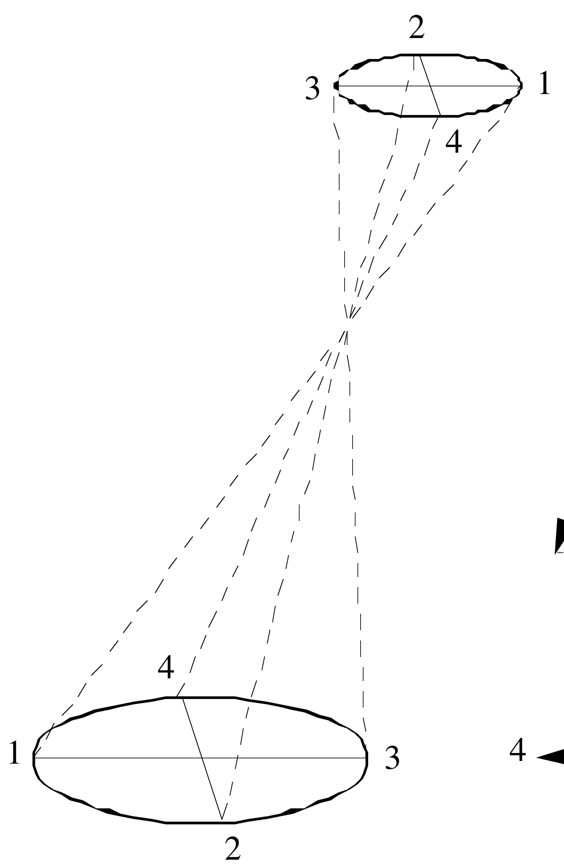
19th Century Ether Theory. The immobile ether of Fresnel versus the dragged-along ether of Stokes

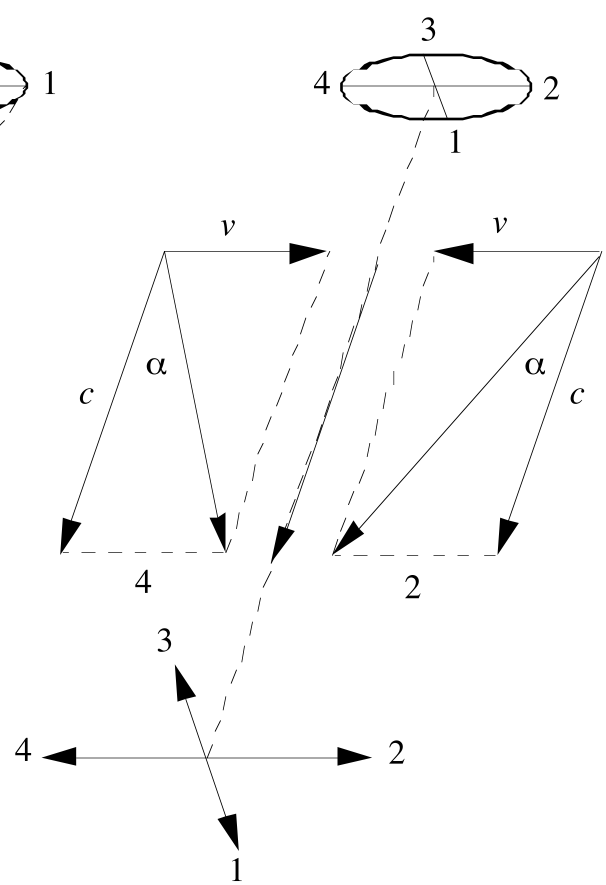
Thomas Young (1773–1829): "Upon considering the phenomena of the aberration of the stars I am disposed to believe, that the luminiferous [= light-carrying] ether pervades the substance of all material bodies with little or no resistance, as freely perhaps as the wind passes through a grove of trees"

From "Experiments and Calculations relative to physical Optics." *Philosophical Transactions of the Royal Society* (1804).

