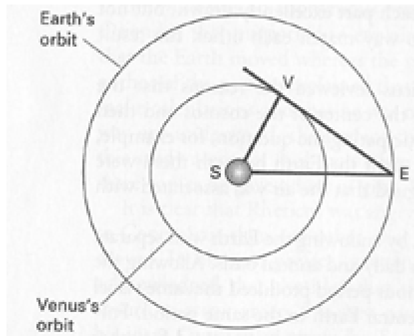
- Rotation on axis and what it achieved
- Revolution and what it achieved
- "Rotation of earth's axis" (to retain constant orientation in space)
- Tiny shortening of earth's annual revolution (to explain "precession of the equinoxes")

· **Advantages of Copernican system**

- No equant
- Slightly better fit (was not hugely better)
- Internal harmony (one geometry of heavens, not 7 individual account s of
- planets)
- Order of planets sure



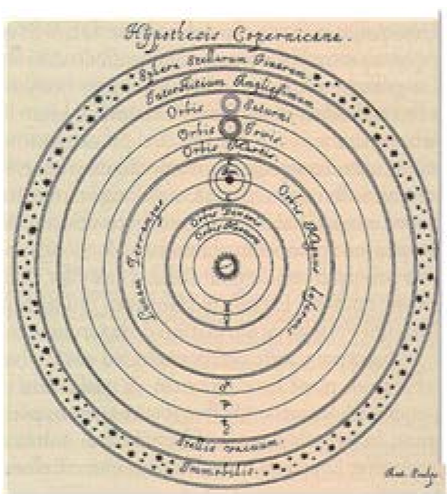
The Ptolemaic System



The Copernican System

· **Disadvantages of Copernican system**

o Not appreciably less complex (still plenty of epicycles, etc.)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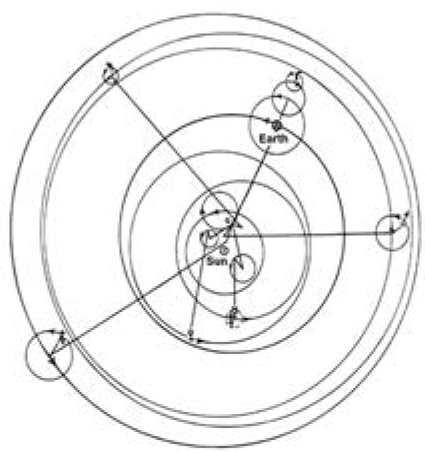


for calculations

o Sun the center of stars, not planets

o Physics of motion inconsistent with predicted experience (if earth in motion)

o Challenge to understanding of scripture (Joshua)

o Lack of parallax: why can't we see difference in angle to given star in summer and winter (parallax baseline = 2 x 93,000,000 miles!)? (Ans: because the stars are *really* far away. Such parallax measurements were possible 4 centuries later with telescopes.)

**September 20**

**Remarks on *de Revolutionibus* reading**

Most of what Copernicus says here in his summary we have encountered before: arguments why the Earth must be moving. But there are some new, interesting remarks as well:

- Comments on the fact that planets are at some times *brighter* than others. This is natural to explain if they are going at different velocities around the sun at different distances, but hard to explain if the Earth is at the center and each planet is a fixed distance away (of course there could be epicycles…)
- Worries about the integrity of the heavenly sphere of stars. Says if it were really moving around by "inconceivable power of revolution" a) stars would be driven outward, further and further away; and b) since it has to go around in 24 hours, outward force would be ever greater. Continued indefinitely, velocities would become infinite! Better explanation: stars are stationary, Earth rotates!
- Arguing against the argument that Earth can't rotate because we would notice – things would fly off, land in the wrong place, etc. : Maybe we wouldn't notice; after all, if you're on a ship you are moving, but for you everything is as if you were standing still and the sea were moving. This is a primitive expression of relativity, as formulated by Galileo 50 years after C's death.
- Note discussion of "double motion" of an object rising and falling after being thrown up at the Earth's surface. He discusses the *combination* of rectilinear (up & down in straight line) and circular motion. Galileo and Newton will both revisit this theme.

**Copernicus identified 4 types of motion needed to explain Earth's motion in his system**

- Rotation (spinning of Earth)
- Revolution (of Earth around sun)
- Rotation of axis so that Earth's axis always pointed in (nearly) same direction (he needed to add this because tendency to stay pointing in same direction did not seem natural)
- Precession of equinoxes

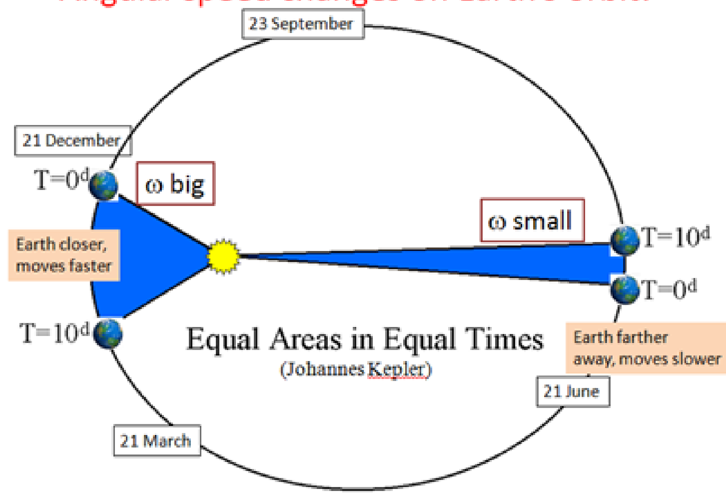
**More discussion of circular motion**

- Radians
- Defnition of angular velocity
- Relevance: different angular velocities of Earth on its orbit at different times of the

year

- Definition of angular acceleration
- Period and Frequency
- Some examples: earth’s angular velocity, linear velocity of a point at surface

Angular speed changes on Earth’s orbit!

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# Relationship between angular and linear quantities in circular motion

- Displacement

$$\Delta s = r\,\Delta\theta$$

- Speed

$$v_t = \omega r$$

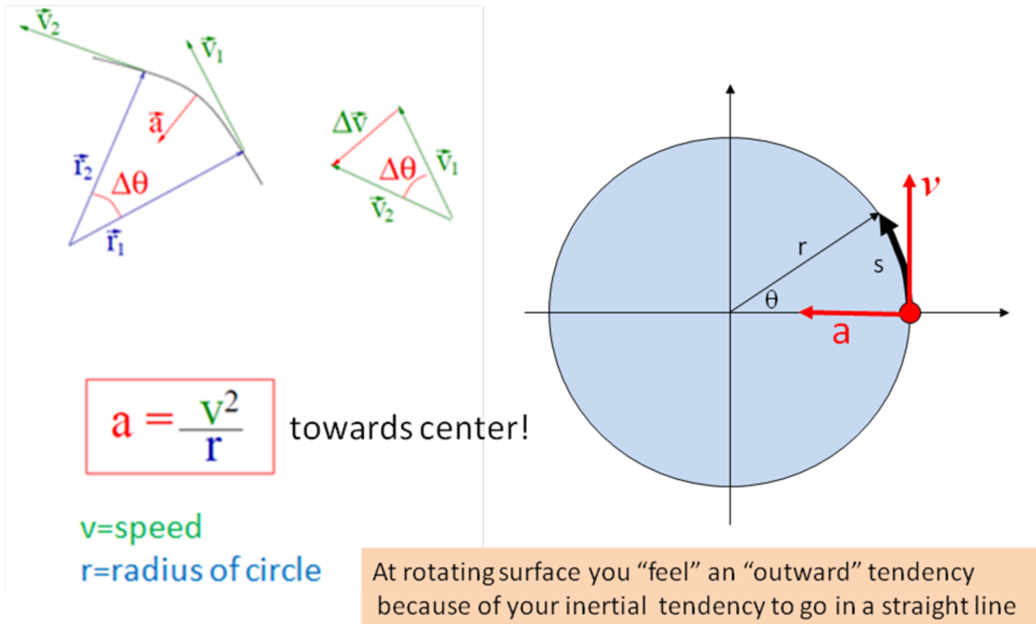
- Acceleration

$$a_t = \alpha r$$

- Every point on the rotating object has the same angular motion
- Not every point on the rotating object has the same linear motion

Subscript “t” means “tangential”

# Centripetal vs. centrifugal




**Angular velocity of someone at the Earth's surface:**

2π radians (full circle) is swept out in one rotation, or 1 day. So $\omega = 2\pi/(1\text{day})$

**Linear velocity of someone at the Earth's surface**

$$v = 2\pi R_E / T$$
$$\approx 24000 \text{ miles}/1 \text{ day}$$
$$= 24000 \text{ miles}/24 \text{ hours}$$
$$= 1000 \text{ mi/hr}$$

*(Note this calculation was for someone at the equator. The linear speed for someone in Florida is somewhat less, since the circumference of the circle he/she travels is smaller!)*

**Centripetal acceleration of someone at the Earth's surface**

$$a = v^2/R_E \approx (1000\ \text{mi/hr})^2/(4000\ \text{mi})$$
$$= 250\ \text{mi/hr}^2$$
$$= \frac{250\ \text{mi} \times (1609\ \text{m/mi})}{(1\ \text{hr} \times 3600\ \text{sec/hr})^2} = 0.03\ \text{m/s}^2$$

Recall acceleration of falling bodies at Earth's surface $g=9.8\ \text{m/s}^2$:
$0.03\ \text{m/s}^2$ is 0.3% $\Rightarrow$ you weigh 0.3% because the Earth is rotating

**September 22**

**Bronowski Film ("The Starry Messenger")**

This video focuses on the resistance of the Catholic Church in the 17th century to the heliocentric (Copernican) universe, and in particular to Galileo, who is brought to trial by the inquisition. At the end, he is forced, under threat of torture, to publicly renounce, as heresy, espousing (1) that the sun is the center of the universe, and does not move, and (2) the earth is not the center of the universe, and moves with a double motion (rotation about its axis and revolution about the sun). The effect was to suppress scientific research in Catholic countries around the Mediterranean, so that the center of scientific progress moved north, into protestant countries (Protestantism is also not terribly sympathetic to these ideas, but is more willing to tolerate them).

Bronowski mentions Galileo's early achievements, and states, "Galileo is the creator of the modern scientific method.... [In what he did with the telescope] he really did for the first time what we think of as practical science: build the apparatus, do the experiment, publish the results."

Between September of 1609 and March of 1610, culminating in the publication in Venice of the famous Siderius Nuncius or (in English translation) The Starry Messenger, Galileo published his most important astronomical discoveries. Each undermined the Ptolemaic picture of the universe (See Gregory Ch. 6). The discoveries Bronowski mentions include:

(1) New stars that had never been seen before.

(2) The moons of Jupiter

(3) Craters and mountains on the moon

(4) The phases of Venus

**September 27**

Tycho Brahe's compromise

**Discussion of Supermoon**
**Discussion of water on Mars**
**Discussion of film, "The Starry Messenger"**

The Wittenberg interpretation of Copernicus's achievement
- Copernicus's system represents an advance in astronomy
  - Slightly better fit - good basis for new astronomical tables
  - Got rid of "horrid equant"
- Can we keep the good things about Copernicus, but get rid of the earth's motion?

Tycho's unusual youth
- Did not aspire to become a knight, which befitted noble youths
- Was interested in intellectual pursuits, especially astronomy
- Learned about instrument construction on his tour of Europe

The New Star of 1572 (was actually a supernova)
- It represented change in the heavens, thus should be below the moon
- Tycho showed it displayed no diurnal parallax when the moon showed ~1 deg
  - Diurnal parallax is due to the shift in baseline of observation because of daily rotation
  - Since there was no diurnal parallax for the New Star, it was beyond the moon

The Comet of 1577
- More difficult to assess for diurnal parallax since it was only visible near the sun, so there was not a lot of time after sunset to measure for parallax. Tycho nevertheless concluded there was no parallax visible
- Tycho consulted Maestlin's tables for the comet a decade later and saw great variation in the comet's distance from the earth
- He then concluded that the path of the comet passed through the celestial spheres of several planets. Therefore there could not be celestial spheres carrying the planets. He has no explanation for what carries planets in their orbits

Rejecting Copernicus: Tycho rejected the Copernican system because he could not detect parallax for heavenly objects that should show it at 6 month intervals

The Tychonic System
- The visit of Paul Wittich to Uraniborg showed Tycho a compromise system: Moon,

Sun, Mars, Jupiter, Saturn orbited the earth, Mercury and Venus orbited the Sun

Tycho rejected Wittich's system because Copernicus's system dictated the relative size of planetary orbits, which Wittich ignored

Tycho's system had moon and Sun orbiting earth and all other planets orbiting the Sun

This system is *observationally equivalent* to Coperncus's system; i.e., one cannot tell from observations which system one is in. Proof is given on website assigned for reading, but is easy to see by looking at simulator.

Advantages of Tycho's system

No problem with the Aristotelian physics of motion (since earth isn't moving)

No problem with interpretation of Scripture (since earth is not moving)

When the old Danish king died and was replaced, Tycho no longer in favor

New requirement laid on Tycho resulted in his leaving Denmark

Tycho spent his last days in Prague as Imperial Mathematician to the Holy Roman Emperor, Rudolph II

## September 29

**Johannes Kepler, 1571-1630 (compare Tycho 1546-1601, Galileo 1564-1642)**

Kepler son of mercenary and innkeeper's daughter, attended school irregularly
Early training at monastery school at Maulbronn near Heidelberg, and mystical/spiritual disposition – search for god in perfection of mathematics

Combined both Platonist and Aristotelian sides
Platonist: search for beauty & spiritual fulfillment through mathematics & perfection
Aristotelian: study nature, observe carefully to obtain spiritual fulfillment

**+ 1 new aspect! Kepler asks one question neither Plato nor Aristotle think of: *why* do planets move the way they do – what is the cause? Carl Sagan: "Before Kepler…science lacked the slightest notion of underlying physical law."**

Early career, after Maulbronn, university at Tübingen under Mästlin, the man whose observations of the comet of 1577 had influenced Tycho, open to Copernicanism (note most of Germany is protestant at this time, so these ideas could be discussed openly). Kepler became Copernican also, but was obsessed with mathematics of celestial motions, felt structure of cosmos, e.g. distance between planets, could not be accident but must be part of god's design.   After Tübingen he's sent to teach math at Graz (catholic Austria), and during class supposedly realizes that the radii of the planets orbits are very close to those of a set of nested platonic solids.  He's excited because he thinks he has explained why there are 6 planets, and why they are spaced the way they are, all by geometry.  (He also asks himself a 3rd question early on: why do the planets have the speeds they are observed to had; no answer yet.)

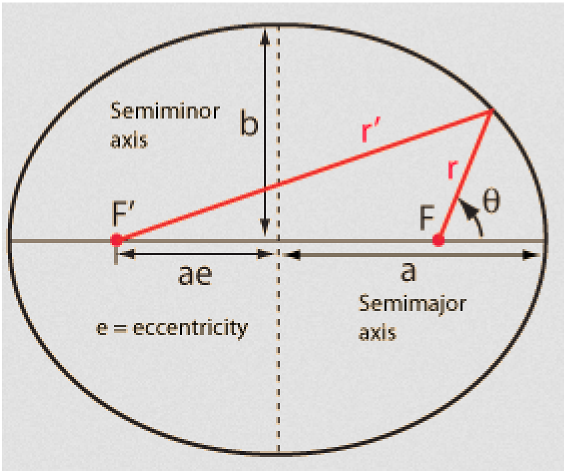
But upon closer inspection, the radii of the spheres enclosing the solids don't fit the orbits perfectly; Kepler suspects the data are flawed, and seeks out Tycho, the precision of whose data is legendary.  Tycho invites him to come to Prague, convenient since Graz is in turmoil.

