PHYS 3313 – Section 001
Lecture #4

Monday, Feb. 2, 2015

Dr. Jaehoon Yu

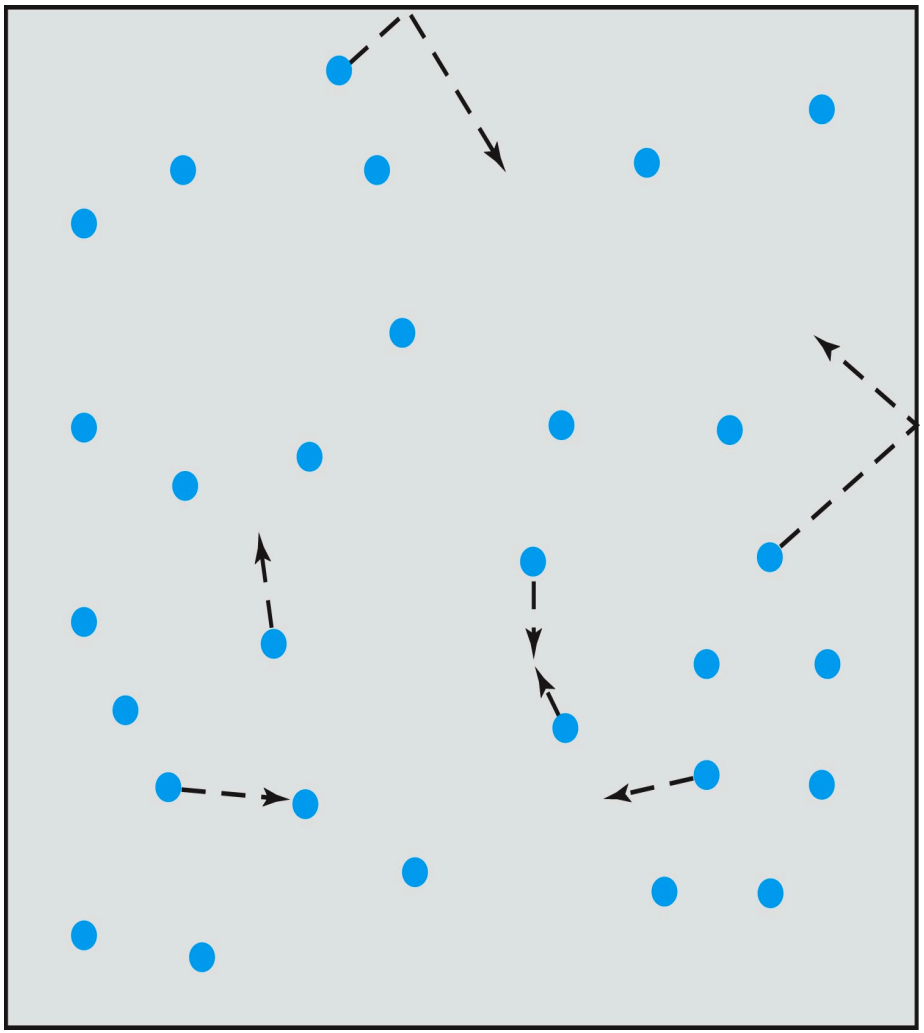
- Atomic Theory of Matter
- Unsolved Questions of 1895 and New Horizon
- Unsolved Questions Today!
- Galilean Transformation
- Do we need Ether?
- Michelson-Morley Experiment
- Einstein's postulates

Announcements

- Reading assignments: CH 2.10 (special topic), 2.13 and 2.14
  - Please go through eq. 2.45 through eq. 2.49 and example 2.9
- Homework #1
  - chapter 2 end of the chapter problems
  - 17, 21, 23, 24, 32, 59, 61, 66, 68, 81 and 96
  - Due is by the beginning of the class, Monday, Feb. 9
  - Work in study groups together with other students but PLEASE do write your answer in your own way!
- Quiz #1 results
  - Class average: 17.1/75
    - Equivalent to 23/100
  - Top score: 48/75

Relevance of Gas Concept to Atoms

- The idea of gas (17th century) as a collection of small particles bouncing around with kinetic energy enabled concept of small, unseen objects
- This concept formed the bases of existence something small that makes up matter



The Atomic Theory of Matter

- Concept initiated by Democritus and Leucippus (~450 B.C.) (first to use the Greek *atomos*, meaning "indivisible")
- In addition to fundamental contributions by Boyle, Charles, and Gay-Lussac, Proust (1754 – 1826) proposes the **law of definite proportions**➔ A compound of 2 or more elements, the weight proportion of the elements is always same
- Dalton advances the **atomic theory of matter** to explain the law of definite proportions
- Avogadro proposed that all gases at the same temperature, pressure, and volume contain the ***same number of molecules (atoms)***; viz. 6.02×10^{23} atoms
- Cannizzaro (1826 – 1910) makes a distinction between atoms and molecules advancing the ideas of Avogadro.

