- The Need for Aether
- The Michelson-Morley Experiment
- Einstein's Postulates
- The Lorentz Transformation
- Time Dilation and Length Contraction
- Addition of Velocities
- Experimental Verification
- Twin Paradox
- Space-time
- Doppler Effect
- Relativistic Momentum
- Relativistic Energy
- Computations in Modern Physics
- Electromagnetism and Relativity

Albert Michelson
(1852-1931)

It was found that there was no displacement of the interference fringes, so that the result of the experiment was negative and would, therefore, show that there is still a difficulty in the theory itself…

- Albert Michelson, 1907

The Need for Aether

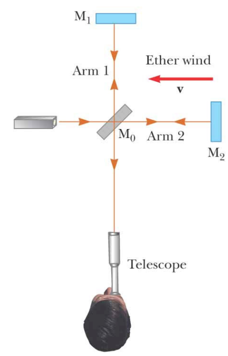
- The wave nature of light seemed to require a propagation medium. It was called the **luminiferous ether** or just **ether (or aether)**.
  - Aether had to have such a low density that the planets could move through it without loss of energy.
  - It had to have an elasticity to support the high velocity of light waves.

The Michelson-Morley Experiment

- If light propagates through the ether, then the Earth also passes through it
  - Like a ship creating a wind on deck, some direction is into the wind, and another is across the wind
  - Try to measure the difference in the speed of light in two different directions
  - Since the speed of the Earth in its orbit is about 3×10^4 m/s, need to measure fractional differences in the speed of light of about 10^{-4}!
  - Have to use an interferometer!

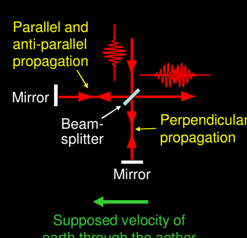
The Michelson-Morley Experiment

- Two arms, same length, one into the wind, one across
  - Time for Arm 1 (cross wind)

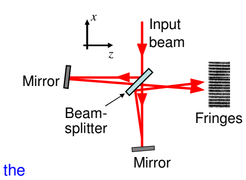


Michelson-Morley experiment

Michelson and Morley realized that the earth could not always be stationary with respect to the aether. And light would have a different path length and phase shift depending on whether it propagated parallel and anti-parallel or perpendicular to the aether.



The Michelson Interferometer and Spatial Fringes



- The Michelson Interferometer can yield spatial fringes.
- If the input beam is a plane wave, the irradiance cross term becomes:

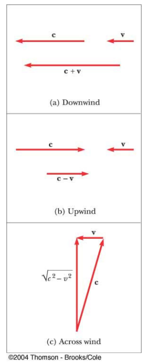
$$\mathrm{Re}\left\{E_0 \exp\left[i(\cancel{\omega t - kz\cos\theta}) - kx\sin\theta\right] E_0^* \exp\left[-i(\cancel{\omega t - kz\cos\theta}) + kx\sin\theta\right]\right\}$$
$$\propto \mathrm{Re}\left\{\exp\left[-2ikx\sin\theta\right]\right\}$$
$$\propto \cos(2kx\sin\theta)$$

Changing the phase delay of one beam with respect to the other (by τ) shifts the fringes (by ωτ).

The Michelson-Morley Experiment

- Two arms, same length, one into the wind, one across
  - Time for Arm 1 (cross wind)

$$t_1 = \frac{2L}{c'} = \frac{2L}{\sqrt{c^2 - v^2}}$$

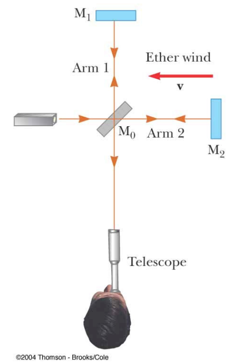


The Michelson-Morley Experiment

- Two arms, same length, one into the wind, one across
  - Time for Arm 1 (cross wind)

$$t_1 = \frac{2L}{c'} = \frac{2L}{\sqrt{c^2 - v^2}}$$

  - Time for Arm 2 (up wind)



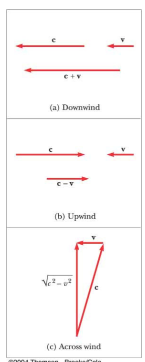
The Michelson-Morley Experiment

- Two arms, same length, one into the wind, one across
  - Time for Arm 1 (cross wind)

$$t_1 = \frac{2L}{c'} = \frac{2L}{\sqrt{c^2 - v^2}}$$

  - Time for Arm 2 (up wind)

$$t_2 = \frac{L}{c - v} + \frac{L}{c + v} = \frac{2Lc}{c^2 - v^2}$$



The Michelson-Morley Experiment

- Two arms, same length, one into the wind, one across
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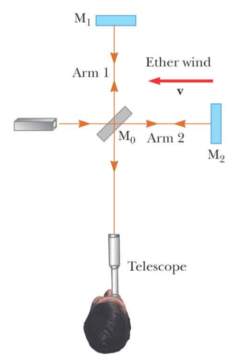
$$t_1 = \frac{2L}{c'} = \frac{2L}{\sqrt{c^2 - v^2}}$$

