IPP-SR-3: The Michelson-Morley experiment and Lorentz's programme

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HT25

The course

1. Newton's laws
2. Galilean invariance
3. The Michelson-Morley experiment
4. Einstein's 1905 derivation of the Lorentz transformations
5. Spacetime structure
6. General covariance
7. Relativity and conventionality of simultaneity
8. Frame-dependent effects
9. The twin paradox
10. Dynamical and geometrical approaches to relativity
11. Presentism and relativity
12. Acceleration and redshift

Today

Invariance groups

The Michelson-Morley experiment

Lorentz's programme

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- The lack of boost invariance would then imply (up to translations and spatial rotations) the existence of a preferred frame!

Maxwell's equations

$$\nabla \cdot \mathbf{E} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mathbf{J} + \frac{\partial \mathbf{E}}{\partial t}$$

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- In this frame, with respect to what is light moving? 19th century answer: some background structure: *the ether*.
- So (the thought goes) light moves at c in the rest frame of the ether—and this is the preferred frame in which Maxwell's equations hold.

Empirical testability

- That light moves at c only in the rest frame of the ether, and moves at $c \pm v$ in a frame moving at velocity v with respect to the ether (because, from Maxwell's equations, the speed of light is independent of the speed of the source—cf. sound waves), is an *empirical hypothesis*, which should be testable.

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- In the 19th century, physicists indeed did attempt to test this hypothesis—all tests ended in *null results*.
- The most famous of these experiments is the *Michelson-Morley experiment*, which we will today consider in detail.

Feynman on light propagation

One of the consequences of Maxwell's equations is that if there is a disturbance in the field such that light is generated, these electromagnetic waves go out in all directions equally and at the same speed c, or 186,000 mi/sec. Another consequence of the equations is that if the source of the disturbance is moving, the light emitted goes through space at the same speed c. This is analogous to the case of sound, the speed of sound waves being likewise independent of the motion of the source.

This independence of the motion of the source, in the case of light, brings up an interesting problem ...

Feynman on light propagation (ctnd.)

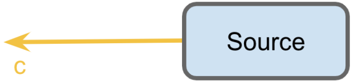
Suppose we are riding in a car that is going at a speed u, and light from the rear is going past the car with speed c. Differentiating [the Galilean transformation for position] gives

$$\frac{dx'}{dt} = \frac{dx}{dt} - u,$$

which means that according to the Galilean transformation the apparent speed of the passing light, as we measure it in the car, should not be c but should be $c - u$. For instance, if the car is going 100,000 mi/sec, and the light is going 186,000 mi/sec, then apparently the light going past the car should go 86,000 mi/sec. In any case, by measuring the speed of the light going past the car (if the Galilean transformation is correct for light), one could determine the speed of the car. A number of experiments based on this general idea were performed to determine the velocity of the earth, but they all failed—they gave no velocity at all. (Feynman 2010, vol. 1, lecture 15)

It’s very important to be clear on the setup here, so I’ll go through a few case studies, as a warmup to the ether theorists’ way of thinking.

Case 1: Source at rest with respect to the ether



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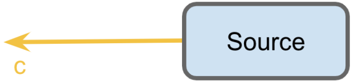

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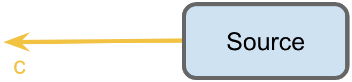
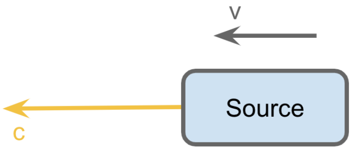


- Imagine a source at rest with respect to the ether, which emits a light ray with velocity c.
- In the ether rest frame—which is also the source's rest frame!—the light propagates at c.