Further Advances in Atomic Theory

- Maxwell derives the speed distribution of atoms in a gas
- Robert Brown (1753 – 1858), a botanist, observes microscopic "random" motion of suspended grains of pollen in water (Brownian motion)
- Einstein in the 20th century explains this random motion using atomic theory

Opposition to the Atomic Theory

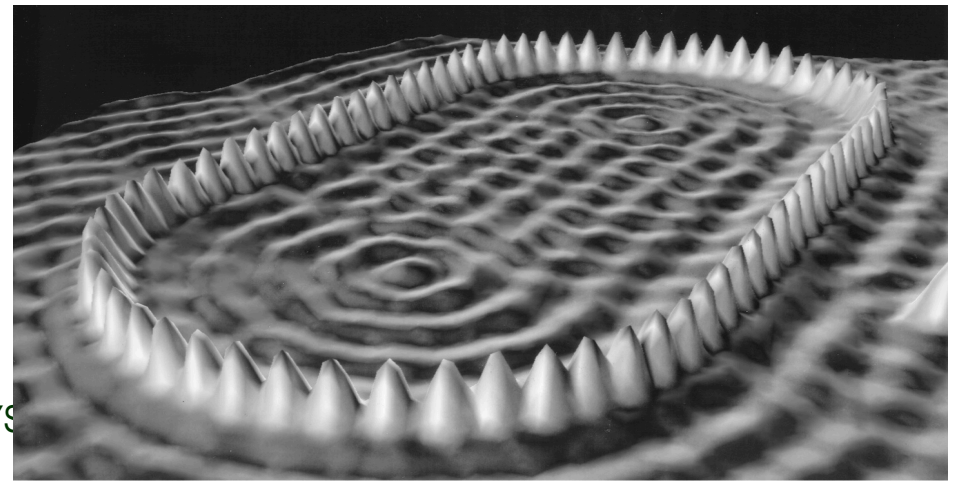
- Ernst Mach (1838 – 1916) opposes the theory on the basis of logical positivism, i.e., atoms being *"unseen" questions their reality*
- Wilhelm Ostwald (1853 – 1932) supports Mach's premise and called atoms hypothetical structures for bookkeeping based on experimental results of radioactivity, discrete spectral lines, and the formation of molecular structures

Overwhelming Evidence for Existence of Atoms

- Max Planck (1858 – 1947) advances the concept to explain blackbody radiation, using submicroscopic "quanta"
- Boltzmann requires existence of atoms for advances in statistical mechanics
- Albert Einstein (1879 – 1955) uses molecules to explain Brownian motion and determines the approximate value of their sizes and masses
- Jean Perrin (1870 – 1942) experimentally verifies Einstein's predictions

Unresolved Questions and New Horizons

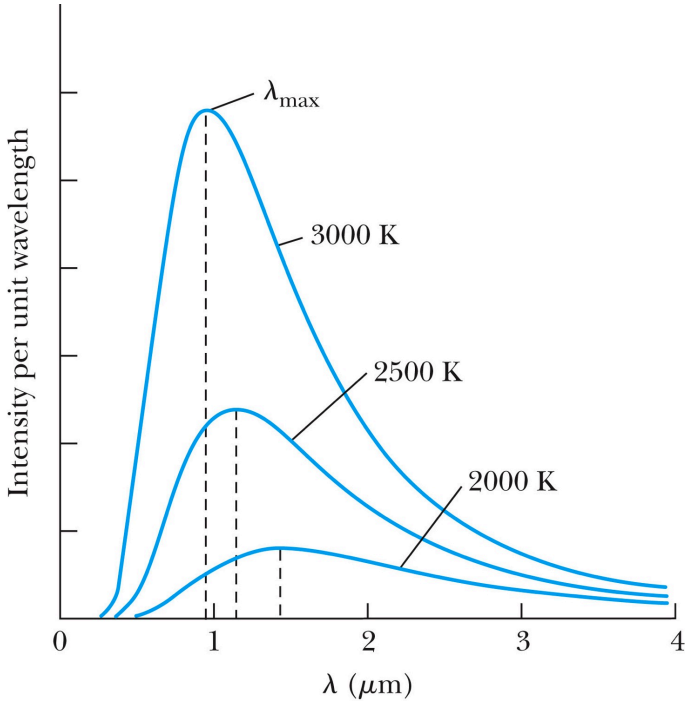
- The atomic theory controversy raises fundamental questions
  - It was not universally accepted
  - The constituents (if any) of atoms became a significant question
  - The structure of matter remained unknown with certainty
  - Experimental precisions were insufficient to discern this level of small scale



