Imperial College London

Relativity

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Details

- 10 lectures over 4 weeks
- 4 problem sheets
- 3 weeks of coursework (2 MCQ, 1 open)
- Office hours: Fridays 12-1
- Blackboard

Aims

- To understand both the motivation and content of Einstein's postulates, and their implications.
- To be able to apply the Lorentz transformation equations.
- To understand the basic properties of energy and momentum in special relativity.

Textbooks

- **Young and Freedman**, *University Physics*: has main points without much detailed derivation. They use *u* and *v* differently than almost every other book I've come across.

- **P. Koppenburg** Lecture notes (from a previous lecturer).

- **Martin McCall**, *Classical Mechanics, a Modern Introduction*: (2nd edition) contains a two chapters on special relativity at just the right level for this course (and easy to contact the author!).

- Most electromagnetism texts have some discussion of relativity, as do many mechanics textbooks.

The Relativity Principle

Galileo Galilei first explicitly stated the relativity principle in 1632:

The laws of motion are the same to all observers who move with constant velocity relative to each other.

Definition:

"Laws are the same" = "Covariant"

19th century physics

- 1820's: Ampere/Oersted show electric currents produce magnetic forces.
- 1830's: Faraday investigates electromagnetic induction.
- 1865: Maxwell unified all electric and magnetic physics in a single set of equations. This theory predicted that light was an electromagnetic wave. The speed of light was given by electric and magnetic constants, $c = 1/\sqrt{\mu_0 \varepsilon_0}$.
- 1887: Hertz proved that Maxwell's theory was correct by discovering free space transverse electromagnetic waves.

Implications of Maxwell's theory of EM

- Maxwell's equations say that the velocity of light is independent of the source velocity!

What is waving? Think of water waves, sound waves ...

- Light waves were hypothesized to propagate in a medium: the "ether". One should be able to measure a local velocity relative to the ether.

ELEMENTARY

TEXT-BOOK

OF

PHYSICS.

BY J. D. EVERETT, M.A.,
D.C.L., F.R.S., F.R.S.E.,
PROFESSOR OF NATURAL PHILOSOPHY IN THE QUEEN'S COLLEGE, BELFAST.

ILLUSTRATED BY NUMEROUS ENGRAVINGS ON WOOD.

FIFTH EDITION.

LONDON:
BLACKIE & SON, 49 & 50 OLD BAILEY, E.C.;
GLASGOW, EDINBURGH, AND DUBLIN.
1889.

with considerable accuracy by observations on "diffraction"—a subject which does not come within the scope of the present treatise; and by dividing the wave-length into the distance travelled over in a second, we obtain the number of vibrations per second. Red light makes about 400 millions of millions of vibrations per second, and violet light nearly twice as many. In passing out of one medium into another the rapidity of vibration remains unaltered, but the wave-length changes in the same ratio as the velocity. This remark is true of sound as well as light.

430. Sound cannot be propagated through a vacuum. Light, on the other hand, is propagated for immense distances through the interplanetary and interstellar spaces, which are more perfect vacua than any that can be artificially obtained. Hence it is inferred that light is propagated by the vibrations of some medium different from ordinary matter. The immense velocity of light shows that this medium is incomparably more resilient in proportion to its density than any of the forms of ordinary matter. This medium, whose existence is now universally accepted by physicists, is called the *luminiferous ether*.

431. There is another difference between sound and light in the direction of their vibrations. The vibrations by which sound is propagated through gases and liquids, and probably also through solids, are longitudinal,—that is to say, each particle of the medium travels backwards and forwards along a line which points in the direction in which the sound is travelling; there is no transverse motion. In luminous vibration, on the contrary, the most important part of the motion is transverse, as is proved by the phenomena of polarized light.

432. Phonograph.—Mr. Edison of New York has been successful in constructing an instrument which can reproduce articulate sounds spoken into it. The voice of the speaker is directed into a funnel, which converges the sonorous waves upon a diaphragm carrying a style.

But what about the Relativity Principle?

1. Maxwell's equations are wrong.

2. There is a relativity principle for Newton's laws, but electromagnetism selects a preferred frame of movement: the ether. Not all frames are the same - it is possible to define an absolute velocity.

