

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

James Read¹

¹Faculty of Philosophy, University of Oxford, UK, OX2 6GG

HT24

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

Today

Invariance groups

The Michelson-Morley experiment

Lorentz's programme

Invariance groups

- We have seen that Newtonian mechanics is invariant under Galilean transformations—i.e., translations, spatial rotations, and Galilean boosts.

Invariance groups

- ▶ We have seen that Newtonian mechanics is invariant under Galilean transformations—i.e., translations, spatial rotations, and Galilean boosts.
- ▶ We have also seen that electromagnetism is invariant under Poincaré transformations—i.e., translations, spatial rotations, and Lorentz boosts.

Invariance groups

- ▶ We have seen that Newtonian mechanics is invariant under Galilean transformations—i.e., translations, spatial rotations, and Galilean boosts.
- ▶ We have also seen that electromagnetism is invariant under Poincaré transformations—i.e., translations, spatial rotations, and Lorentz boosts.
- ▶ Suppose we lived in a world in which both of these theories were true. Then the overall invariance group of the physical laws of the world would be the intersection of these two groups, i.e., the group of translations and spatial rotations (no boosts).

Invariance groups

- ▶ We have seen that Newtonian mechanics is invariant under Galilean transformations—i.e., translations, spatial rotations, and Galilean boosts.
- ▶ We have also seen that electromagnetism is invariant under Poincaré transformations—i.e., translations, spatial rotations, and Lorentz boosts.
- ▶ Suppose we lived in a world in which both of these theories were true. Then the overall invariance group of the physical laws of the world would be the intersection of these two groups, i.e., the group of translations and spatial rotations (no boosts).
- ▶ The lack of boost invariance would then imply (up to translations and spatial rotations) the existence of a preferred frame!

Maxwell's equations

$$\nabla \cdot \mathbf{E} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mathbf{J} + \frac{\partial \mathbf{E}}{\partial t}$$

A preferred frame?

- ▶ From Maxwell's equations, one can derive that the speed of light is c (see e.g. Jackson 1998).

A preferred frame?

- ▶ From Maxwell's equations, one can derive that the speed of light is c (see e.g. Jackson 1998).
- ▶ It is natural to identify this statement as holding true in the above-mentioned preferred frame.

A preferred frame?

- ▶ From Maxwell's equations, one can derive that the speed of light is c (see e.g. Jackson 1998).
- ▶ It is natural to identify this statement as holding true in the above-mentioned preferred frame.
- ▶ In this frame, with respect to what is light moving? 19th century answer: some background structure: *the ether*.

A preferred frame?

- ▶ From Maxwell's equations, one can derive that the speed of light is c (see e.g. Jackson 1998).
- ▶ It is natural to identify this statement as holding true in the above-mentioned preferred frame.
- ▶ 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.

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.
- ▶ In the 19th century, physicists indeed did attempt to test this hypothesis—all tests ended in *null results*.

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.
- ▶ 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.)

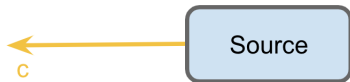
Suppose we are riding in a car that is going at a speed u , and light from the rear is going past the car with speed c . Differentiating [the Galilean transformation for position] gives

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

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



Case 1: Source at rest with respect to the ether



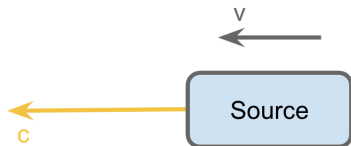
- Imagine a source at rest with respect to the ether, which emits a light ray with velocity c .

Case 1: Source at rest with respect to the ether

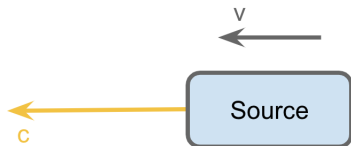


- ▶ Imagine a source at rest with respect to the ether, which emits a light ray with velocity c .
- ▶ In the ether rest frame—which is also the source's rest frame!—the light propagates at c .

