PHYS 250

Introduction to Modern Physics

Prof. Thomas Mattison
UBC Dept. of Physics & Astronomy
Summer 2025

Today

Administrivia

Course Overview

Michelson-Morley Experiment

Simultanity is Frame-Dependent

Transformation Laws

Moving Clocks Tick Slower

Moving Objects Look Shorter

~~Relativistic Velocity Addition~~

About Me

Grew up in Chicago suburbs, near Fermilab (particle accelerator lab)
B.Sc. in physics from MIT (bubble chamber data thesis)
Ph.D. in physics from MIT (neutrino experiment at Fermilab)

Post-doctoral job at Stanford Linear Accelerator Centre
(e^+e^- linear collider accelerator, Mark II detector for Z^0s)

CERN for a few years (ALEPH detector for Z^0s at LEP, before LHC)

Back to SLAC (PEP-II B-Factory accelerator)

At UBC since 1999 (BaBar detector at SLAC for CP-violation)

These days mostly I help UBC Rocket

Piazza & Emails

You can use Piazza to ask questions, and other students can answer them as well as me.

For registration issues, go to Eileen Campbell, Hennings 333A, or email enph@physics.ubc.ca

Prof. Thomas Mattison mattison@physics.ubc.ca
Hennings 276 (south corridor, enter at E or W end of building)

Please use your regular email rather than the email system built into Canvas (it takes a bunch of extra steps to reply to emails that come from inside Canvas).

Please include your name and student number (it can be hard to figure out who someone is from their email address).

Typical Week

On the weekend, do the textbook readings for the week.

Lecture Monday & Wednesday 8:30-10:30 in Hennings 200
Will also be "simulcast" on Zoom and recorded.

Homework (WeBWorK) questions posted online, Wednesday midnight.
Homework due the following Monday midnight.

Tutorial Friday 8:30-10:00 in Hennings 200
Worksheet problems posted online. Work in groups in class.
Pick one student as "scribe" to write names and emails into a file, and write your group's work and solution into the file. You can continue to work after class.
Scribe shares final file with the group, and each member submits a copy online.
Worksheets due Friday midnight.

PHYS 250

From the Calendar:
"Wave-particle duality of matter, special relativity, processes in atomic, nuclear and solid state, and introduction to quantum mechanical devices and techniques."

Modules (one week each)

1. Relativity: Speed of light, space & time transforms, energy, momentum, mass
2. Photons: Blackbody Radiation, Photoelectric Effect, X-rays, Compton
3. Atomic Spectra & Bohr Model
   Midterm
4. Schrodinger Equation in 1D
5. Lasers & Semiconductors
6. Schrodinger Equation in 3D & Atoms

Fits into Summer Term 1, does not extend into finals week

Textbook

University Physics with Modern Physics, Young & Freedman

We only use a few chapters, as pre-reading. It's the Physics 157-158 textbook, but the UBC paperbacks doesn't have the chapters we use. It's easy to find online a version with all the chapters.

Supplemental:
Kenneth Krane, Modern Physics
Paul Tipler & R. Llewellyn, Modern Physics
Stephen Thornton & A. Rex, Modern Physics for Scientists & Engineers

Extra problems: Schaum's Outlines: Modern Physics

Grades

5% from clicker questions in lecture

10% from group tutorial worksheets (shared grade).

10% from online WeBWorK homework.

30% from midterm
  Date TBA

45% from final exam
  During regular exam period, date not yet known

Academic Integrity

www.vpacademic.ubc.ca/integrity/policies.htm

"Cheating includes, but is not limited to: falsifying any material subject to academic evaluation; having in an examination any materials other than those permitted by the examiner; and using unauthorized means to complete an examination (e.g. receiving unauthorized assistance from a fellow student)."

It's OK (and expected!) to work together on tutorial worksheets.

It's OK to help each other on homework.
It's not OK to post solutions (and I'll pull them down).

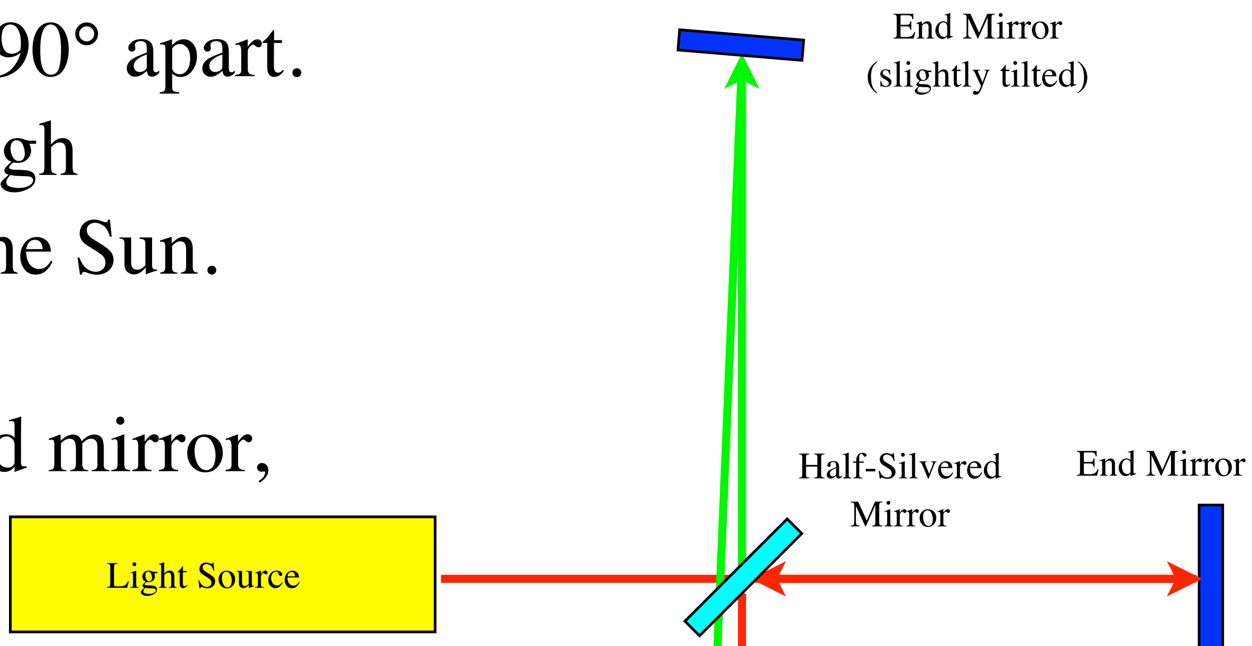
It's not OK to copy, or help each other on the midterms or final.
You can bring 1 page (both sides) of notes to midterm, 2 pages to final.
Calculators OK. No wireless devices, computers, or tablets.

Michelson Interferometer

In the 1880’s, it was believed that light propagates through some medium, and your motion through the “aether” determines the apparent speed of light.

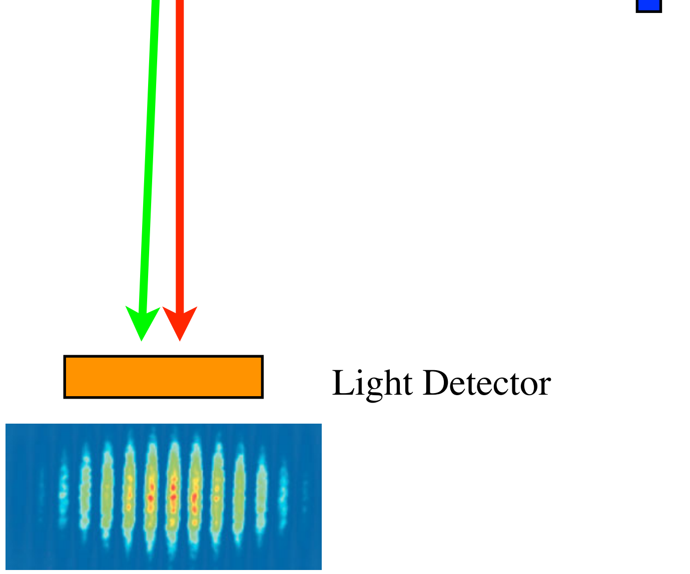
Albert Michelson in 1881 used an <u>interferometer</u> to compare the speed of light in directions 90° apart. He thought it could be done precisely enough to see the Earth’s 30 km/s motion around the Sun.

Half the light goes through the half-silvered mirror, is reflected back by the end mirror, then reflected to the light detector.