Tycho gives Kepler problem of the orbit of Mars – hardest to fit into a circular orbit in Tychonic scheme.  Kepler begins thinking (as a Copernican), in 2 ways:

a) Accurate mathematical description of Mars' orbit
b) Physically, what caused Mars to move as it did? (!)

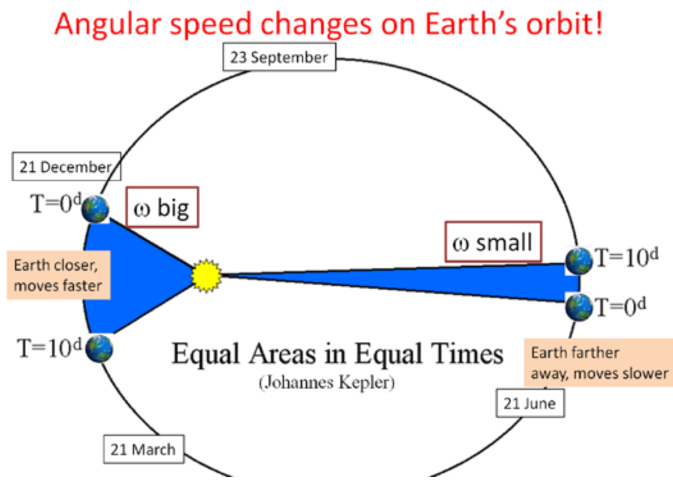
Mars problem could be solved by moving Sun away from center of circle,  then it would sometimes be slower and further away.    Didn't quite work with highly accurate data of Tycho, so he realized he needed a new orbit shape; eventually tried ellipse & it worked (after correcting an initial error)

**Kepler's 1st law: planets move around the sun in elliptical orbits, with the sun at one focus.**




Recent publication of *de Magnete* (Gilbert, 1600) led K to think about Sun exuding magnetic force that pushed planets around in their orbits.  Force should get weaker farther away from Sun (like magnet), so planets further from sun on their elliptical orbits would be slower. He guessed "law of equal areas and equal times":

**Kepler's 2nd law: as planet moves around its orbit, it sweeps out equal areas in equal times.**




1st and 2nd laws published in 1609 in *The New Astronomy: based on causes, or celestial physics.* Gregory: "the marriage of physics and astronomy".

Jupiter and Saturn conjunction

1618 publishes *The Harmony of the World*, about harmonies in mathematics, music, astronomy, and nature. Note Kepler, who famously said that "God is geometry itself", never abandoned his picture of the nested platonic solids, despite the fact that he knew the construction could not explain the planets' spacing after all (nor, it turns out, their number). This happens often in science, that scientists, who are human, manage to live with and accommodate this kind of cognitive dissonance until someone else insists that the two things are blatantly contradictory.

Answer to question 3 about planetary velocities: the third law, in *The Harmony of the World*.

**Kepler's 3rd Law. the period and average radius of the planets' orbits are related to each other by** $T^2 \propto R^3$

**Final question: *why* Kepler's 2nd law: equal areas in equal times?** Note that when Earth closer to sun, it goes faster. Let's get quantitative: 147.1 million kilometers at perihelion (closest to sun), 152.1 million kilometers at aphelion (farthest away). Speeds are 109,033 km/h at perihelion, 105,448 km/h at aphelion. Now notice something: if distance gets bigger, speed gets smaller and vice versa. Just for fun, let's multiply distance R and speed v together. At aphelion, Rv= $(1.521 \times 10^8)(1.0545 \times 10^5)=1.60389 \times 10^{13}$ . At perihelion $(1.471 \times 10^8)(1.0903 \times 10^5)=1.60383 \times 10^{13}$ . Whoa! They are the same. The product of the speed and the distance *does not change* as the Earth goes around the sun. This is a special case of something called *angular momentum conservation* in physics,

$$m\, v\, R = \text{const.}$$

and it's the same thing as what happens to a figure skater when he/she pulls in his or her arms in a spin – he/she speeds up! In our case here the mass m of the Earth didn't change between perihelion and aphelion, so we left it out.

Definitions: p=mv the *momentum* of a body
L = m v R = p R the *angular momentum* of a body

Q: have we fully explained *why* Kepler's 2nd law works? Not really, just given a clue to what might be going on.

## October 4 Inertial motion and Galileo's pendulum

### Galileo Galilei 1564-1642

- Studied medicine at university in Pisa, but real interest was math
- Impressed Jesuit mathematician, was able to obtain teaching position at Pisa
- Early indications of Copernicanism, e.g. letter to Kepler; however did not avow publicly
- Unlike many other philosophers, liked to write in vernacular rather than latin – astute political sense

### Galileo and falling bodies

Aristotle must be wrong--a "thought experiment"

Consider two bodies, one weighing twice as much as the other.
Aristotle would say 1 would fall twice as fast as 2, $v_1=2v_2$

Galileo: tie the two together. Light one should retard heavy one, since it wants to fall more slowly. So speed of total is $v_{tot}<v_1 = 2v_2$

But one can equally well regard the two as a composite object weight which should fall with three times the speed of the light body, so $v_{tot}=3v_2$ *Internal contradiction*

- Story from biographer: G dropped balls of different weight from tower, found they hit bottom at same time

- Galileo rejected Aristotle, but believed (early years) that all objects would accelerate until they reached *terminal velocity* characteristic of specific material

Reminder: *terminal velocity* is the velocity an object falling in a fluid ultimately reaches, when it is no longer accelerating. The resistance due to, e.g. a skydiver falling in air increases with his velocity until the force of gravity and the air resistance cancel; after this the motion is uniform at the terminal velocity. Terminal velocity for a skydiver is about 120 mph for falling in the prone (belly-down) position.

**Video:** Brian Cox demonstrates that bowling ball & feather fall at same rate in a (near) vacuum
https://www.youtube.com/watch?v=E43-CfukEgs&feature=share

Although Galileo probably didn't do the leaning tower expt. as legend would have it, he would have loved to do the expt. with the vacuum pump, since he developed the technique of *idealization* in physics. For example, he asked

What would happen if I removed the air?
What would happen if I removed friction?

and generally came to the correct conclusion (which also helps). This approach was very unlike the Greeks, who felt it was imperative to take all the details into account to describe "corrupt, earthly" motion. G's approach has been adopted into modern physics, which tries to approach a problem by first eliminating all extraneous variables, and design experiments where only one thing is changed at a time.

This has led to a metaphor and lots of jokes:

The farmer's cow wasn't giving milk; he had tried everything, & nothing worked. So he called a theoretical physicist, who said she would think about it. The next day she visited the farmer, who was eager to hear the solution. The physicist went to the blackboard, and began, “Consider a spherical cow…”  (This is the punch line :-)).

The spherical cow is simplification reduced to absurdity, but in many cases simple models that leave out details can be justified and provide physicists with their most powerful reasoning tools.

Galileo proved a number of quantitative things about the pendulum, which was  a kind of falling body with acceleration slowed by its horizontal motion.  The story (apocryphal?) was that he was bored in mass one day at Pisa Cathedral, and noticed the chandelier swinging back and forth.  The air currents would set it in motion back and forth, sometimes with large amplitude, sometimes with small amplitude (*amplitude* is the maximum *extent* of the oscillatory motion).  Timing the swings with his pulse, Galileo noticed that the period (time for 1 swing back & forth) did not change regardless of the amplitude.  (see lab 6)

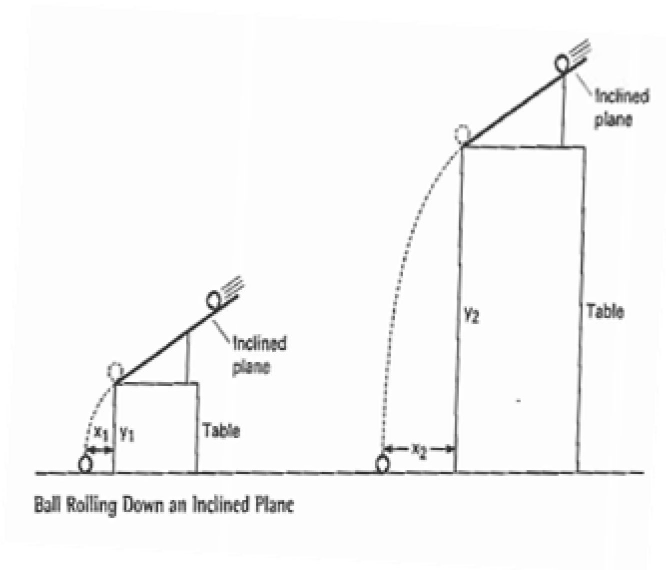
The inclined plane was another way to slow down the vertical motion of a falling body so that it could be measured more accurately.  Galileo’s expts. with inclined planes convinced him that mathematics could be   applied to earthly as well as celestial realm.  First Galileo showed that height of falling body varied as (time to ground)$^2$, or $y \sim t^2$.  Galileo observed that vertical distance traversed in equal times increased in accordance with sequence of odd numbers:

e.g 1 foot, 3 feet, 5 feet, 7 feet… in 1st 4 sec
*Total* distance fallen:  1,1+3,1+3+5,1+3+5+7
= 1,4,9,16        in 1st 4 sec

He deduced $y \sim t^2$ (const. acceleration).  Then he looked at how far in the horizontal directions objects falling from inclined planes from different heights traveled.

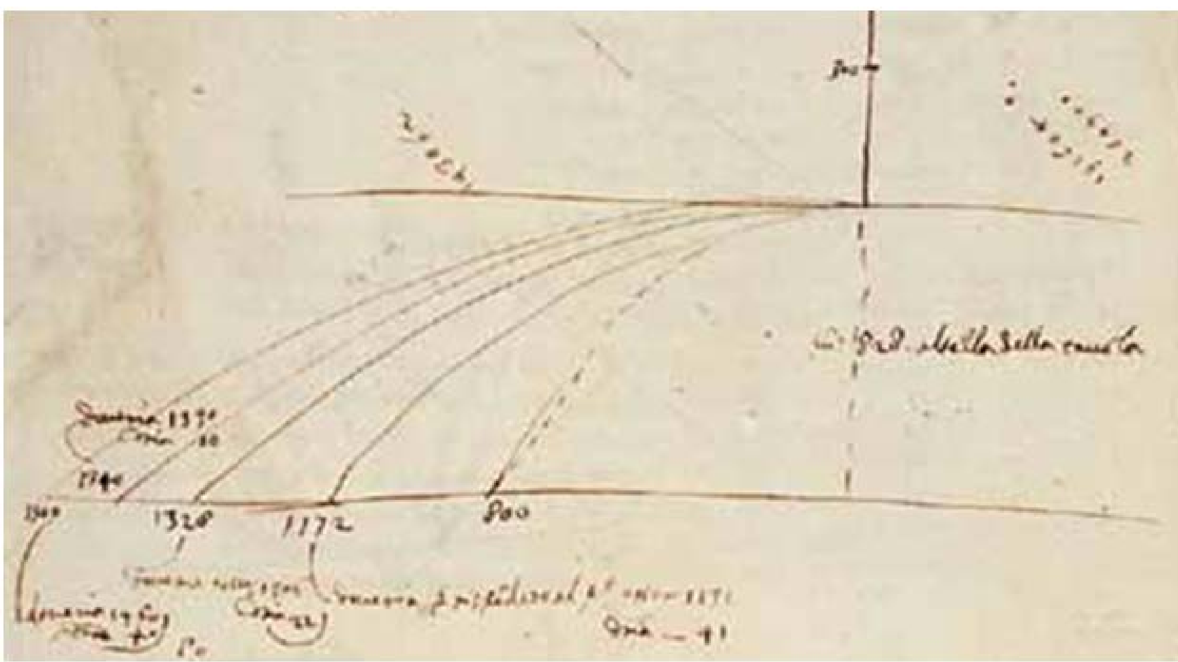
G’s measurements showed that

heights $y \sim x^2$
ranges  $x \sim t$  (time in air)




(From Gregory p. 118)

Galileo analyzed motion in terms of composite ("double") motion in both x and y simultaneously. Taken together, his two observations imply $y \sim t^2$ as before.




Importance of Galileo's approach to understanding motion: 1st combined use of empirical measurements and mathematical analysis!

**Oct. 11 Galileo's *Starry Message* and the *Dialogues***

Galileo heard about the telescope in 1609 and built one for himself. He showed it to the brokers on the Campanile and gave it to them to identify ships coming into Venice.

He turned the telescope onto the heavens and observed three things, which he put into a new book, The Starry Message, in 1610:

- Craters on the moon
- Many more stars than had ever been seen
- Four moons around Jupiter

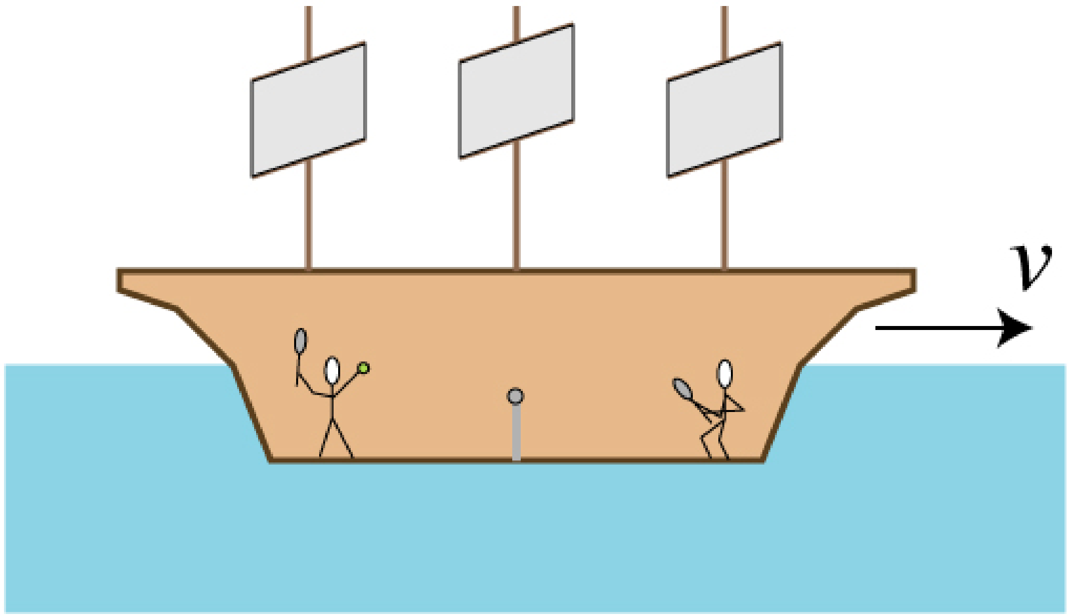
The book was a sensation and was effective in getting Galileo promoted to Court Philosopher in Florence, thereby raising his salary and, equally importantly, his social status. He now was a philosopher, which, while not as high in the ranking as a theologian, is certainly higher than being a mathematician (astronomer).

Near the end of the year he observed that Venus had phases, something not possible in the Ptolemaic system though called for by the systems of Tycho and Copernicus. Galileo begins to defend Copernicus but ignores Tycho's system.

Galileo's fame disurbs some in the church who worry about the implications of Copernicus for understanding the Bible. Some force the issue by denouncing Galileo publicly. Galileo went to Rome on his own in 1616 "to see what is permissible to hold." He is instructed by the pope that he is not to hold or defend the Copernican system, a command he accepts. Cardinal Bellarmine gave him an affidavit that he can consider it as an hypothesis.