Case 2: Source moving with respect to the ether

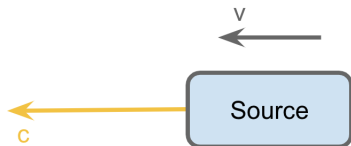


Case 2: Source moving with respect to the ether



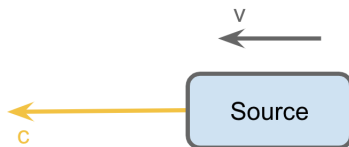
- Imagine a source moving with respect to the ether with velocity v , which emits a light ray with velocity c .

Case 2: Source moving with respect to the ether



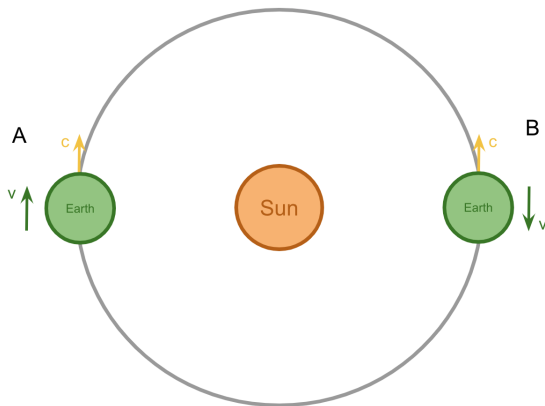
- Imagine a source moving with respect to the ether with velocity v , which emits a light ray with velocity c .
- In the ether rest frame, the light propagates at c .

Case 2: Source moving with respect to the ether



- ▶ 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



Case 3: Solar system at rest with respect to ether

- From the point of view of the ether rest frame (= Sun's rest frame), light emitted from Earth at A has velocity c .

Case 3: Solar system at rest with respect to ether

- ▶ From the point of view of the ether rest frame (= Sun's rest frame), light emitted from Earth at A has velocity c .
- ▶ From the point of view of the ether rest frame (= Sun's rest frame), light emitted from Earth at B has velocity c .

Case 3: Solar system at rest with respect to ether

- ▶ From the point of view of the ether rest frame (= Sun's rest frame), light emitted from Earth at A has velocity c .
- ▶ From the point of view of the ether rest frame (= Sun's rest frame), light emitted from Earth at B has velocity c .
- ▶ From the point of view of Earth's rest frame at A, light emitted from Earth at A has velocity $c - v$.

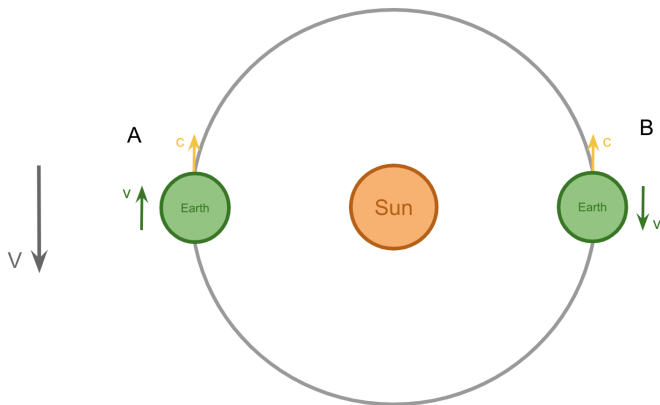
Case 3: Solar system at rest with respect to ether

- ▶ From the point of view of the ether rest frame (= Sun's rest frame), light emitted from Earth at A has velocity c .
- ▶ From the point of view of the ether rest frame (= Sun's rest frame), light emitted from Earth at B has velocity c .
- ▶ From the point of view of Earth's rest frame at A, light emitted from Earth at A has velocity $c - v$.
- ▶ From the point of view of Earth's rest frame at B, light emitted from Earth at B has velocity $c + v$.