How James Bradley (1692–1762) went looking for stellar parallax and found stellar aberration instead (1720s)



Parallax

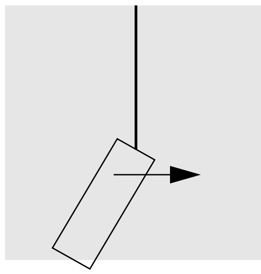


Stellar Aberration

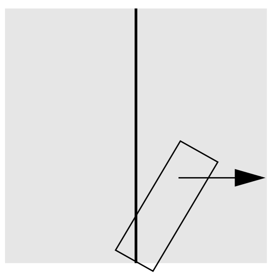
Why stellar aberration calls for stationary (or immobile) ether [earth moving through ether without disturbing it] **and is incompatible with dragged-along ether** [earth carrying along ‘ether atmosphere’]

Immobile Ether

Light enters telescope



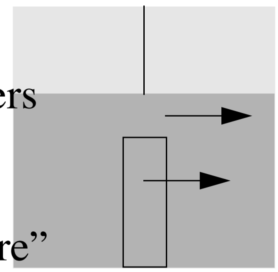
Light exits telescope



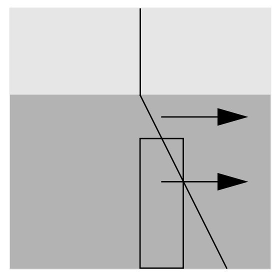
For the light to go straight through the telescope, you have to keep the telescope tilted
(just as you have to keep your umbrella tilted when walking in the rain).

Dragged-Along Ether

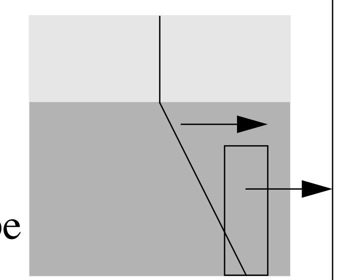
Light enters earth’s “ether atmosphere”



Light enters telescope



Light exits telescope



Since telescope and ether atmosphere have the same velocity with respect to the ether at higher altitude, you don’t have to keep your telescope tilted.

Since we do observe stellar aberration, Young was led to believe that the situation is the one on the left (immobile ether)

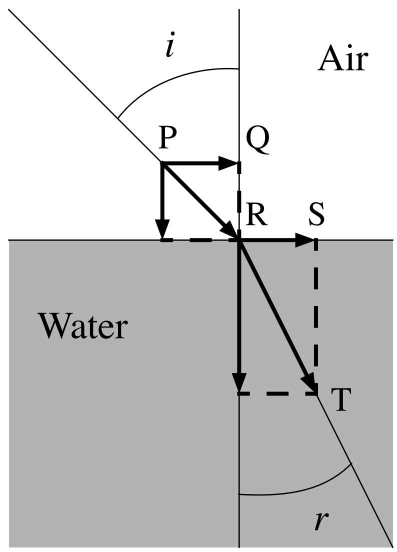
Refraction in particle theory and in wave theory

Law of refraction: $\sin i = n \sin r$

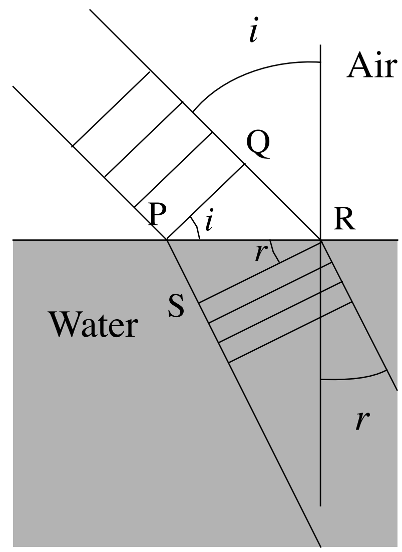
n = index of refraction of water ($n > 1$)
i = angle of incidence
r = angle of refraction

To account for this law in the **particle theory**, one has to assume that in water the velocity of light is **greater** than in air: $c_{\text{water}} = n \times c_{\text{air}}$

To account for this law in the **wave theory**, one has to assume that in water the velocity of light is **less** than in air: $c_{\text{water}} = c_{\text{air}}/n$



Particle theory



Wave theory

- $\sin i = n \sin r \rightarrow \dfrac{PQ}{PR} = n\dfrac{RS}{RT}$.
- Refraction comes from light particles being attracted to the water; nothing happens to horizontal velocity component $\rightarrow PQ = RS$.
- Hence: $\dfrac{RT}{PR} = \dfrac{c_{\text{water}}}{c_{\text{air}}} = n$