Further Complications

Three fundamental problems:

- The (non) existence of a medium that transmits light waves from the sun
- The observed differences in the electric and magnetic fields between stationary and moving reference systems
- The failure of classical physics to explain blackbody radiation in which characteristic spectra of radiation that cover the entire EM wavelengths were observed depending on temperature not on the body itself



Additional Experimental Discoveries Contribute to the Complications

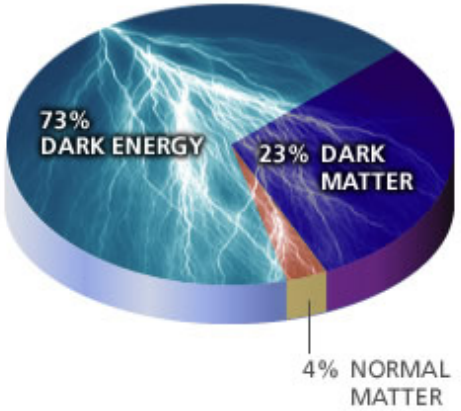
- Discovery of x-rays (1895, Röntgen)
- Discovery of radioactivity (1896, Becquerel)
- Discovery of the electron (1897, Thompson)
- Discovery of the Zeeman effect (1896, Zeeman), the dependence of spectral frequency on magnetic field

The Beginnings of Modern Physics

- These new discoveries and the many resulting complications required a revision of the fundamental physical assumptions culminated on the successes of the classical foundations
- To this end, the introduction of the modern theory of **relativity and quantum mechanics** becomes the starting point of this most fascinating revision

Unsolved Problems Today!

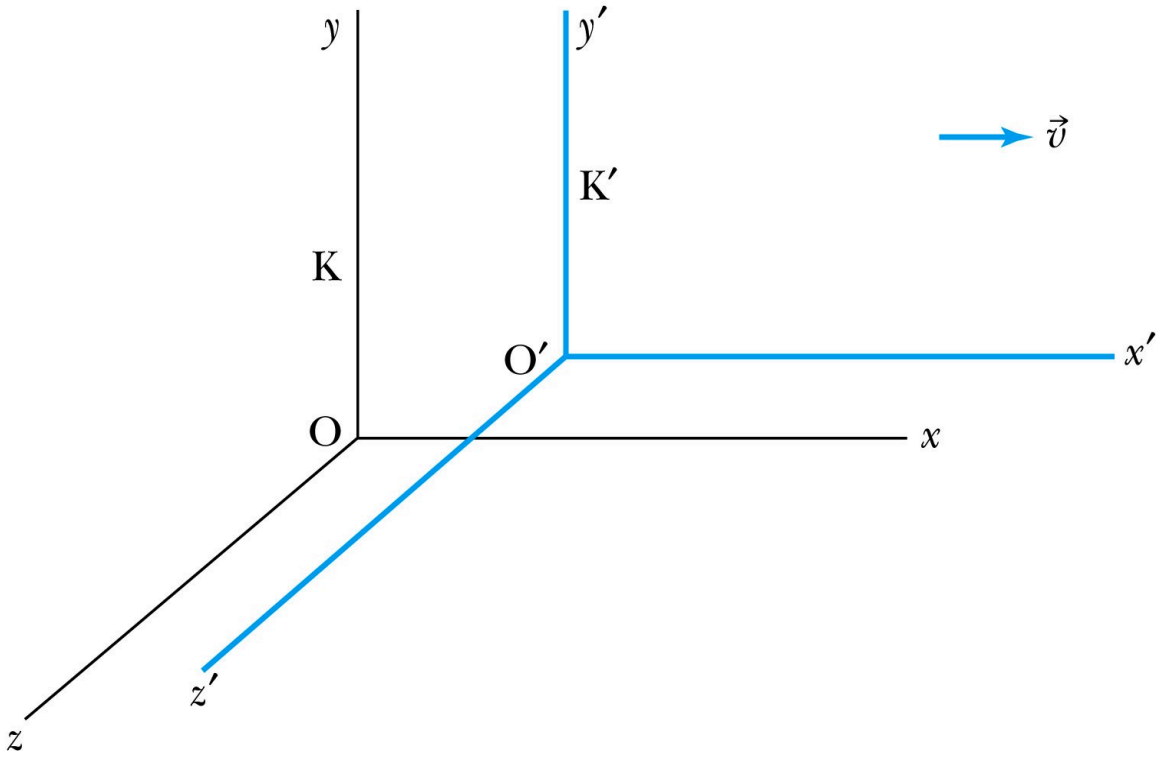
- Why are there three families of quarks and leptons?
- Why is the mass range so large ($0.1m_p$ – $175\ m_p$)?
- How do matters acquire mass?
  - Is the new particle we've discovered the Higgs particle?
- Why is the matter in the universe made only of particles?
  - What happened to anti-particles? Or anti-matters?
- Do neutrinos have mass & what are the mixing parameters?
- Why are there only three apparent forces?
- Is the picture we present the real thing?
  - What makes up the 96% of the universe?
  - How about extra-dimensions?
- How is the universe created?
- Are there any other theories that describe the universe better?
- Many more questions to be answered!!



