JF PY1T10: Special Relativity

Lecture 2:

- Michelson-Morley Experiment
- Einstein’s Postulates of Special Relativity
- Synchronizing Clocks

Special Relativity Dr. Nuala Caffrey

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- 16 Lectures (including Tutorial Classes)

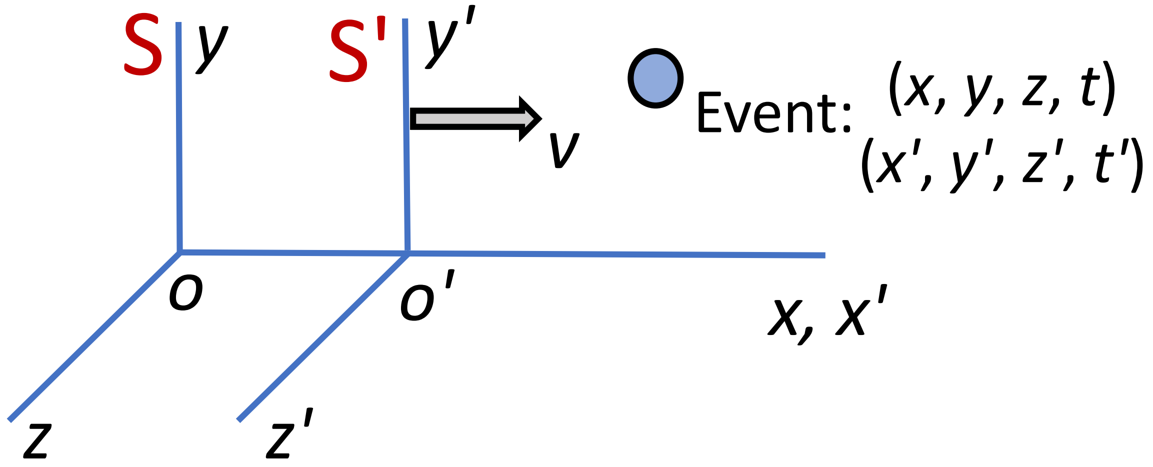
- Textbooks:
  - **Special Relativity (A. P. French)**
    [Some copies in library, E-book also available via library website]
  - University Physics (Young & Freedman), Chapter 37
  - An Introduction to Mechanics (Kleppner & Kolenkow)

- Lecture notes will be available on Blackboard.

Summary of Lecture 1

Inertial Reference Frames:

In Newtonian mechanics, a set of well-verified laws applies in an inertial frame of reference defined by the first law. Any frame moving at a constant velocity with respect to an inertial frame is also an inertial frame.



Inertial frame S' moves with velocity v relative to inertial frame S, along the x-axis. Origins coincide at $t = 0$ and $t' = 0$.

Galilean Transformations:

$$x = x' + vt \qquad y = y' \qquad z = z' \qquad t = t'$$

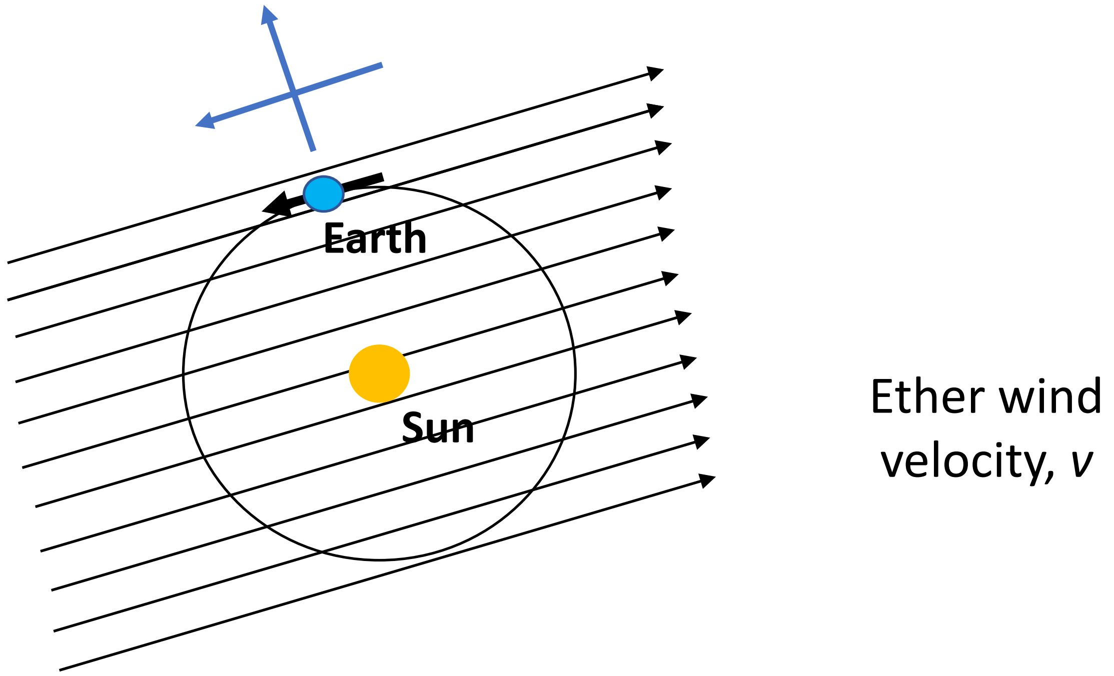
$$u_x = u_x' + v \qquad u_y = u_y' \qquad u_z = u_z'$$

