LECTURE 6: PRINCIPLES OF SPACE AND TIME

- Coordinate systems and reference frames
- Galilean relativity
- Cosmological principle
- Cracks in Newton's theory
- The speed of light problem

This week: please finish Ch 6 of text and start Ch 7

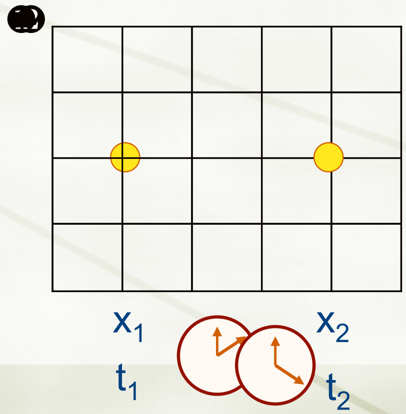
Coordinate systems

- Scientific observations involve making measurements
- Fundamental measurements are always of events in terms of their coordinates in space and time
- Space-time coordinates are often written as (x,y,z,t)
- Coordinates are convenient labels, not fundamental attributes of space and time
  - We are free to choose whatever units we want (e.g. m, km, foot,…), and whatever coordinate origin we want
  - What matters is the *intervals* in time and space, not absolute numbers. For Event 1 at (x_1,y_1,z_1,t_1) and Event 2 at (x_2,y_2,z_2,t_2), the time interval is $\Delta t=t_2-t_1$, and using the Pythagorean theorem generalized to 3D, the space interval (distance) is

$$\Delta s = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

Review- Velocities and accelerations

- Velocities are rates of change of vector *positions*
- Accelerations are rates of change of vector *velocities*
- For motion in a *given* direction, the velocity is equal to the change in position $\Delta \underline{x} = x_2 - x_1$ divided by the corresponding change in time $\Delta t = t_2 - t_1$: $\underline{v} = \Delta x / \Delta t$
- Similarly, $\underline{a} = \Delta \underline{v} / \Delta t$



Re-cap: Inertial and non-inertial frames of reference

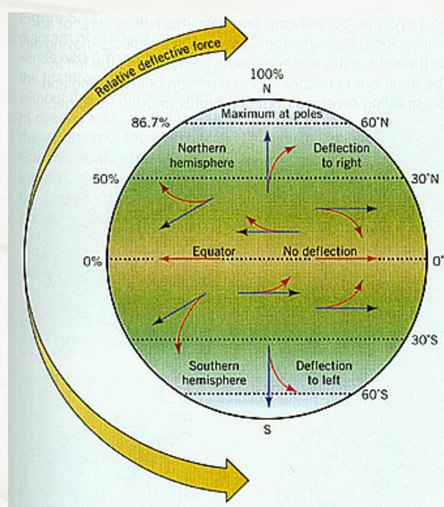
- Newton's laws are powerful. But they also lead to some puzzles, particularly relating to reference frames.
- We have already come across idea of frames of reference that move with constant velocity. In such frames, Newton's laws (esp. N1) hold. These are called **inertial frames of reference**.
- Suppose you are in an accelerating car looking at a freely moving object (i.e., one with no forces acting on it). You will see its velocity changing because you are accelerating! *In accelerating frames of reference, N1 doesn't hold* – this is a **non-inertial frame of reference**- and it can have 'fake' forces(last lecture: Coriolis, centrifugal forces) .

Coriolis force: a fictitious force

Inertial frame

Noninertial frame

Coriolis at work



Real and fictitious forces

In non-inertial frames you might be fooled into thinking that there were forces acting on free bodies, because velocities change.

- Such forces are call "fictitious forces".

Examples –

- G-forces in an accelerating vehicle.
- Centrifugal forces in amusement park rides.
- The Coriolis force on the Earth.

- Fictitious forces point opposite to the direction of acceleration measured in an inertial frame
- Fictitious forces are always proportional to the inertial mass of the body.