Case 2: Source moving with respect to the ether



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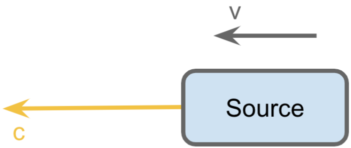

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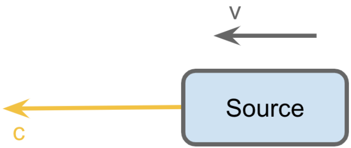

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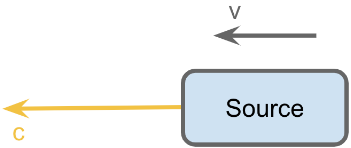
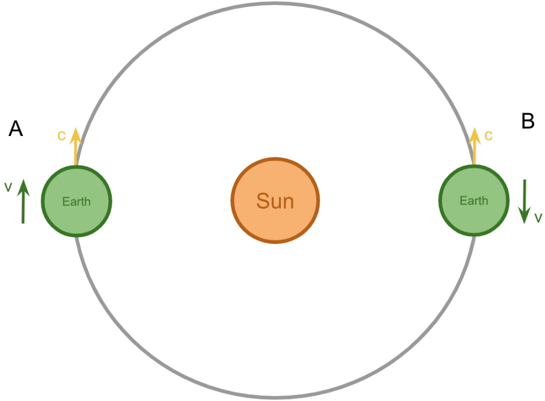


- Imagine a source moving with respect to the ether with velocity v, which emits a light ray with velocity c.
- In the ether rest frame, the light propagates at c.
- In the *source's* rest frame, the light propagates at $c - v$.

Case 3: Solar system at rest with respect to ether



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- Note that at every point in its orbit, the Earth has some velocity with respect to the ether, in this scenario.

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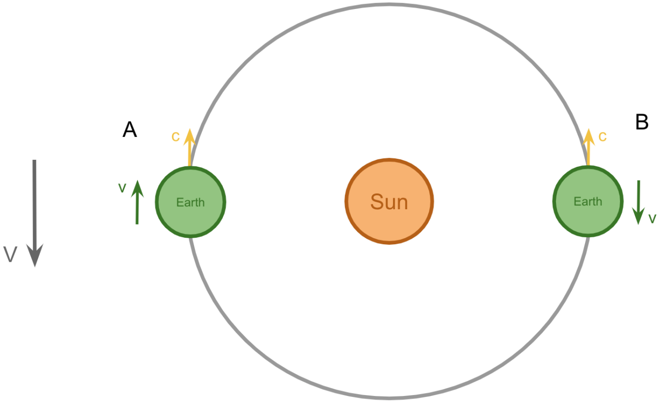

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- But, of course, this can't happen at every point in the Earth's orbit!

Today

Invariance groups

The Michelson-Morley experiment

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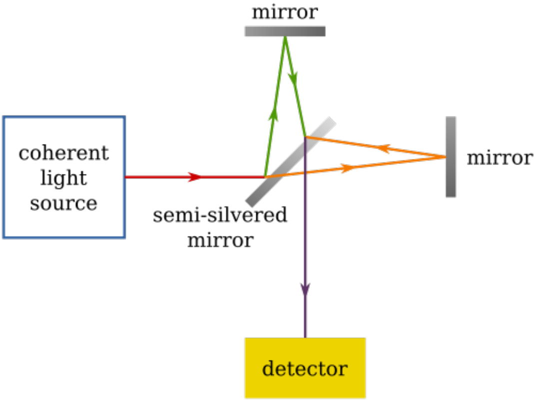
The experimental setup



(For much more detail on the Michelson-Morley experiment, see (Brown 2005).)

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4. The observed pattern will depend on
   - the lengths of the arms A and B, and
   - *the speed of travel of the light along each arm in each direction*.

Qualitative rationale

- In a lab that is moving relative to the ether with speed v, the speed of light relative to the lab frame is expected to be *anisotropic*: it should be $c - v$ in the direction of the lab's motion, $c + v$ in the opposite direction, and $\sqrt{c^2 - v^2}$ in directions perpendicular to that of the lab's motion.

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- ... However, regardless of the arm lengths, *rotating* the apparatus should *change* the interference pattern in a predictable manner in a moving frame, and would not if the apparatus were at rest with respect to the ether.
- Thus we look for this post-rotation change as a signature of the ether wind.