Mitchelson & Morley Experiment – 1

- Light: Particle or wave? These theories were long believed to be mutually exclusive.
- By 19^{th} century wave theory of light was triumphing. In 1861, Maxwell produced his electromagnetic theory of light. Could predict the speed of light.
- But waves require a medium, the so-called *ether*.
- The velocity of light measured by an observer will depend on his motion *w.r.t.* the ether.
- If we measure velocity of light in different directions, we should be able to detect our motion through the ether:
  - ✓Same in both directions – we are stationary
  - ✓Not the same in both directions – we are moving.
- Mitchelson & Morley tried to measure this effect.

Michelson–Morley Experiment – 2

The ether should appear to be moving from the perspective of an observer on the sun-orbiting Earth.



As a result, light would sometimes travel in the same direction as the ether, and others times in the opposite direction.

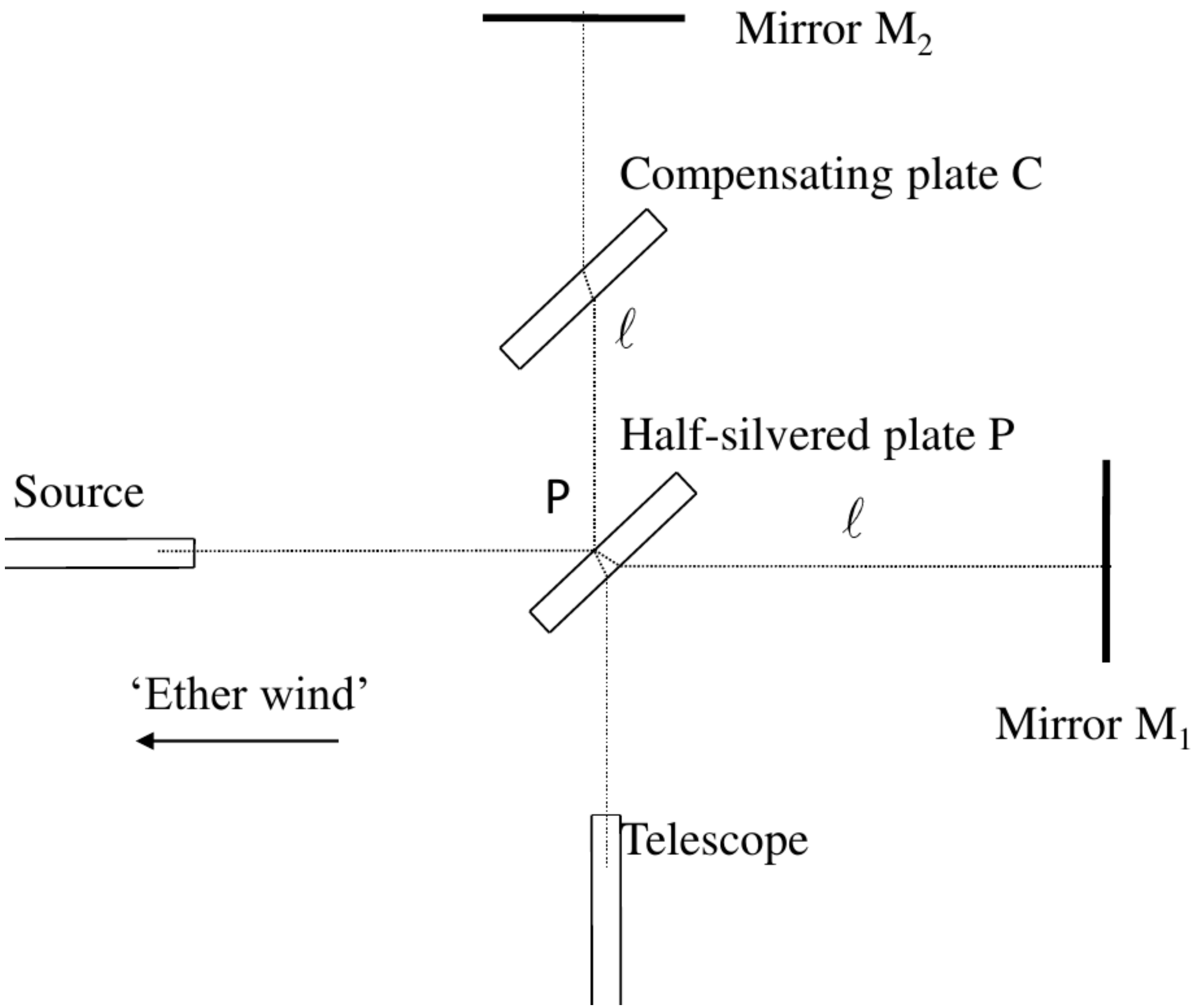
Aim: measure the speed of light in different directions in order to measure speed of the ether relative to Earth, thus establishing its existence.