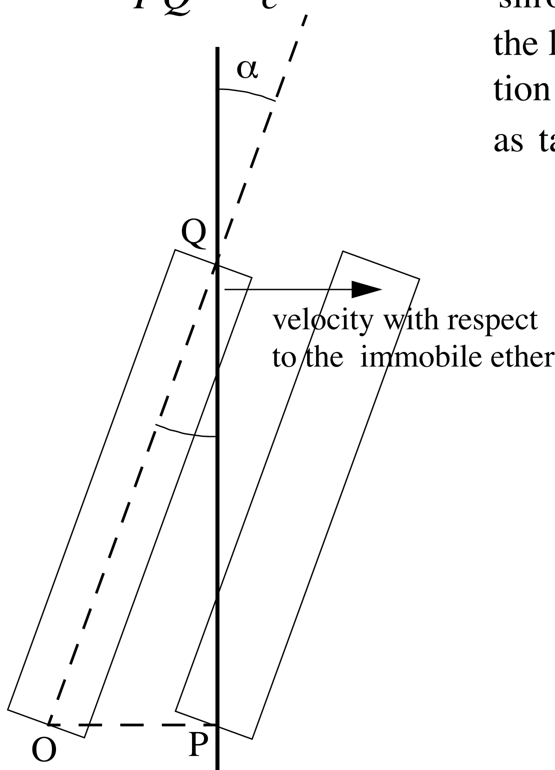
- Analogy: the wave front PQ entering the water is like a row of soldiers marching from a paved road into a ditch.
- $\sin i = n \sin r \rightarrow \dfrac{RQ}{PR} = n\dfrac{PS}{PR}$.
- Hence: $\dfrac{RQ}{PS} = \dfrac{c_{\text{air}}}{c_{\text{water}}} = n$

Settled in favor of the wave theory in 1850 when velocity of light could finally be measured in the laboratory. Jean Foucault (1819–1868); Hippolyte Fizeau (1819–1896).

Refraction calls for amendment to immobile ether theory.

Consider stellar aberration with a telescope filled with water.

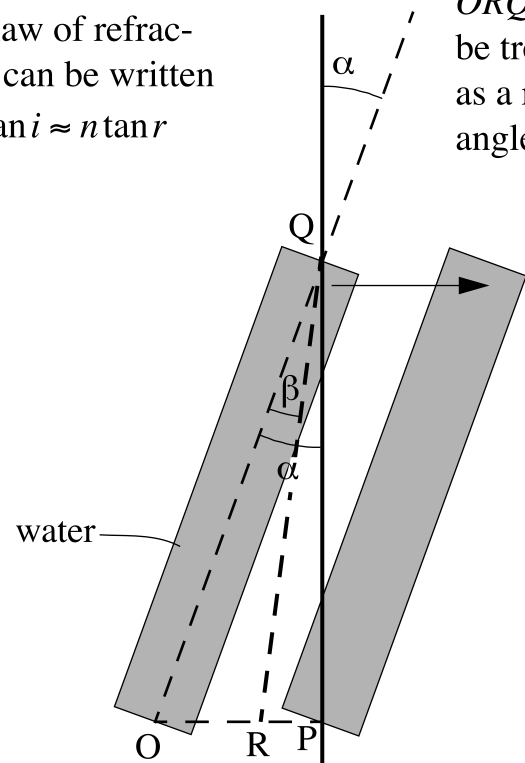
$$\tan\alpha = \frac{OP}{PQ} = \frac{v}{c}$$



$$\tan\alpha = n\tan\beta \longrightarrow \tan\alpha = n\frac{OR}{RQ}$$

For small angles $\sin\alpha \approx \tan\alpha$ and the law of refraction can be written as $\tan i \approx n\tan r$

Note: angle ORQ can be treated as a right angle



- Without further assumptions, the immobile ether theory predicts that light goes to R (refraction). Observation indicates that light goes to P (aberration angle = α, both with water and with air in the telescope).
- Assume that water drags along ether with a fraction f of its velocity v. Task: Find formula for f so that the immobile ether theory *plus* this special dragging assumption predict that the path of the light is QP.
- $\tan\alpha = \frac{v}{c}$ and $\tan\alpha = n\frac{OR}{RQ} \rightarrow \frac{v}{c} = n\frac{(OP - RP)}{RQ} = n\frac{(v - fv)}{c/n}$

  since $OP = v\Delta t$, $QR = (c/n)\Delta t$, $RP = fv\Delta t$.