Newtonian (Classical) Relativity

- It is assumed that Newton's laws of motion must be measured with respect to (relative to) some reference frame.
- A reference frame is called an **inertial frame** if Newton's laws are valid in that frame.
- Such a frame is established when a body, not subjected to a net external force, is observed to move in rectilinear motion at constant velocity
- ➔ Newtonian Principle of Relativity (Galilean Invariance): If Newton's laws are valid in one reference frame, then they are also valid in another reference frame moving at a uniform velocity relative to the first system.

Inertial Frames K and K'

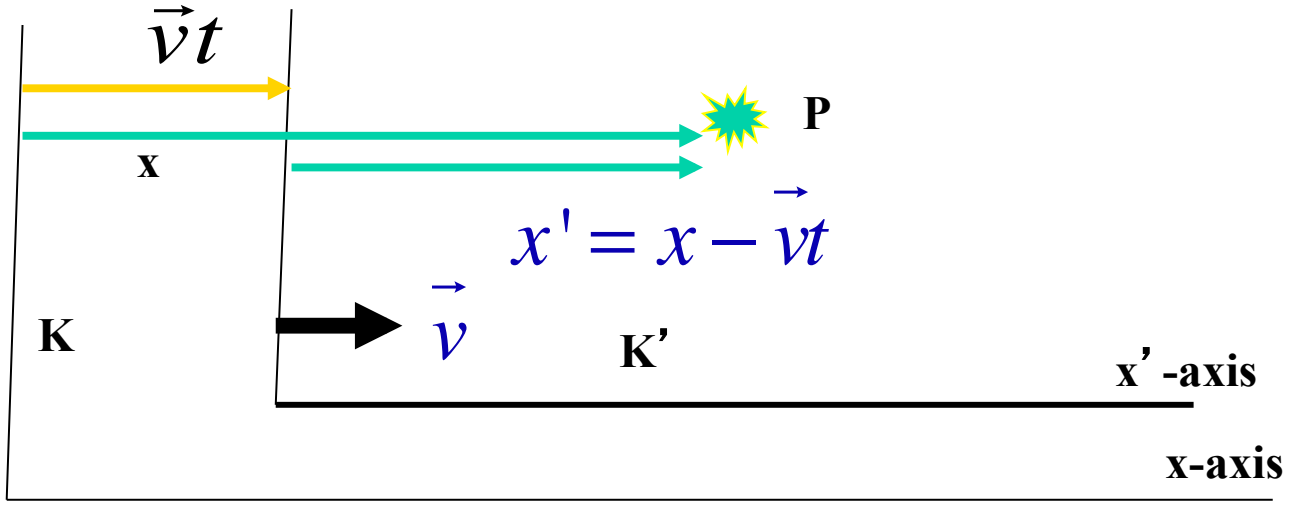


- K is at rest and K' is moving with a constant velocity $\vec{v}$
- Axes are parallel
- K and K' are said to be *INERTIAL COORDINATE SYSTEMS*