Galileo privately set to work on a discussion of the Copernican system. He develops a new physics of motion to answer the objection to Copernicus that says we should be able to sense the motion of the earth. Galileo argues that uniform circular motion, such as that the earth has in both its rotation and revolution around the sun, is a natural state of being like rest; i.e., it will continue forever unless interrupted. Our experience at rest or in uniform circular motion will be identical - we will not be able to tell which condition pertains unless we have reference to an external source outside our immediate frame of reference. This conclusion later becomes known as Galilean relativity of motion.

In the ship moving at uniform velocity without friction (below) you can play tennis in the hold (assuming there's light) just as you could if the ship was at anchor in still water. You would not know if you were moving or no because rest and uniform motion are equivalent states of being. (Galileo thought the uniform motion had to be in a circle - others later changed it to uniform motion in a straight line.)




Galileo also developed his theory of tides, which he believes proves the earth moves. The combination of the earth's rotation and revolution will cause the oceans to slosh (tides), which the oceans would not do if the earth were at rest. But by his own theory of circular inertial motion, there should not be tides.

Galileo's friend Mafeo Barberini, was elected pope in 1623. Galileo visited him in Rome in 1624 and had 6 conversations with him. We don't know exactly what they talked about, but the pope was well aware of Galileo's intent to write a work on the Copernican system. He made clear two requirements that any discussion Galileo might produce must meet:
It had to consider the Copernican system as an hypothesis
It could not be named *On the Ebb and Flow of the Sea,* Galileo's preferred title. (Galileo thought the tides *proved* the earth's motion, a result Pope Urban VIII would not concede.)

Although Galileo cleared the work with some authorities in Rome, when his *Dialogues of the Two Chief Systems of the World* appeared in 1633 it quickly rallied his critics against him. He was summoned to Rome, where his trial hinged on the 1616 meeting in Rome. The commandment from Cardinal Bellarmine was uncovered in the Vatican archives (All those who had first hand knowledge of the meeting were dead, except for Galileo himself.) Another document was uncovered, which said Galileo was prohibited from considering Copernicus "in any way whatsoever." Galileo was unaware of this document, which was likely a draft of a document prepared in case Galileo resisted the commandment of Cardinal Bellarmine, which he did not. The trial would turn on this document and Galileo was found guilty of heresy. In any event, the church authorities did not believe that Galileo had considered Copernicus "hypothetically" in the *Dialogue*s.

Although threatened with torture, Galileo was not tortured, He publicly recanted his belief in the Copernican system. After a brief stay in Sienna at the residence of the archbishop, he was placed under house arrest. He died in 1642, the same year Isaac Newton was born.

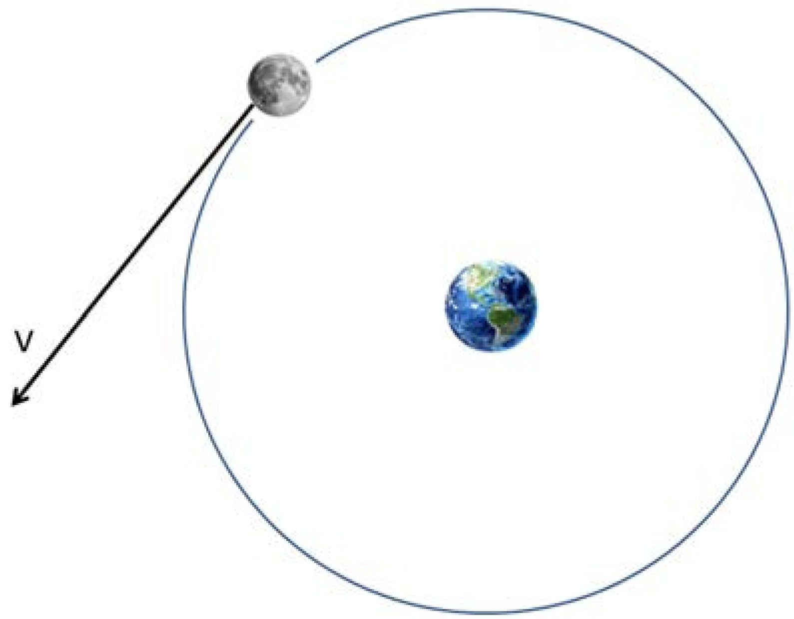
## October 13 Newton's Laws of Motion

**Reminder: importance of the Earth-moon problem:** centuries of separation between study of earthly and celestial motions broken down (process started by Galileo with his circular inertia, but finished by Newton).

Basic solution to Earth-moon problem done early in early life, during 1665-67 Cambridge closed for plague. Newton resisted publishing in part because results were not quite accurate. Later, in Principia 1687, he cites new measurements by Huygens of g which confirm his estimates with higher precision.

### Evolution of Newton's ideas about inertia

Note that during his early study of the Earth-moon system, Newton's ideas about motion were a little confused, like any beginning physics student. He felt that the Moon in its orbit had a natural tendency to recede from the Earth due to an active force present in its matter, i.e. a force pushing it away, counteracted by the gravitational force. In 1679 Robert Hooke, president of royal society, wrote Newton a letter asking for his ideas about celestial motion. Newton apparently went back and read Hooke's publications, and realized that Hooke had put forward the notion that the moon's orbital motion resulted not from the combination of a force pushing out and one pulling in, but simply the moon's tendency to go in a straight line unless it was pulled in by an inward force.

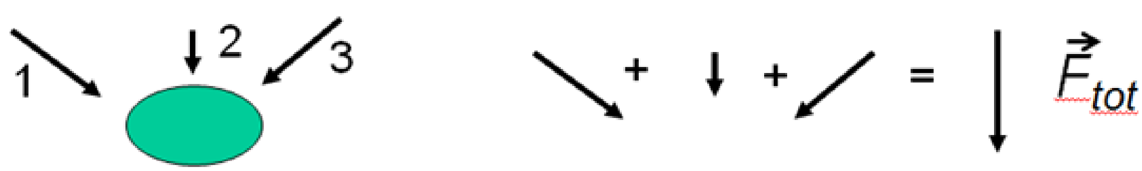



A picture of the moon's instantaneous velocity, or, the way it would actually move if you turned off gravity at the position shown. The actual motion is a combination of the sideways motion and a continuous falling towards the center of the Earth.

To his credit, although Hooke was already a rival, Newton adopted this point of view, and stated it later so forcefully in the Principia that we now associate the notion with him. To wit:

**Newton's 1st law**

*An object moves with a velocity that is constant in magnitude and direction, unless acted on by a nonzero total force*

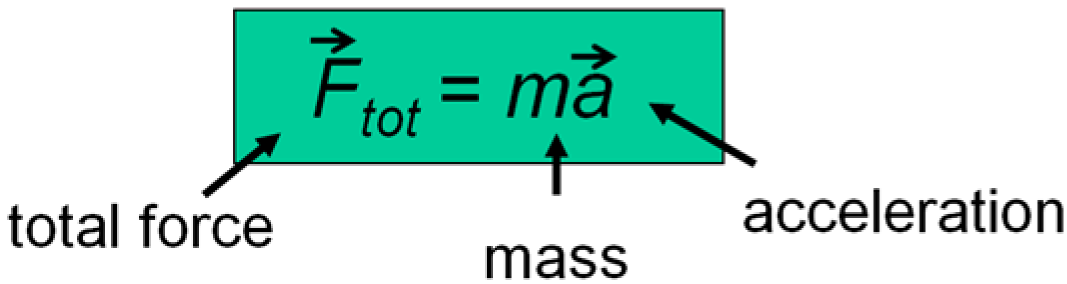



If you have a light object and a heavy object, it's harder to make the heavy object change its state of motion: either to speed it up starting from rest, or to change its constant velocity.

Newton said that each object is characterized by a *mass*, which is a measure of *inertia*, or ability to resist changes in the state of motion. We measure mass in grams or kilograms, or something called slugs in the English system. Pounds, which you are used to, are a measure of weight, which is a force. Let's quantify the notion of force by introducing Newton's 2nd law from the Principia.

**Newton's 2nd law**

*The acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass.*




The SI unit of force is Newtons, named after Sir Isaac. 1 N = 1 kg-m/s$^2$. In other words, if you measure mass in kg, acceleration in m/s$^2$, you get force in Newtons.

**Weight**

An object at the earth's surface accelerates in free fall at g=9.8 m/s$^2$ downwards. Newton's hypothesis was that this was because of the gravitational force of the Earth. Applying the 2nd law, and calling the force W, we see that W=mg. A 100kg person weighs (9.8 m/s$^2$)(100kg)=980N.

**Newton's law of universal gravitation.**

$$F_g = G\frac{m_1 m_2}{r^2}$$

where $m_1$ is one mass, $m_2$ is another, and r is the distance between them. G is Newton's constant of universal gravitation equal to G=$6.673\times10^{-11}$ N. (m/kg)$^2$. Newton's great achievement lay not only in showing that a central 1/r$^2$ force led to a quantitative description of the Moon's orbit, but to elliptical orbits for all the planets as well (as Edmund Halley discovered during the famous visit to Cambridge in 1684). He also derived Kepler's 3rd law. Note that he made an enormous intellectual leap from considering the Earth-Moon system to applying his law to every mass in the universe. Almost immediately this sparked ideas about the formation and shape of the Earth itself, which was just a spinning ball of mass subject to all of Newton's laws. Newton predicted the earth should bulge at the center, which was not confirmed until after his death, but served to solidify his growing international reputation.

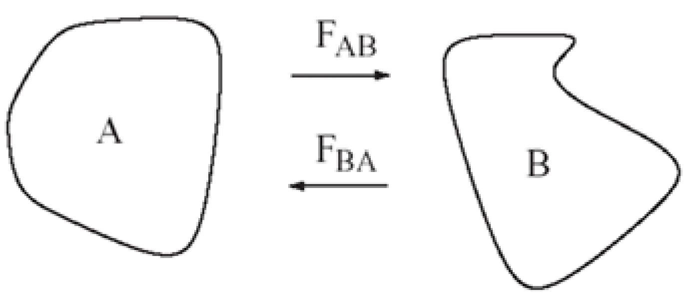
Q: Why, if all objects attract each other, don't we feel pulled to the wall, or attracted (literally) to the person standing next to us? Put in some numbers for two people 100 kg each 1 meter apart:

$$F= 6.673\times10^{-11}\ \text{N.}\ (\text{m/kg})^2\ (100\ \text{kg})^2/(1\text{m})^2=6.77\times10^{-7}\ \text{N}$$

so this is a *really* tiny force, more than a billion times smaller than your weight.

**Newton's 3rd law**

*``to every action there is an equal and opposite reaction"*




*or,*

*``For every object A which exerts a force on B, B exerts an equal and opposite force on A".*

NB: these forces are equal and opposite, but *they do not cancel* because they are applied to different bodies. An object moves according to the $F_{tot}$ applied to it and it only.

Lazy horse example: “I can’t pull the cart because it is pulling on me with the same force that I am pulling on it.” Fallacy! The cart moves because the rope pulls it forward, and the horse moves despite the fact that the rope is pulling backwards on it, because it is able to exert more force on the ground, which therefore pushes forward on it, overcoming the rope pull.

Reaction cart demo

## October 18 Newton and the Moon

Newton was born on Christmas Day, 1642 under a full moon. This, plus the fact that he survived a sickness as a baby, led him to think of himself as special, linked to the line of biblical prophets like Moses (who also escaped death as a baby). Once his intellectual talents became clear Newton was able to attend Cambridge University at Trinity College 1661. At the university the curriculum was dominated by Aristotle’s thought, but Newton read on his own from the works of Descartes, Galileo, Kepler, and others. When plague hit Cambridge in 1665 he returned home for over a year. It was during this time that he experienced the so-called “miraculous year,” in which he invented new mathematical techniques of the calculus and also undertook to solve the problem of the moon’s motion.

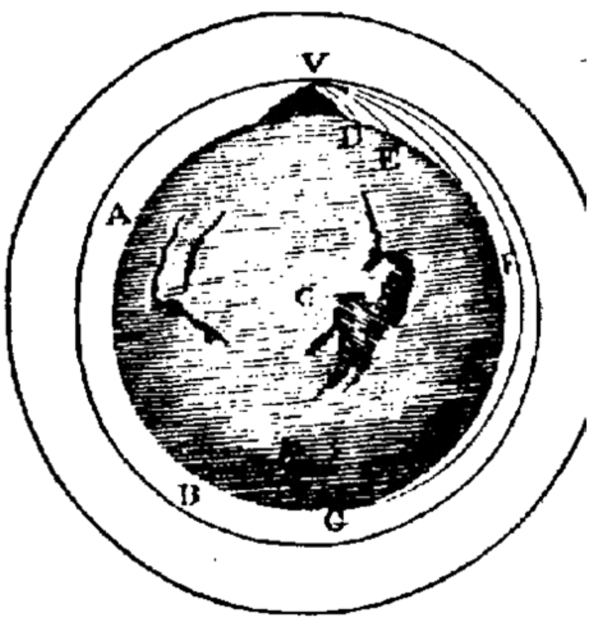
Newton had concluded that Galileo was correct to identify uniform motion as a state of being equivalent to rest, but he disagreed that the uniform motion was in a circle. Like Descartes, he argued that what has become known as inertial motion should be in a straight line - an object in rectilinear (straight-line) uniform motion (or at rest) will continue in that state forever unless acted on by an outside force. This later became known as Newton’s First Law of Motion. As almost a corollary to this conclusion, wherever the First Law does not obtain, some force must be changing things. But to change the circumstance where the First Law applies one would have to change the uniform motion or rest - i.e. change the velocity (which is 0 in the case of rest). Changing velocity is the definition of acceleration, so Newton’s corollary, which becomes his Second Law of Motion, is that f=ma.

Perhaps Newton came to his First Law by an experience like twirling a rock on a string. When the string breaks the rock flies off in a straight line, so once all constraining forces are gone, the natural state of rectilinear inertial motion obtains.

From Newton’s perspective all motion *not* going at a uniform velocity in a straight line must be explained; i.e., we have to be able to identify the force that is causing the curved motion. He encountered this problem famously in puzzling over why the moon “is retained in her orbit.” Why does it not fly off? What is the “cosmic string” holding it in orbit.?

When he saw an apple fall in the garden at Woolsthorp (his home), he had an idea. The apple shared something with the moon. They were both falling bodies. It's clear for the apple, but what about the moon? Why is it falling?

Newton included the diagram below in one edition of his famous book, published much later. It shows a mountain at the earth's north pole. Imagine, he said, firing a cannon ball from the top of the mountain in a direction horizontally tangent to the earth. This horizontal motion will be uniform once the ball leaves the cannon. But the cannon ball will also fall in an accelerated motion toward the earth. The combination of these motions will follow, as Galileo showed, a parabolic path. Newton depicted several different parabolic paths the cannon ball might follow, each depending on how much force was imparted to the ball in a horizontal direction. From the diagram you can see that if just the right amount of force is imparted to the ball it will "fall" without ever hitting the earth - it will be a satellite. So the moon and the apple share the property of both being falling bodies.




Newton now engages in a piece of ingenious reasoning, namely, that perhaps whatever makes the apple fall (he doesn't need to know what it is, just that something makes the apple fall) is also what makes the moon "fall." This force for an object twirling around a center is a centripetal force, directed toward the center of the motion.