Half the light is reflected to the slightly tilted end mirror, goes straight through the half-silvered mirror to the detector.

The beams interfere at the detector, producing “fringes.”



Michelson Interferometer Analysis

Assume the aether wind u is parallel to the horizontal arm of length L. The aether wind adds to the speed of light in one direction, and subtracts in the other. The round trip time is

$$T_{\parallel} = \frac{L}{c+u} + \frac{L}{c-u} = \frac{L(c-u)+L(c+u)}{c^2-u^2} = \frac{2L}{c}\frac{1}{1-u^2/c^2}$$

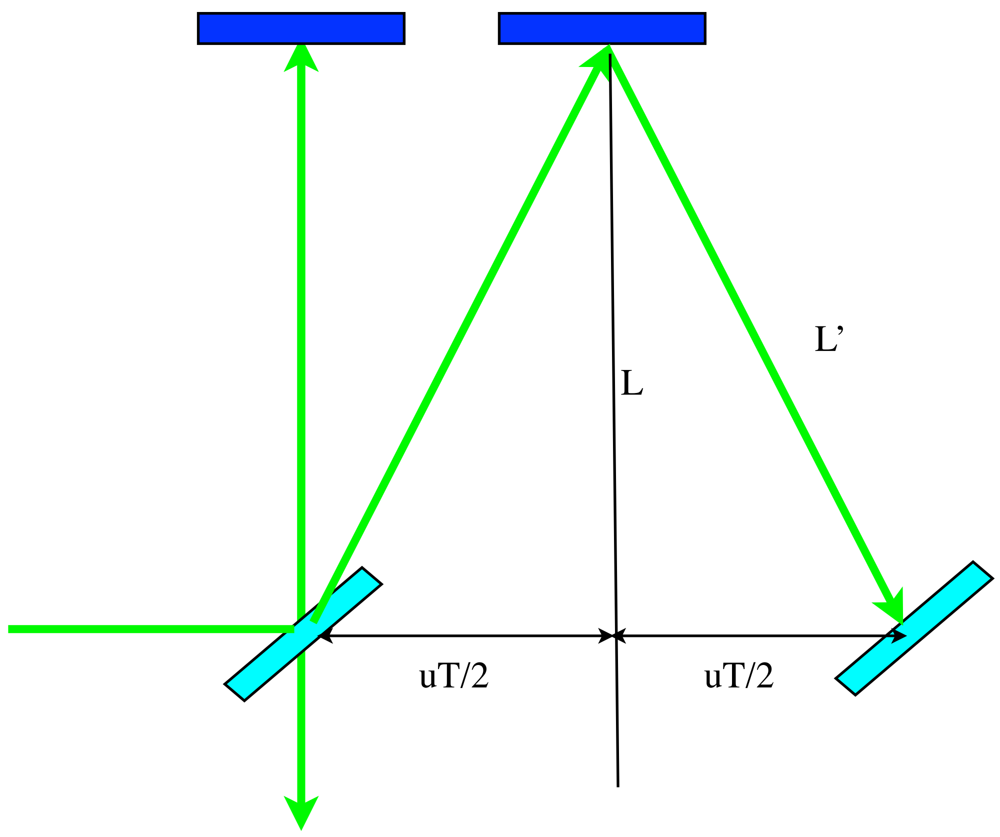
So the effects don't exactly cancel. However, instead of a 10^{-4} effect from 30 km/s, we only get a 10^{-8} effect.

To get the time in cycles, divide by the period (or multiply by the frequency $f = c/\lambda$).

$$\text{cycles}_{\parallel} = \frac{c}{\lambda}\frac{2L}{c}\frac{1}{1-u^2/c^2} = \frac{2L}{\lambda}\frac{1}{1-u^2/c^2} \approx \frac{2L}{\lambda}\left(1+\frac{u^2}{c^2}\right)$$

Michelson Interferometer Analysis 2

Actually, there's also an effect of velocity on the <u>other</u> arm too, because the path of the light through the aether is a bit longer than twice the arm length.



$$L'^2 = L^2 + \left(uT_\perp/2\right)^2 \qquad T_\perp = 2L'/c$$

$$L'^2 = L^2 + \left(u\cdot\left[2L'/c\right]/2\right)^2 = L^2 + \left(L'\cdot\frac{u}{c}\right)^2$$

$$L'\cdot\left(1-\frac{u}{c}\right)^2 = L^2 \rightarrow L' = \frac{L}{\sqrt{1-u^2/c^2}}$$

$$T_\perp = \frac{2L}{c}\frac{1}{\sqrt{1-u^2/c^2}}$$

$$\text{cycles}_\perp = T_\perp\cdot f = T_\perp\cdot\frac{c}{\lambda} = \frac{2L}{c}\frac{1}{\sqrt{1-u^2/c^2}}\cdot\frac{c}{\lambda} = \frac{2L}{c}\frac{1}{\sqrt{1-u^2/c^2}} \approx \frac{2L}{\lambda}\left(1+\frac{1}{2}\frac{u^2}{c^2}\right)$$

Michelson Interferometer Analysis 3

The perpendicular-arm extra delay has the same sign and is half as much as in the parallel arm, so the net effect is cut in half.

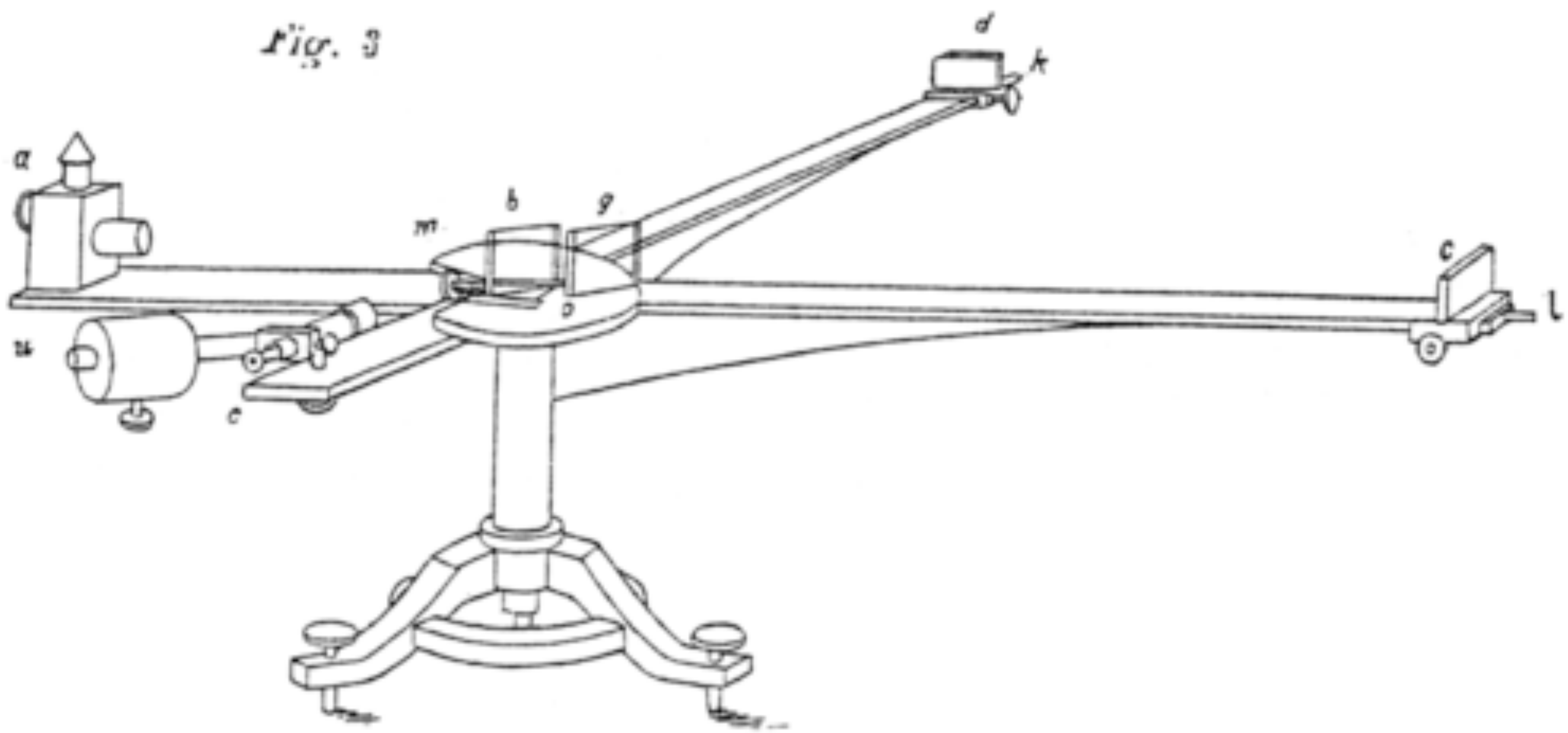
$$\text{fringe shift} = \text{cycles}_{\parallel} - \text{cycles}_{\perp} \approx \frac{2L}{\lambda} \times \frac{1}{2}\frac{u^2}{c^2} = \frac{L}{\lambda}\frac{u^2}{c^2}$$

The wavelength of the sodium D-line is 0.589 microns, so L/λ is about 2 million for a 1 meter arm length, so the shift should be about 2% of a fringe for 30 km/s where $u^2/c^2 \simeq 10^{-8}$.