The Galilean Transformation

For a point P

- In system K: P = (x, y, z, t)
- In system K' : P = (x' , y' , z' , t')



Conditions of the Galilean Transformation

- Parallel axes between the two inertial reference frames
- K' has a constant relative velocity in the *x*-direction with respect to K

$$x' = x - \vec{v}t$$

$$y' = y$$

$$z' = z$$

$$t' = t$$

- **Time** (*t*) for all observers is a *Fundamental invariant*, i.e., the same for all inertial observers
  - Space and time are separate!!

The Inverse Relations

Step 1. Replace $\vec{v}$ with $-\vec{v}$

Step 2. Replace "primed" quantities with "unprimed" and "unprimed" with "primed"

$$x = x' + \vec{v}t$$

$$y = y'$$

$$z = z'$$

$$t = t'$$

The Transition to Modern Relativity

- Although Newton's laws of motion had the same form under the Galilean transformation, Maxwell's equations did not.
- In 1905, Albert Einstein proposed a fundamental connection between space and time and that Newton's laws are only an approximation.

They Needed Ether!!

- The wave nature of light suggested that there existed a propagation medium called the *luminiferous ether* or just **ether**.
  - Provides an inertial reference frame
- The properties of ether
  - Very low density for planets to move through it without loss of energy
  - Sufficiently high elasticity to support the high velocity of light waves (c=?)

Ether as the Absolute Reference System

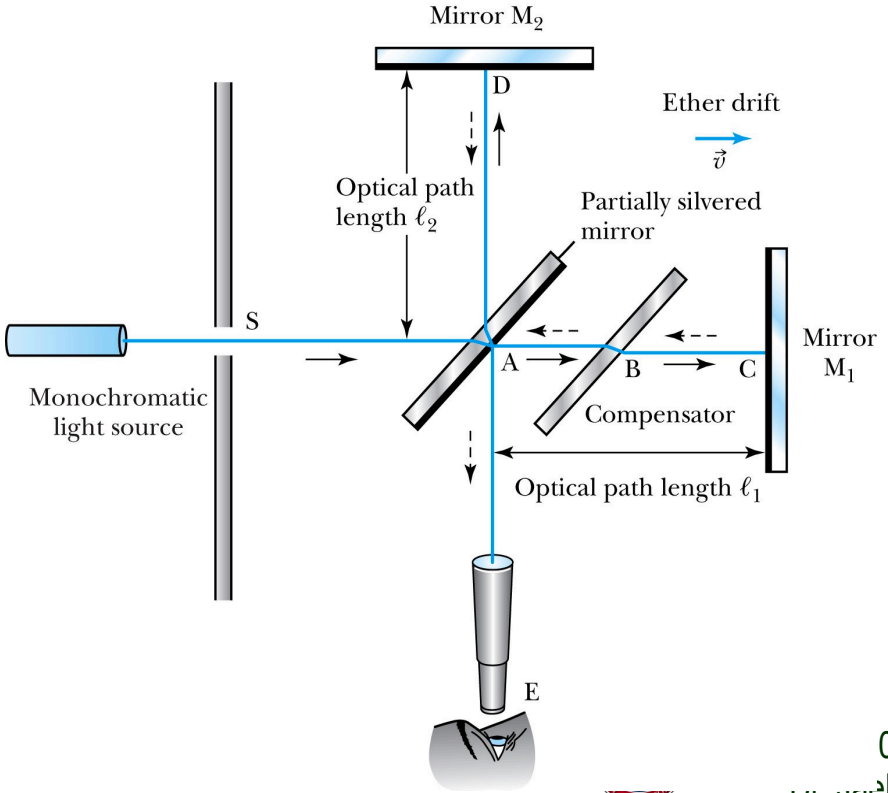
- In Maxwell's theory, the speed of light is given by

