NAME: _____________

# Michelson-Morley

The Michelson-Morley experiment is one of the most famous, and important, "failed" experiments. It was an attempt to measure the movement of the earth through the so-called aether – a substance that was thought to fill the universe and in which light traveled. The experiment failed not because it was poorly designed, but because the aether doesn't exist.

## Background

In 1873 James Clerk Maxwell published his work that reduced all of electricity and magnetism to just four differential equations (now called Maxwell's equations.) One of the consequences of these equations is that an electromagnetic wave can only travel at one speed. Since light is an electromagnetic wave, that means that light can travel at only one speed, which is about $3 \times 10^8$ m/s.

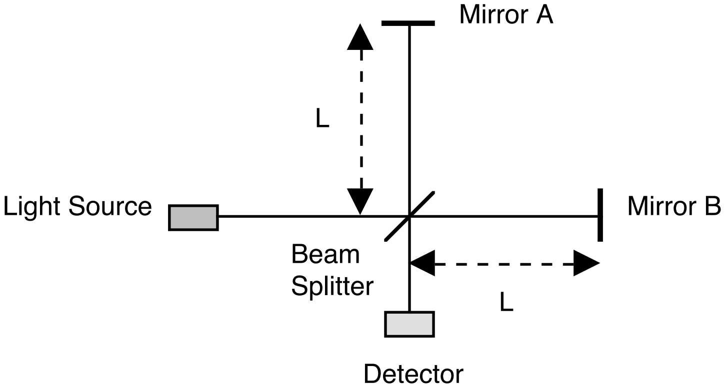
Mechanical waves are really just a disturbance that travels rapidly through something, called the medium. The speed of a wave depends on the physical properties of the medium, and if there is no medium, there is no wave. (One of the classic blunders in science fiction movies is showing spaceships fighting complete with noisy explosions and slow moving laser beams – there is no sound in outer space because it is a vacuum, and light travels really fast.)

It turns out that an electromagnetic wave does not need anything to "wave" in; it does not require a medium to travel in. In the end of the 19th century, physicists did not yet realize this, and so imagined that the universe was filled with something they called the aether. The aether is what light traveled in, and it was thought that the speed of light had to be constant in the aether.

Michelson was a premier experimenter and had perfected what is now called the Michelson interferometer which was capable of measuring distances very accurately. (In fact Michelson got his first recognition from his experiments that determined that the length of the standard meter was so many wavelengths of particular color light.) Michelson designed an experiment to determine the motion of the earth through the aether by carefully observing two rays of light that are traveling perpendicular to each – one parallel to the velocity of the earth in the aether, the other perpendicular to that.

## The Experiment

(This is a simplified version of the actual experiment.)



A ray of light was sent through a beam splitter that allowed half of the light to continue straight and half of the light to be deflected up perpendicular to the other. Each ray of light traveled a distance L, hit a mirror, and reflected back to the beam splitter. Half of each of these beams then was sent down to a detector. (Actually, the two beams would be combined at the detector and make what is called an interference pattern. The pattern made would depend on whether the two beams of light arrived at the same time, or different times – and the time difference could be determined by the actual pattern made.) Since the two distances were the same, if the lab was not moving, then the two rays of light would get to the detector at the same time. However, it was thought that since the earth was moving in the aether,

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there would be a measurable time difference between the two rays of light, if one of the rays was traveling parallel to the earth's velocity in the aether and the other perpendicular to it.

## Analysis

If the interferometer was stationary in the aether, then there would be no time difference between the two rays of light. The time, $t_0$, for each of the rays to travel from the beam splitter to a mirror and back to the beam splitter would be

$$t_0 = \frac{2L}{c}$$

where L is the distance between the beam splitter and mirror and c is the speed of light.

If the experimental apparatus is moving parallel to the earth's velocity, then the two times will be different. Let's do the ray of light sent perpendicular to mirror A first. Assume the experiment is traveling to the right with speed v, from the aether's frame of reference. From the aether's point of view, the ray of light starts at the beam splitter, travels up and to the right, hits the mirror, and then travels down and to the right, getting back to the beam splitter. If we call t the time it takes the beam to travel from the splitter to the mirror (so that the total time is 2t) then we can say the following

$$(ct)^2 = (vt)^2 + L^2$$

Solving for t gives

$$t = \frac{L}{\sqrt{c^2 - v^2}}$$

So that the total time, $t_A$ is

$$t_A = \frac{2L}{\sqrt{c^2 - v^2}}$$

Factoring out a c from the radical gives

$$t_A = \frac{2L}{c\sqrt{1 - \frac{v^2}{c^2}}} = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

The time for the other ray of light is different. In this case, the ray of light travels with speed c in the aether. Since the experiment is moving to the right with speed v, from the experiments frame of reference, the ray of light is traveling to the right with speed c-v, and then travels to the left with speed c+v. If we call $t_1$ the time it takes the ray of light to go to the right and $t_2$ the time it takes the ray of light to go to the left, then we can say

$$L = (c - v)t_1$$

$$L = (c + v)t_2$$

Solving for the times and adding them for the total time $t_B$ gives

$$t_B = t_1 + t_2 = \frac{L}{c - v} + \frac{L}{c + v}$$

We can rewrite this as

$$t_B = \frac{L(c + v) + L(c - v)}{c^2 - v^2}$$

$$t_B = \frac{2Lc}{c^2 - v^2}$$

$$t_B = \frac{2L}{c\left(1 - \frac{v^2}{c^2}\right)}$$

In terms of the rest time $t_0$, we get

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$$t_B = \frac{t_0}{1 - \frac{v^2}{c^2}}$$

If we define the following

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

then we can rewrite the times as

$$t_A = \frac{2L}{c}\gamma = t_0\gamma$$

$$t_B = \frac{2L}{c}\gamma^2 = t_0\gamma^2$$

In an attempt to explain the “failure” of the experiment to show any difference in the light beams, Lorentz and Fitzgerald had suggested that if somehow the length of the table were compressed in the direction of motion, so that the effective length of that mirror trip were $L/\gamma$, then there would be no time difference. They also suggested that if time were also somehow slowed down because of the motion, then there would be no difference between the rest frame and the moving frame.

It turns out they were correct, but they did not generalize their ideas in the way that Einstein did.