Rotating the apparatus by 90° flips the sign,
so there would be a 4% peak to peak amplitude vs rotation angle.

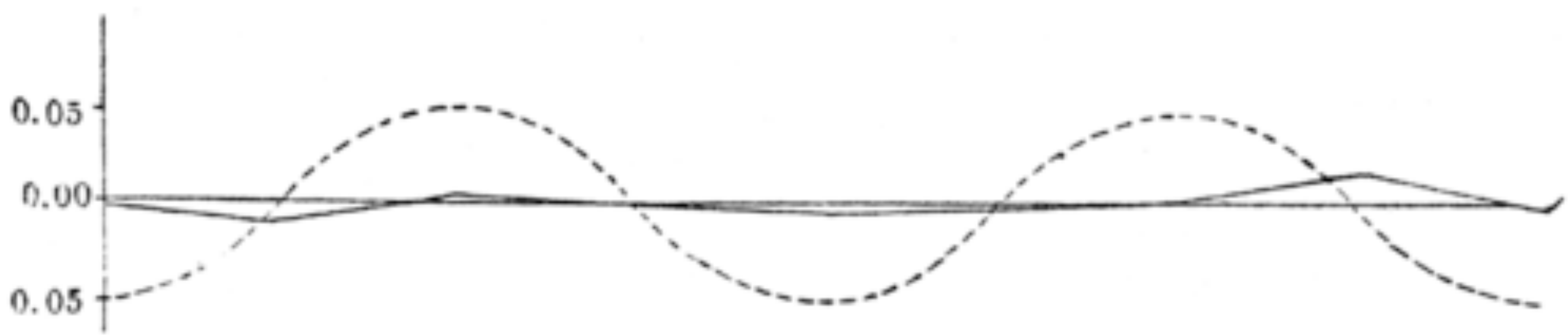
It's possible to see shifts of a small fraction of a fringe, so this seemed doable.

Michelson 1881 Apparatus & Result



Below (solid) is Michelson's 1881 data with 1.2 meter arms vs rotation angle. The dashed sine wave is the expected effect (times 2 because he didn't include the partial cancellation).

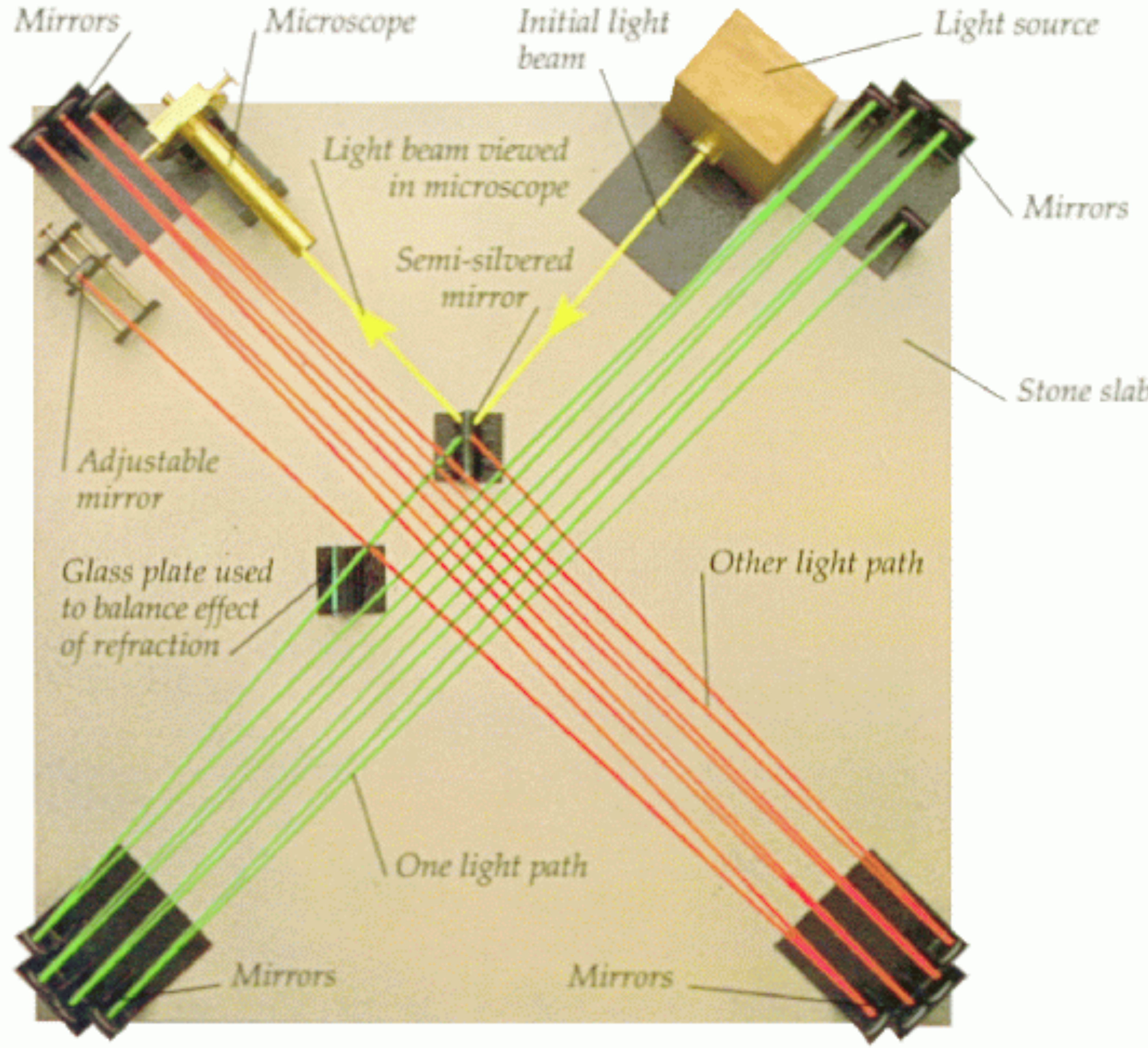
4.