Newton knows that a centripetal force is given by $f = \propto mv^2/r$, where v for the Moon can be given as below where d is one circumference of the Moon's orbit and t is the Moon's period.

$$v = d/t = 2\pi r/T$$

$$f \propto m(2\pi r/T)^2 /r = m(4\pi^2 r^2/T^2) \times 1/r$$

$$\frac{m4\pi^2 r^{\not 2}}{T^2} \times \frac{1}{\not r} = \frac{m4\pi^2 r}{T^2}$$

At this point Newton assumes that Kepler's Third Law applies to the Moon, so he replaces the $T^2$ with $R^3$

$$\text{So } f \propto \frac{m4\pi^2 r}{T^2}$$

But, from Kepler's Third Law

$$T^2 \propto r^3$$

$$\frac{m4\pi^2 r}{T^2} = \frac{m4\pi^2 \not r}{r^{\not 3 2}} = \frac{m4\pi^2}{r^2}$$

$$\text{Thus} \quad f \propto \frac{k}{r^2}$$

Newton has, by applying Kepler's Third Law, shown that the force of the "cosmic string" holding the Moon in its orbit, gets weaker (is inversely proportional) as the square of the distance away the Moon is.

Fine, but what good is it? It's all based on the assumption that whatever makes the apple fall also makes the Moon "fall." What if I don't buy that assumption?

Well Newton, being the genius that he is, recognizes that he has uncovered enough information to test his assumption about the apple force and the Moon. He realizes, because $f \propto a$ that $a \propto 1/r^2$. He knows the rate of acceleration of a falling body at the surface of the earth (1 earth radius from the earth's center). He also knows that the Moon is 60 earth radii from the earth. So whatever the acceleration is at the surface of the earth, the acceleration of the Moon's "fall" is 1/3600 of that.

Newton next determined how far the Moon actually fell in 1 minute using an argument from geometry that had nothing to do with his assumption about apples and got 16 ft. He also calculated how far the Moon would fall in one minute based on his assumption of the apple force applying to the Moon and got a result that matched "pretty nearly." He later discovered that some of the data about the Moon's distance was faulty and, when corrected, the result came out beautifully. So his assumption that the Moon was held in its orbit by the same force that made apples fall had predicted a correct result. Impressive enough to remove suspicion about the assumption.

Note the structure of Newton's argument:
If the apple force holds the Moon in orbit, then the Moon should fall 16 ft in one minute
The Moon does fall 16 ft in one minute

Therefore the apple force holds the Moon in its orbit

Although this is the structure of many scientific arguments, it is not a proof in the strictest sense of the term since other factors may either be responsible for or contribute to the successful prediction.

## October 25: Development of Newtonian Physics in 18th Century

We began by mentioning the three competing systems at the beginning of the 18th century – the Cartesians, Leibnizians, and Newtonians. Descartes's cosmos was completely filled with matter, Newton's largely empty but filled with gravitational force. Leibniz's system was like both Descartes's and Newton's in his insistence that nature's laws be expressed mathematically, but his conception of matter was different from both figures.

The first development we explored was the so-called *vis viva* controversy between Leibniz and the Cartesians. It had to do with the measure of the force of motion, or the force a moving mass exerted when it encountered another mass. Descartes had proposed mv as the measure of the force of motion, but, since everyone in the 18th century agreed that God would conserve the motion with which he had created the world and would not allow the universe to run down, problems with inelastic collisions appeared to run counter to that assumption. By equating the amount of effort required when raising a mass with the "force of motion" exerted by dropping it, Leibniz proposed that a better measure involved m and the square of velocity, a quantity that could not be negative and so would always preserve a positive amount of "motion" of matter (even if it had to refer to the motion of the particles of a mass). Although the Dutchman Willem 's Gravesande showed experimentally by dropping different masses onto clay surfaces that Leibniz's formula of ½ $mv^2$ was consistent with the results while Descartes's was not, many refused to accept *vis viva* as anything real because it seemed to be so abstract. We then examined two different cases in which Newton's inverse square law was challenged and two in which it received new confirmation and praise. The first challenge came from the French claim that the shape of the earth was like an egg on its end (a prolate spheroid), which resulted from a careful mapping of France when the arc of a degree of longitude appeared to decrease as one traveled north. Newton had predicted that the shape of the earth was an oblate spheroid, resembling an egg on its side. When in 1735 Pierre-Louis Maupertuis took an expedition to Lapland (which, being near the pole would accentuate any change in a degree to measure) he found that the earth was an oblate spheroid and declared victory for Newton. Maupertuis's posturing of the issue as one between Newtonians and Cartesians was not accurate, however, because some Cartesians agreed that the earth should be an oblate spheroid. We next followed Alexis Clairaut, who in 1747 announced to the Paris Academy the need to change Newton's famous inverse square law. He declared that the mass of the Sun should be taken into account when calculating the Moon's orbit, something Newton had not done. He hoped by doing so he could account for some irregularities the Moon exhibited. Applying the inverse square law to the Sun- Earth-Moon system (the horrendously difficult three-body problem) could only be done using approximations, but Clairut's application of the approximations put the Moon in positions it was not observed to actually occupy. Clairut announced that the inverse square law therefore had to be amended with an additional factor of $1/r^4$. A year later Clairaut realized that an apparently harmless assumption he (and others) had made when approximating the solution to the three-body problem was not harmless after all. When he corrected his mistake he found that he need not correct the inverse square law to approximate the solution, that Newton had been right after all.

In the 17th century Edmund Halley had asserted that the comet of 1682 was identical to one recorded on four previous occasions and that it would return again in late 1758. He wasn't precise in his prediction because the comet would pass close to Saturn and the even larger mass of Jupiter this time. Clairaut, expert on such three-body problems, took the masses of Saturn and Jupiter into account and announced in the fall of 1758 that the comet would be delayed to the spring of 1759, within thirty days of April 15. The comet appeared on March 13, just two days outside the predicted span. This was seen as testimony to the greatness of the inverse square and its author, Isaac Newton. Finally, Edmund Halley had uncovered another problem from his study of ancient astronomical records. He realized that Newton's system, if run backwards, would predict eclipses to have happened at times different from when ancient records said they had occurred. Halley proposed that if the Moon's orbit had been shrinking very slowly, Newtonian celestial mechanics would agree with the dates of the eclipses. But that meant that the stability of God's world machinery was in question since the Earth-Moon system would then be degrading. In the late 1780s Pierre Laplace showed that the interaction of the planets, Sun, Earth, and Moon resulted in a shrinking of the Moon's orbit. But that effect, while long acting, would be reversed in the future and the Moon's orbit would expand. This long-acting (secular) fluxuation in the Moon's orbit was stale after all, detectable only because of the application of Newtonian mechanics. By the end of the century Newton's fame stood higher than it had ever been.

We began by taking stock of how far we've come regarding the question of humanity's place in the universe. From the Greek conception of a closed cosmos we have proceeded to the infinite universe of the 17th century. It was perfected into the eternal and stable clockwork universe of Laplace by the end of the 18th century. A characteristic of Newtonian celestial mechanics as perfected by Laplace was its reversibility; i.e Newton's system could be run backwards or forwards. (Halley had relied on this when calculating when the eclipses of the medieval period had occurred so he could compare them with historical records.) That picture is about to be challenged by developments in physics that uncovered irreversible processes that would lead to the heavens slowing down.

Near-term goals are as follows: 1. To lay the goundwork for the undoing of Laplace's universe. 2. To look at some of the other forces of nature than just the contact forces we have been consiering (electrical, magnetic, chemical, optical, thermal). 3. To meet examples of how these forces are interconvertible. To begin to see how there is something special about heat.

Descartes' mechanical cosmos and his notion of God's action, whatever else they did, underscored the idea that for there to be any activity in the universe, matter must move. If there is no motion of matter, there is really no existence as we know it, so natural philosophers wanted to know all they could about how matter comes to be in motion.,

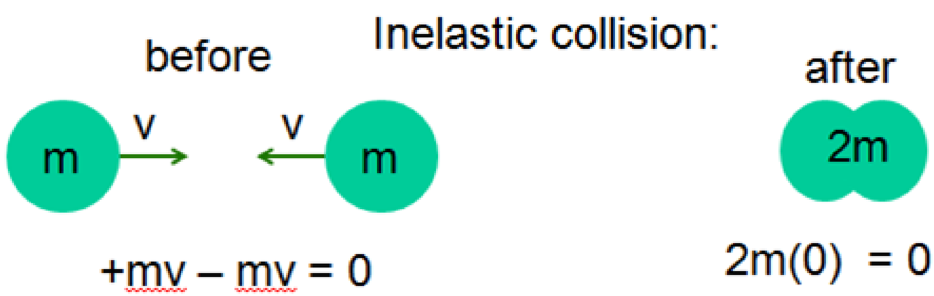
Descartes was only concerned with the contact force of collisions in his discussion of why matter moves. In the wake of the discussions about *vis viva* over the course of the eighteenth century natural philosophers began new experiments with other forces than motive forces (forces exerted by matter already moving) at the beginning of the nineteenth century. They began to realize that there was a counterpart to such "living forces" – forces that were being exerted that did not result in the motion of matter. These "dead" forces could sometimes be turned into living forces and vice versa. But first they just began investigating the properties of these other forces. They found that there were numerous ways in which nature's forces were interconvertible.

## Oct. 27: The Era of Many Forces

Reminder:

18th cent. *vis viva* controversy: does the universe run down?
Descartes: universe consists of many parts colliding with each other, but in each collision God ensures that "no motion is lost"
His guess for what physical quantity stayed the same in a collision: "force of motion" mv [today: mv=momentum]

Huygens: yes, but remember to include the sign of v! e.g. inelastic collision, 2 clay balls stick together.




Leibniz: doesn't like Cartesian proposal, since inelastic collisions will still run universe down. Proposed instead *vis viva*, $mv^2$
Vis viva survives inelastic collisions, since clay particles move afterwards (clay heats up)
'sGravesande corrected to ½ $mv^2$[today: ½ $mv^2$ =kinetic energy]

Electrical force was investigated in the 18th century primarily through static electricity that had been built up and then discharged. We met Benjamin Franklin's idea that electricity was an imponderable (i.e. weightless) fluid that was attracted to matter but that repelled itself. In the 18th century electricity was studied in electrostatic phenomena, primarily through electrical discharges. At the end of the century Lucia Galeazzi and her husband investigated the effect of electrical discharge on muscles, noticing at one point that contact of two metals caused as frog's leg to contract.  Alessandro Volta invented the battery, which was a way of discharging electrical force continuously.  To do so he relied on the chemical properties of metals, showing that chemical force and electrical force were related.  Soon electrical current was used to dissociate water into two gases.  Apparently electrical force could be converted into chemical force and vice versa.

The spectrum of visible light from red to yellow to green to blue to violet was well known. In the late $18^{th}$ century, Herschel a (German born) British natural philosopher, while experimenting on the temperature of the various colors of light, discovered that there was a hot invisible region below the red, which became known as infrared light.  Just after the new century Ritter,  a German experimenter, while experimenting on the ability of colored light to darken a chemical compound known then as the muriate of silver (silver chloride), discovered that red prevented darkening, green had no effect, but blue and violet increasingly darkened the compound.  He then discovered that beyond violet there was a region that darkened it most.  It became known as ultraviolet light.

Finally, heat engines, a means of using heat to produce motion in matter, had been in operation during the $18^{th}$ century in the textile industry that was fueling the industrial revolution.  It soon became clear that there was something special about heat force.  It seemed to accompany all the transformations of one force into another.  In France in the 1820s Sadi Carnot noted that in order to use heat to produce mechanical force, there had to be a fall from a higher temperature to a lower one; i.e., heat that existed at one temperature only was, as he put it, "useless" when it came to making matter move.  The heat from a hot body had be given to a cold body.  While Carnot believed that heat was merely a vehicle utilized to produce motion in a heat engine in the same manner that water is utilized to turn a millwheel (so that the heat, like the water, is not used up but can be used again), others argued that heat became mechanical force in heat engines.

In England James Joule was able to determine experimentally how much heat corresponded to how much mechanical force, settling the question of whether heat was conserved or not (it was not).   Rudolf Clausius in Germany then explained that both Carnot and Joule had contributed important insights.  Carnot was correct about the necessity of having a temperature difference to use heat to produce mechanical force (though he was wrong about heat being conserved).  Joule was right about there being a mechanical equivalent of heat, but *not all* the heat involved was turned into mechanical force.  Some of the heat was always merely cooled from the higher temperature to the lower one.

**Ideas about energy and heat in $18^{th}$ & $19^{th}$ centuries**

- "Force" gradually evolves from a word expressing the cause of any change in nature, to one (Newton) meaning the cause of a change of the state of motion of an object.
- Electricity (Franklin, Galvani, Volta) thought of as weightless fluid that could be transferred.  Galvani: electric "force" could be transformed into motive force (frog leg moved) – relation of electricity to life?  Volta: electric "force" could be stored (in Volta's pile, or battery)

- Studies of heat driven by industrial revolution, need to understand how engines work, …

- Sadi Carnot: to run an engine you need reservoirs with two *different* temperatures. Heat is a fluid that is *conserved*: doesn't get created or destroyed, like water in water wheel (Carnot's view!!!)
- Hermann v. Helmholtz: heat not conserved, sum of "motive" and "tensive" "forces" conserved
- James Joule: there is a mechanical equivalent of heat
- Rudolph Clausius: Carnot was right about need for temperature differential to run an engine, *but* heat is not conserved separately, but can be transformed into "motive force". Heat cannot be *completely* transformed!

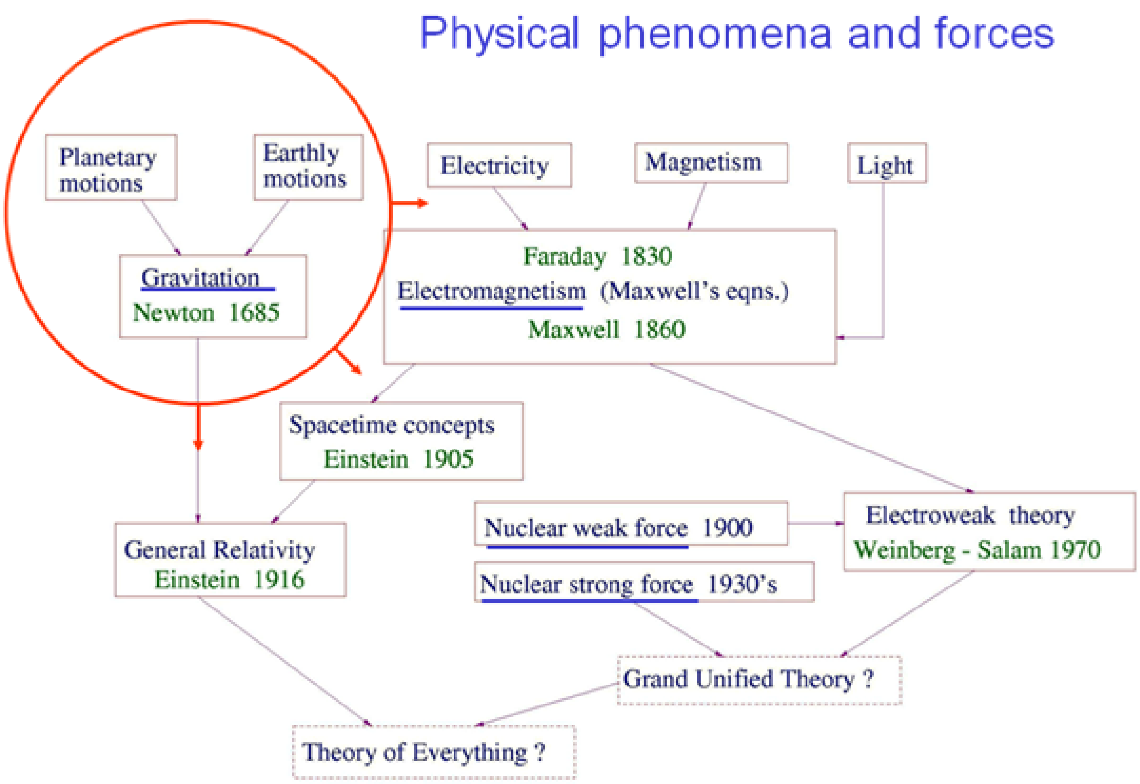
**Momentum conservation**

Q: What about Descarte's original "force of motion" mv?
(v = velocity, has a sign or direction)
A: It's conserved too!