Case 3: Solar system at rest with respect to ether

- ▶ From the point of view of the ether rest frame (= Sun's rest frame), light emitted from Earth at A has velocity c .
- ▶ From the point of view of the ether rest frame (= Sun's rest frame), light emitted from Earth at B has velocity c .
- ▶ From the point of view of Earth's rest frame at A, light emitted from Earth at A has velocity $c - v$.
- ▶ From the point of view of Earth's rest frame at B, light emitted from Earth at B has velocity $c + v$.
- ▶ Note that at every point in its orbit, the Earth has some velocity with respect to the ether, in this scenario.

Case 4: Solar system moving with respect to ether



Case 4: Solar system moving with respect to ether

- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at A has velocity $c + V$.

Case 4: Solar system moving with respect to ether

- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at A has velocity $c + V$.
- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at B has velocity $c + V$.

Case 4: Solar system moving with respect to ether

- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at A has velocity $c + V$.
- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at B has velocity $c + V$.
- ▶ From the point of view of Earth's rest frame at A, light emitted from Earth at A has velocity $c - v + V$.

Case 4: Solar system moving with respect to ether

- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at A has velocity $c + V$.
- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at B has velocity $c + V$.
- ▶ From the point of view of Earth's rest frame at A, light emitted from Earth at A has velocity $c - v + V$.
- ▶ From the point of view of Earth's rest frame at B, light emitted from Earth at B has velocity $c + v + V$.

Case 4: Solar system moving with respect to ether

- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at A has velocity $c + V$.
- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at B has velocity $c + V$.
- ▶ From the point of view of Earth's rest frame at A, light emitted from Earth at A has velocity $c - v + V$.
- ▶ From the point of view of Earth's rest frame at B, light emitted from Earth at B has velocity $c + v + V$.
- ▶ If $v = V$, then the Earth at A would be at rest with respect to ether, and light, in the rest frame of the Earth at A, would propagate at c —in which case (to anticipate what's coming!), one would observe Michelson-Morley null results.

Case 4: Solar system moving with respect to ether

- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at A has velocity $c + V$.
- ▶ From the point of view of the Sun's rest frame (which is no longer the ether rest frame!), light emitted from Earth at B has velocity $c + V$.
- ▶ From the point of view of Earth's rest frame at A, light emitted from Earth at A has velocity $c - v + V$.
- ▶ From the point of view of Earth's rest frame at B, light emitted from Earth at B has velocity $c + v + V$.
- ▶ If $v = V$, then the Earth at A would be at rest with respect to ether, and light, in the rest frame of the Earth at A, would propagate at c —in which case (to anticipate what's coming!), one would observe Michelson-Morley null results.
- ▶ But, of course, this can't happen at every point in the Earth's orbit!

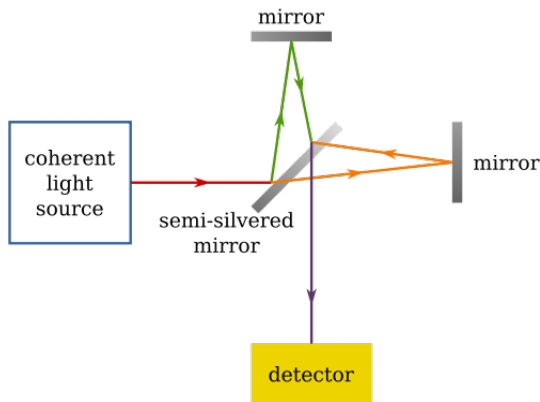
Today

Invariance groups

The Michelson-Morley experiment

Lorentz's programme

The experimental setup



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

The experimental setup

1. The interferometer sends a beam of light towards a half-silvered mirror.

The experimental setup

1. The interferometer sends a beam of light towards a half-silvered mirror.
2. Here the beam is split into two components that continue at right angles to one another: one down 'arm A' and the other down 'arm B'.