  - Time for Arm 2 (up wind)

$$t_2 = \frac{L}{c - v} + \frac{L}{c + v} = \frac{2Lc}{c^2 - v^2}$$

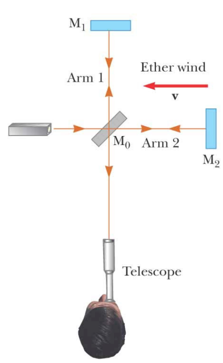
  - Thus

$$t_2 = \frac{c}{\sqrt{c^2 - v^2}} t_1 = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} t_1$$



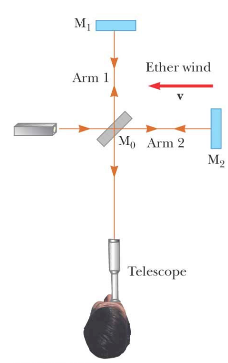
The Michelson-Morley Experiment

- Two arms, same length, one into the wind, one across
  - Since times are different, should see fringes *change* as the two arms are rotated by 90°



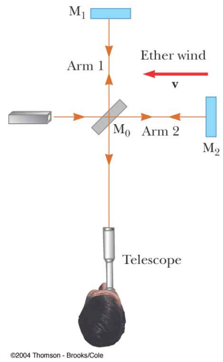
The Michelson-Morley Experiment

- Two arms, same length, one into the wind, one across
  - Since times are different, should see fringes *change* as the two arms are rotated by 90°
  - What if Earth is at rest with respect to the ether?
    - Wait 6 months!



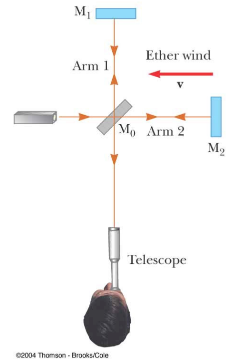
The Michelson-Morley Experiment

- Michelson and Morley did this experiment, but saw absolutely no shift in the fringes!



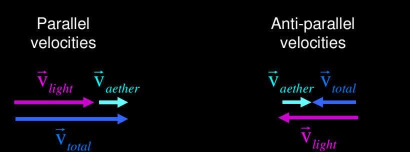
The Michelson-Morley Experiment

- Michelson and Morley did this experiment, but saw absolutely no shift in the fringes!
- Have to add a postulate to Galilean Relativity



Michelson-Morley Experiment: Details

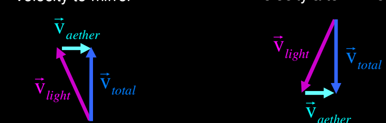
If light requires a medium, then its velocity depends on the velocity of the medium. Velocity vectors add.



$$v_{total} = v_{light} + v_{aether} \qquad v_{total} = v_{light} - v_{aether}$$

Michelson-Morley Experiment: Details

In the other arm of the interferometer, the total velocity must be perpendicular, so light must propagate at an angle.

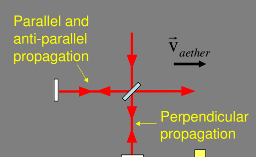


$$v_{total} = \sqrt{v_{light}^{\;2} - v_{aether}^{\;2}}$$

Michelson-Morley Experiment: Details

Let c be the speed of light, and v be the velocity of the aether.

$$\Delta t_{\parallel} = \frac{L}{c-\mathrm{v}} + \frac{L}{c+\mathrm{v}} = \frac{L(c+\mathrm{v})}{c^2-\mathrm{v}^2} + \frac{L(c-\mathrm{v})}{c^2-\mathrm{v}^2} = \frac{2Lc}{c^2-\mathrm{v}^2} = \frac{2L}{c}\frac{1}{[1-\mathrm{v}^2/c^2]}$$



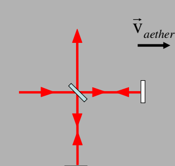
$$\Delta t_{\perp} = \frac{2L}{\sqrt{c^2-\mathrm{v}^2}} = \frac{2L}{c}\frac{1}{\sqrt{1-\mathrm{v}^2/c^2}}$$

The delays for the two arms depend differently on the velocity of the aether!