Michelson–Morley Experiment – 3

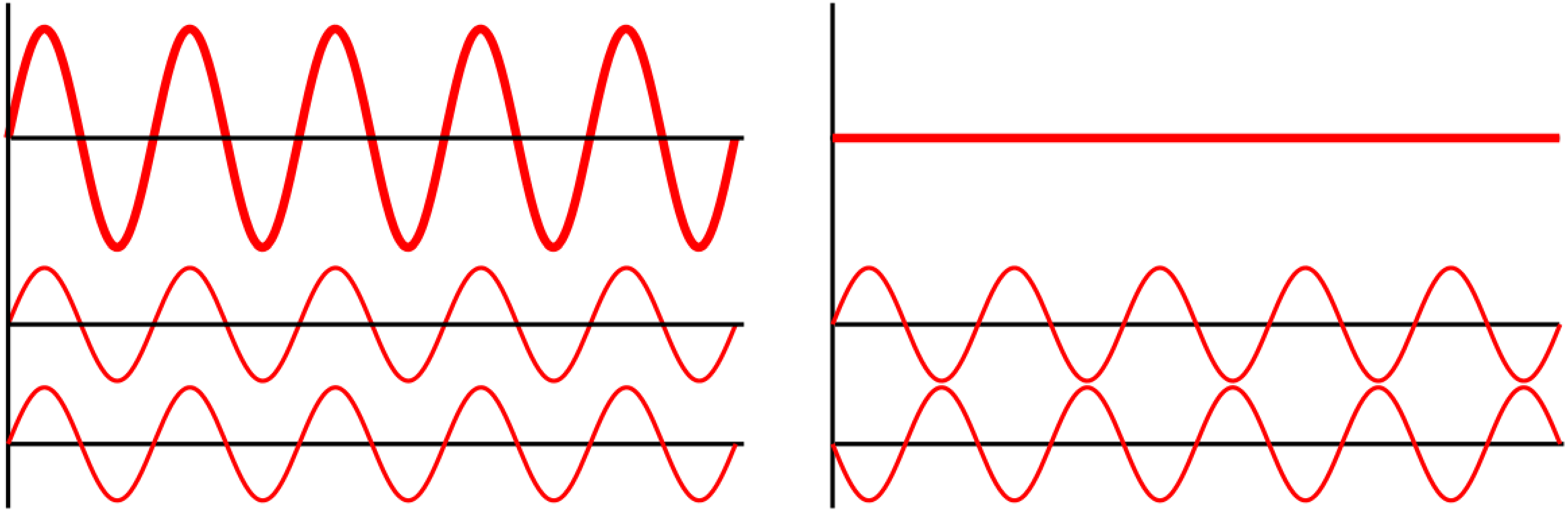
Rather than measure the effect of the ether on the time of transit of a single light beam, Michelson observed the *difference* between the transit time of two light beams.