The experimental setup

1. The interferometer sends a beam of light towards a half-silvered mirror.
2. Here the beam is split into two components that continue at right angles to one another: one down 'arm A' and the other down 'arm B'.
3. A short distance later, each half-beam encounters a second (fully silvered) mirror, and is reflected back. The beams are recombined, and the resulting interference pattern is observed on a screen.

The experimental setup

1. The interferometer sends a beam of light towards a half-silvered mirror.
2. Here the beam is split into two components that continue at right angles to one another: one down 'arm A' and the other down 'arm B'.
3. A short distance later, each half-beam encounters a second (fully silvered) mirror, and is reflected back. The beams are recombined, and the resulting interference pattern is observed on a screen.
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.

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.
- ▶ *If* we could ensure that the arms were exactly equal in length, then anything other than constructive interference would indicate the presence of an ether wind.
Unfortunately ensuring this is not technologically feasible ...

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.
- ▶ *If* we could ensure that the arms were exactly equal in length, then anything other than constructive interference would indicate the presence of an ether wind.
Unfortunately ensuring this is not technologically feasible ...
- ▶ ... 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.

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.
- ▶ *If* we could ensure that the arms were exactly equal in length, then anything other than constructive interference would indicate the presence of an ether wind.
Unfortunately ensuring this is not technologically feasible ...
- ▶ ... 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.

Quantitative calculation of expected fringe shift

- Suppose (for simplicity) that the two arms are of equal length, L .

Quantitative calculation of expected fringe shift

- ▶ Suppose (for simplicity) that the two arms are of equal length, L .
- ▶ Then, the out-and-back time for light to travel along the arm that is parallel to the ether drift should be

$$\Delta t_{\parallel} = \frac{L}{c - v} + \frac{L}{c + v} = \frac{2Lc}{c^2 - v^2}.$$

Quantitative calculation of expected fringe shift

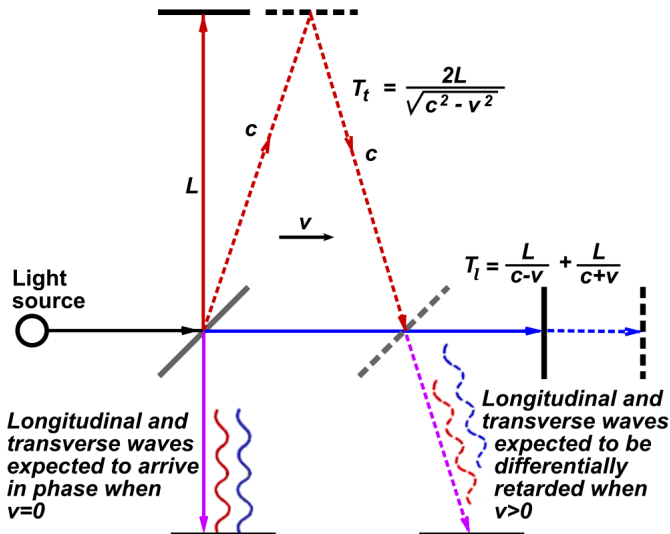
- ▶ Suppose (for simplicity) that the two arms are of equal length, L .
- ▶ Then, the out-and-back time for light to travel along the arm that is parallel to the ether drift should be

$$\Delta t_{\parallel} = \frac{L}{c - v} + \frac{L}{c + v} = \frac{2Lc}{c^2 - v^2}.$$

- ▶ 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



Quantitative calculation of expected fringe shift

- The time difference before rotation is given by

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

Quantitative calculation of expected fringe shift

- The time difference before rotation is given by

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

- By multiplying by c , the corresponding length difference before rotation is

$$\Delta_1 = 2 \left(\frac{L}{1 - \frac{v^2}{c^2}} - \frac{L}{\sqrt{1 - \frac{v^2}{c^2}}} \right).$$

Quantitative calculation of expected fringe shift

- The time difference before rotation is given by

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

- By multiplying by c , the corresponding length difference before rotation is

$$\Delta_1 = 2 \left(\frac{L}{1 - \frac{v^2}{c^2}} - \frac{L}{\sqrt{1 - \frac{v^2}{c^2}}} \right).$$

- 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:

$$n = \frac{\Delta_1 - \Delta_2}{\lambda} \approx \frac{2Lv^2}{\lambda c^2}.$$

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:

$$n = \frac{\Delta_1 - \Delta_2}{\lambda} \approx \frac{2Lv^2}{\lambda c^2}.$$

- ▶ 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 ’).