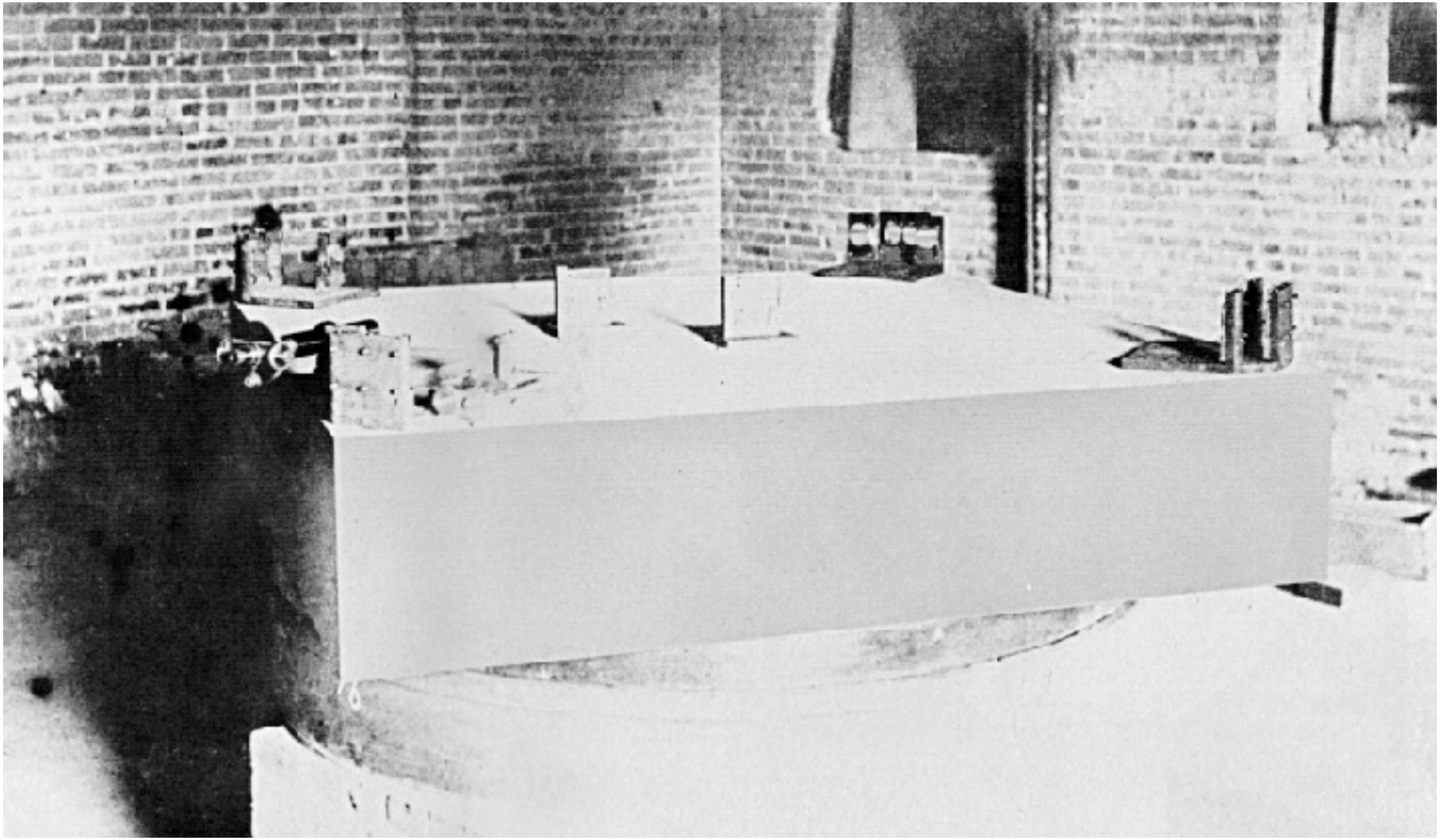
Michelson-Morley Apparatus

The improved 1887 version done with Edward Morley used many mirrors to give a longer path length (11 meters) to increase the signal.

The whole apparatus was on a sandstone block floated on mercury that could be rotated.



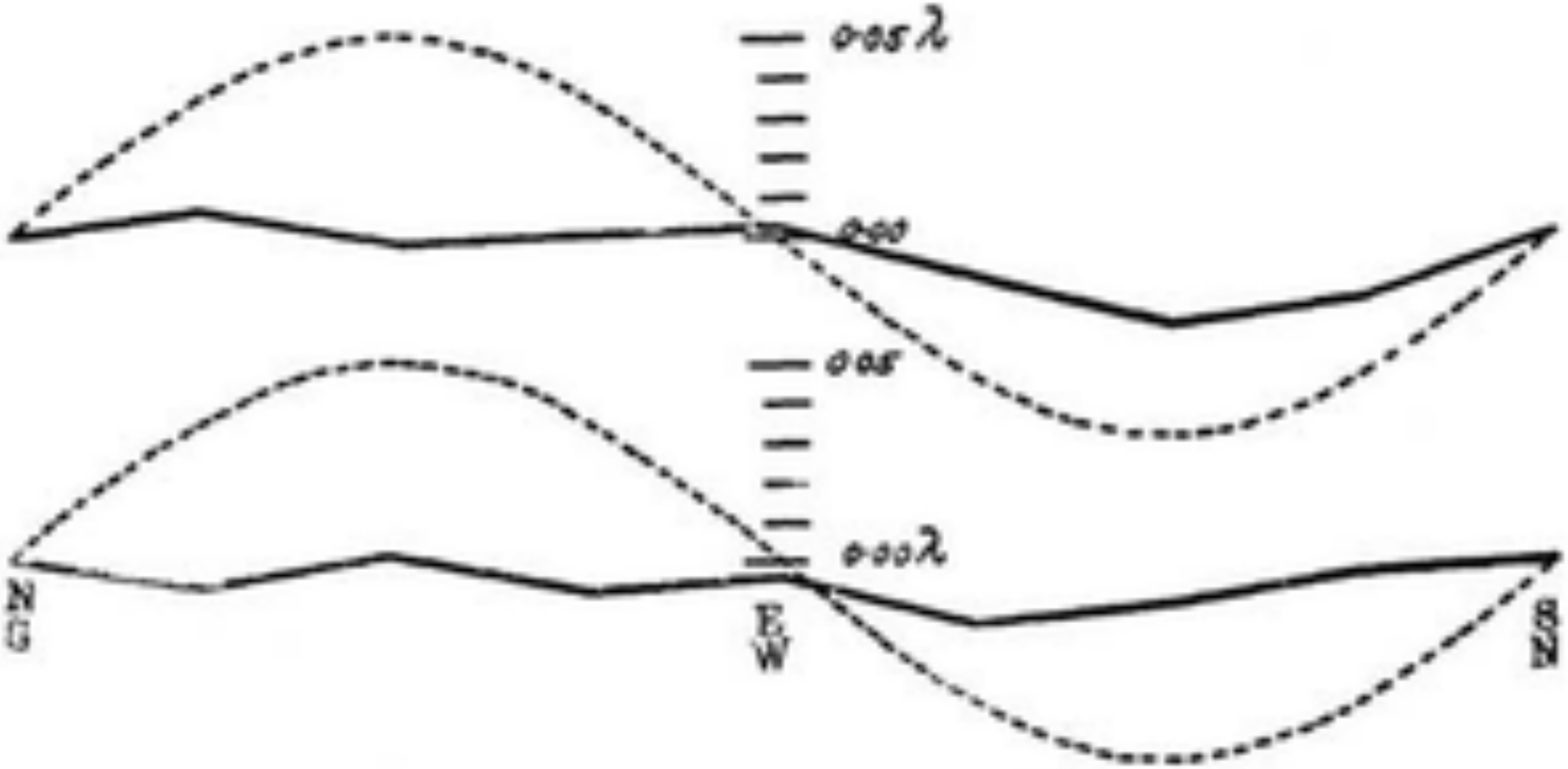
Michelson-Morley Apparatus



1887 Michelson-Morley Results

The improved interferometer should have given an amplitude of about 20% of a fringe as the interferometer was rotated.

But the data (noon and nighttime) was again consistent with zero within the estimated errors.



The dashed curves are sine waves with 5% amplitude, 1/4 the expected effect.

Astronomical Motions

The Earth moves $2\pi \cdot 150 \times 10^6$ km around the Sun
in $365.25 \cdot 24 \cdot 60 \cdot 60 = 3.16 \times 10^7$ sec, so u = 29.86 km/s

The Sun also orbits around the centre of mass of the galaxy.
This is estimated to be about 200 km/s, 6.7 times faster than Earth vs Sun.

The cosmic microwave background radiation looks a bit colder in one direction (more red-shifted) and a bit warmer in the opposite direction (less red-shifted).
This implies that our <u>galaxy</u> is moving at about 630 km/s, 21 times Earth vs Sun.

So Michelson should have seen a <u>huge</u> signal.

Red-shift is the ratio of observed wavelength to original wavelength.
A red-shift of 1.1 means the source is moving away at 10% the speed of light.

The largest red-shift observed so far is 11, which in a classical universe would mean the galaxy is moving away at 10 times the speed of light!

Speed of Light is Independent of Motion

An observer in the other galaxy would consider
Earth to be moving at 10 times the speed of light!