Frames of reference, again

- The frame of reference in which a measurement is made consists of the spatial coordinates (the grid) and time coordinate (the clock) that are used to make the measurement
- Note that in general, we use a "clock" that is attached to the spatial coordinate system we are using (why this matters will become apparent soon!)
- The reference frame may potentially have any arbitrary motion and/or acceleration. However, reference frames that have $a \neq 0$ are fundamentally different from those with $a=0$
- "Inertial frame" = unaccelerated frame
- "Non-inertial frame" = accelerated frame
- *How can an observer inside the frame tell the difference?*
  - In an inertial frame, a free particle (no forces acting) has constant velocity (including v=0 special case)
  - In a non-inertial frame, a free particle's velocity (speed and/or direction) varies
  - Note that for humans, even if we don't have a free particle handy for experiments, we can sense accelerations physiologically

…does this seem familiar?

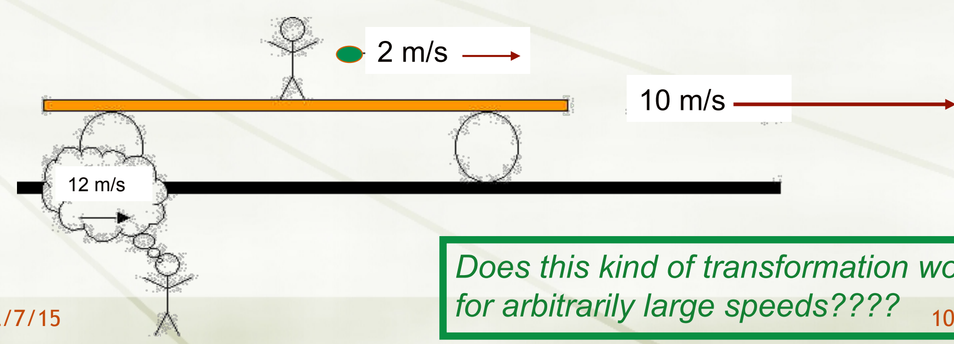
Recall that from weak equivalence principle, inertial mass=gravitational mass ⇒ *gravitational force is proportional to inertial mass.*

Maybe gravity is a fictitious force…

… and we live in an accelerating frame of reference???

Relativity

- "Relativity" refers in general to the way physical measurements made in a given inertial frame are related to measurements in another frame.
- An inertial observer is one whose rest frame is inertial
- A quantity is invariant if all inertial observers obtain the same value
- Under Galilean relativity, measurements are transformed simply by adding or subtracting the velocity difference between frames:
- v_{ball}(measured on ground)=v_{train} (measured on ground)+v_{ball}(measured on train)
  12 m/s = 10m/s + 2 m/s
- V_{ball}(measured on train)=v_{ground}(measured on train)+ v_{ball}(measured on ground)
  2 m/s = -10m/s + 12 m/s



Does this kind of transformation work for arbitrarily large speeds????

Cosmological principle

- The physical universe is described in terms of its properties in space and time- this seems obvious, but various cultures have included other attributes
- Confined to Earth, we are unable to *visit* all of space (or obtain information from all of time) **but** we can observe the universe far back in time and far away in space
- From Copernicus onward, it was realized that *Earth is not a special place; this is extended to include the solar system, our galaxy and to the idea that* no *place in the universe is special with respect to its position in space* (however with respect to time we have the initial singularity of the Big Bang).