If the two arms of the Michelson interferometer are identical, the light will recombine to give a bright field of view.

If either beam suffers a delay – the two waves interfere.



Light wave Interference

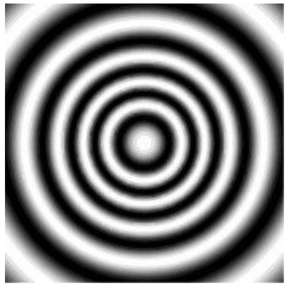


Michelson–Morley Experiment – 4

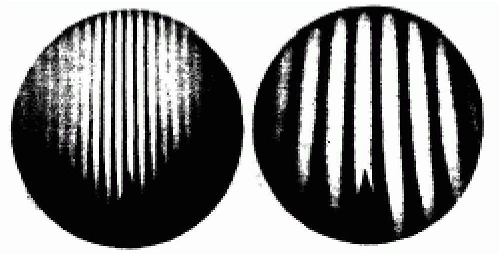
In the **MM** experiment, one of the mirrors was slightly tilted.

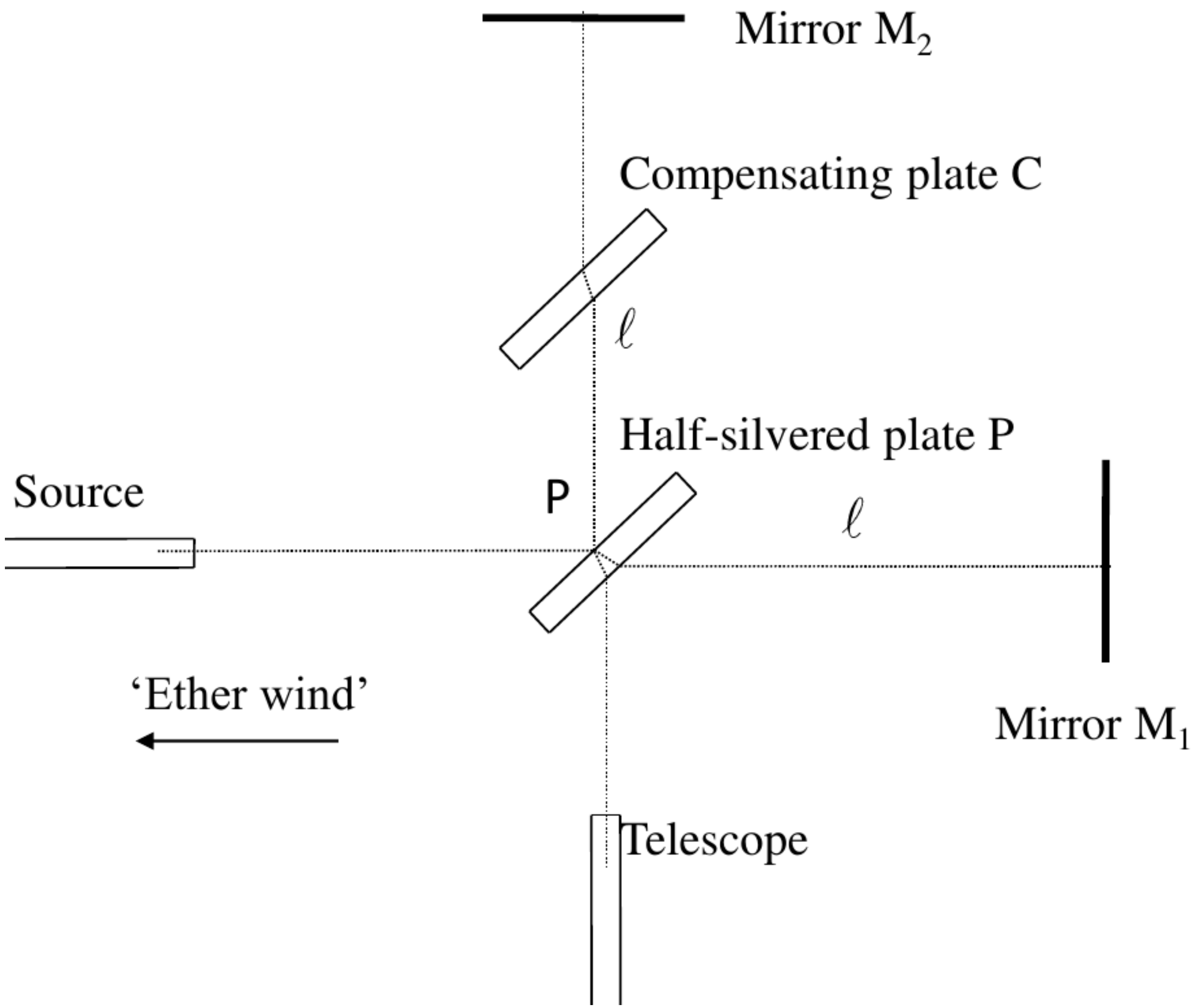
This produced a gradual time delay across the returning wave-front. The two interfering waves go in and out of phase.