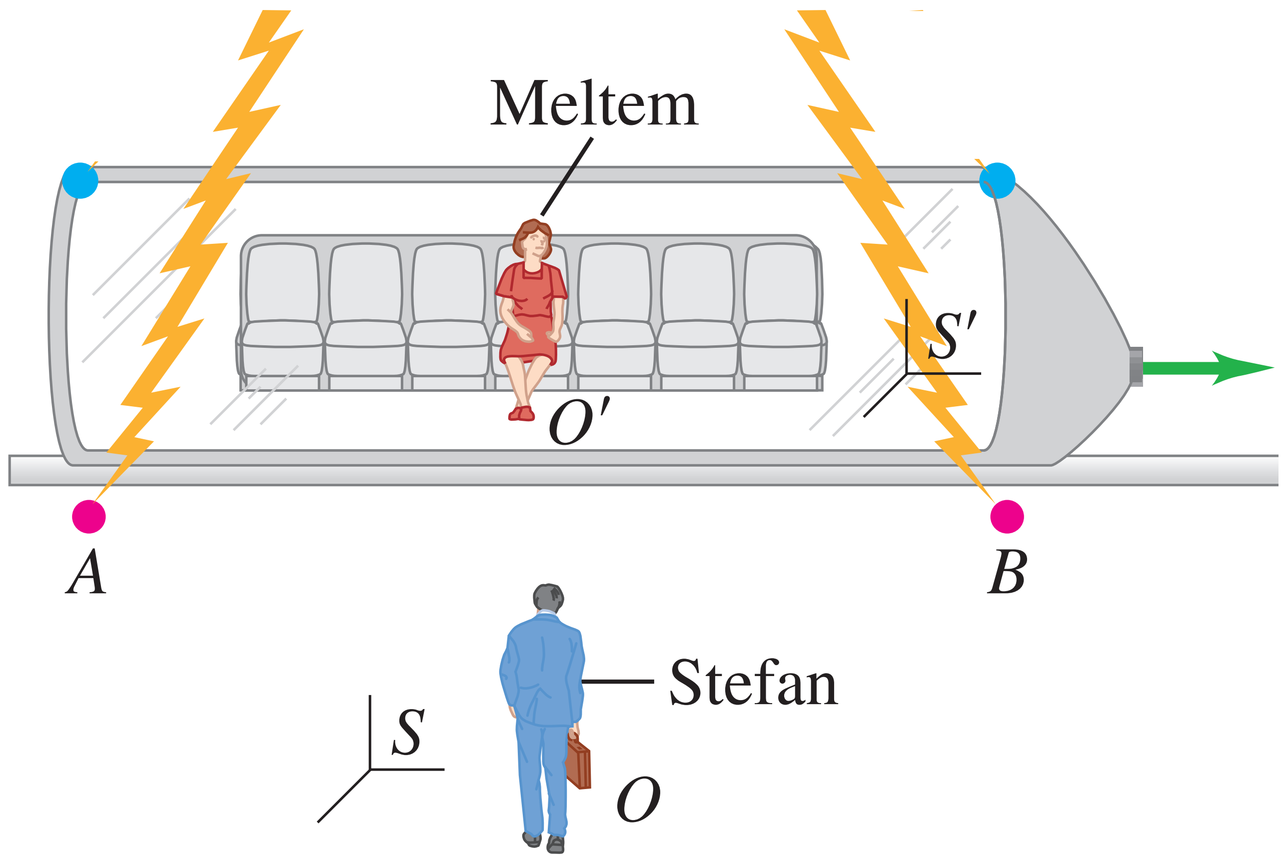
If Earth is "moving" faster than the speed of light, it would be super-obvious:
light from "downstream" objects wouldn't get to you, even in the same room!

With modern astronomical knowledge, it's much easier to believe that
the speed of light is independent of motion than it is to believe in "aether."

Thought Experiment

A 6-meter train car moves at velocity $u = 0.2c$ with a passenger in the middle.

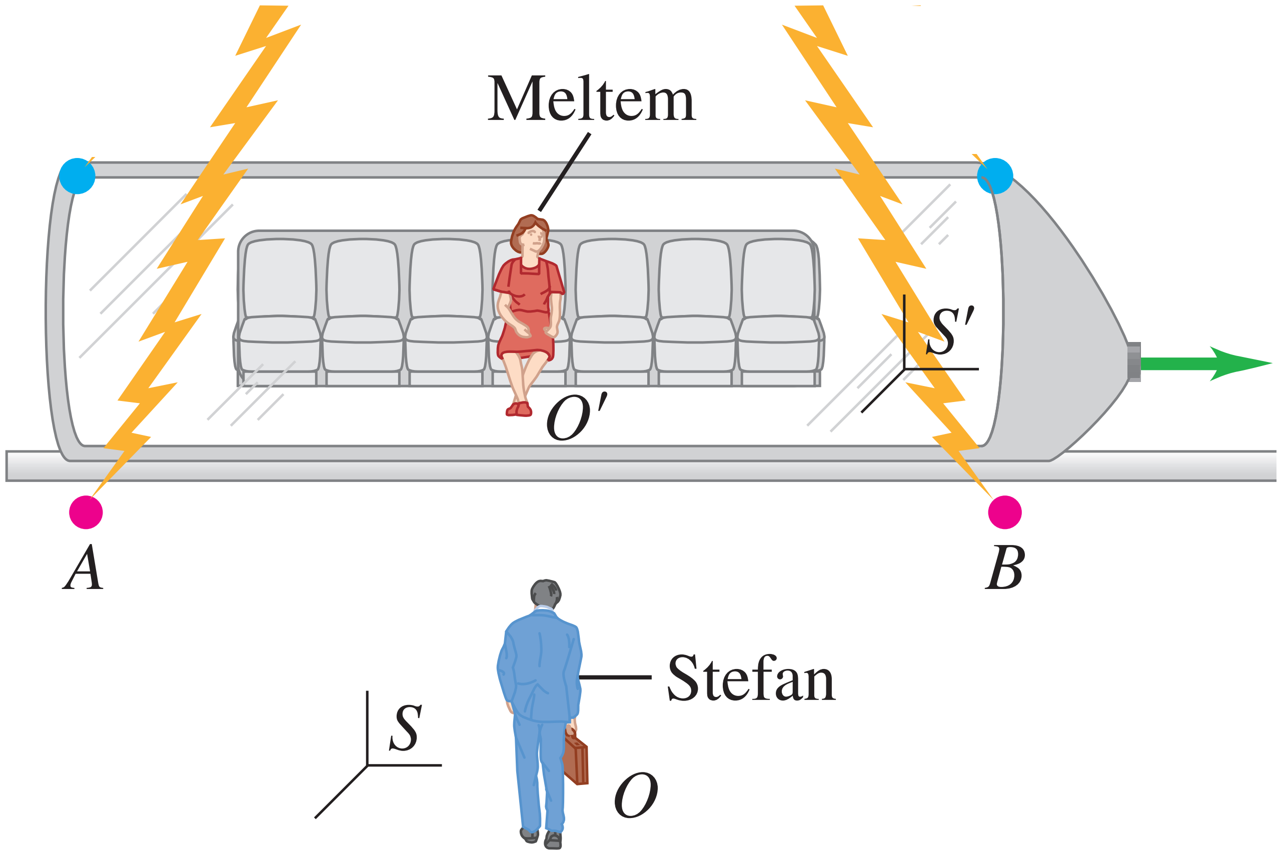
An observer on the ground outside sees lightning hit the front and back ends of the car when the passenger is closest to him.



The observer sees the flash of light from B get to the passenger first, because the passenger is moving toward point B.
The observer sees the flash of light from A get to the passenger a bit later, because the passenger is moving away from point A.

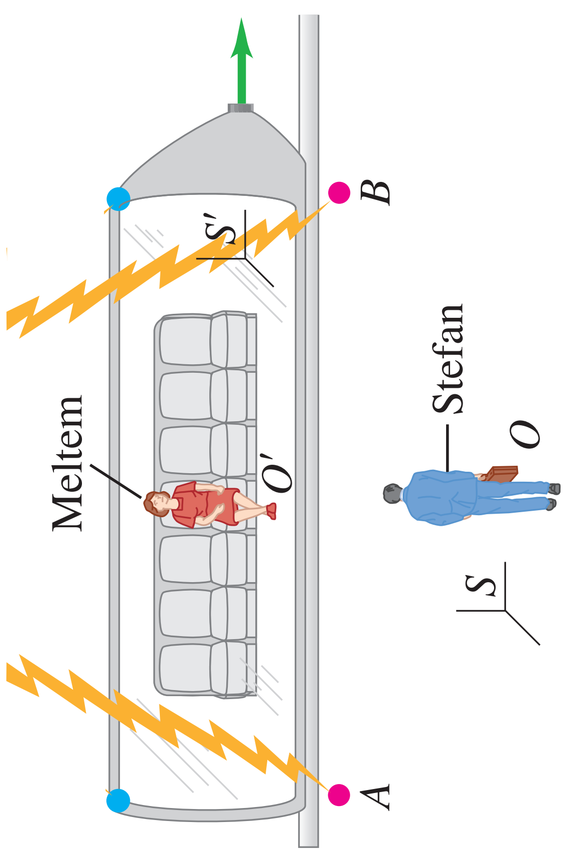
What Does the Passenger See?