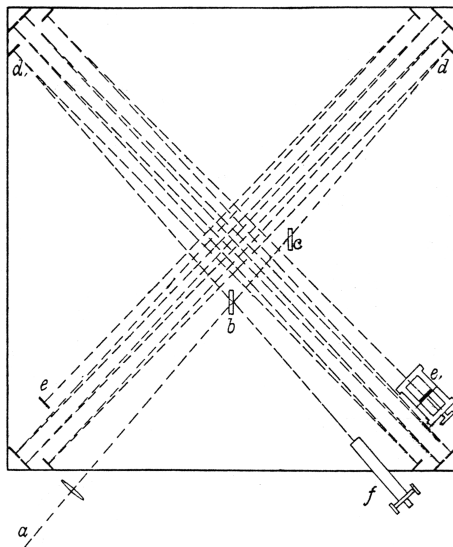
Length of the arms

- ▶ Question: $L = 11\text{ m}$ is pretty long for the length of the arms of the Michelson-Morley experiment—surely the apparatus wasn't that big?

Length of the arms

- ▶ Question: $L = 11\text{ m}$ is pretty long for the length of the arms of the Michelson-Morley experiment—surely the apparatus wasn't that big?
- ▶ Answer: Michelson and Morley used mirrors to bounce the light down the arms multiple times, giving an *effective* length of 11 m .

4.



The result

- ▶ The result of Michelson-Morley experiment was *null*—rotating the apparatus did not lead to a fringe shift.

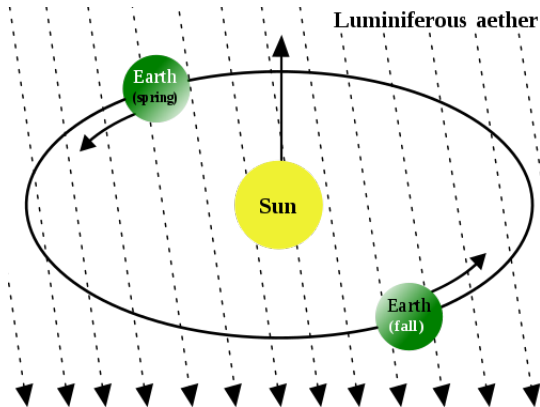
The result

- ▶ The result of Michelson-Morley experiment was *null*—rotating the apparatus did not lead to a fringe shift.
- ▶ Michelson and Morley concluded that “if there be any relative motion between the earth and the luminiferous ether, it must be small” (Michelson and Morley 1887, p. 341); here ‘small’ means “probably less than one-sixth of the earth’s orbital velocity, and certainly less than one-fourth.”

The result

- ▶ The result of Michelson-Morley experiment was *null*—rotating the apparatus did not lead to a fringe shift.
- ▶ Michelson and Morley concluded that “if there be any relative motion between the earth and the luminiferous ether, it must be small” (Michelson and Morley 1887, p. 341); here ‘small’ means “probably less than one-sixth of the earth’s orbital velocity, and certainly less than one-fourth.”
- ▶ 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?



Galileo's 'Earth'

- ▶ Suppose that the Earth is at rest with respect to the ether at some point in its orbit.

Galileo's 'Earth'

- ▶ Suppose that the Earth is at rest with respect to the ether at some point in its orbit.
- ▶ Then the Earth will be moving with respect to the ether at some later point in its orbit.