Cosmological principle

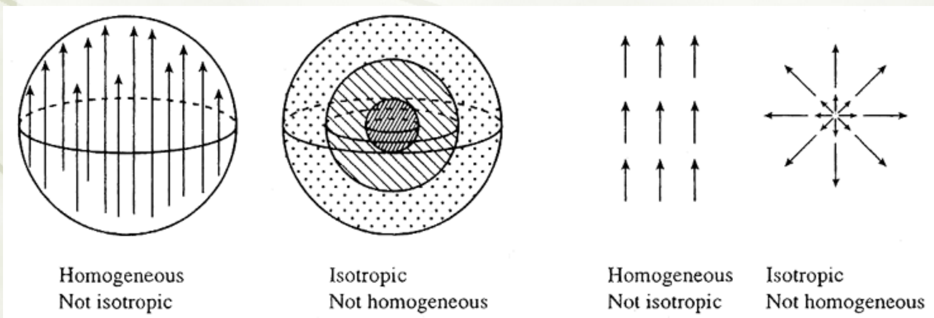
- In formulating cosmological models, we extend this idea to the much larger scale of the whole Universe
  - Fundamental principle is that any place in the Universe is "just about the same" as any other place. The Universe is essentially *uniform* (on large scales).

  or to phrase it differently
- On sufficiently large distance scales, there are no preferred directions or preferred *places* in the Universe.
  - The two testable structural consequences of the cosmological principle are homogeneity and isotropy.
  - *Isotropic:* Uniform in all *directions*

    e.g., surface of a sphere is isotropic, surface of a cylinder is anisotropic
  - *Homogeneous:* Similar conditions at all *locations*
  - Notes:
    1. isotropy as seen from every location implies homogeneity
    2. Homogeneity everywhere need not imply isotropy; e.g. surface of smooth, infinitely long cylinder is homogeneous but not isotropic

Cosmological principle

- Isotropy : there are no special directions to the Universe (e.g. no center)
- Homogeneous : there are no special places in the Universe.
  1. isotropy as seen from every location implies homogeneity
  2. Homogeneity everywhere need not imply isotropy; e.g. surface of smooth, infinitely long cylinder is homogeneous but not isotropic



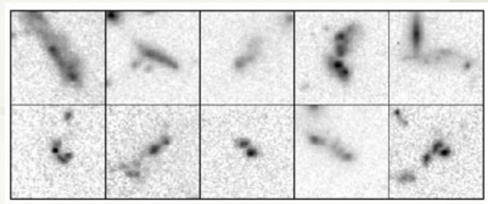
http://abyss.uoregon.edu/~js/cosmo/lectures/lec05.html

To Beat a Dead Horse

- :
  - Imagine that the whole universe is an infinitely large field with one perfectly symmetrical hill, which you are seated atop. Look around: you see an isotropic universe, since the hill is equally green and equally steep in all directions. But the universe is not homogeneous: it has a hill! http://curious.astro.cornell.edu/question.php?number=508
- These concepts are important-
  - most modern cosmology is based on the "cosmological principle," it is assumed that, on large scales, the universe is both homogeneous and isotropic. Studies of large-scale structure in the universe and analysis of the microwave background radiation help confirm that this assumption is justified.

Perfect Cosmological Principle

- The Perfect Cosmological Principle, that the Universe is homogenous and isotropic in <u>space and *time*</u>. That is, the universe looks the same everywhere (on the large scale), the same as it always has and always will- **<u>This is not true</u>**
- **<u>The universe was different in the past</u>**



Galaxies in the distant universe

Some Tests of Isotropy and (Homogenity)