3. Newton's equations are wrong, since they predict velocities add linearly.

Ether theories

1. ~~Stationary Ether~~

But: observations of stars showed a constant refraction

2. Fresnel: Partial Ether Dragging

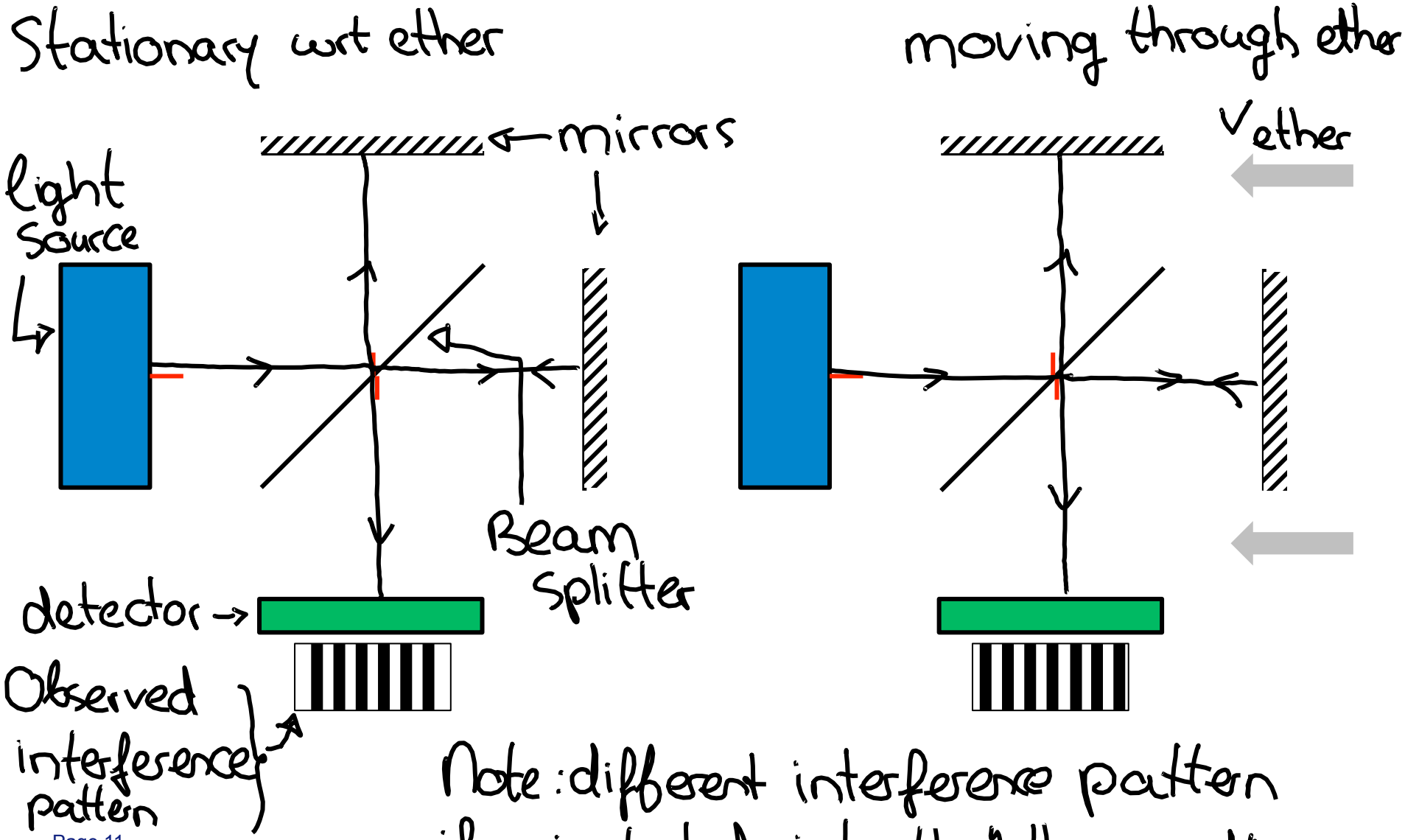
Supported by the Fizeau experiment (1851):
light is dragged by water, but much less than expected

3. Stokes: Complete Ether Dragging

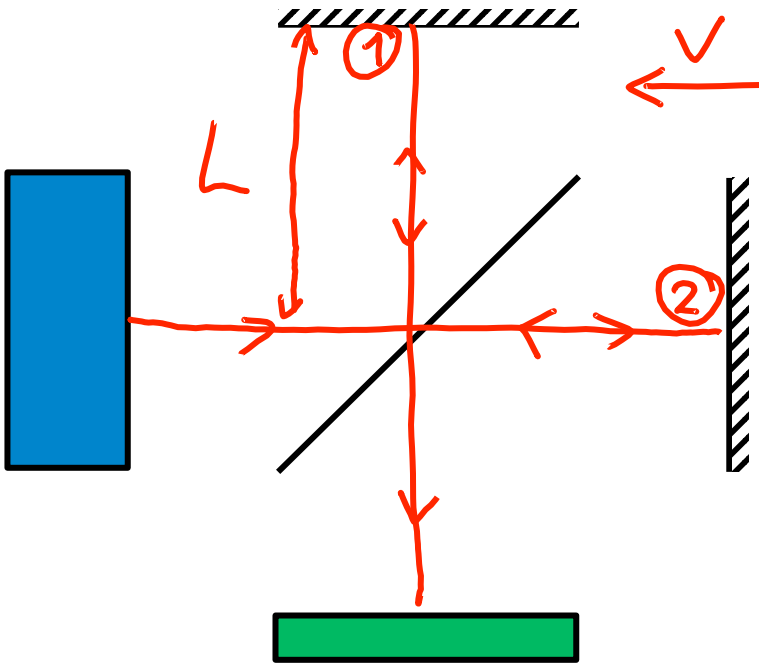
↓

"Drag coefficient"