Michelson-Morley Exp't: More Details

Because we don't know the direction of the ether velocity, Michelson and Morley did the measurement twice, the second time after rotating the apparatus by 90°.

$$\Delta t_{\parallel} = \frac{2L}{c}\frac{1}{[1-\mathrm{v}^2/c^2]}$$



The delay reverses, and any fringe shift seen in this second experiment will be opposite that of the first.

$$\Delta t_{\perp} = \frac{2L}{c}\frac{1}{\sqrt{1-\mathrm{v}^2/c^2}}$$

Actually, the rotated the apparatus continuously by 180º looking for a sinusoidal variation in the shift with this amplitude.

Michelson-Morley Experiment Analysis…

Copying: $\Delta t_{\parallel} = \frac{2L}{c}\frac{1}{[1 - \mathrm{v}^2/c^2]}$ $\qquad \Delta t_{\perp} = \frac{2L}{c}\frac{1}{\sqrt{1 - \mathrm{v}^2/c^2}}$

Upon rotating the apparatus by 90°, the optical path lengths are interchanged producing the opposite change in time. Thus the time difference between path differences is given by:

$$2\left(\Delta t_{\parallel} - \Delta t_{\perp}\right) = 2\frac{2L}{c}\left(\frac{1}{1-\mathrm{v}^2/c^2} - \frac{1}{\sqrt{1-\mathrm{v}^2/c^2}}\right)$$

Assuming v << c:

$$\approx 2\frac{2L}{c}\left[\left(1+\mathrm{v}^2/c^2\right) - \left(1+\mathrm{v}^2/2c^2\right)\right] = 2\frac{2L}{c}\frac{\mathrm{v}^2}{2c^2}$$

$$\Rightarrow \boxed{2\left(\Delta t_{\parallel} - \Delta t_{\perp}\right) \approx 2L\frac{\mathrm{v}^2}{c^3}}$$

Michelson-Morley Experimental Prediction

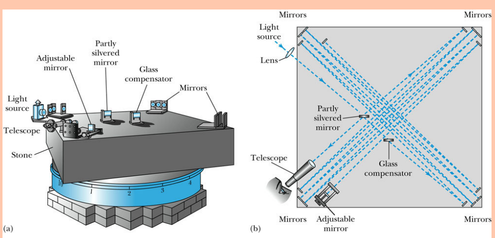
$$2\left(\Delta t_{\parallel} - \Delta t_{\perp}\right) \approx 2L\frac{\mathrm{v}^2}{c^3}$$

Recall that the phase shift is ω times this relative delay: $2\omega L\frac{\mathrm{v}^2}{c^3}$ or: $\boxed{4\pi\frac{L}{\lambda}\frac{\mathrm{v}^2}{c^2}}$

- The Earth's orbital speed is: $\mathrm{v} = 3 \times 10^4$ m/s
- and the interferometer size is: $L = 1.2$ m
- So the time difference becomes: 8×10^{-17} s
- which, for visible light, is a phase shift of: 0.2 rad
- Although the time difference was a very small number, it was well within the experimental range of measurement for visible light in the Michelson interferometer, especially with a folded path.

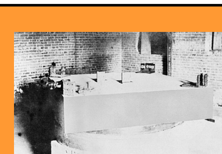
Michelson's and Morley's set up

They folded the path to increase the total path of each arm.



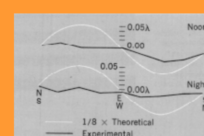
Michelson-Morley Experiment: Results

The Michelson interferometer should've revealed a fringe shift as it was rotated with respect to the aether velocity. MM expected 0.4 periods of shift and could resolve 0.005 periods. They saw none!



Their apparatus

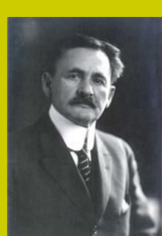
Interference fringes showed no change as the interferometer was rotated.



Michelson and Morley's results from A. A. Michelson, *Studies in Optics*

Michelson's Conclusion

- In several repeats and refinements with assistance from Edward Morley, he always saw *a null result.*
- He concluded that the hypothesis of the stationary aether must be incorrect.
- ***Thus, aether seems not to exist!***



Albert Michelson (1852-1931)

Edward Morley (1838-1923)

Another way to interpret the null result of MM experiment is this that we simply conclude that the speed of light, i.e. c, is the same in all directions and in all the inertial frames.

The later result leads to:

$$\mathrm{v} + \mathrm{c} = \mathrm{c}$$

If we accept the above result then if both arms of the MM experiment are equal to each other, then the null result could be expected

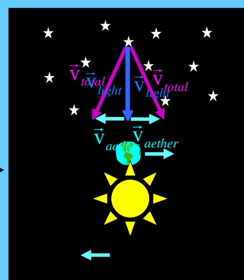
But at that time no one could believe it.