Sir Isaac:

| | |
|---|---|
| | $$F_{tot} = ma = m\frac{v_f - v_i}{t_f - t_i} = \frac{\Delta p}{\Delta t}$$ |

So if there is no total force applied to the system, the total momentum doesn't change!




## Energy

### Mechanical Energy

Def: *mechanical energy*: energy which is associated with the position or motion of macroscopic objects.

*kinetic energy:* energy of motion

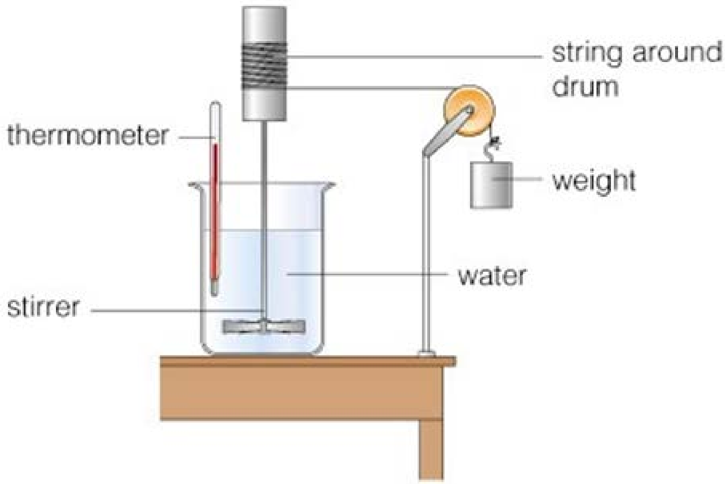
$$KE = ½\, m\, v^2$$

*potential energy:* energy of position, can take various forms. The most common form is the gravitational potential energy an object has near the Earth's surface, when we can say

$$PE = m\, g\, h$$

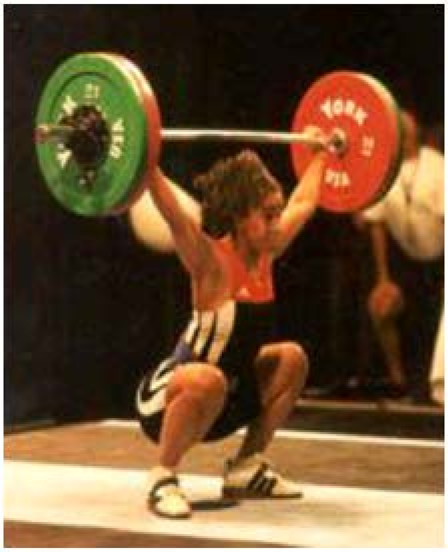
where $h$ is the object's height above the Earth's surface

**Work**




*F*×*d* is energy supplied by an external force acting through a distance (James Joule)
Joule's experiment showing that mechanical work can be turned into heat

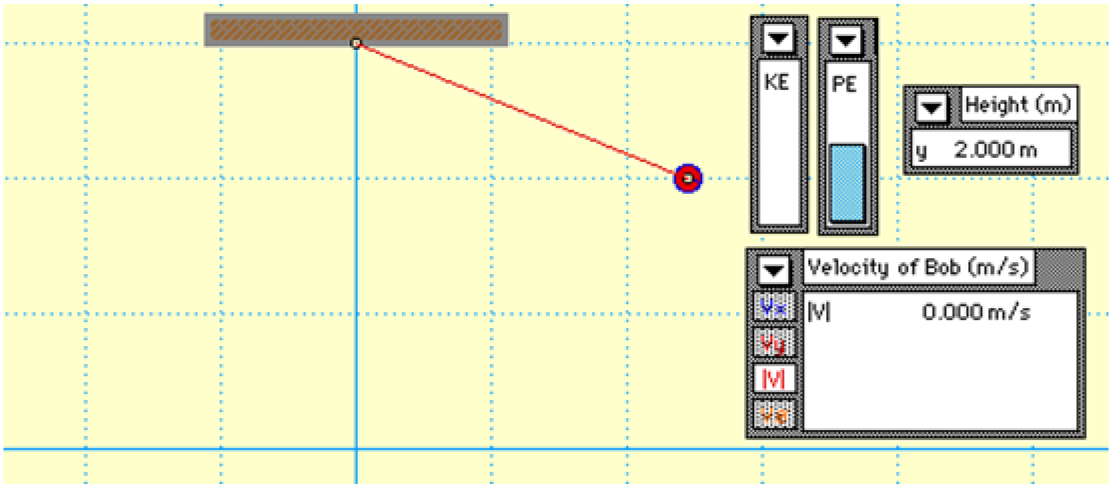
When we lift a barbell massing 50 kg a distance of 1 meter, we do work. If the barbell starts at rest and ends at rest, we have only changed its *potential energy* by *mgh*, i.e. 50 kg • 9.8 $m/s^2$ • 1m = 490 J. That energy is available to do work on something else.



**Conservation of mechanical energy**

If no friction is present, and no external force does work on a system, the system obeys conservation of mechanical energy (KE+PE=*const*.).

Example: pendulum. In this case, PE=*mgh*. When you let pendulum go, it has maximum height and zero speed, so max. PE and no KE.  At the bottom, PE is minimum and KE maximum. The sum KE+PE is always the same.



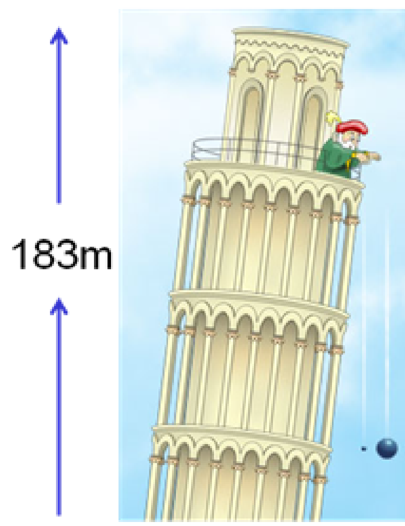

Example: what's the velocity of a ball dropped from leaning tower when it hits the ground?

Old way:

$h = \frac{1}{2} g t^2$

$\Rightarrow t = \sqrt{(2h/g)}$

$v = gt = \sqrt{2gh}$




Energy conservation:

before: E=PE+KE=mgh
after: E=PE+KE= $\frac{1}{2}mv^2$

$mgh = \frac{1}{2}mv^2$

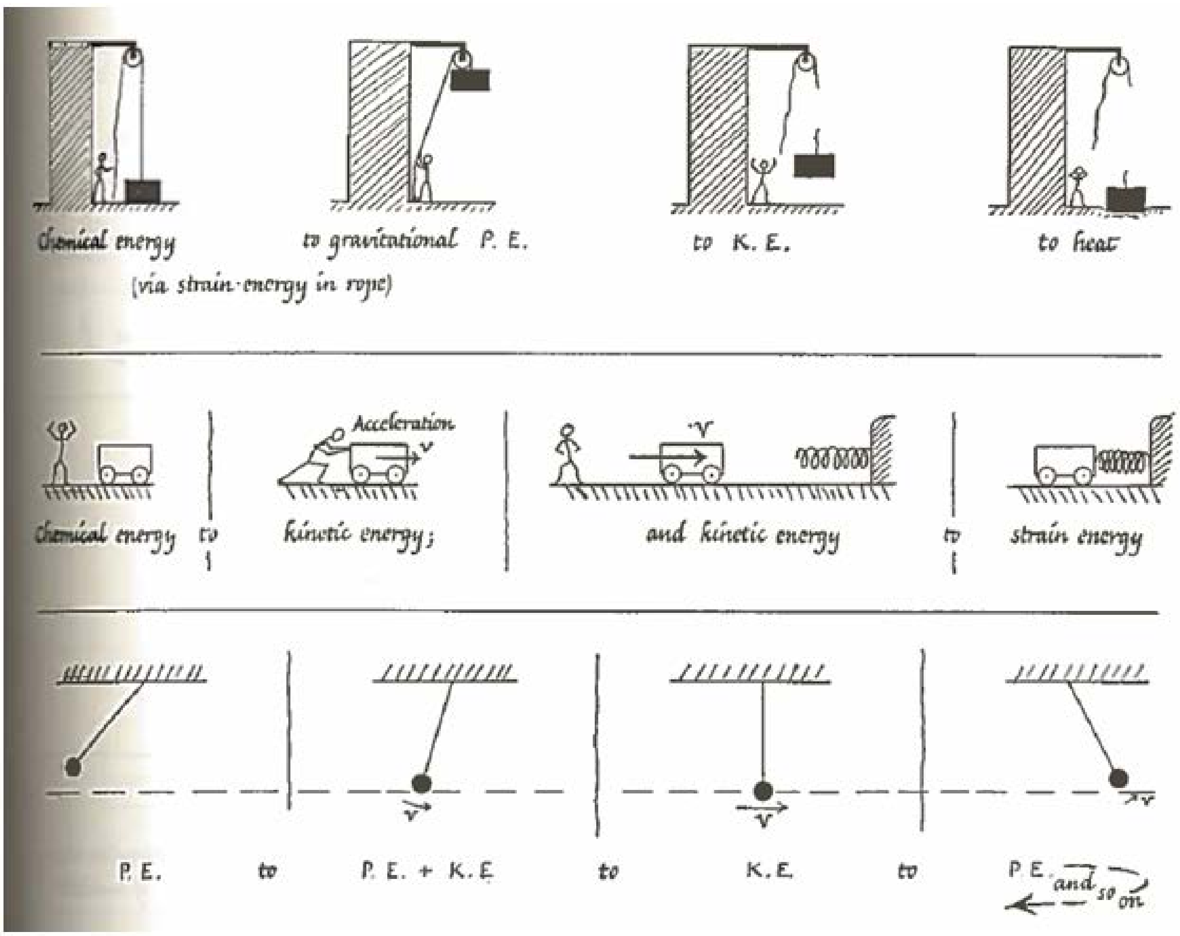
$v = \sqrt{2gh}$

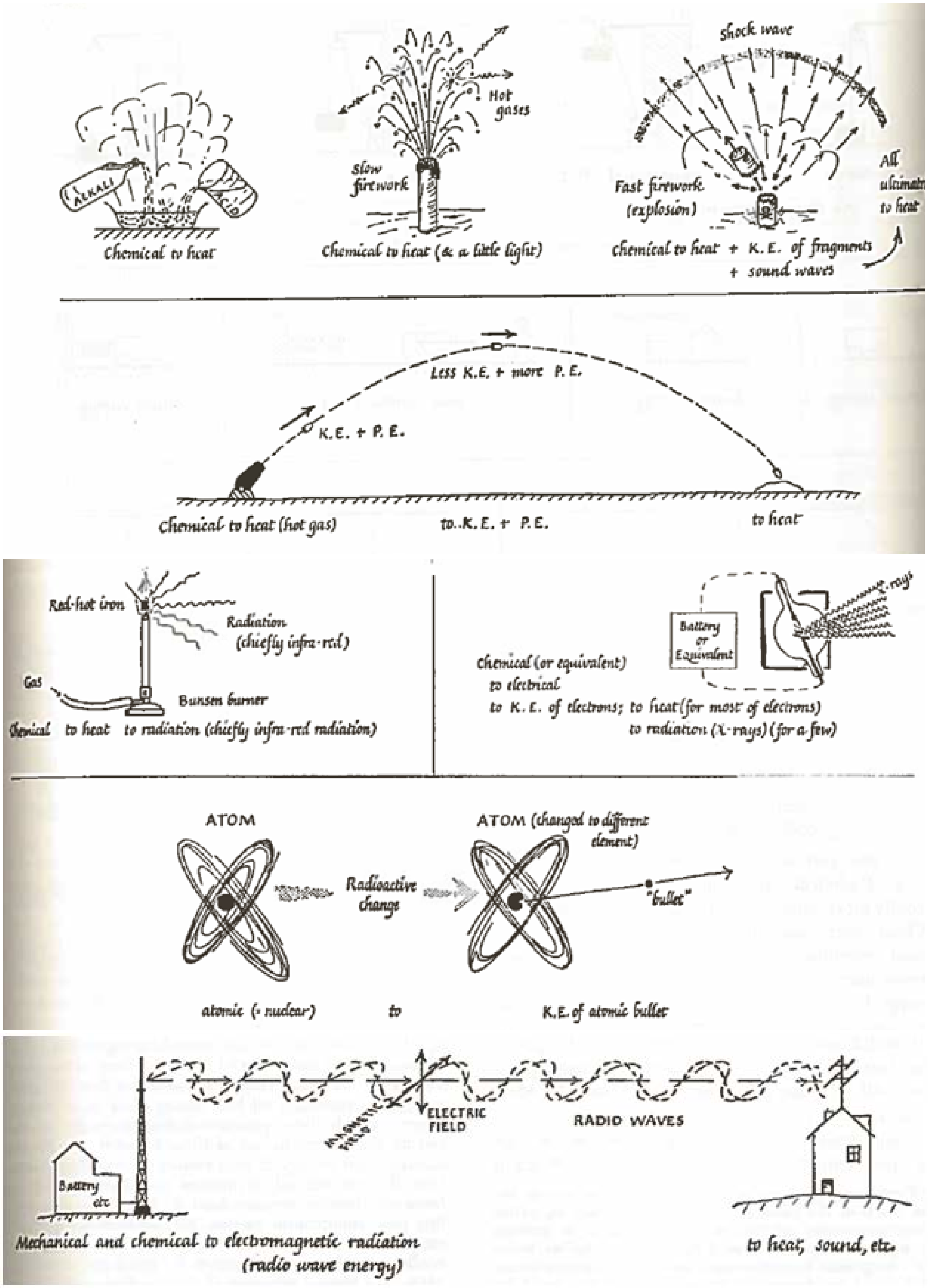
$v = \sqrt{2gh} = 60$ m/s (down)

**Different kinds of energy besides mechanical:**

Chemical, nuclear, solar, electrical, geothermal….

Different kinds of energy can be transformed,  one into another, such that total amount stays the same.




ALKALI
ACID
Chemical to heat
Hot gases
Slow firework
Chemical to heat (& a little light)
Shock wave
Fast firework (explosion)
Chemical to heat + K.E. of fragments + sound waves
Less K.E. + more P.E.
K.E. + P.E.
Chemical to heat (hot gas)
to K.E. + P.E.
to heat
Red-hot iron
Radiation (chiefly infra-red)
Gas
Bunsen burner
Chemical to heat to radiation (chiefly infra-red radiation)
Battery or Equivalent
X-rays
Chemical (or equivalent) to electrical to K.E. of electrons; to heat (for most of electrons) to radiation (X-rays) (for a few)
ATOM
Radioactive change
ATOM (changed to different element)
"bullet"
atomic (= nuclear) to K.E. of atomic bullet
MAGNETIC FIELD
ELECTRIC FIELD
RADIO WAVES
Battery etc
Mechanical and chemical to electromagnetic radiation (radio wave energy)
to heat, sound, etc.

Energy conservation: the "1st law of thermodynamics"
"Total energy is *conserved*, neither created nor destroyed"

NB: this is a fundamental principle of modern physics, *but* no one has *proven* that it is correct. We believe it because it has survived every experimental challenge for hundreds of years

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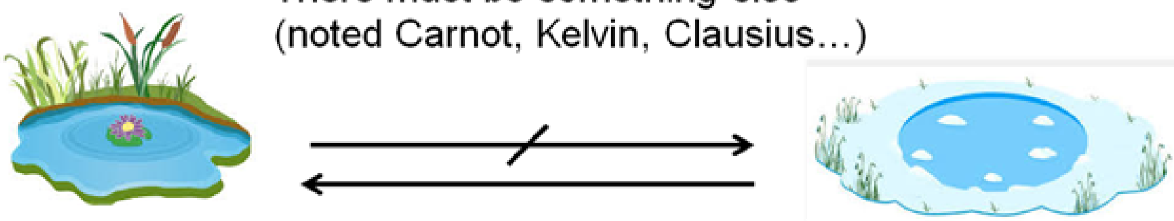
There must be something else
(noted Carnot, Kelvin, Clausius…)



A pond on a hot summer day *never* freezes, giving up its heat to the air!