The observer sees a fringe pattern of parallel lines in the telescope.



Tilt one of the mirrors:





Michelson–Morley Experiment – 5

P = glass plate with semi-transparent metal coating on its front face. At 45° to the source beam. Splits the light beam in two.

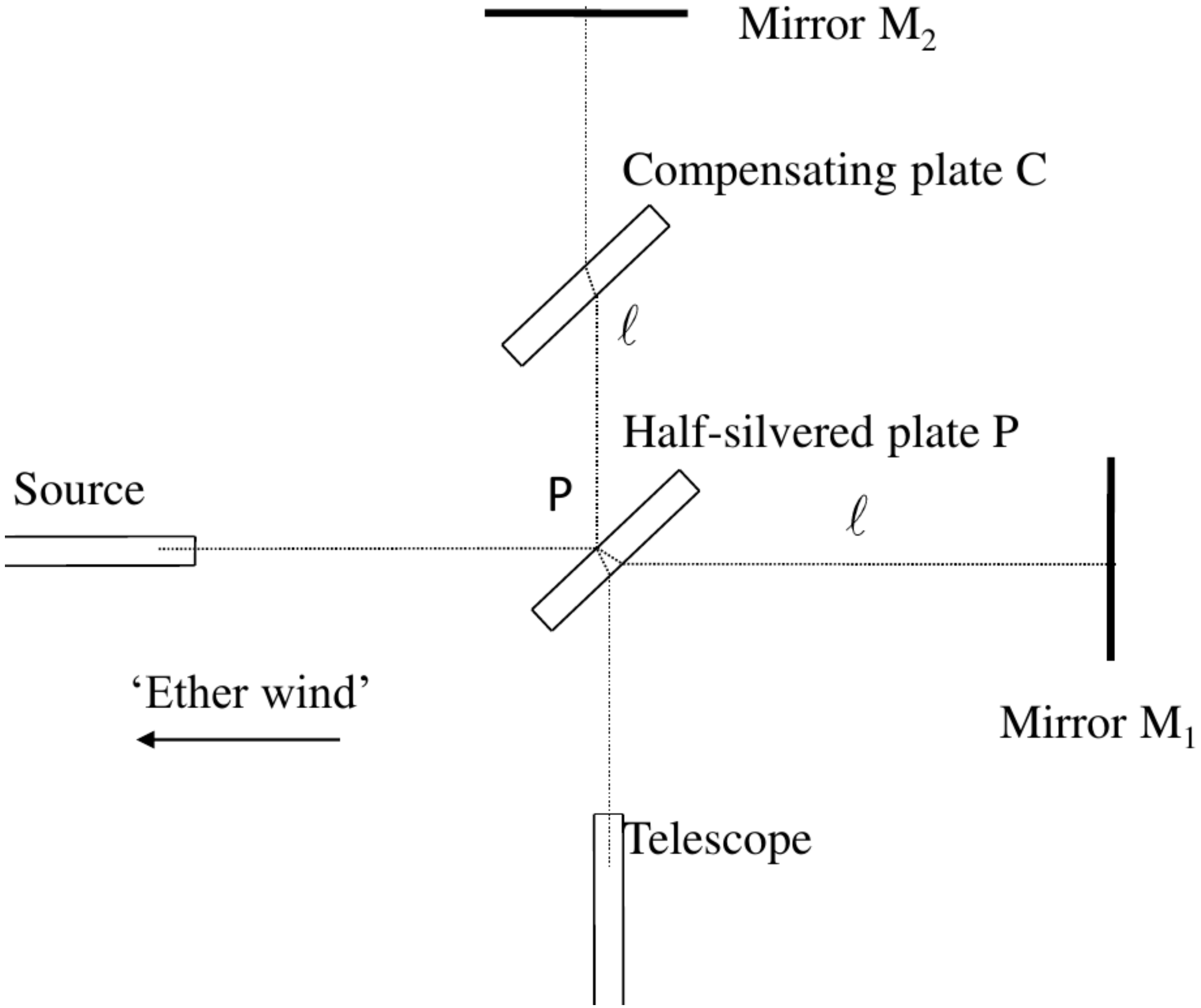
M$_1$, M$_2$ = Two mirrors.