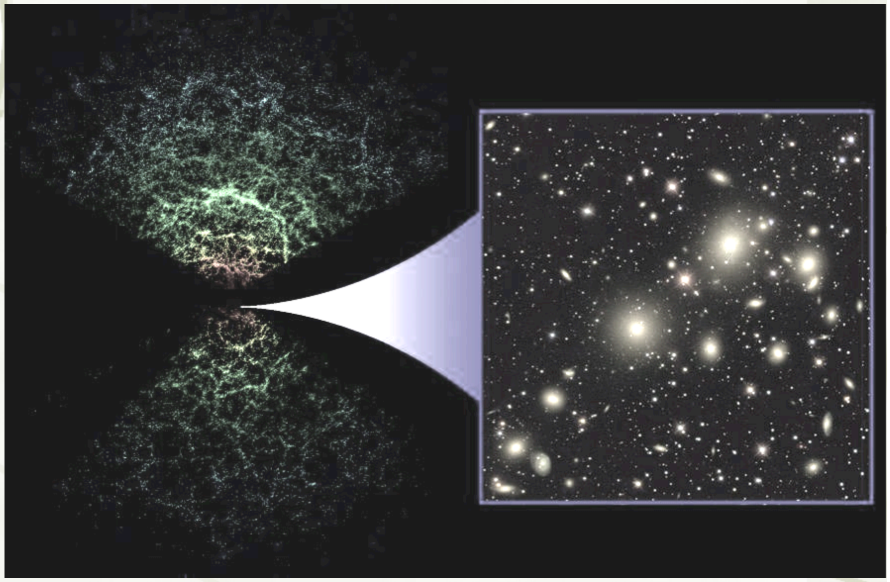
- (i) the large scale spatial distribution of galaxies, which form a *randomly* tangled web of clusters and voids up to around 400 megaparsecs* in width.
- ii) the distribution of radio galaxies, which are *randomly* distributed across the entire sky.
- (iii) the cosmic microwave background radiation, the relic radiation produced by the expansion and cooling of the early universe, constant temperature in **all** directions to one part in 10^5
- (iv) spatial distribution of gamma-ray bursts, objects at cosmological distances

Homogenity is very difficult to test since the universe is evolving- use consistency relations between distances and expansion rates: a bit messy to show

* megaparsec= 10^6pc=3.0856×10^{22} m

Large Scale distribution of normal galaxies

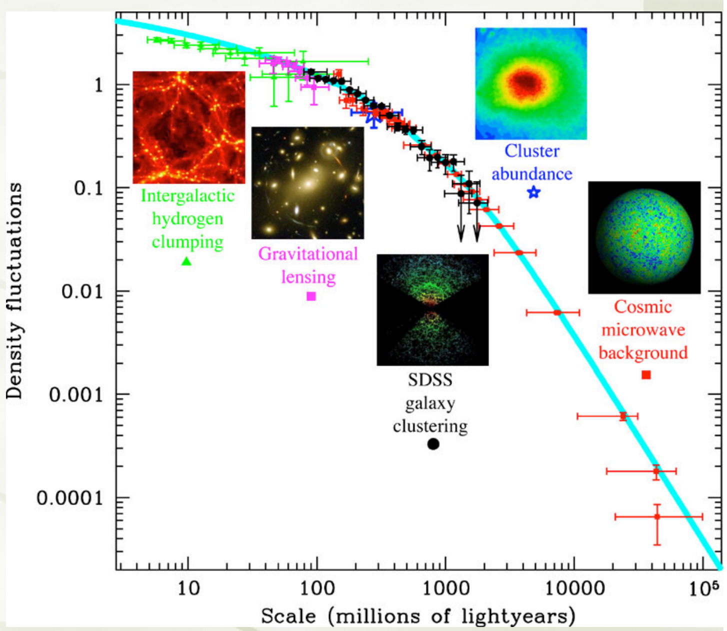
- On scales <100 Mpc the universe is 'lumpy'- e.g. non-homogenous
- On larger scales it is homogenous- and isotropic



Sloan Digital Sky Survey- http://skyserver.sdss3.org/dr8/en/

- As one goes to larger scales the universe gets less lumpy (on average)