Q: Such a situation does not violate 1st law of thermodynamics, yet it never happens. Why???

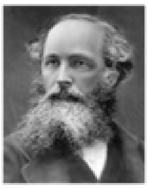
A: 2nd law of thermodynamics: total entropy (disorder) always increases

**2nd law of thermodynamics (there are various ways of saying it)**

Carnot's statement:
The *maximum* efficiency of an engine depends only on the temperatures of the two heat baths, efficiency=$(T_2-T_1)/T_1$ (ideal gas) This is an *upper bound* on how much work can be extracted from an engine for given heat put in.

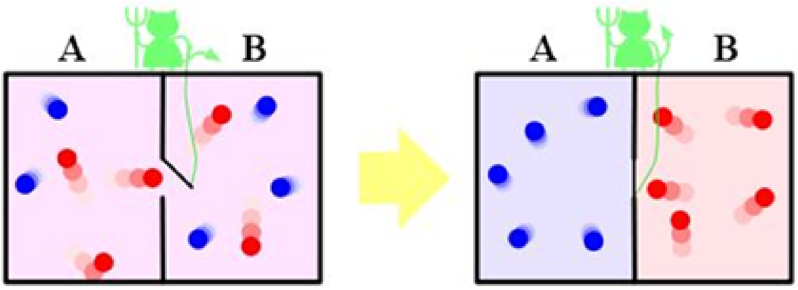
N.B. efficiency<1 -- no perpetual motion machines!

Note the 2nd law is only a *statistical* statement!



James Clerk Maxwell

Maxwell's Demon:

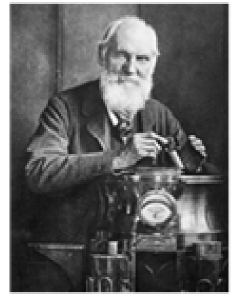



Entropy decreases!

2nd law could be violated by a demon – except what is the increase in his entropy? Nature has no such demons – usually!

# "Heat death" of the universe?

William Thompson, Lord Kelvin (1852)



Interactions of hot and cold bodies generally lead to equilibrium, coming to common temperature. If this continues indefinitely, universe will be at uniform temperature, no work can be done $\Rightarrow$ universe is "dead"



(…or Newton's God, who can wind up the universal clockwork again…)

Best estimate of time to heat death : $10^{100}$ years (wikipedia)

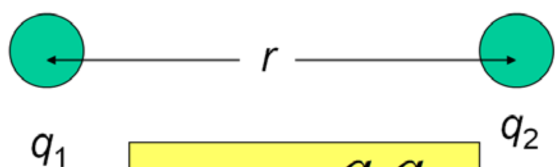
**November 1**

## Oersted, Faraday and the unification of electricity and magnetism

### I Oersted and Ampere: electricity can affect magnetism

**Electric force:**

- Electric charges come in two types, positive and negative (Franklin), unit of charge is Coulomb (C). Charge on electron is -1.6 x 10^-19 C, proton +1.6 x 10^-19 C.
- Demo -- charging an electroscope by induction
- Charles Augustin de Coulomb (1736-1806) did a delicate experiment proving that the force between two charges varied as 1/r^2, just like gravity. Formulated in Coulomb's law:




$$F = k\frac{q_1 q_2}{r^2}$$

- Note we don't often see manifestations of electric force, since most charges are bound up in to neutral atoms.
- Note difference with gravity. The source of gravity (mass) has only one sign, so gravity is always attractive, whereas Coulomb force can be either (like charges repel, unlike attract).

### Magnetism: brief history

- Ancients knew about lodestone, naturally occuring magnets, static electricity, lightning , even electric fish. In general these phenomena were not necessarily considered related
- **<u>100 A.D. China</u> Invention of Compass.** Known in Europe only by 12th century A.D. Immediately found use in Europe as navigational device, unlike China, where it remained largely a curiosity.
- 1269 A.D. Petrus Peregrinus experimented with magnets and iron filings, noticed lines of aligned filings converged at N and S poles of magnet.
- 1600 Publication of de Magnete William Gilbert. Repeated Peregrinus' experiments, great exponent of experimental method. Disproved superstitions saying garlic, onion, and diamonds could rob magnets of their power.Recognized that earth itself was a magnet, and that magnetic poles did not quite coincide with real poles.
- 1600-1820. Questions about connection between electricity and magnetism. 1681,

ship struck by lightning has compass reversed.

- 1820 Oersted experiment. Hans Christian Oersted, prof. at U. Copenhagen, shows that an electric current in a wire deflects a compass needle.

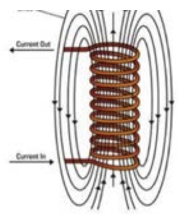
Oersted's life 1805-1875

a) Pharmacist's son
b) Doctorate in philosophy U. Copenhagen, admirer of Kant's philosophy of nature
c) Kant rejected French school of atomism, particles colliding (Descartes), preferred Newton's description of bodies acted upon by disparate forces. Attracted forces explained why bodies congealed into many observed shapes
d) Kant believed matter must also be repelled by repulsive forces, to prevent two bodies from occupying the same space. Hardness of surface due to this repulsive force. This *conflict of forces* (attractive and repulsive) led to solid bodies.
e) Oersted like many others was interested in understanding connection between electricity & magnetism, perhaps showing them to be aspects of the same phenomenon, as electricity and chemistry had been shown to be related in late $18^{th}$ cent. From his *philosophical* standpoint, there should have been a connection.
f) Famous expt. was performed as an apparently spontaneous experiment in front of his class to try to demonstrate the connection between e&m. Signal was "feeble" but unambiguous, may have been confused by circular nature of magnetic force.

- Sept 11- Nov 16 1820. Rapid scientific progress on electromagnetism. Arago communicates Oersted's expt to Paris Academy, reports that current in wire can align iron filings like ordinary magnet. Andre Marie Ampere reports theory of permanent magnetism due to molecular circulating currents. He reports own experments indicating a force between two current-carrying wires. Finally both Ampere and Davy report that a current in a coil of wire can turn an iron needle into a permanent magnet.
- Magnetic field. Faraday (see next lecture) showed that there were lines of force emanating from N and S poles of a magnet, envisioned magnetic influence as a "field" that filled all of space.
- Permanent magnets are materials where all the atomic or molecular *magnetic moments* are aligned. Each molecule acts as a little bar magnet with a N and S pole.
- The Earth is a permanent magnet (Gilbert), which is why the compass works!

# November 3

We've used electricity to produce magnetism (Oersted, Ampere)

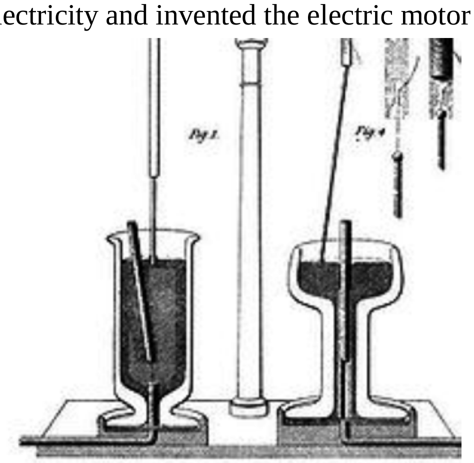



Faraday asked if we can use magnetism to produce electricity

Faraday's life:

- Humble upbringings
- Sandemanian: member of extremely conservative religious group, appeared able to "compartmentalize", i.e. religion did not influence his very creative, progressive science
- Apprenticed to bookbinder – read books he was binding, learned from them
- Lucky break: he attended lectures at the Royal Institution in London to learn more. Met Sir Humphrey Davy (chemist – showed chlorine & iodine were elements)
- Davy blinded temporarily by lab accident, hired Faraday as note-taker (amanuensis), saw that he was smart & creative. Eventually hired him as lab assistant and allowed him to do his own experiments
- Worked out influence of magnetism on electricity essentially without math (in contrast to Ampere, who was a great mathematician)
- Einstein called him one of the most creative minds in science
-

First Faraday experimented with electricity and invented the electric motor



The electric motor uses electricity to produce mechanical motion

He passed a current through a wire and caused a magnet to move in circles around it

He also made a current carrying wire to move around a stationary magnet

Faraday envisioned lines of magnetic force in the space surrounding a magnet

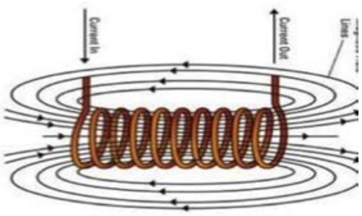
Later Faraday tried to produce electricity from magnetism

He passed a current through one wire and tried to induce a current in a second wire

He noticed that there was a spurt of current in the second wire only when he turned the current on or off

He realized that current could be generated when a magnetic field changes

Cutting the lines of force in a field generates electricity

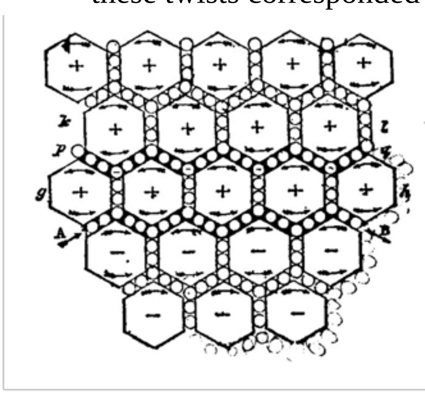




The question arose: were there really lines of force out there in space?

This question was raised again when James Maxwell gave an explanation of how electricity and magnetism were related

Maxwell said twists in the ether corresponded to magnetic effects while the movement of these twists corresponded to electrical effects



This mechanical analog so upset the French school that one,  Pierre Duhem said “Here is a book intended to expound a new theory. In it are nothing but strings which move around pulleys, which roll around drums, which go through pearl beads ... toothed wheels which are geared to one another and engage hooks. We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory.”

*However* Maxwell also described the twists and their motion mathematically in what has become known as Maxwell's Equations, which are wave equations

This result confirmed Faraday's assumption that electromagnetism was waves in the ether

From quantities (*measurable in the lab*) in these equations he found that the speed of electromagnetic waves was c (known quantitatively from Roemer's expts. in 1676, and refined several times before Maxwell to be $3x10^8$ m/s). Connection between light, electricity and magnetism had not been anticipated earlier.

**Realism**

The success of Maxwell's model plus that of the Kinetic Theory of Gases suggested to many that models described nature "as it really is"

The goal of seeing the world "realistically" became a watchword for the second half of the 19th century, which has been labeled the Age of Realism by historians

It is also visible in other aspects of life at the time - in politics, art, and literature

New developments would soon expose an outlook of realism as naive

## Nov. 8
## Michelson-Morley experiment

**Context of MM expt.**

Late $19^{th}$ century: period where scientists have a successful theory of mechanics and the solar system (Newton), as well as heat & energy. Attitude characterized by

a)*Realism*: Confidence that physics has captured nature "as she really is" -- complete description of objective reality possible

b) *Determinism:* Belief in a precise description of cause and effect. *In principle,* we can calculate everything!

Pierre-Simon Laplace (1814):

"*We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe* *and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes."*

In other words, once we know the laws of how particles interact, *in principle* we can run the equations for the universe backwards or forward in time and calculate everything.

Timeline:

- o Understanding of light as electromagnetic wave (Maxwell, 1865)
- o Reliable submarine telegraph cable 1866
- o Periodic table of elements (Mendeleev, 1869)
- o Discovery of cathode rays (Crookes, 1875)
- o Telephone (Bell, 1876)
- o Phonograph (Edison, 1877)
- o Light bulb (Edison, 1879)
- o Discovery of radio (electromagnetic) waves (Hertz, 1887)

Most physicists were confident that nature would soon be understood.

**Albert Michelson (1852-1931)**

•Son of Polish immigrant who came to California for gold rush

• Early research on interferometry and laboratory measurements of speed of light, at US Naval Academy and Case School (now Case Western)

• Spent career attempting measurements of the earth's velocity with respect to the *ether* – medium supporting *electromagnetic waves*

**Ether**

•Logic (faulty): light is transported to us over vast distances from the stars. Light is a wave. Therefore there must be a medium, filling all of space, which supports light waves the way air supports sound waves.

• Light goes very fast, so the ether must be very *stiff*.

• Yet things moving through it experience *no resistance*!

• The Earth moves through the ether, so from our perspective we would experience an "ether wind" which blows over us in the direction opposite to our motion. The difference in wind direction between summer and winter should be detectable.

• Michelson and collaborator Morley built an interferometer to detect the effects of the ether wind on the time it took to reach a detector along two different paths (see simulator).

• Experiments in 1881,1885,1905, .. showed no effect -- there was no ether!

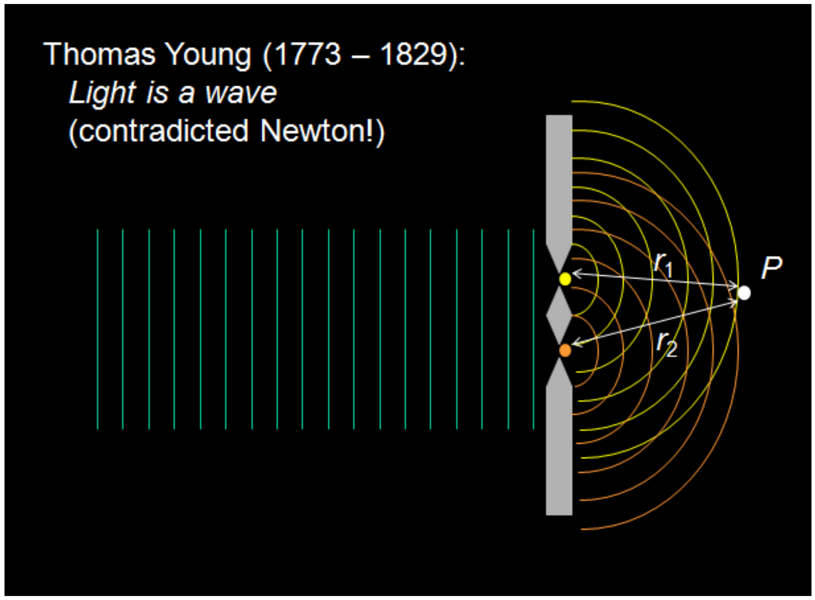
**Light, interference, double slit experiment**

• Light is an electromagnetic wave. Visible light is in the wavelength range between 3000A and 8000A, a small part of the electromagnetic spectrum, which extends from radio waves (wavelength meters or many meters) to gamma rays (wavelength comparable to the size of an atomic nucleus).