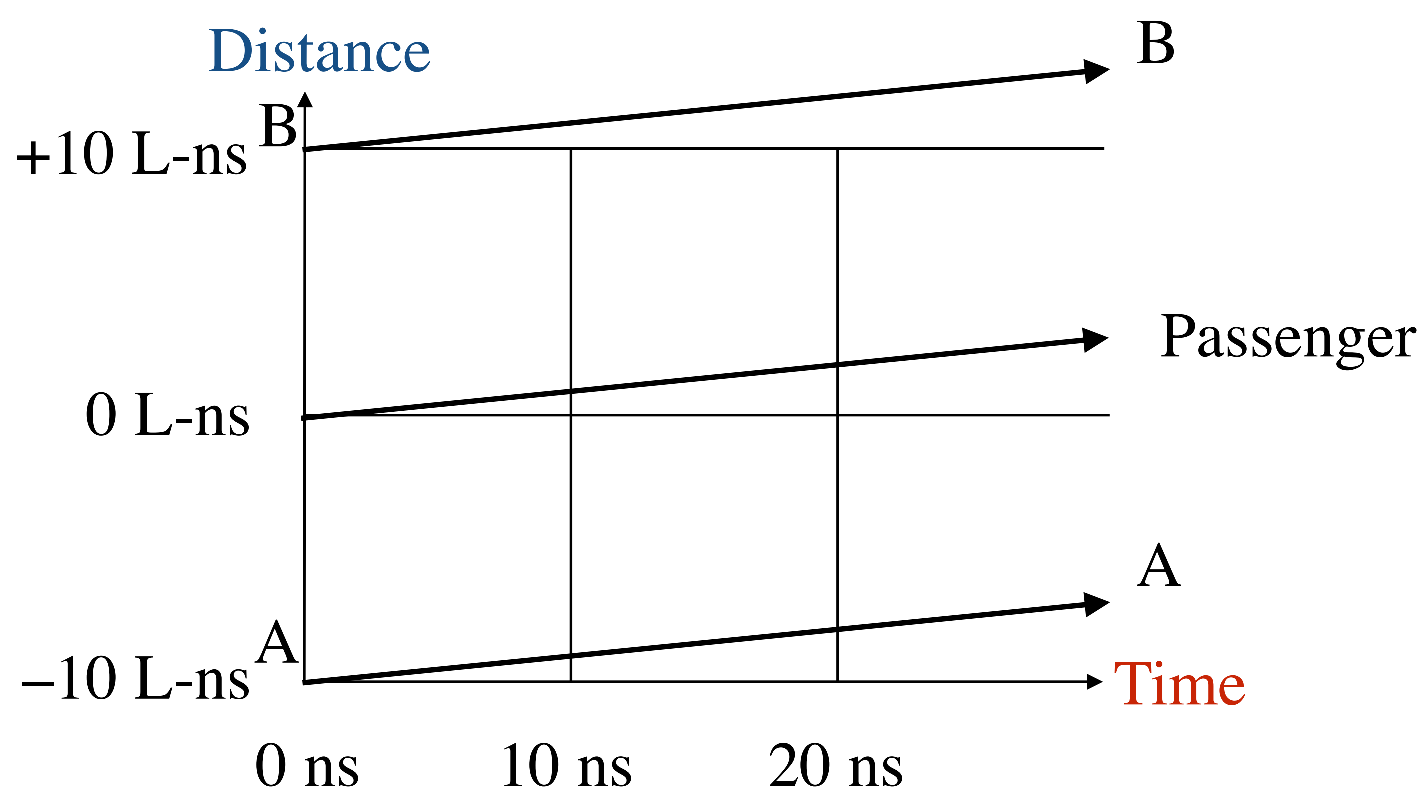
A. The passenger sees light from A and B simultaneously
B. The passenger sees light from A then light from B
C. The passenger sees light from B then light from A
D. Everything is relative
E. You can't honestly expect me to think this early in the day



Observer's Space-Time Diagram

Time is the horizontal axis, with units of nanoseconds.
Distance is the vertical axis, with units of light-nanoseconds.
One light-nanosecond (L-ns) is 29.98 cm, which we round to 30 cm.
The car is 6 m long, or 20 light-ns, moving at $u = 0.1\ c$.