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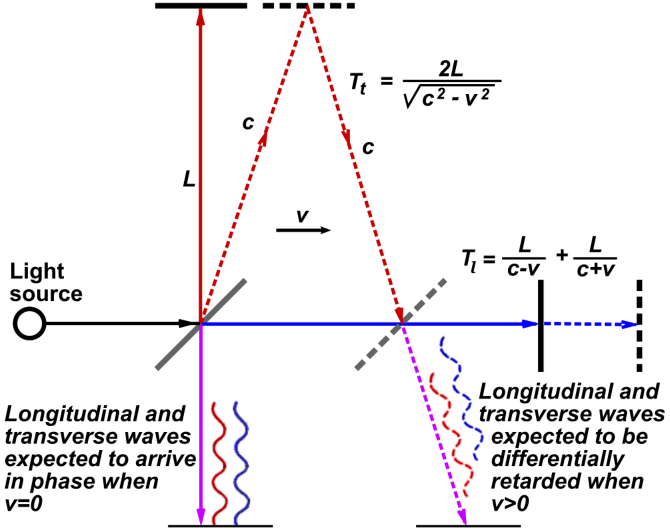
- The out-and-back time for light to travel along the arm that is *perpendicular* to the ether drift should be

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

Visualising the time differentials



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- The time difference before rotation is given by

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

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- After rotation, the length difference is given by

$$\Delta_2 = 2\left(\frac{L}{\sqrt{1-\frac{v^2}{c^2}}} - \frac{L}{1-\frac{v^2}{c^2}}\right).$$

Quantitative calculation of expected fringe shift

- Dividing $\Delta_1 - \Delta_2$ by the wavelength λ of the light used in the interferometer, the fringe shift n is found:

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- If $L = 11m$, $\lambda = 550nm$ and $v = 30kms^{-1}$, this gives an expected fringe shift of $\Delta n \approx 0.4$—certainly large enough to be observable (*despite* the fact that the effect is 'second order in v^2/c^2').

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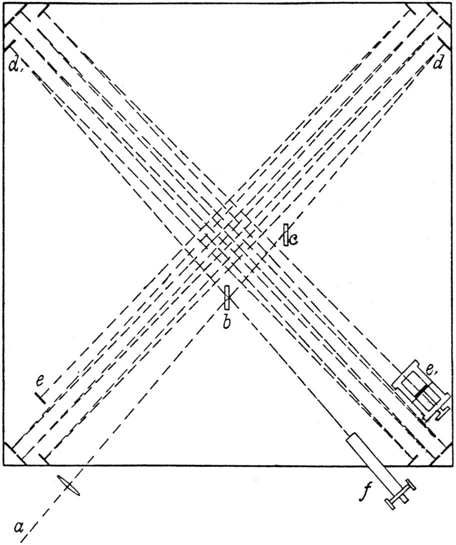
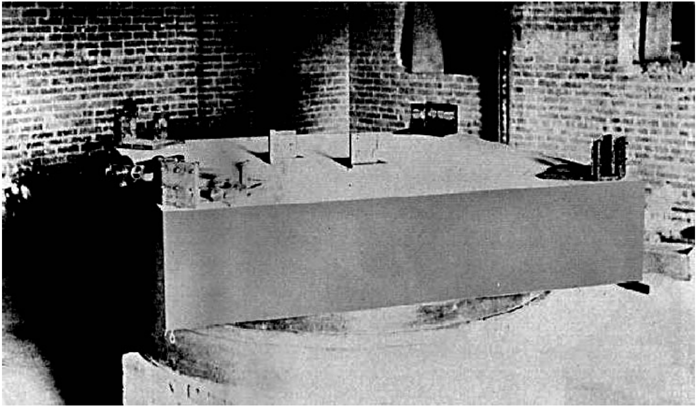
- Answer: Michelson and Morley used mirrors to bounce the light down the arms multiple times, giving an *effective* length of $11m$.

4.





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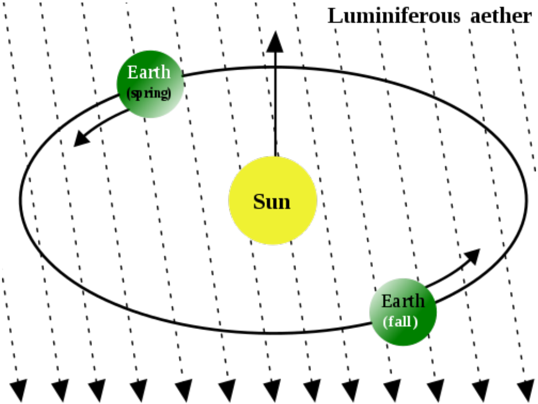
- This null result was a mystery: this “small relative motion” might obtain by luck at any given instant, but it is difficult to see how it could obtain *throughout* the Earth’s orbit.