Lumpiness of universe



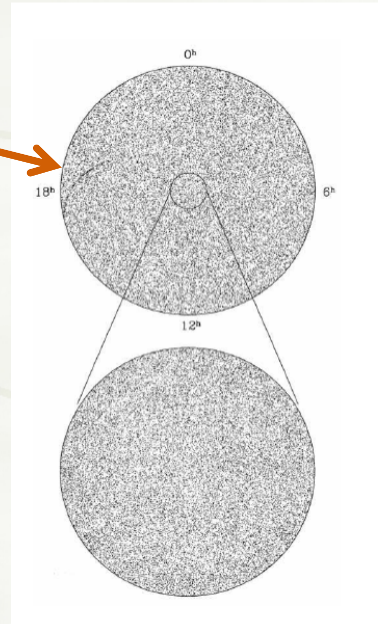
Tegmark 2004

size of box

*Distribution of Radio Galaxies**

- Position of 40,000 brightest radio sources in northern sky
- 40,000 brightest sources near celestial north pole
- Mean distance between sources is ~10^7 pc- probe very large distances up to when universe was 2 billion years old

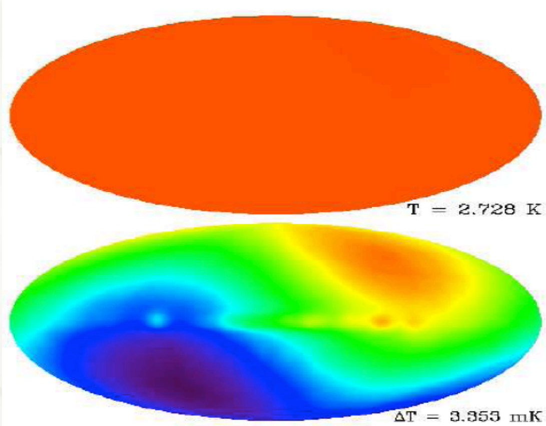
*radio galaxies are a special type of galaxy whose radio luminosity is produced by a supermassive black hole

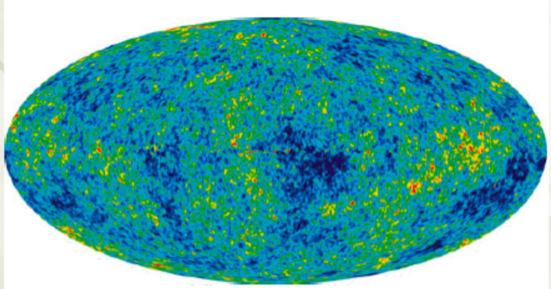


Condon 1999 PNAS97,4756

Microwave Background- relic of the big bang

- CMB probes whole universe at 300,000 yrs after Big Bang
  - isotropic to $\Delta T/T \sim 10^{-5}$

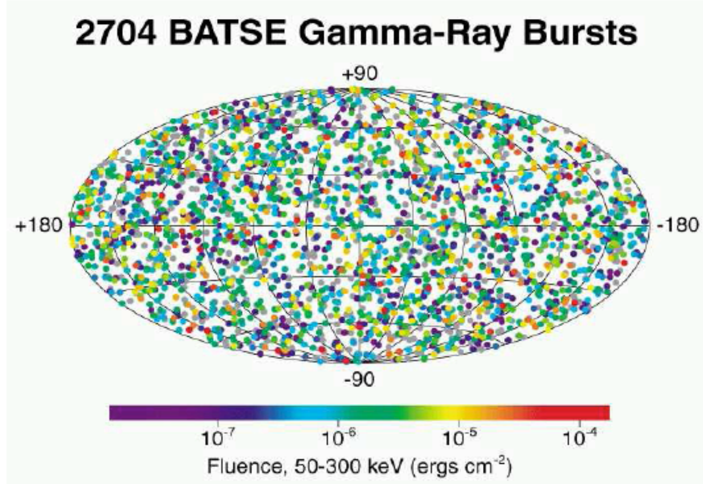




CMB temperature map from WMAP showing anisotropies at level of 10^{-5}

Gamma-Ray Bursts

- Gamma-ray bursts come from very far away, on average
- The mean *redshift* is z~1 (half the 'age' of the universe)- very isotropic



Position of γ-ray bursts on the sky in galactic coordinates derived from the Gamma-ray observatory satellite BATSE experiment- color is proportional to brightness of burst