  Hence: $\frac{v}{n^2} = (1-f)v$ or $\boxed{f = 1 - \frac{1}{n^2}}$ **Fresnel Drag Coefficient**

Amendment to Immobile Ether Theory (Augustin Jean Fresnel (1788–1827), 1818): transparent matter drags along the ether inside of it with a fraction that depends on its index of refraction. Fizeau experiment (1851): direct evidence for Fresnel coefficient

Support for dragged-along ether

Polarization in 1810s:

Étienne Louis Malus (1775–1812)
David Brewster (1781–1868)

Explanation in wave theory: waves not longitudinal [in the direction of propagation] but transverse [vibrations perpendicular to the direction of propagation]

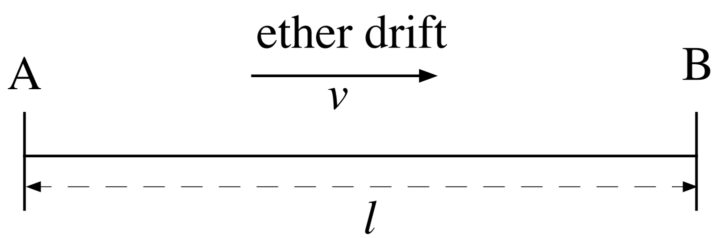
Ether has to be a rigid solid

George Gabriel Stokes (1819–1903), 1840s: “silly putty”-ether. Dragged-along ether. Benefit: more plausible picture of matter moving through rigid solid. Price: very complicated explanation of aberration.

The experiments of Michelson (1881) and Michelson and Morley (1886, 1887)

<u>Question to be settled by these experiments</u>: Is the ether immobile (Fresnel) or dragged-along (Stokes)?

James Clerk Maxwell (1831–1879) to Nautical Almanac Office



(1879):
Travel time for round-trip ABA

- w/out ether drift ($v = 0$): $\frac{2l}{c}$ (with c the velocity of light)
- with ether drift ($v \neq 0$): $\frac{l}{c+v} + \frac{l}{c-v} \approx \frac{2l}{c}\left(1 + \frac{v^2}{c^2}\right)$

(for $v = 30$ km/s, velocity of earth in orbit around the sun: $\frac{v^2}{c^2} \approx 10^{-8}$)

Objection: doesn't the effect of the ether wind on the second half of the journey (where light has velocity c – v) cancel out its effect on the first half (where light has velocity c + v)?

Answer: NO

Example: compare two cars driving up and down a 100 mile stretch of highway.

Car #1 goes 100 miles/hour the whole time

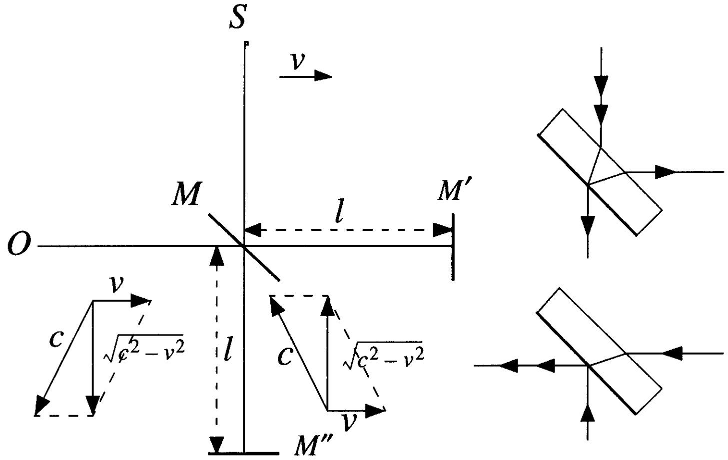
Car #2 goes 150 miles/hour on the way out and 50 miles/hour on the way back in

Car #1: round-trip takes 2 hours

Car #2: trip out takes 40 minutes; trip back takes 2 hours. Total: 2 hours and 40 minutes