The Michelson-Morley experiment



The Michelson-Morley experiment



$\leftarrow v$

$$\boxed{t_1 = \frac{2L}{c}} \qquad t_2 = \frac{L}{c-v} + \frac{L}{c+v} =$$

$$= \frac{L}{c}\left(\frac{1}{1-\frac{v}{c}} + \frac{1}{1+\frac{v}{c}}\right)$$

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

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

Note: $(1+x)^n \simeq 1 + nx + \ldots$ (Binomial exp.)

$$\Rightarrow t_2 \simeq \frac{2L}{c}\left(1+\left(\frac{v}{c}\right)^2\right)$$

The Michelson-Morley experiment

frequency

$\nu t_2 = \text{no. of waves} \equiv n = \frac{\nu}{c} 2L\left(1+\left(\frac{v}{c}\right)^2\right) \quad \left[\frac{\nu}{c} = \frac{1}{\lambda}\right]$

$\Rightarrow \frac{2L}{\lambda}\left(1+\left(\frac{v}{c}\right)^2\right)$

$\Delta n = \nu t_2 - \nu t_1 = \frac{2L}{\lambda}\left(\frac{v}{c}\right)^2$

$\Delta n = 0.4$

Should be detectable -

$L = 11\ m$

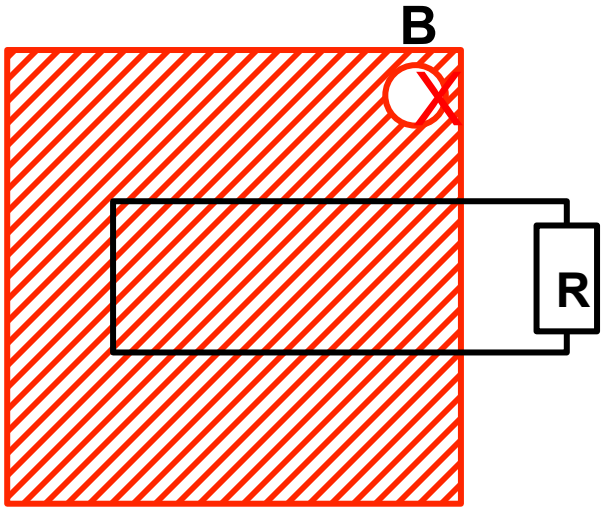
$\lambda = 550\ nm$

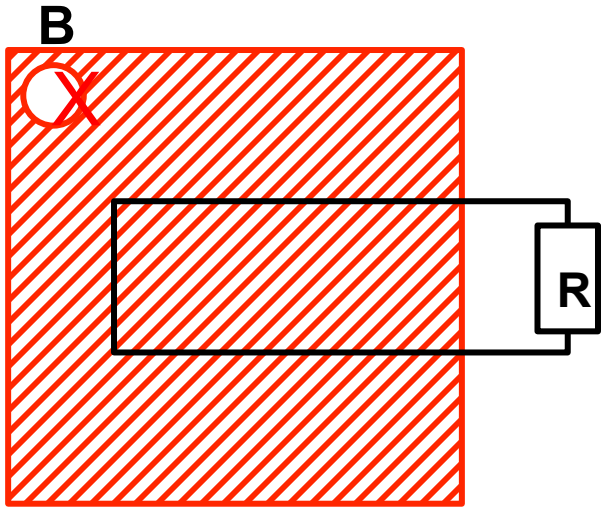
$v = 3 \times 10^4\ m/s$

$c = 3 \times 10^8\ m/s$

But: no effect observed

The moving magnet and conductor problem





Lorentz force on charges in wire

$\vec{F} = q\vec{v} \times \vec{B}$

Faraday's law of induction -> electric field

Diffeent laws, but same result

Conclusions of the experiments

- Maxwell's equations say that the speed of light is *independent* of the speed of the light source.
- The Fizeau experiment says:
  - the speed of light is *independent* of the velocity of an ether that is dragged by matter;
  - when travelling through a medium, the speed of light is determined by a 'dragging coefficient'.
- The Michelson-Morley experiment could not find a preferred 'ether frame'.
- The moving magnet and conductor problem only depends on *relative* motion.

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1905: Einstein's Special Relativity postulates

1. The laws of physics are the same in all inertial reference frames.
   ↳ see lecture 2
2. The speed of light is independent of the speed of the source or observer.

2b. The speed of light in vacuum is constant in all inertial frames.