- we will be defining redshift in a later lecture, but for now we can call it a proxy for distance

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- Cosmological principle → physical laws are assumed to be the same everywhere (can now measure atomic transitions in objects at redshifts ~6 when Universe is 1 billion years old and verify than quantum mechanics is the same)
- The cosmological principle of isotropy and homogeneity, like other scientific hypotheses, is testable by confrontation with data.
- So far, observations support this hypothesis

NEWTON'S WORRIES

- Newton himself had concerns about his theory
  - Gravity is "action at a distance" – i.e. gravitation force somehow (mysteriously) reaches across large distances.
    - Newton was very suspicious of this.
    - How is information *communicated* from one gravitating body to another?
  - Problems with a static universe
    - Newton imagined that the Universe was infinite and full of stationary stars, each exerting a gravitational force on the others.
    - this configuration (and any other that Newton could think of) is unstable… the smallest disturbance and it will collapse in on itself! (takes a long time tho)
    - What prevents this collapse?

Physics after Newton and Before Einstein: Electromagnetic waves

- The physics of electricity and magnetism:
  - In the late 1700's to mid 1800's scientists like Coulomb, Oerstead, Ampere, Faraday, Gauss developed ideas of how electricity and magnetism 'worked'-like Kepler and Brahe before Newton
- These quantitative theories of electricity and magnetism were formulated in terms of forces acting at a distance, analogous to Newton's law of gravitation.
- The fields of electromagnetism and understanding of light *were* unrelated and treated as separate branches having no connection.

Physics after Newton and Before Einstein -electromagnetic waves

- James Clerk Maxwell (1831-1879)
  - Developed theory of electromagnetic fields in the 1860's (Maxwell's equations)
  - These unify the electric and magnetic forces in a single theory

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{E} = \rho$$

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$$

$$\nabla \times \mathbf{B} = 4\pi \mathbf{J} / c + (1/c)\partial \mathbf{E} / \partial t$$

These vector equations are just written out for 'fun'… you do not need to know them!

Notice that the speed of light 'c' enters explicitly

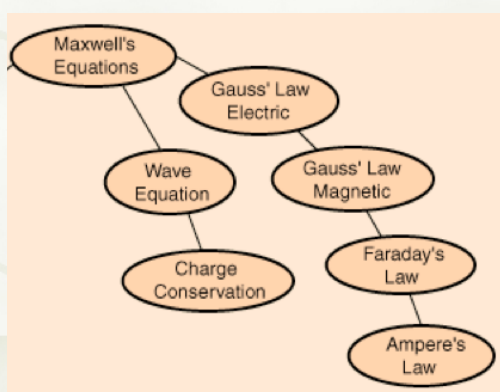
A little bit more detail?

- Maxwell discovered a speed equal to the speed of light from a purely theoretical argument based on experimental determinations of forces between currents in wires and forces between electrostatic charges.
- This led to the realization that light is an electromagnetic *wave.* (and that there must be other such waves with different wavelengths).
- Hertz detected other waves, of much longer wavelengths, experimentally, and this led directly to radio, tv, radar, cellphones

Maxwell's equations are an elegant and concise ways to state the fundamentals of electricity and magnetism.

They are core to an understanding of electricity, magnetism and light. but require a level of mathematical sophistication to understand

The speed of light is related to 2 constants that come out of the laws describing electric and magnetic forces



THE SPEED OF LIGHT PROBLEM

- Maxwell's equations:
  - Predict "waves" of electromagnetic energy – and it was quickly realized that these are light waves!
  - The speed of light "c" appears as a **fundamental constant** in the equations.
  - c = 299,792.458 km/s (**3×10^5 km/s**)- in vacuum*
  - **BUT, what frame of reference is this measured relative to???**
  - If Light is a Wave, What is Waving?

*speed of light is slower air ,water and in other mediums but is never faster!