Galileo's 'Earth'

- ▶ Suppose that the Earth is at rest with respect to the ether at some point in its orbit.
- ▶ Then the Earth will be moving with respect to the ether at some later point in its orbit.
- ▶ It look like the Earth is, therefore, a Galileo ship-type subsystem, which has been actively boosted.

Galileo's 'Earth'

- ▶ Suppose that the Earth is at rest with respect to the ether at some point in its orbit.
- ▶ Then the Earth will be moving with respect to the ether at some later point in its orbit.
- ▶ It look like the Earth is, therefore, a Galileo ship-type subsystem, which has been actively boosted.
- ▶ If all physics were Galilean invariant, we would expect the same physical laws on the Earth in the two scenarios.

Galileo's 'Earth'

- ▶ Suppose that the Earth is at rest with respect to the ether at some point in its orbit.
- ▶ Then the Earth will be moving with respect to the ether at some later point in its orbit.
- ▶ It look like the Earth is, therefore, a Galileo ship-type subsystem, which has been actively boosted.
- ▶ If all physics were Galilean invariant, we would expect the same physical laws on the Earth in the two scenarios.
- ▶ But electromagnetism was known *not* to be Galilean invariant—so (the thought goes) we should expect violations of the relativity principle...

Galileo's 'Earth'

- ▶ Suppose that the Earth is at rest with respect to the ether at some point in its orbit.
- ▶ Then the Earth will be moving with respect to the ether at some later point in its orbit.
- ▶ It look like the Earth is, therefore, a Galileo ship-type subsystem, which has been actively boosted.
- ▶ If all physics were Galilean invariant, we would expect the same physical laws on the Earth in the two scenarios.
- ▶ But electromagnetism was known *not* to be Galilean invariant—so (the thought goes) we should expect violations of the relativity principle...
- ▶ ...manifesting themselves in different detected velocities of light in the two cases.

Galileo's 'Earth'

- ▶ Suppose that the Earth is at rest with respect to the ether at some point in its orbit.
- ▶ Then the Earth will be moving with respect to the ether at some later point in its orbit.
- ▶ It look like the Earth is, therefore, a Galileo ship-type subsystem, which has been actively boosted.
- ▶ If all physics were Galilean invariant, we would expect the same physical laws on the Earth in the two scenarios.
- ▶ But electromagnetism was known *not* to be Galilean invariant—so (the thought goes) we should expect violations of the relativity principle...
- ▶ ...manifesting themselves in different detected velocities of light in the two cases.
- ▶ How to explain that this was never observed?

Today

Invariance groups

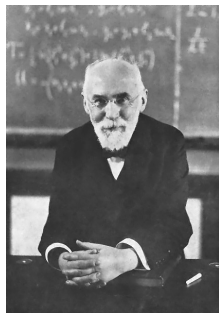
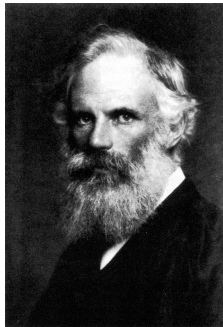
The Michelson-Morley experiment

Lorentz's programme

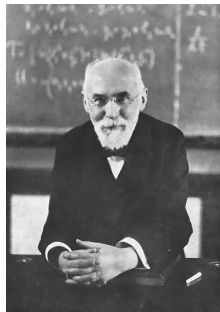
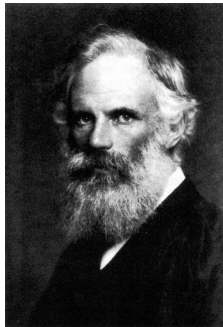
Contraction hypotheses

We'll look now at how physicists responded initially to null results 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.*
(Fitzgerald 1889)

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.*
(Fitzgerald 1889)

- ▶ 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

- ▶ Lorentz arrived at the same idea in 1892.

The trailblazers: Lorentz and Larmor

- ▶ Lorentz arrived at the same idea in 1892.
- ▶ Larmor would also adopt the idea in his 1900 book, *Aether and Matter*.