C = Compensating plate to ensure both beams travel through the same amount of glass.

See interference fringes in telescope.

Used multiple reflection to extend the optical path.

For rotation, the whole interferometer was floated in a bath of mercury.

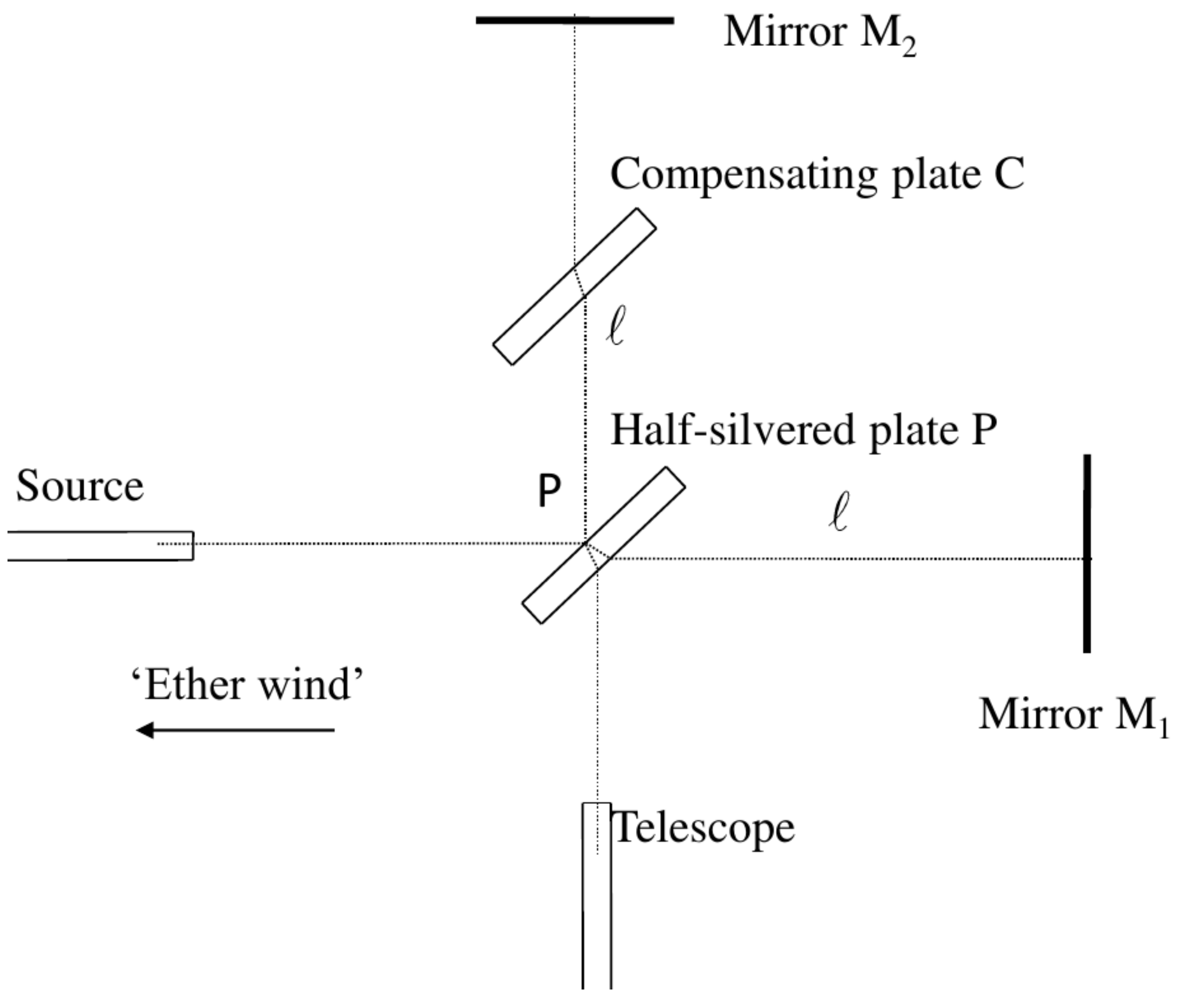


Michelson–Morley Experiment – 6

If the length of either arm is changed, the fringe pattern changes.

Change the path by one wavelength (λ) causes the pattern by one fringe. (In this experiment the light transverses each arm twice, so a change in length of either arm of $\lambda/2$ shifts by one fringe).

With care, can measure a small fraction of a wavelength.



Michelson–Morley Experiment – 7

Suppose laboratory is moving at speed *v* in direction $\mathbf{P\text{-}M_1}$ w.r.t. ether (i.e., the ether is moving in direction $\mathbf{M_1\text{-}P}$ w.r.t. laboratory)

Rotate equipment by 90°. Now $\mathbf{P\text{-}M_2}$ points into ether wind.

Expect to see fringe shift:

$$d = 2\,\frac{lv^2}{\lambda c^2} \quad \text{(Why? Derivation in class)}$$

$v = 3 \times 10^4$ m/s, $c = 3 \times 10^8$ m/s, $v/c = 10^{-4}$, $\lambda = 6 \times 10^{-7}$ m

If $\ell = 11$m, $\delta = 0.4$. But max. observed $\delta = 0.01$ (max).