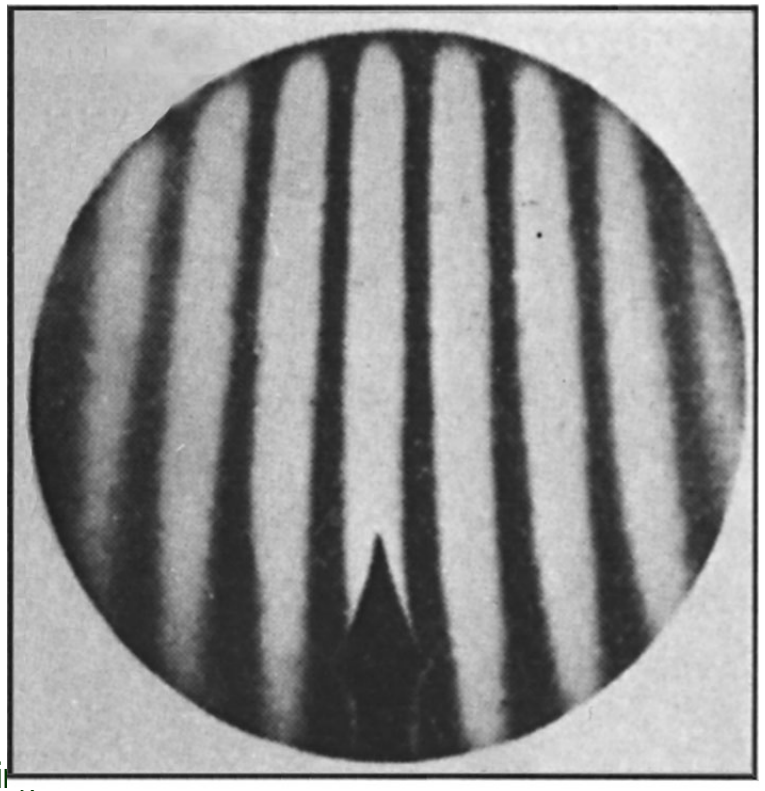
$$v = c = 1/\sqrt{\varepsilon_0 \mu_0}$$

  - The velocity of light between the moving systems must be a constant.
    - Can you see why?
  - Needed a system of medium that keeps this constant!
- Ether proposed as the absolute reference system in which the speed of light is constant and from which other measurements could be made.
- The Michelson-Morley experiment was an attempt to show the existence of ether.

The Michelson-Morley Experiment

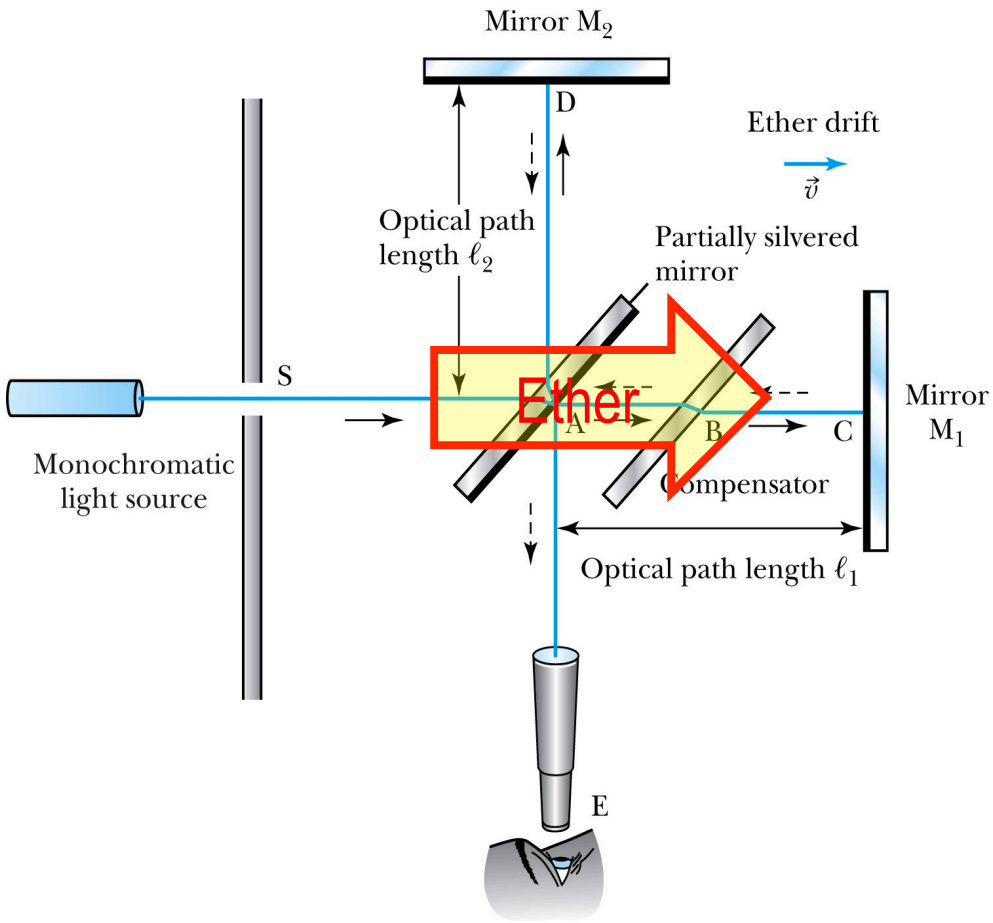
- Albert Michelson (1852–1931) built an extremely precise device called the *interferometer* to measure the phase difference between two light waves traveling in orthogonal directions.