Lorentz

- Lorentz introduced a longitudinal factor $\mathcal{C}_{\parallel} = 1 + \delta$ and a transverse factor $\mathcal{C}_{\perp} = 1 + \epsilon$. He claimed that the null result required

$$\epsilon - \delta \sim \frac{v^2}{2c^2}.$$

Lorentz

- ▶ Lorentz introduced a longitudinal factor $\mathcal{C}_{\parallel} = 1 + \delta$ and a transverse factor $\mathcal{C}_{\perp} = 1 + \epsilon$. He claimed that the null result required

$$\epsilon - \delta \sim \frac{v^2}{2c^2}.$$

- ▶ Contraction in this manner would cancel out the different velocities of light, and lead to no phase shift effects at the detector.

Lorentz

- ▶ Lorentz introduced a longitudinal factor $\mathcal{C}_{\parallel} = 1 + \delta$ and a transverse factor $\mathcal{C}_{\perp} = 1 + \epsilon$. He claimed that the null result required

$$\epsilon - \delta \sim \frac{v^2}{2c^2}.$$

- ▶ 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

- ▶ Lorentz would later push this idea further, with his *theorem of corresponding states* (1895, 1899).

The theorem of corresponding states

- ▶ Lorentz would later push this idea further, with his *theorem of corresponding states* (1895, 1899).
- ▶ This was designed to show that *no* first- or second-order ether-wind effects would be discernible in experiments involving optics and electrodynamics.

The theorem of corresponding states

- ▶ Lorentz would later push this idea further, with his *theorem of corresponding states* (1895, 1899).
- ▶ 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.

The theorem of corresponding states

- ▶ Lorentz would later push this idea further, with his *theorem of corresponding states* (1895, 1899).
- ▶ 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 hocness*

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

- ▶ Next time, we'll look at how Einstein (so the story goes) elevated contraction from dynamics and kinematics, and thereby accounted for all ether wind null results in one swoop, without auxiliary hypotheses.

Einstein's revolution

- ▶ Next time, we'll look at how Einstein (so the story goes) elevated contraction from dynamics and kinematics, and thereby accounted for all ether wind null results in one swoop, without auxiliary hypotheses.
- ▶ 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*.

Reconceptualising boosts

- ▶ Prior to Einstein, it was understood that Galileo's 'Earth' at different points in its orbit was related by Galilean boosts.

Reconceptualising boosts

- ▶ Prior to Einstein, it was understood that Galileo's 'Earth' at different points in its orbit was related by Galilean boosts.
- ▶ Recalling that electromagnetism is invariant under *Lorentz* boosts (not Galilean boosts), this led to the expectation of relativity principle-violating physics.

Reconceptualising boosts

- ▶ Prior to Einstein, it was understood that Galileo's 'Earth' at different points in its orbit was related by Galilean boosts.
- ▶ Recalling that electromagnetism is invariant under *Lorentz* boosts (not Galilean boosts), this led to the expectation of relativity principle-violating physics.
- ▶ This physics was not observed.

Reconceptualising boosts

- ▶ Prior to Einstein, it was understood that Galileo's 'Earth' at different points in its orbit was related by Galilean boosts.
- ▶ Recalling that electromagnetism is invariant under *Lorentz* boosts (not Galilean boosts), this led to the expectation of relativity principle-violating physics.
- ▶ This physics was not observed.
- ▶ Einstein: Instead construe boosts as *Lorentz* boosts.

Reconceptualising boosts

- ▶ Prior to Einstein, it was understood that Galileo's 'Earth' at different points in its orbit was related by Galilean boosts.
- ▶ Recalling that electromagnetism is invariant under *Lorentz* boosts (not Galilean boosts), this led to the expectation of relativity principle-violating physics.
- ▶ This physics was not observed.
- ▶ 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'.