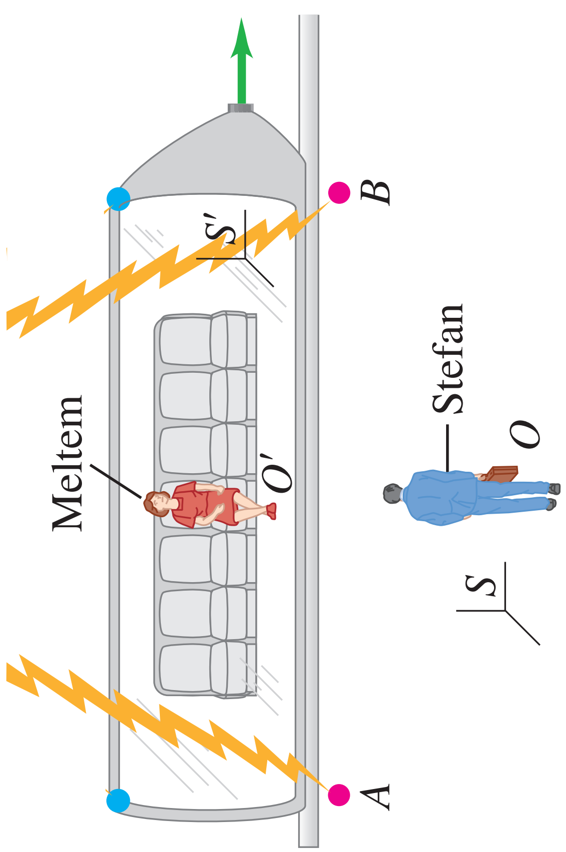


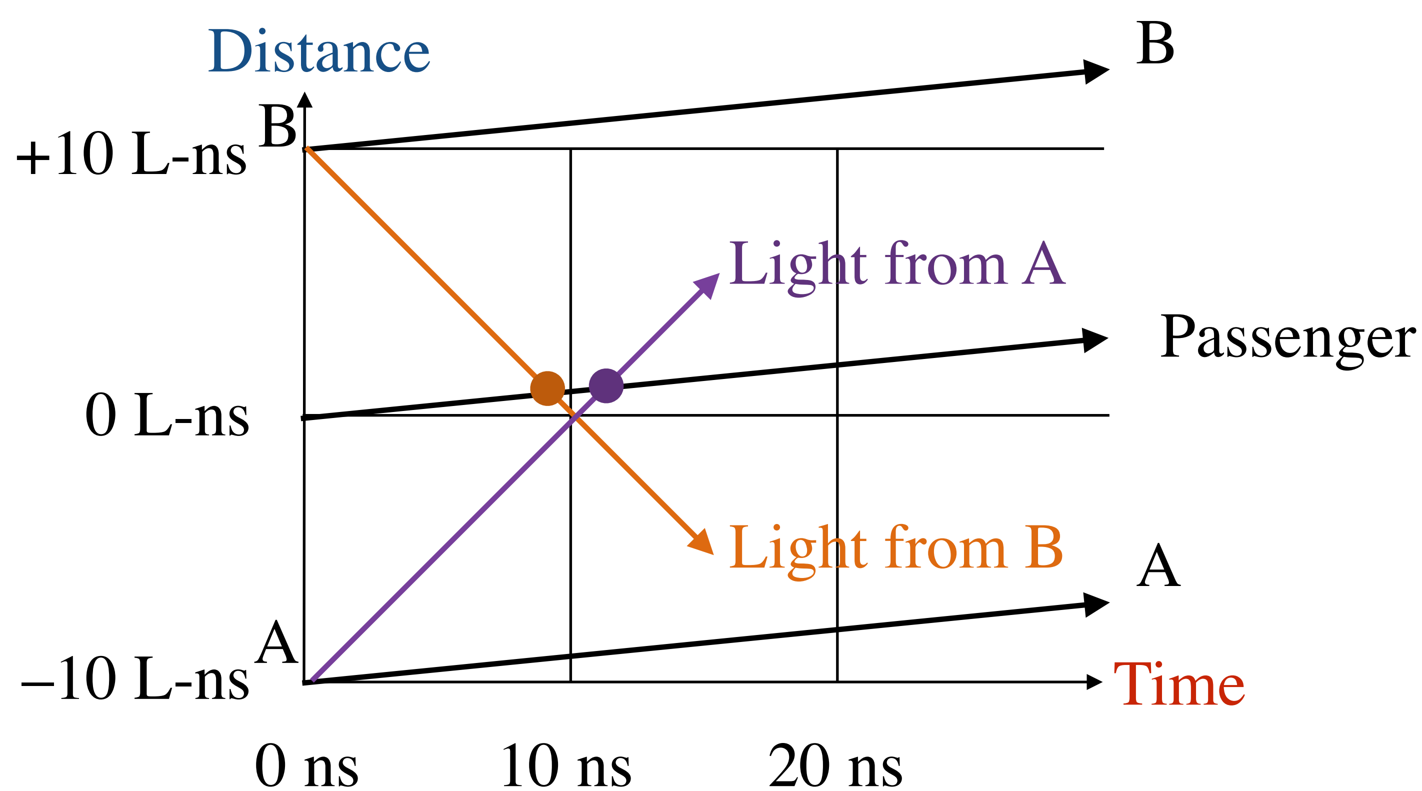


Add the Two Flashes

It's convenient to use the same length on the graph for nanoseconds and light-nanoseconds (L-ns). Then light travels at ±45°.

The dots are when the observer sees the flashes reach the passenger.



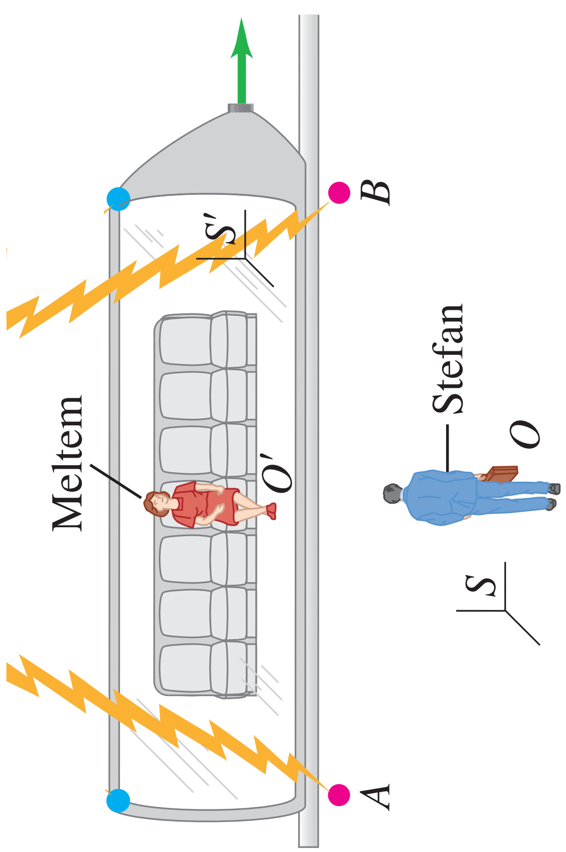


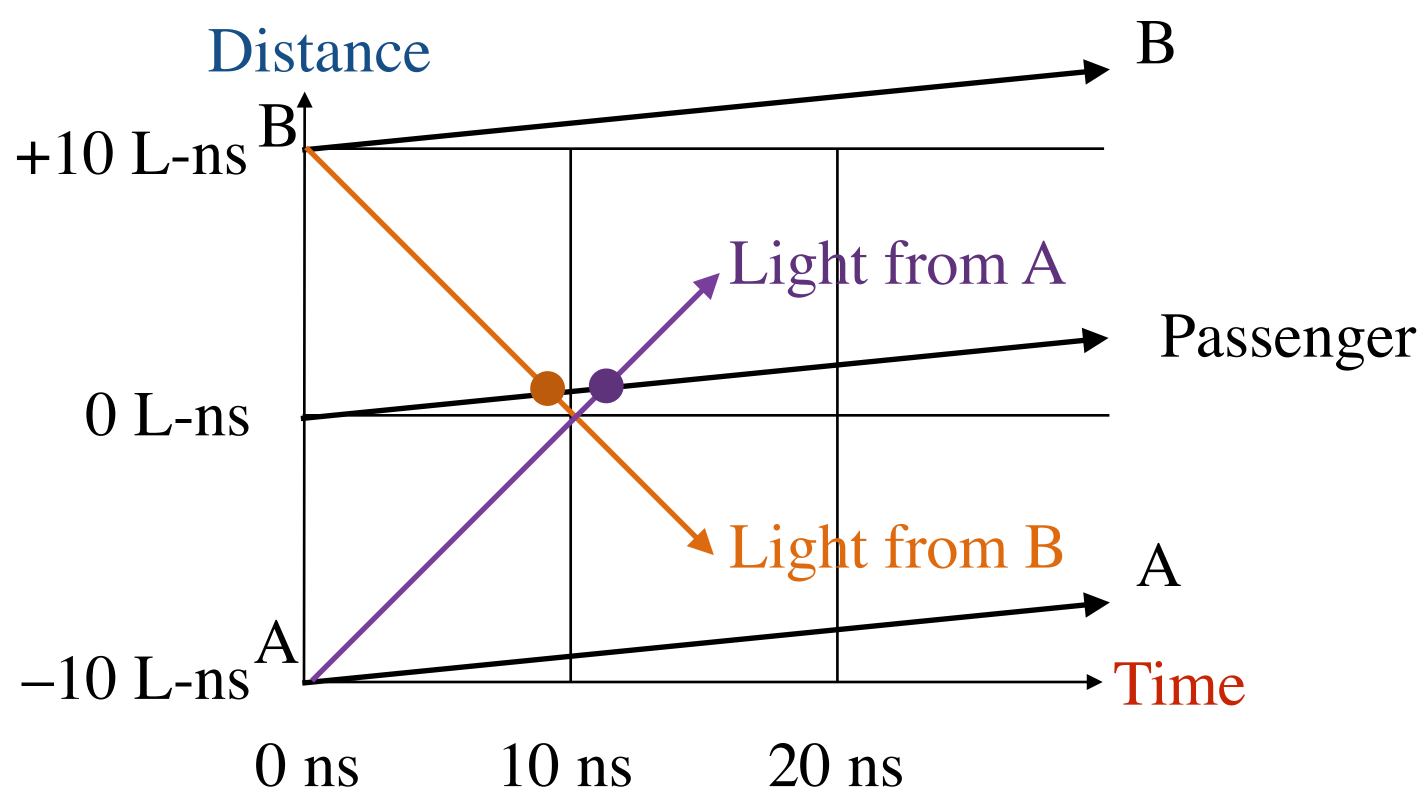
Equations for Flashes and Passenger

$$x_{\text{B-flash}} = +10 - c \cdot t$$

$$x_{\text{passenger}} = 0 + u \cdot t$$

$$x_{\text{A-flash}} = -10 + c \cdot t$$





Solve for the Two Times in Observer Frame

$$x_{\text{passenger}} = 0 + u \cdot t \qquad x_{\text{A-flash}} = -10 + c \cdot t$$

