Einstein for Everyone
Lecture 2: Background to Special Relativity

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Einstein's Two Postulates

1. *Principle of relativity*: "...the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good."
2. *Light postulate*: "... light is always propagated in empty space with a definite velocity independent of the state of motion of the emitting body."

Presentation of Theory

- Einstein admired theories presented in terms of small number of basic postulates (Euclid, Newton, thermodynamics)
- Postulates capture core ideas of the theory

Einstein's Two Postulates

1. *Principle of relativity*
2. *Light postulate*

One striking consequence: "... the introduction of a 'luminiferous ether' will prove to be superfluous."

Questions

- What do these postulates mean? Are they even compatible?
- Relation to earlier ideas in physics? What is the "ether", and why is it unnecessary in Einstein's theory?

Plan of Attack

1. Principle of Relativity
   - Version 1.0: Galileo
   - Einstein's Problem: version 2.0?
2. Light Postulate
   - Light as an Electromagnetic Wave
   - Light and Principle of Relativity

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Definition (Inertial Motion)

Motion in a straight line with uniform velocity (that is, covering equal distances in equal times).

Accelerated Motion

Change in *velocity* (speed up or slow down) or *direction* (*e.g.*, rotation)

Based on...

- *Spatial Geometry*: straight line; distances measured by measuring rods
- *Time*: time elapsed, measured by a clock
- *Location over time*: distance traveled over time

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Inertia and Relativity

Principle of Relativity

All observers in inertial motion (inertial observers) see the same laws of physics.

Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all these things carefully (though doubtless when the ship is standing still everything must happen in this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still. (Galileo, *Dialogue* [1632])

Inertia and Relativity

Principle of Relativity

All observers in inertial motion (inertial observers) see the same laws of physics.

Consequences:

- No experiment can detect inertial motion
- Contrasts: *accelerated* motion; *relative* motion with respect to other objects

Galilean Relativity

- Context: Debate regarding Copernican Hypothesis (1543)
  Objection: we're obviously not moving!
- Galileo's Response
  - Earth moves (*approximately*) inertially; so it will look (*approximately*) as though it were at rest
  - Newton: cannot detect *inertial* motion, formulates principle of relativity as a consequence of his laws

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Einstein's Question

Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. ... And have with you there an instrument that allows you to measure the speed of light very precisely ...

How would this change Galileo's conclusion?

1. Principle of relativity fails: can now detect motion
2. Principle of relativity holds: still cannot detect motion

To answer this need to consider theory describing light...

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1. Detecting Ether Drift
   - Fresnel's Coefficient
   - Michelson-Morley Experiment
     Others: Fizeau, Trouton-Noble,...
2. Lorentz's Response
   - Length Contraction
   - Generalized Contraction Hypothesis
3. Einstein's Response
   - Emission theories?
   - Revise concepts of space and time
   - Simultaneity

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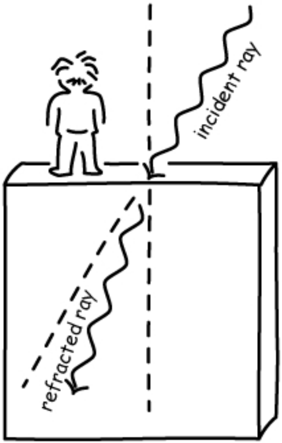
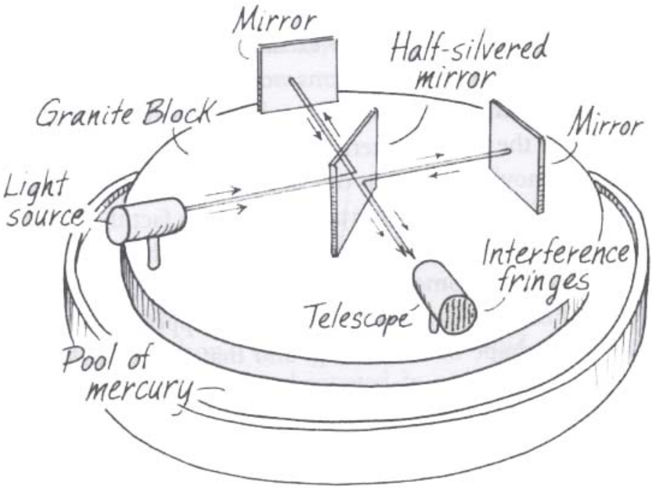
Fresnel's Coefficient



- Light passing through optical medium (e.g., glass block)
  - Ether dragged by medium
  - Depends on refractive index, exactly mimics ordinary refraction
- Guarantees that block's motion is undetectable!