Cancelling the ether wind?



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- How to explain that this was never observed?

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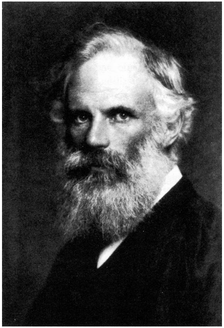
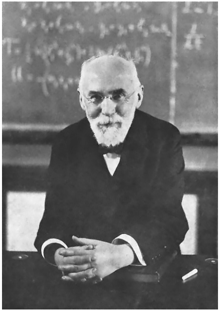
Contraction hypotheses

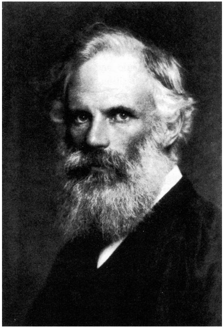
We'll look now at how physicists responded initially to null rests such as that of Michelson and Morley.

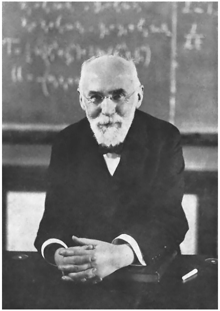
The trailblazers





The trailblazers





(See Brown 2005, ch. 4)

The trailblazers: Fitzgerald

- In 1889, George F. Fitzgerald suggested that “almost the only hypothesis” capable of reconciling the Michelson-Morley experiment with the apparent fact that the Earth dragged a negligible amount of ether was that

  > *the length of material bodies changes, according as they are moving through the ether or across it, by an amount depending on the square of the ratio of their velocities to that light.*
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- He continued:

  > *We know that electric forces are affected by the motion of electrified bodies relative to the ether and it seems a not improbable supposition that the molecular forces are affected by the motion and that the size of the body alters consequently.* (Fitzgerald 1889)

The trailblazers: Lorentz and Larmor

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- Larmor would also adopt the idea in his 1900 book, *Aether and Matter*.

Lorentz

- Lorentz introduced a longditudinal factor $\mathcal{C}_{\|} = 1 + \delta$ and a transvere factor $\mathcal{C}_{\perp} = 1 + \epsilon$. He claimed that the null result required
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- Contraction in this manner would cancel out the different velocities of light, and lead to no phase shift effects at the detector.
- Note that Lorentz's hypothesis is conceptually distinct from special relativistic length contraction effects! (See lecture 8.)

The theorem of corresponding states

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- This was designed to show that *no* first- or second-order ether-wind effects would be discernible in experiments involving optics and electrodynamics.
- In the second version of this theorem, the Lorentz transformations appear in their full glory.
- But until Einstein's work in 1905, Lorentz continued to believe that the true coordinate transformations were the Galilean ones, and that the 'Lorentz' transformations were merely a useful formal device.

General idea

Postulate more relativity principle-violating physics to cancel out the first relativity principle-violating physics, and explain why we don't *see* violations of the relativity principle.

The spectre of *ad hoc*ness

Lorentz noted that the theorem of corresponding states actually implies that the frequency of oscillating electrons in the light source is affected by motion of the source, and it is this fact that gives rise to the change in frequency of the emitted light. But Lorentz realized that the oscillating electrons only satisfy Newton's laws of motion if it is assumed that both their masses and the forces impressed on them depend on the electrons' velocity relative to the ether. The hypotheses in Lorentz's system were starting to pile up, and the spectre of ad hocness was increasingly hard to ignore (as Poincaré would complain).
(Brown 2005, p. 56)

Einstein’s revolution

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- Einstein's idea: Instead of understanding boosts to be *Galilean* boosts, and postulating extra relativity-principle violating physics to explain why we do *not* observe violations of the relativity principle from electromagnetism, instead argue that *we have hitherto misunderstood the nature of boosts*.

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- Einstein: Instead construe boosts as *Lorentz* boosts.
- This would explain why the same speed of light is observed regardless of the state of motion of Galileo's 'Earth'.
- What we need to do to restore the relativity principle is, therefore, to take *all* physics to be invariant under Lorentz boosts (not Galilean boosts).

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More on Einstein's approach next time!

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