Conclusion: No fringe shift when apparatus is rotated.

i.e.: We *<u>cannot</u>* detect any motion relative to ether (absolute space).

What about the ether?

Experiment proves <u>no</u> ether: but 1890s not ready to accept that conclusion

Ether exists, motion through it is real, but compensating effects at work.

It was suggested that the motion of the earth through the ether caused a shortening of one arm of the interferometer by <u>exactly</u> the amount required to eliminate the fringe shift, i.e., by $\left(1 - {v^2}/{c^2}\right)^{\frac{1}{2}}$.

What about the ether?

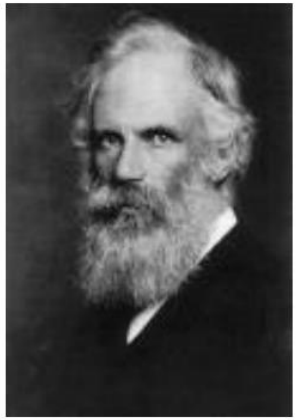
Looks like a fudge, invented just to solve the problem.

But not just an ad hoc idea:

"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" -- G F Fitzgerald, 1889

It turned out that the contraction hypothesis was correct, but for the wrong reason.

Contraction now called "Lorentz-Fitzgerald Contraction" after Fitzgerald and Hendrik Lorentz, who independently derived them.



George Francis Fitzgerald, Dublin (1851-1901)
Professor and Fellow of Trinity College Dublin

Hendrik Lorentz, Leiden (1853-1928)

The Nature of Light – Particle or Wave?