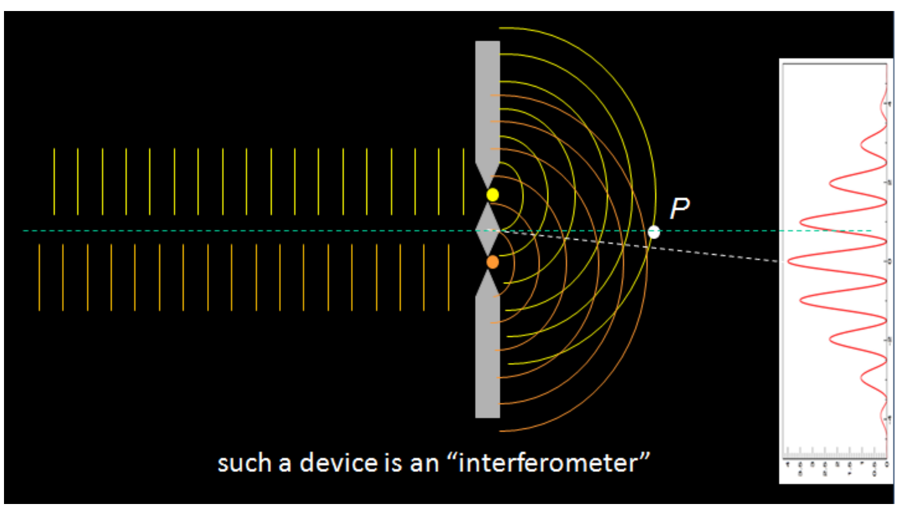
• Wavelength (lambda) is distance between successive crests of a wave. Frequency is 1/T, where period is the period of oscillation or time between crests. Wave speed, wavelength and frequency are related by v=f . lambda.

.

• Thomas Young showed convincingly that light had wavelike properties with his "double slit experiment". At two narrow apertures, waves spread out like two independent sources, then the crests of the two overlap along certain lines ("constructive interference") and another set of lines corresponds to overlapping of crests and troughs ("destructive interference"), just like similar phenomena seen in water waves. In particular, right along the line bisecting the two apertures, there is a maximum, because the crests arrive at the same time.




• This is how Michelson was in principle able to detect two pulses of light that had travelled along two different paths with precisely equal lengths, but one travelling back and forth along the direction of the ether wind, one transverse to it. The times taken are different if there is an ether (see homework). Imagine that one did the same 2-slit experiment as in the figure, but one wave arrived slightly behind the other: you would see a shifted pattern, and in particular the central maximum would no longer be quite in the middle.




• Michelson saw nothing in his 1881 or 1887 experiments. Desperate to see the effect he thought must be there, he spent his career refining the precision of his apparatus. While spurious signals occasionally arose, in the end the scientific community had to confront the fact that there was no ether. So the questions: "what is the speed of light measured relative to?" became extremely pressing.

After Maxwell the question about the status of models gained new impetus. Was, for example, the ether really out there with twists and ball bearings in it? Or was it just a hypothetical entity we make use of to allow us to make calculations and predictions? Two positions in philosophy of science are based on this kind of question: 1) Realism - the entities we use in scientific theories have counterparts in reality. 2) Anti-realism - the goal of the scientist is to come up with a coherent explanation of nature without regard to whether the entities or assumptions employed really exist. Realists ask why predictions based on theories come true if the entities do not really exist. Anti-realists note that the theories of science inevitably lead to contradictions, which suggests we haven't gotten down to reality.

In the 19th century physicists like Oliver Lodge and Henry Rowland emphasized the non-hypothetical nature of the ether. The idea that physicists were getting close to reality in their theories was consistent with the spirit of the time, a period which has become known as the Age of Realism. Other cultural expressions of the age were evident in the art (e.g. Courbet, photography), literature (Flaubert, Hardy), politics (Bismarck's *Realpolitik*), religion (Feuerbach's critique), social theory (Marx), technology (steam locomotives, electrified cities, telegraph) economic change (construction and urban renewal). W.R. Greg summed up much when he said in 1875: "The most salient characteristic of life in the latter portion of the 19th century is its SPEED."

Some scientists expressed a bold confidence that physics was nearing a complete explanation of nature a the century came to a close:

"The next 100 years is not likely to duplicate the 19th century where great, original, and far-reaching discoveries in electricity is concerned."

Thomas Mendenhall. AAAS president, 1887

"An eminent physicist has said that the future truths of physical science are to be looked for in the 6th place of decimals."

Albert Michelson, 1894

These statements were made on the eve of two major "original and far-reaching discoveries: relativity and quantum mechanics.

## November 13

## Einstein's theory of Special Relativity ["Mechanical universe" movie]

Galileo came to the conclusion that rest and uniform motion were equivalent states. This is called **Galilean Relativity.** Two inferences from this assumption are

1) It is impossible to tell whether or not one is moving **from within a given frame of reference**

2) The laws of physics are the same for all observers in uniform motion

A question that arises is: Do we mean **all** the laws of physics? Galileo was referring to the laws of mechanics. What about, for example, the laws of electromagnetism, a relatively new branch of physics at the end of the 19th century.

In mechanics we get the velocity of an object for an observer by finding the resultant sum of all the component motions. Example: a ball thrown forward on a moving train adds the ball's velocity and the train's velocity for an observer standing alongside the tracks. We expect, according to Galilean relativity, the same method to apply for electromagnetism, for example, a beam of light.

At 16 Albert Einstein came up with a thought experiment that cast doubt on applying this method for light. Einstein asked if the train were traveling at the speed of light, would he see his reflection in a mirror held out in front of him. Since he was going the same speed as light, then it could not get ahead of him to the mirror to be reflected. But if he didn't see it, then he would know, from within his frame of reference, that he was moving, a No No for Galilean relativity. A simulation of this thought experiment is at https://www.youtube.com/watch?v=vVKFBaaL4uM

It seemed that he would either have to give up Galilean relativity or conclude that light was special. He had no intention of giving up Galilean relativity. He concluded that he **would** see his reflection in the mirror. He postulated that the speed of light was independent of the frame of reference, that all observers in uniform motion would measure light's speed to be the same. (In other words, one cannot add up the component motions of light to get the resultant sum like we did for the ball on the train.) This postulation then meant that distance (space) and time, the parameters in which velocity is measured, would have to change together simultaneously to accommodate the constancy of light's speed.

**Time dilation in special relativity**

Imagine observing a clock moving with respect to you with speed $v$. Einstein says you observe this clock running slower than yours. That is, a tick $\Delta t$ in the clock's rest frame is shorter than the tick $\Delta t'$ you observe when you are looking at the clock in the the moving frame. Now any clock is equivalent (it turns out) to a "light clock" consisting of light bouncing back and forth between two mirrors. Suppose we position the clock perpendicular to the direction of motion, and consider its motion to the right for one "tick", consisting of the light going back and forth once:

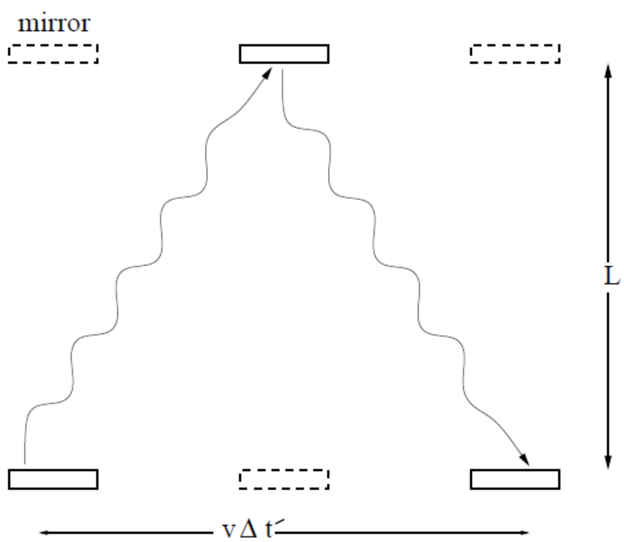



Figure 5: a) mirror clock moving for one tick

The distance traveled by the light pulse is $2\sqrt{L^2 + (v\Delta t'/2)^2}$, so a tick lasts a time equal to the distance/speed, or $\Delta t' = 2\sqrt{L^2 + (v\Delta t'/2)^2}/c$. Squaring both sides, we get

$$c^2(\Delta t')^2 = v^2(\Delta t')^2 + 4L^2$$

$$\begin{aligned} \Rightarrow \quad (\Delta t')^2(1 - v^2/c^2) &= 4L^2/c^2 = (\Delta t)^2 \\ \Rightarrow \quad \Delta t' &= \frac{\Delta t}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \gamma \Delta t \end{aligned}$$

where I used the fact that in the rest frame a tick is just $\Delta t = 2L/c$, and defined a new quantity

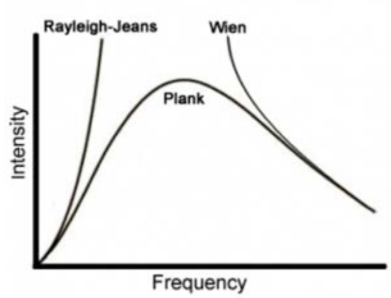
$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}.$$

This factor, which will always be $> 1$ since $v < c$ always, appears all over the place in the theory of relativity. If the velocity $v$ is anything reasonable, i.e. much less than $c$, $\gamma$ is approximately 1, and we can forget about relativity. But if $v$ is a significant fraction of $c$, $\gamma$ gets big. In this case we can see that $\Delta t' = \gamma \Delta t$, i.e. "moving clocks run slower". What this really means is, if you observe a clock in another frame moving at a uniform velocity with respect to yours, you measure it to run slower than the equivalent clock at rest in your frame.

**November 15**
**Quantum theory**

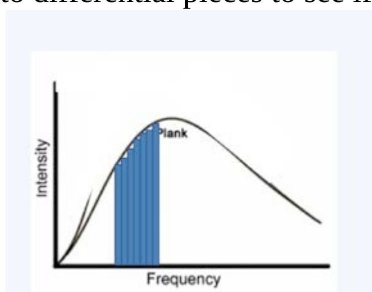
Maxwell's ether model and Einstein's relativity ideas challenged physicists at the end of the $19^{th}$ century. Another problem that was puzzling physicists at the turn of the century was the distribution of light energy from glowing solids and liquids. In general the amount of energy radiated at different wavelengths (the "color balance") correlates with the temperature. The challenge was to find a general result that would show how energy was distributed across the electromagnetic spectrum for a given temperature T.

Lord Rayleigh and James Jeans had found a curve that captured the low frequency end of the spectrum, and Ludwig Wien had a curve for the high frequency end. Max Planck announced a curve in the fall of 1900 that took the best from each of these earlier curves and also covered the middle range of frequencies.



These physicists were assuming a model that explained how heated matter produced radiation. They imagined a charged particle in the walls of the heated solid that vibrated, producing changing electric and magnetic fields (i.e., an electromagnetic wave). According to this model at low frequencies the energy would be low and at high frequencies the energy produced would be high; in fact, there was no upper limit for the amount of energy produced in the high frequency end of the spectrum (this result was called the ultra-violet catastrophe since ultra-violet was among the highest frequency electromagnetic radiation known at the time). But experimental results showed that this did not happen at high frequencies.

Planck set out to rectify the model with experimental data. To do so he returned to a problem in thermodynamics he had worked on for a long time, hoping it would help him. Although he had little patience with the approach of Ludwig Boltzmann, an Austrian physicist who used a statistical approach in his work, Planck, in desperation, decided to break the energy distribution into differential pieces to see if it would help.

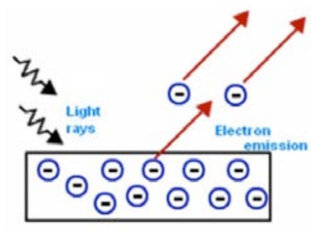



In fact doing this made him realize that he could get the curve he had obtained for the experimental data. But unlike Boltzmann, who always allowed the number of pieces to become infinite, Planck did not “add them up” in this fashion.

He defined the energy of each piece as E = hf, where f was the frequency of the piece and h was a constant, now known as Planck’s constant. By leaving them in this form it was possible to explain how, although the pieces at the high frequency end each had a high energy, collectively they might add up to a relatively small amount when compared to the total energy of the middle range frequencies. In this way the ultra-violet catastrophe was averted.

The implication of identifying pieces of energy, or quanta as Planck named them, was that energy was radiated and absorbed in discrete packets, not continuously as physicists had unconsciously assumed. Energy was like eggs, not like milk – it came in discrete amounts, not in just any amount.

Planck's technique received confirmation when his idea of energy quanta helped explain the photoelectric effect.




Light shined on certain metals produces electrical current

Light shined on certain metals produces electrical current. It did not seem to vary with the brightness of the light, but did with the color. It made sense that the energy packets of red light (whose frequency was relatively low, so hf was low) did not produce current, but blue energy packets (with higher frequency and higher energy packets) did knock out electrons from the metal to obtain current.
Quantizing energy would soon receive approval from other quarters when it was used to help establish the Rutherford-Bohr atom.

**Bohr atom and de Broglie wavelength**
Balmer series was a series of discrete spectral lines observed in heated hydrogen gas, named after the Swedish schoolteacher who discovered the mathematical pattern in their frequencies

$$\frac{1}{\lambda} = R_H\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$

Niels Bohr, a young Danish physicist, developed the Bohr model of the atom (1913) that reproduced precisely these results by assuming Planck's quantization (with the same Planck's constant h!) applied not just to electromagnetic radiation but to the wavelengths of electrons in orbit around the atomic nucleus. The discreteness of the allowed energies helped to explain why orbiting electrons, which were accelerating, did not radiate away all their energy as Maxwell might have predicted classically. de Broglie (1924) later generalized this idea to suggest that all particle can be considered as a wave with wavelength h/p, where p is the particle's momentum.

**Schroedinger and Heisenberg: the new quantum mechanics**

For a few years in the early twenties, both Erwin Schroedinger and Werner Heisenberg were advocating apparently different mathematical frameworks of quantum mechanics that purported to explain the Bohr model, blackbody radiation etc. that were the cornerstones of the old quantum theory. Schroedinger came up with his wave equation describing the mathematical behavior of particles as waves and how they responded to external forces. He invented it during a trip to the mountains in Switzerland with his mistress. The equation was based on a "wave function" called $\psi(x)$ that represented the "probability amplitude" (probability is $|\psi(x)|^2$, as proven by Max Born) of finding a particle at x. It was intrinsically statistical and uncertain. Werner Heisenberg's framework was based on mathematical objects called matrices.  Quantum theory took a great leap forward and was more generally accepted by mainstream physics when it was shown that the two formulations were rigorously equivalent.  Meanwhile, Heisenberg explored the “wave-particle duality” of the theory, and argued that waves and particles were classical concepts, while actual electrons, for example, had aspects of both.  He argued that the act of observation of an electron was important in the outcome of an experiment, and put limits on how much could be known about a physical system, encapsulated in his “uncertainty principle”,

$$\boxed{\Delta x \, \Delta p \approx \hbar}$$

Where $\Delta$x is the uncertainty in the knowledge of a particle’s position, $\Delta$p is the uncertainty in the knowledge of a particle’s momentum, and hbar is Planck’s constant divided by $2\pi$. One cannot know both a particle’s momentum and its position perfectly well at the same time.

Heisenberg led the German atomic bomb project during the war, while Bohr lived in England and assisted the British bomb effort coordinated with the Manhattan project in the US.  Michael Frayn’s “Copenhagen”  is a fictional accounting of conversations they had or could have had when Heisenberg visited Bohr in England just before the war.

## November 17

Film, “Knowledge or certainty”, Jacob Bronowski, *Ascent of Man* series.

## November 29

Final discussion of quantum theory, discussion of Bronowski film

## December 1

### General Relativity and Cosmology I

[guest lecture by Guido Mueller, who covered some of the material below, which comes from another lecture.  His slides posted on notes page.]

### Einstein’s Principle of Equivalence

- Statement of principle: there is no way to distinguish an accelerating frame from one acted on by a gravitational force

- Discussed how Galileo’s experiment with falling bodies would work perfectly well in accelerating rocket far from any stars or planets
- A rock thrown horizontally moving at constant velocity wrt an observer in a frame moving at uniform velocity, when entering the accelerating rocket, would appear to “fall”, looks like parabola to observer inside.
- Do the same experiment with light: the observer in the accelerating rocket must observe the light bending, just as the rock’s trajectory did.
- Using the principle of equivalence, light must bend in the presence of a gravitational field.