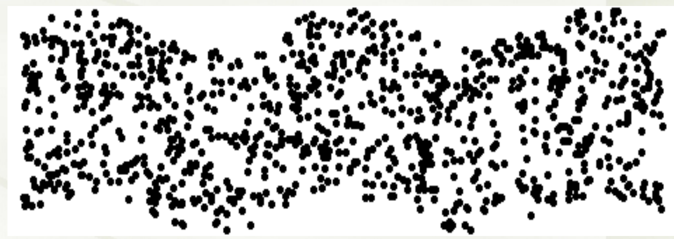
Known to greater accuracy than legnth of meter

Ether and light waves

- Luminiferous Ether (19^{th} century)
  - Hypothetical substance that fills space - provides a "medium" through which light can travel.
  - Idea was that Maxwell's equations would apply only in frame of ether
  - This would explain why the speed of wave propagation "c" is a constant in the equations
  - If speed of light in aether is "c" , and *if Galilean relativity holds*, **then speed of light measured in other frames would be *different* from** "c"
  - Albert Michelson & Edward Morley attempted (1887) to measure motion of Earth through ether…

Waves

- Before Maxwell all waves (sound, pressure waves in earthquakes etc) were known to be disturbances in the substance (water, air) through which they traveled and are generally not accompanied by a motion of the medium occupying this space as a whole
- sound waves propagate via air molecules bumping into their neighbors



http://www.kettering.edu/physics/drussell/Demos/waves/wavemotion.html

Michelson-Morley Experiment

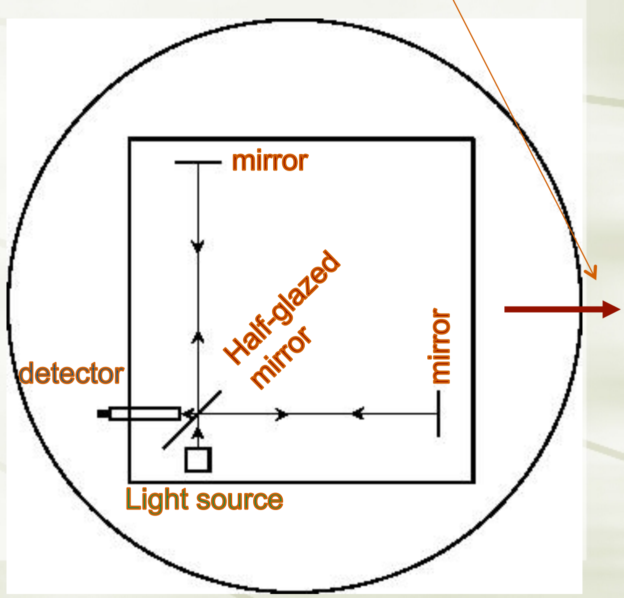
• Light leaves source, and is partly reflected 45°/partly transmitted at half-glazed mirror

•Light returning from both paths is collected at detector

•Path length of light along either "arm" of apparatus is the same

•If one arm is along Earth's motion through ether, and the other arm is perpendicular to motion through ether, then light travel time was expected to be shorter for perpendicular arm

Motion of earth



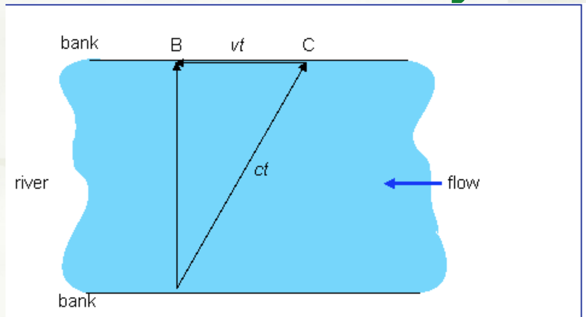
http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/mmexpt6.htm