How does Michelson Interferometer work?

1. AC is parallel to the motion of the Earth inducing an "ether wind"
2. Light from source S is split by mirror A and travels to mirrors C and D in mutually perpendicular directions
3. After reflection the beams recombine at A slightly out of phase due to the "ether wind" as viewed by telescope E.



The analysis – Galilean X-formation

- Travel time t_1 for a round trip over AC (the ether direction) is

$$t_1 = \frac{l_1}{c+v} + \frac{l_1}{c-v} = \frac{2l_1 c}{c^2 - v^2} = \frac{2l_1}{c}\frac{1}{1-v^2/c^2}$$

- Travel time t_2 for a round trip over AD (perpendicular direction to ether) is

$$t_2 = \frac{2l_2}{\sqrt{c^2 - v^2}} = \frac{2l_2}{c}\frac{1}{\sqrt{1-v^2/c^2}}$$

- The time difference is

$$\Delta t = t_2 - t_1 = \frac{2}{c}\left(\frac{l_2}{\sqrt{1-v^2/c^2}} - \frac{l_1}{1-v^2/c^2}\right)$$

The analysis

- After rotating the machine by 90°, the time difference becomes

$$\Delta t' = t_2' - t_1' = \frac{2}{c}\left(\frac{l_2}{1-v^2/c^2} - \frac{l_1}{\sqrt{1-v^2/c^2}}\right)$$

- The difference of the time differences

$$\Delta t' - \Delta t = \frac{2}{c}\left(\frac{l_1+l_2}{1-v^2/c^2} - \frac{l_1+l_2}{\sqrt{1-v^2/c^2}}\right) = \frac{2}{c}(l_1+l_2)\left(\frac{1}{1-v^2/c^2} - \frac{1}{\sqrt{1-v^2/c^2}}\right)$$

- Since v (the Earth's speed) is 10^{-4} of c, we can do binomial expansion of the above

$$\Delta t' - \Delta t = \frac{2}{c}(l_1+l_2)\left[\left(1+\frac{v^2}{c^2}+\cdots\right) - \left(1+\frac{v^2}{2c^2}+\cdots\right)\right] \approx \frac{v^2}{c^3}(l_1+l_2)$$

The Results

- Using the Earth's orbital speed as:

$$V = 3 \times 10^4 \text{ m/s}$$

together with

$$\ell_1 \approx \ell_2 = 1.2 \text{ m}$$

So that the time difference becomes

$$\Delta t' - \Delta t \approx v^2(\ell_1 + \ell_2)/c^3 = 8 \times 10^{-17} \text{ s}$$

- Although a very small number, it was within the experimental range of measurement for light waves.
- Later with Morley, they increased the path lengths to 11m and improved precision better than a factor of 10
- Yet, Michelson FAILED to "see" the expected interference pattern

Conclusions of Michelson Experiment

- Michelson noted that he should be able to detect a phase shift of light due to the time difference between path lengths but found none.
- He thus concluded that the hypothesis of the stationary ether must be incorrect.
- After several repeats and refinements with assistance from Edward Morley (1893-1923), again *a null result.*
- ***Thus, ether does not seem to exist!***
- Many explanations ensued afterward but none worked out!
- This experiment shattered the popular belief of light being waves