Reconceptualising boosts

- ▶ Prior to Einstein, it was understood that Galileo's 'Earth' at different points in its orbit was related by Galilean boosts.
- ▶ Recalling that electromagnetism is invariant under *Lorentz* boosts (not Galilean boosts), this led to the expectation of relativity principle-violating physics.
- ▶ This physics was not observed.
- ▶ 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).

Summary

In this lecture, we've seen that:

Summary

In this lecture, we've seen that:

1. The combination of Newtonian mechanics and Maxwell electrodynamics leads naturally to the existence of a preferred frame.

Summary

In this lecture, we've seen that:

1. The combination of Newtonian mechanics and Maxwell electrodynamics leads naturally to the existence of a preferred frame.
2. Physically, this frame was identified with the rest frame of the ether.

Summary

In this lecture, we've seen that:

1. The combination of Newtonian mechanics and Maxwell electrodynamics leads naturally to the existence of a preferred frame.
2. Physically, this frame was identified with the rest frame of the ether.
3. These hypotheses led to the prediction of ether wind effects—but no such wind was ever observed.

Summary

In this lecture, we've seen that:

1. The combination of Newtonian mechanics and Maxwell electrodynamics leads naturally to the existence of a preferred frame.
2. Physically, this frame was identified with the rest frame of the ether.
3. These hypotheses led to the prediction of ether wind effects—but no such wind was ever observed.
4. Lorentz and others sought to account for these null results via dynamical contraction hypotheses.

Summary

In this lecture, we've seen that:

1. The combination of Newtonian mechanics and Maxwell electrodynamics leads naturally to the existence of a preferred frame.
2. Physically, this frame was identified with the rest frame of the ether.
3. These hypotheses led to the prediction of ether wind effects—but no such wind was ever observed.
4. Lorentz and others sought to account for these null results via dynamical contraction hypotheses.
5. Einstein's approach was, rather, to reconceptualise the nature of boosts.







Summary

In this lecture, we've seen that:





1. The combination of Newtonian mechanics and Maxwell electrodynamics leads naturally to the existence of a preferred frame.
2. Physically, this frame was identified with the rest frame of the ether.
3. These hypotheses led to the prediction of ether wind effects—but no such wind was ever observed.
4. Lorentz and others sought to account for these null results via dynamical contraction hypotheses.
5. Einstein's approach was, rather, to reconceptualise the nature of boosts.

More on Einstein's approach next time!

References I

-  Harvey R. Brown, *Physical Relativity: Spacetime Structure from a Dynamical Perspective*, Oxford: Oxford University Press, 2005.
-  Richard Feynman, *The Feynman Lectures on Physics*, Basic Books, 2010.
-  George F. FitzGerald, “The Ether and the Earth’s Atmosphere”, *Science* 13, p. 390, 1889.
-  Michael Friedman, *Foundations of Space-Time Theories*, Princeton, NJ: Princeton University Press, 1983. §III.5.
-  John David Jackson, *Classical Electrodynamics*, third edition, New York: John Wiley & Sons, 1998.
-  Joseph Larmor, *Aether and Matter*, Cambridge: Cambridge University Press, 1900.

References II

-  Hendrik A. Lorentz. “De relative beweging van de aarde en den aether”, *Koninklijke Akademie van Wetenschappen te Amsterdam, Wis-en Natuurkundige Afdeeling, Verslagen der Zittingen* 1, pp. 74-79, 1892. Reprinted in English translation, “The Relative Motion of the Earth and the Ether”, in P. Zeeman and A. D. Fokker (eds.), *Collected Papers*, pp. 219-223, The Hague: Nijhoff, 1937.
-  Hendrik A. Lorentz, *Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern*, Leydon: Brill, 1895.
-  Albert Abraham Michelson and Edward Morley, “On the Relative Motion of the Earth and the Luminiferous Ether”, *American Journal of Science* 34(203), pp. 333-345, 1887.
-  Albert Shadowitz, *Special Relativity*, New York: Dover, 1988.