Michelson-Morley results

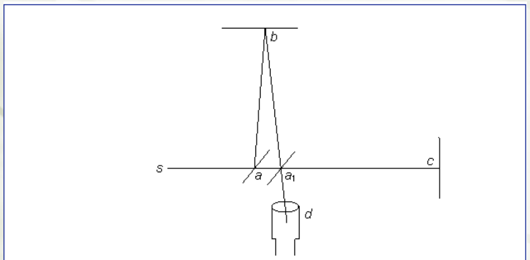
- Travel time difference would be measured using interference fringes of light from two paths
- Apparatus could be rotated to make sure no effects from set-up
- Repeated at different times of year, when Earth's motion differs; Earth's speed around the Sun is ~30 km/s
- Experiment performed in 1887
- Results
  - M-M showed that speed of light was same in any direction to within 5 km/s
  - Modern versions of the experiment show constancy to better than 10^{-6}m/s
- So, what's going on??

Michelson-Morley

- Michelson's critical idea was to construct an a race for pulses of light, with the aether wind playing the part of the river.
- expected difference in time is ~ 2(pathlength/c)x($v^2/2c^2$)- where v is the velocity of the aether



In time *t*, the swimmer has moved *ct* relative to the water, and been carried downstream a distance *vt*.



This is also from the original paper, and shows the expected path of light relative to the aether with an aether wind blowing.

Tried to measure annual effect effect to due rotation of earth and at different altitudes-nothing seem

http://galileoandeinstein.physics.virginia.edu/home.html

Michelson-Morley Extra Slide

- Michelson's explanation of his experiment to his children
- Suppose we have a river of width w (say, 100 feet), and two swimmers who both swim at the same speed v feet per second (say, 5 feet per second). The river is flowing at a steady rate, say 3 feet per second. The swimmers race in the following way: they both start at the same point on one bank. One swims directly across the river to the closest point on the opposite bank, then turns around and swims back. The other stays on one side of the river, swimming upstream a distance (measured along the bank) exactly equal to the width of the river, then swims back to the start. Who wins?

- The algebra for deciding which swimmer goes the fastest (each swimmer can swim at 5 ft per sec)
- Consider the swimmer going upstream and back. Going 100 feet upstream, the speed relative to the bank is 2 feet per second, takes 50 seconds. Coming back, the speed is 8 feet per second, takes 12.5 seconds, total time of 62.5 seconds.
- the 2nd swimmer must aim upstream at the correct angle. Thus, the swimmer is going at 5 feet per second, at an angle, relative to the river, and being carried downstream at a rate of 3 feet per second. If the angle is correctly chosen so the movement is directly across, in one second the swimmer must have moved four feet across: the distances covered in one second will form a 3,4,5 triangle. So, at a crossing rate of 4 feet per second, the swimmer gets across in 25 seconds, and back in the same time, for a total time of 50 seconds. The cross-stream swimmer wins

Taken from http://galileo.phys.virginia.edu/classes/109N/lectures/michelson.html

see http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/mmexpt6.htm for nifty graphics

Attempts to deal with M-M results

- Maybe the ether "sticks" to the Earth?
  - Gets "dragged" as Earth spins and orbits Sun…
  - Possibility at the time, but no-longer viable.
- Maybe the ether squeezes the arms of the M-M experiment and distorts the result? "Fitzgerald contraction" (1889)?
  - A contraction (in the direction parallel to motion through ether) would change the light travel time to compensate for the difference expected due to different speed of light

$$L = L_0\sqrt{1 - V^2 / c^2}$$

- Major mystery ("crisis") in 19th century physics – two highly successful theories seemed incompatible!
  - Mechanics – Galilean Relativity and Newton's laws
  - Electromagnetism – Maxwell's equations

Next time…

Apparently light is not like sound, with a definite speed relative to some underlying medium. However, it is also not like bullets, with a definite speed relative to the source of the light. When one measure its speed always get the same result. How can all these facts be interpreted in a simple consistent way?

Einstein to the rescue!-

Read Chapter 7

Homework #2 to be handed out