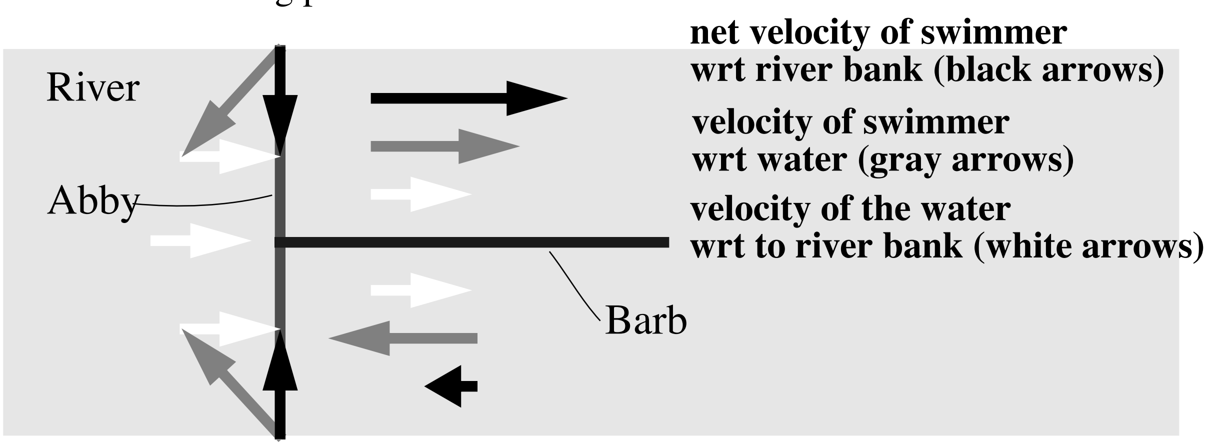
Note: Car #2 is driving at 50 miles/hour for a **longer period of time** than it is driving at 150 miles/hour. Hence, the average speed will be less than 100 miles/hour

Experimental set-up to measure the effect mentioned by Maxwell: the Michelson interferometer



Travel time in arm parallel to ether drift | greater than | Travel time in arm perpendicular to ether drift

Analogy: A river is L feet wide and is flowing east with velocity v. Abby and Barb are equally good swimmers. Ally is to swim, at top speed c, across the river and back to her starting point. Barb is to swim, at top speed c, L feet downstream and back to her starting point.

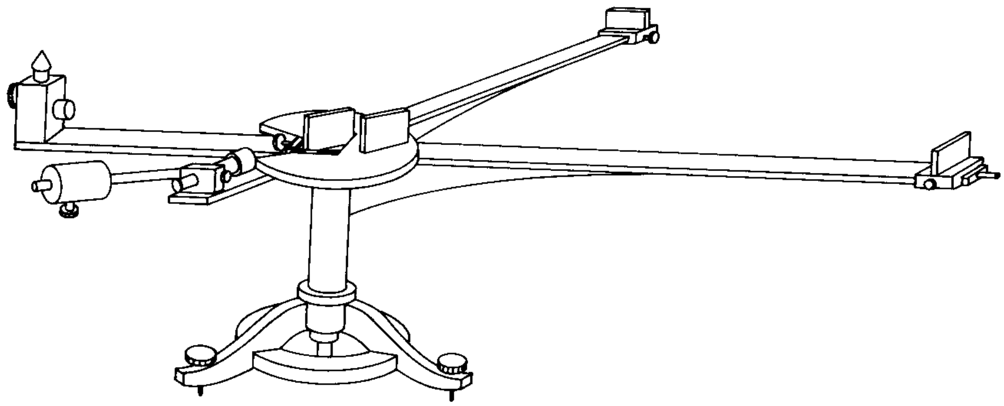


Travel time for Barb: $$\frac{L}{c+v} + \frac{L}{c-v} = \frac{2L}{c}\left(\frac{1}{1 - v^2/c^2}\right) \approx \frac{2L}{c}\left(1 + \frac{v^2}{c^2}\right)$$

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

Travel time for Abby: $$\frac{2L}{\sqrt{c^2 - v^2}} = \frac{2L}{c}\left(\frac{1}{\sqrt{1 - v^2/c^2}}\right) \approx \frac{2L}{c}\left(1 + \frac{1}{2}\frac{v^2}{c^2}\right)$$