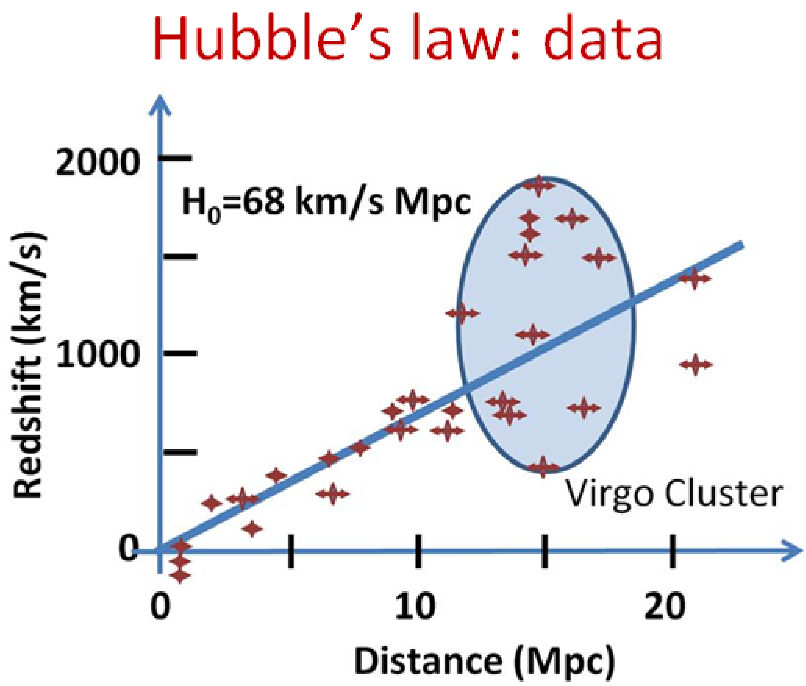
**Eddington Eclipse experiment 1919**

**Distances to stars and galaxies: (Henrietta Leavitt)** At beginning of 20th century there was little understanding of absolute or relative distances of celestial objects beyond the nearest stars, where parallax measurements were possible. One of the first essential contributions to the quest to find a “standard meter stick” -- a way to measure stellar distances -- was provided by Henrietta Leavitt at Harvard, who in 1908 studied Cepheid variables – stars that oscillate in brightness.
She found an intrinsic relation between brightness and period. Now it was possible to compare different stars with the same period; if they were dimmer, they were further away, since brightness decreases as 1/r^2 as a function of the distance of the star.

**Composition of stars: mostly H and He (Cecelia Payne)** Another Harvard astrophysicist, Cecelia Payne (later Payne-Gaposchkin), studied the composition of the sun and other stars using the new tools of spectroscopy. She found, against expectation, that the composition of the sun was almost entirely hydrogen and helium (very few heavier elements, as found, e.g. in the Earth). She was said to have written “the most brilliant Ph.D. dissertation in astrophysics ever”. Nevertheless both Payne and Leavitt experienced difficulties during their careers because they were women.

The composition of the sun established by Payne was later crucial to the understanding of the mechanism by which stars produce energy. Hans Bethe showed in 1939 that nuclear fusion -- a reaction whereby four hydrogens fuse to produce a He atom -- produced most of the energy.

**Redshift: Doppler effect for light. Light from star moving away is shifted towards red (lower frequency)** A second way of measuring distances was provided by measurements of stellar and galactic redshifts. The term redshift applies to the Doppler shift of a spectral line from its frequency observed at rest to the lower frequency side due to motion of the emitting object away from the observer. The Doppler effect is observed for any wave phenomenon when the emitter and observer are in relative motion, but is most familiar from sound. When a car passes you and you hear the tone of the engine or a horn fall in pitch, this is a “redshifted” sound.




Data on galactic redshift (velocity) vs. distance. Note that Hubble's law holds only on the average. It does not account for local motions of galaxies in a region where there is a lot of clustering, i.e. a bunch of galaxies gravitationally bound to one another.

**Galaxies are receding at velocity which grows linearly with distance $v=H_0d$**

In 1924, Edwin Hubble's observations of remote galaxies, and the redshift of their spectral lines led him to observe that the further away the galaxy, the greater the redshift of its spectral lines. Note that an independent measurement of distance (e.g. Leavitt's variable stars) was needed to reach this conclusion. This linear relationship is called Hubble's Law. Galaxies are getting farther apart as time progresses, therefore the universe is expanding. Note this is not an expansion from a single center, as one might imagine. Rather the universe is like a loaf of raising bread expanding as it bakes. Any raisin (galaxy) gets further apart from any other raisin during this process. Einstein didn't like the expanding universe notion, and had introduced his cosmological constant in order to avoid expanding universe solutions to his equations. Later, when he had accepted Hubble's conclusions, he allegedly called this attempt to keep a static universe "the greatest blunder of my life".

**Running Hubble's law backwards d->0 gave age of universe $1/H_0$ ~ 13.4 billion years.** If they are moving farther apart now, running time backwards gives a time of $1/H_0$ when the galaxies all were together at one point. This timescale is about 13.4 billion years, roughly the modern estimate for the age of the universe.

**Question re Olber's paradox: why the sky is not white.** In the 19th century a physicist named Heinrich Wilhelm Olbers pointed out that if one assumed the universe was infinite, the brightness reaching our eyes from an infinite number of stars with brightness decaying as 1/r^2 would make the night sky white, not black (for a cool simulation, see http://en.wikipedia.org/wiki/Olbers%27_paradox). This is not the case, both because Olbers did not account for the red shift of the light of distant stars, and because we are not causally connected to the entire universe, just that part of it up to a distance $c/H_0$ where light started towards us 13.4 billion years ago.

## December 6
## Cosmology II

[Only some of the material below was covered in lecture. None of it will be on the final exam. Summary of course, science and religion, …]

**Origins of Big Bang theory:**

Belgian priest Georges Lemaître (1927) considered idea of expanding universe, realizing that the universe was smaller yesterday than today, and so on until a "day that would not have had a yesterday": the moment of creation.

•This idea wasn't widely accepted at first: Fred Hoyle dismissed "this hot Big Bang", noting that there wasn't any record or remnants. He argued for a "steady state" universe.

**George Gamow (1948) suggested that if the universe was created with a "hot Big Bang".** Consequences were

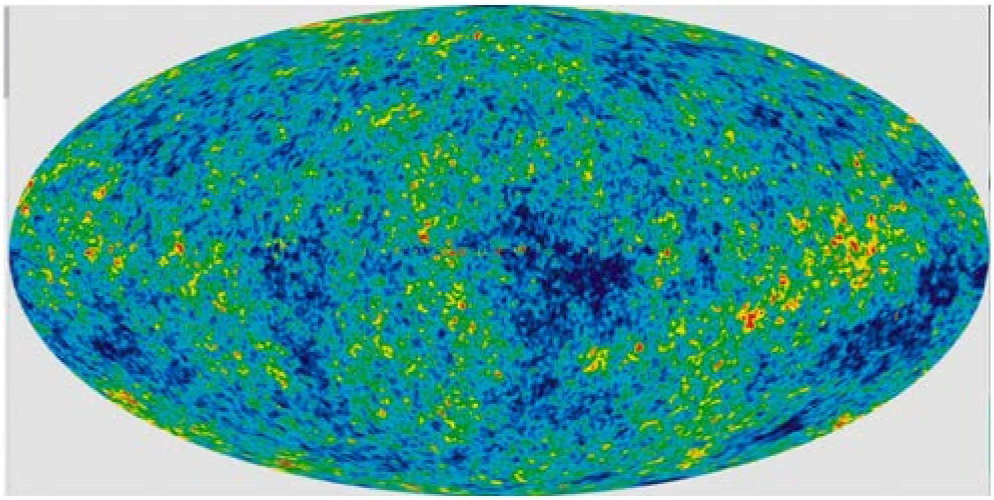
–Various elements, such as H and He, would be produced for a few minutes immediately after the Big Bang due to the extremely high temperatures and density of the universe at this time.

–The high density would cause rapid expansion.

–As the universe expanded, H and He would cool and condense into stars and galaxies.

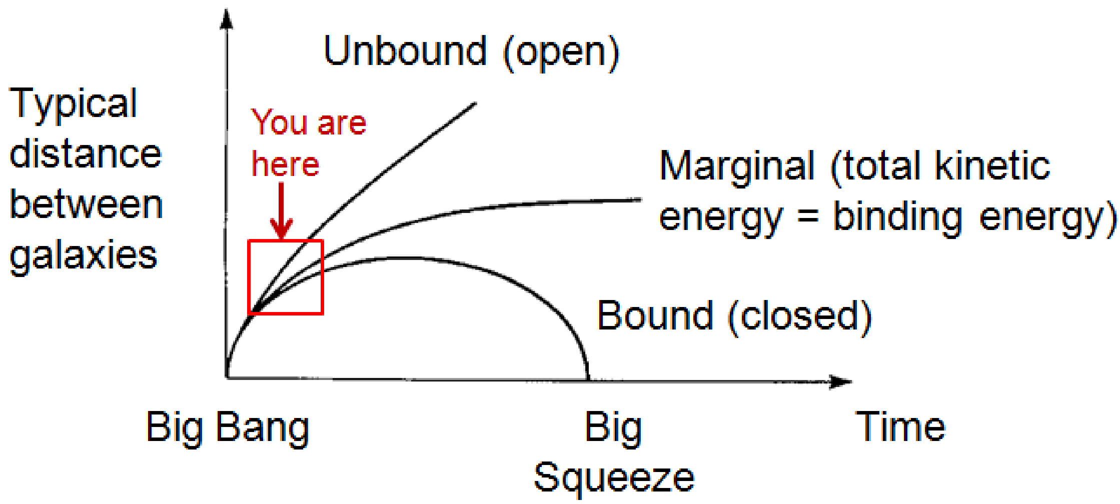
–Today, due to continued cooling, radiation left over from the epoch of recombination, when neutral atoms formed (~380,000 years after Big Bang) should be about 3K (he said 10K!).

**Attempts to detect remnants of big bang.** Robert Dicke and Jim Peebles at Princeton recognized that one could try to detect radiation from the big bang in the microwave (wavelength a few centimeters) range with microwave antennas. They were in the process of refining the resolution of their failed first experiment when they were approaced by Robert Wilson and Arno Penzias from Bell Laboratories, who had been experimenting with microwave telephone communications, and were bothered by a persistent "hiss" in their instruments when they pointed them at the sky. Their initial suspects was pigeons; Dicke and Peebles told them they were listening to the beginning of the universe. Penzias and Wilson received the Nobel prize in 1978 for the discovery of this "Cosmic Microwave Background radiation". The CMB radiation has a spectrum very similar to a glowing heated body as studied by Planck, because the early universe was in fact just a glowing ball of radiation and charged elementary particles, before it cooled and combined into neutral atoms and eventually stars and galaxies. The peak of this spectrum, determined by the temperature of the glowing body, has fallen to only 3 degrees Kelvin because the universe has expanded and cooled; simultaneously the wavelength of the radiation heading towards our eyes has been drastically redshifted (wavelength stretched).



Distribution of microwave radiation at 3K in the sky (WMAP).

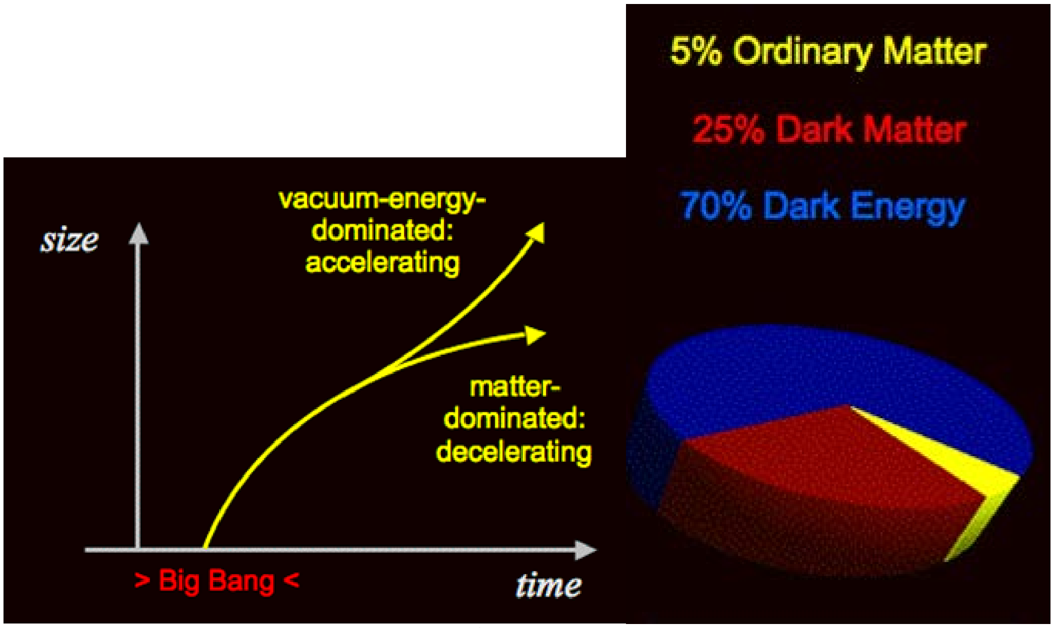
Several early experiments to detect the full spectrum and anisotropy of the CMB radiation were done in high-altitude balloons and U-2 planes to get above the atmosphere, which absorbs microwaves. More recently, the Cosmic Microwave Background Explorer (COBE) and Wilkinson Microwave Anisotropy Probe (WMAP) satellites have provided high-resolution data. Why is the anisotropy of the radiation (intensity slightly different in one part of the sky than another) important? If the universe had been completely homogeneous and isotropic at the beginning, it would have stayed that way while it expanded. The fact that we see some anistropy (not much -- the signal is tiny!) tells us about the “initial conditions” of the big bang -- what the universe was like when it started.




Expanding universe solutions to Einstein's equations

**Is the universe open or closed?** Expanding universe solutions to Einstein's equations depend on the density of matter. All three expanding solutions predict that the matter in the universe was concentrated at earlier times, and that the expansion started as an explosion of this concentration. If the density is low, the universe continues to expand forever; if too high, it stops expands and begins to contract eventually. There is a critical density between these two. The solutions correspond to spacetime curvature negative, positive, and zero, respectively. In principle measurements should be able to determine how much mass there is, and therefore enable us to decide the ultimate fate of our universe.

**Dark matter?** Even 30 years ago it was understood that we did not see a good deal of the matter in the universe, that is it was not bound up in luminous objects like stars. Luminous "normal" matter is only about 10% of the critical density. Using Newton's law of gravitation, one can calculate the speed of stars in a rotating galaxy, and if the only mass were in stars, the velocity at a given radius from the galactic center would have been very different than is actually observed. Therefore it was understood that some additional, nonluminous mass must be present. This could be lots of largish planet-size objects not associated with stars, or exotic weakly interacting elementary particles ("Axions" or "WIMPS").



From Sean Carroll, Caltech. Acceleration of universe's expansion due to vacuum energy. Percent of all mass-energy tied up in various kinds of matter.

**Acceleration of the universe and "Dark energy"** In the past 10 years or so there has been increasing evidence for not only an expanding universe, but one whose expansion rate is increasing in time. Accounting for these data turns out to require a large cosmological constant, or "vacuum energy", sometimes referred to as "dark energy". It now looks as though this dark energy makes up 70% of the universe. It's a field that pervades everything, but difficult? impossible? to detect directly. Stay tuned