TABLE 2-1: EVIDENCE BEARING ON THE NATURE OF LIGHT

	Particle model	*Wave/ether model*
1. Light travels in straight lines	✓	OK if wavelength $\ll$ beam width
2. Interference and diffraction effects	No convincing explanation	✓
3. Polarization of light	No convincing explanation	✓
4. Light velocity independent of source velocity	*Definite disagreement*	✓
5. Speed of light greater in air than in water	*Definite disagreement*	✓
6. Fizeau experiment and Airy (water-filled telescope) experiment	Requires partial drag of light by medium	Requires partial drag of light by medium
7. Stellar aberration (Bradley)	✓	OK if earth moves with respect to ether
8. Michelson-Morley experiment	✓	Implies that earth does *not* move with respect to ether

Einstein viewed the troublesome problem with the ether not as fault of electromagnetic theory, but arising from an error in *basic dynamical principles*.

He argued that the speed of light, *c*, must be a universal constant, the same for all observers, independent of their motion.

Einstein's Postulates

Postulate 1: All inertial frames are equivalent w.r.t. the laws of physics.

Postulate 2: The speed of light in empty space always has the same value, *i.e.*, the speed of light is independent of the motion of the source or receiver.

P2 explains the null result of the M-M expt. M-M does not prove **P2**.

Use Galilean transformations (GT) to describe Newtonian mechanics in different inertial frames. But **P2** is not consistent with GT – need to find new set of transformations.

Before we can find these new transformations, need to consider carefully how to determine the coordinates of events.

Coordinates of an Event

We can not rely on metaphysical notions about time. Rather, we make observations with physical devices – clocks (pendulum clock, watch with vibrating quartz crystal , rotating earth, vibrating molecule…)

Consider a single observer. They see a flash of light at the origin at $t = 0$, and at a time t_A the pulse is at $x_A = ctA$. But to make such an observation, the observer would have to had reached x_A before the light pulse: Impossible.

Instead, assume we have many observers stationed throughout space, each with their own clock. They can note the time an event occurs at their position.

For this to work, all the clocks must be *synchronized*.

Need to define what we mean by same time at two different locations.

Synchronising Clocks

If we could transmit signals at infinite speed, no problem.

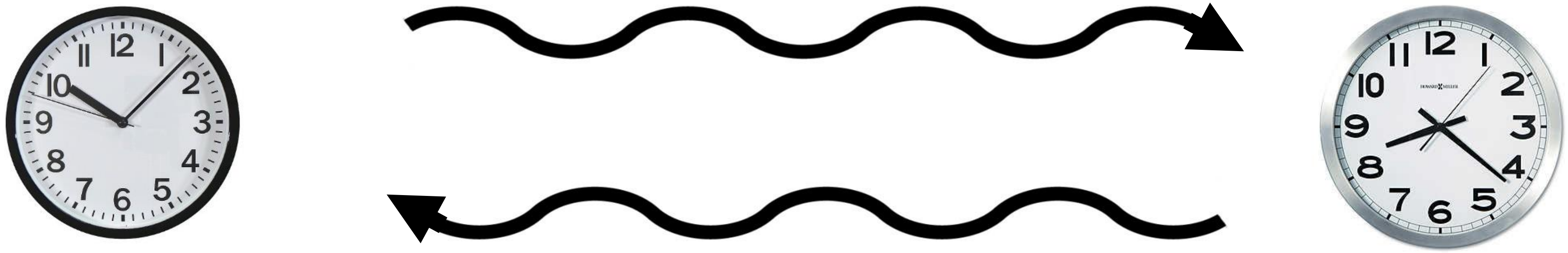
Instead, we use large, but finite speed of light.

Observation stations **A** and **B** at rest in same frame of reference.

Clock at **A** can record time of events that occur in immediate vicinity of **A**. Similarly for **B**.

We have: **A** time and **B** time. How can we synchronise the two clocks?

Synchronising Clocks



To establish common time:

Definition: time for light to travel **A** → **B** equals time for **B** → **A**
Send out light signal from **A** at $t = 0$
Reflect light at **B** and return to **A** at time $t = t_0$
Time when light arrives at **B** is *defined* as $t = t_0 /2$

We have synchronised the clocks at **A** and **B**