The Apparatus (Michelson and Morley 1887)



Testing for Ether Drift

Travel time for arm 1 (parallel to ether flow):

$$\frac{l}{c+v} + \frac{l}{c-v} = \frac{2lc}{c^2 - v^2} \tag{4.1}$$

Travel time for arm 2 (perpendicular to ether flow):

$$\frac{2l}{\sqrt{c^2 - v^2}} \tag{4.2}$$

Conclusion

Travel time differs along the two arms, depends on velocity with respect to ether (by an amount $\frac{l}{c}\frac{v^2}{c^2}$).

Measure difference in travel time $\rightarrow$ measure velocity!

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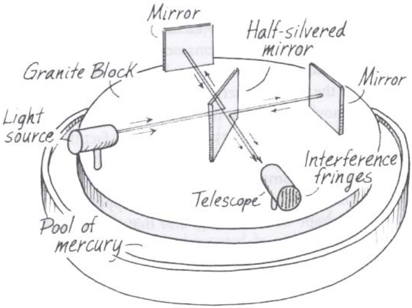

- Interferometer
  - Interference pattern between light rays
  - Change in travel time $\rightarrow$ shift in interference fringes
- Rotation
  - Rotate entire apparatus by 90°
  - Prediction: shift in interference fringes (depends on v)

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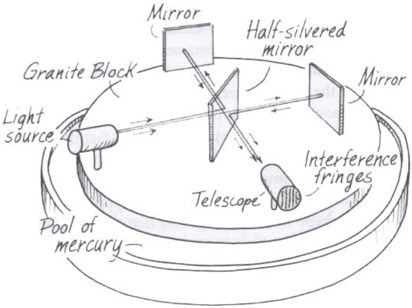

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Null Result

- Result: *no shift in interference fringes*!
  - Travel times along interferometer arms *unaffected* by rotation
- Other Experiments
  - Michelson-Morley (1902, 1904): similar approach; null result
  - Trouton-Noble (1903, ...): effect of motion on capacitor; null result
  - ... *several others* ...: all null results

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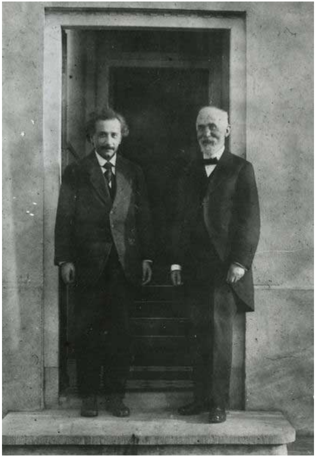
Hendrik A. Lorentz (1853 - 1928)



Einstein and Lorentz in Leiden (1921)

"Electrodynamic World Picture"

- 1890s - : Electrodynamics, including Fresnel coefficient and null results
- 1902: Nobel Prize (with Pieter Zeeman), discovery of the Zeeman effect
- 1909: *Theory of Electrons*

Response to the Null Results

- Lorentz's further development of Maxwell's theory
  - Matter composed of "ions" or "electrons,"; emit and absorb electromagnetic radiation
  - Stationary, immobile ether
- Goal: *calculate* consequences of motion in this theory
  - First Result (1884): explanation of Fresnel's coefficient, as a consequence of interaction of light with electrons in matter
  - Second Result (1892): explanation of Michelson-Morley's null result
  - 1904: General result regarding failure of other experiments

Michelson-Morley Reconsidered

- Implications of Experimental Result
  - *Calculation*: different travel times along arms
  - *Observation*: travel times appear to be equal, insensitive to orientation
- Conflict avoidance?
  - What if the length of the two arms is not the same?
  - Arm 1 *shorter* (by amount that depends on v) $\rightarrow$ travel times equal

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Generalized Contraction Hypothesis

- Contraction Hypothesis (Fitzgerald-Lorentz)
  - Consider arms of interferometer as composed of electrons held together by electromagnetic forces
  - Lorentz's calculation: moving configuration contracts *by exactly the right amount*
- "Generalized Contraction Hypothesis"
  - For any inertial observer, *dynamical effects* of motion insure that the velocity with respect to the ether cannot be measured
  - Length contraction, time dilation, ...

Conventional Wisdom ca. 1905

- Principle of Relativity *fails* ...
  - True rest state of the ether
  - Motion through the ether has *real* dynamical effects
- ... but we cannot directly establish failure observationally
  - Dynamical effects *block* all attempts to measure motion through ether
  - Lorentz: *not* a question of limited precision; theoretical *prediction*
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Chasing A Beam of Light

If I pursue a beam of light with the velocity c (velocity of light in a vacuum), I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating.

There seems to be no such thing, however, neither on the basis of experience nor according to Maxwell's equations.

From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest. For how should the first observer know or be able to determine, that he is in a state of fast uniform motion? (Einstein 1946)

"On the Electrodynamics of Moving Bodies" Einstein (1905)

Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise — assuming equality of relative motion in the two cases discussed — to electric currents of the same path and intensity as those produced by the electric forces in the former case.

Einstein (1905) continued

Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the “light medium,” suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good.