The rotating interferometer of 1881



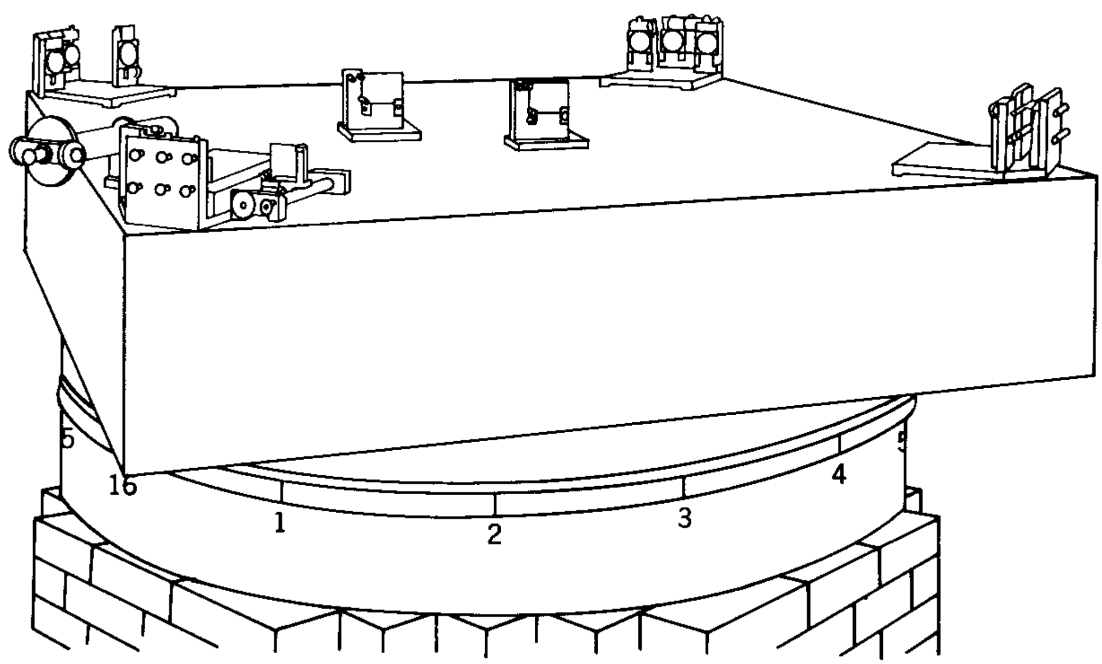
Michelson's conclusion in 1881: "The interpretation of these results is that there is no displacement of the interference bands. The result of the hypothesis of a stationary ether is thus shown to be incorrect, and the necessary conclusion follows that the hypothesis is erroneous" Fresnel wrong, Stokes right.

Michelson and Morley (1886). Repetition of Fizeau experiment.

Conclusion: "the result of this work is therefore that the result announced by Fizeau is essentially correct: and that the luminiferous ether is entirely unaffected by the motion of the matter which it permeates." <u>Fresnel right, Stokes wrong</u>.

Hendrik Antoon Lorentz (1853–1928): Stokes' fully dragged-along ether incompatible with aberration (1886)

The famous Michelson-Morley experiment (1887). Repetition of 1881 ether drift experiment:



Conclusion: : "It appears, from all that precedes, reasonably certain that if there be any relative motion between the earth and the luminiferous ether, it must be small."
<u>Both Fresnel and Stokes wrong</u>.

Reconciling the result of the Michelson-Morley experiment with the theory of an immobile ether.

The Lorentz-FitzGerald contraction hypothesis

Immobile ether theory predicts:

Travel time in arm parallel to ether drift	greater than	Travel time in arm perpendicular to ether drift

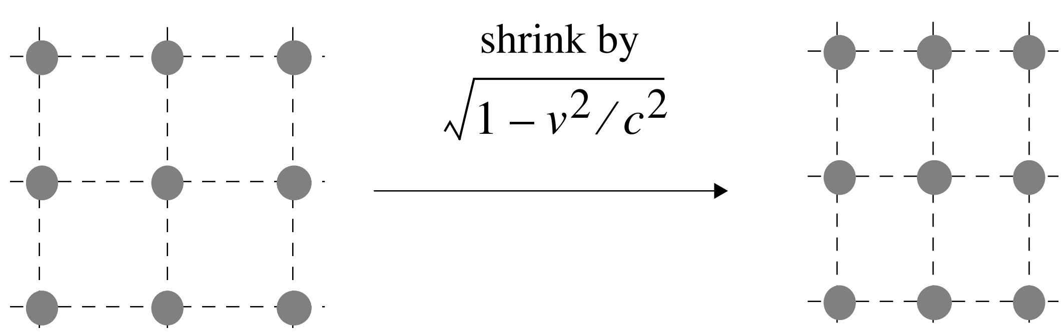
Experimental result suggests

Travel time in arm parallel to ether drift	equal to	Travel time in arm perpendicular to ether drift

Explanation of FitzGerald (1889) and Lorentz (1892): compensating effect: length of interferometer arm changes as it rotates: parallel to ether drift it is shorter than perpendicular to the ether drift

Contraction hypothesis: an object moving with a velocity v with respect to the ether contract by a factor $\sqrt{1 - v^2/c^2}$ in the direction of motion.

Lorentz's plausiblity argument for contraction hypothesis



Equilibrium at rest in the ether

Equilibrium in motion through the ether