Possible explanations for MM's null result

•Many explanations were proposed, but the most popular was the aether drag hypothesis.

–This hypothesis suggested that the Earth somehow "dragged" the aether along as it rotates on its axis and revolves about the sun.

–This was contradicted by **stellar abberatio** wherein telescopes had to be tilted to observe starlight due to the Earth's motion. If aether were dragged along, this tilting would not occur.

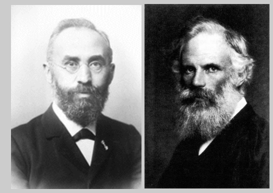


Lorentz-FitzGerald Contraction

•Another idea, proposed independently by Lorentz and FitzGerald, suggested that the length, L, in the direction of the motion contracted by a factor of:

$$\boxed{\sqrt{1-v^2/c^2}}$$

velocity of frame   velocity of light



Hendrik A. Lorentz (1853-1928)   George F. FitzGerald (1851-1901)

So:

$$\Delta t_{\parallel} = \frac{2L}{c}\frac{1}{[1-v^2/c^2]} \rightarrow \frac{2L\sqrt{1-v^2/c^2}}{c}\frac{1}{[1-v^2/c^2]} = \frac{2L}{c}\frac{1}{\sqrt{1-v^2/c^2}} = \Delta t_{\perp}$$

thus making the path lengths equal and the phase shift always zero.
But there was no insight as to why such a contraction should occur.

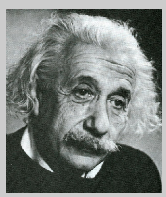
2.3: Einstein's Postulates

•Albert Einstein was only two years old when Michelson and Morley reported their results.

•At age 16 Einstein began thinking about Maxwell's equations in moving inertial systems.

•In 1905, at the age of 26, he published his startling proposal: the Principle of Relativity.

•It nicely resolved the Michelson and Morley experiment (although this wasn't his intention and he maintained that in 1905 he wasn't aware of MM's work…)



Albert Einstein (1879-1955)

It involved a fundamental new connection between space and time and that Newton's laws are only an approximation.

Einstein's Two Postulates

- With the belief that Maxwell's equations must be valid in all inertial frames, Einstein proposed the following postulates:
- The principle of relativity: All the laws of physics (not just the laws of motion) are the same in all inertial systems. There is no way to detect absolute motion, and no preferred inertial system exists.
- The constancy of the speed of light: Observers in all inertial systems measure the same value for the speed of light in a vacuum.

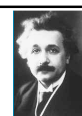
Special Relativity

- Einstein postulated that the only way Maxwell's Equations could be combined with the equivalence principle was that the speed of light was the same in all inertial reference frame!
- Einstein's Principles:
  1) The laws of Physics are the same in all inertial reference frames (Equivalence Principle)
  2) The speed of light is the same for observers in all reference frames

  Corollary: There is no preferred reference frame (no absolute *rest* frame)

Albert Einstein German-American Physicist (1879–1955)
Einstein, one of the greatest physicists of all times, was born in Ulm, Germany. In 1905, at the age of 26, he published four scientific papers that revolutionized physics. Two of these papers were concerned with what is now considered his most important contribution: the special theory of relativity. In 1916, Einstein published his work on the general theory of relativity. The most dramatic prediction of this theory is the degree to which light is deflected by a gravitational field. Measurements made by astronomers on bright stars in the vicinity of the eclipsed Sun in 1919 confirmed Einstein's prediction, and as a result Einstein became a world celebrity. Einstein was deeply disturbed by the development of quantum mechanics in the 1920s despite his own role as a scientific revolutionary. In particular, he could never accept the probabilistic view of events in nature that is a central feature of quantum theory. The last few decades of his life were devoted to an unsuccessful search for a unified theory that would combine gravitation and electromagnetism. (AIP Niels Bohr Library)

1. **The principle of relativity:** The laws of physics must be the same in all inertial reference frames.
2. **The constancy of the speed of light:** The speed of light in vacuum has the same value, $c = 3.00 \times 10^8$ m/s, in all inertial frames, regardless of the velocity of the observer or the velocity of the source emitting the light.



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Relative Strangeness

- Special Relativity is counterintuitive!
  - Imagine that I'm moving and you're at rest
  - If I flash the laser pointer, the pulse of photons moves away from me at velocity *c*
  - Even though I'm moving, you also see the photons moving away from the point where I flashed the pointer at velocity *c*

    $c = c + v\,?$
  - Can only get out of trouble by changing what we mean by time