$$x_{\text{passenger}} = x_{\text{B-flash}}$$

$$0 + u \cdot t = +10 - c \cdot t$$

$$(u + c) \cdot t = 10$$

$$t_{\text{B}} = \frac{10}{u + c} = \frac{10}{0.1 + 1} = 9.091 \text{ ns}$$

$$x_{\text{passenger}} = x_{\text{A-flash}}$$

$$0 + u \cdot t = -10 + c \cdot t$$

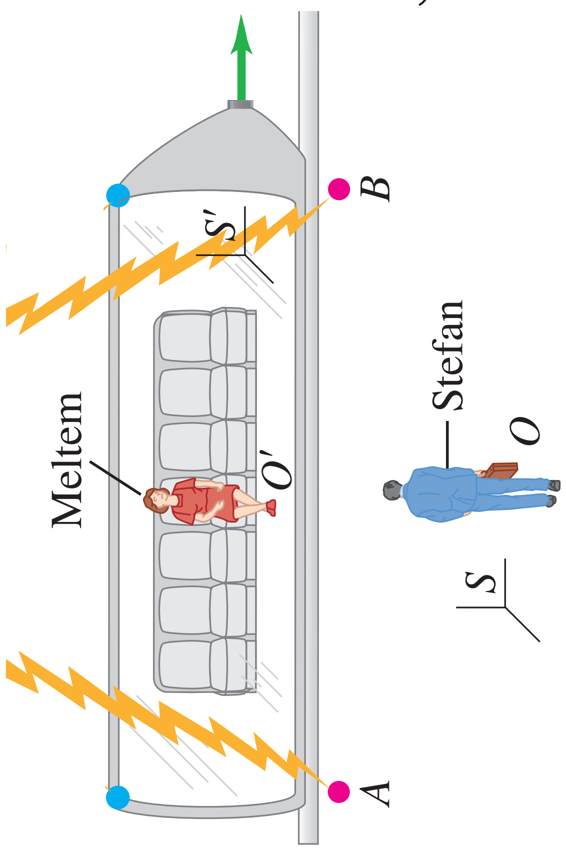
$$(u - c) \cdot t = -10$$

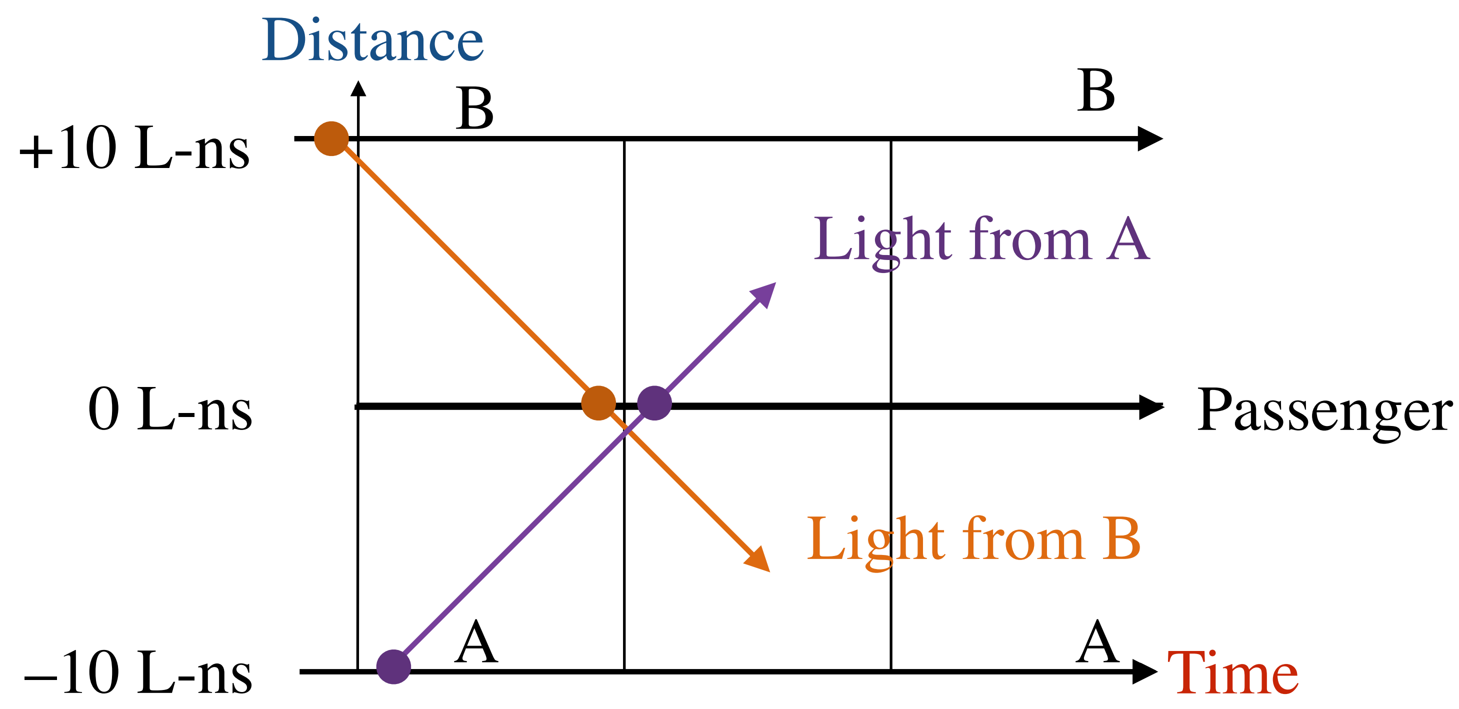
$$t_{\text{A}} = \frac{-10}{u - c} = \frac{-10}{0.1 - 1} = 11.111 \text{ ns}$$

$$\Delta t = 11.111 - 9.091 \text{ ns} = 2.020 \text{ ns}$$

Passenger's Space-Time Diagram

In the car frame, the lines for A, B, and the passenger are horizontal.





The B flash still gets to the passenger about 2 nanoseconds before the A flash.

Einstein, Michelson & Morley say that light still travels at ±45°.

The only way that could work is if passenger sees lightning hit B before it hit A !

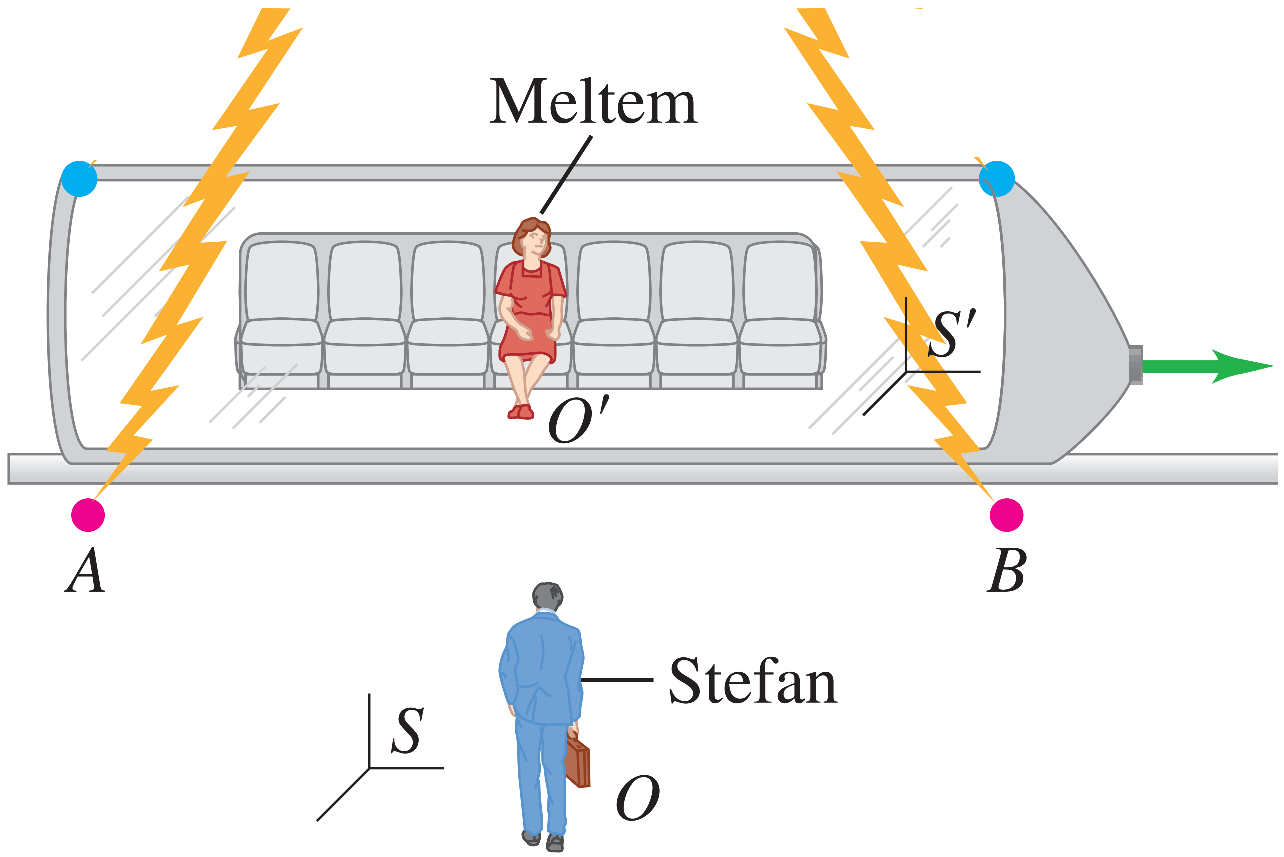
Simultaneity is Frame-Dependent

The observer says lightning struck A and B simultaneously.

The passenger says lightning struck B before it struck A.

They are both right.

The time-order of physically separated events,
like lightning strike A and lightning strike B,
can depend on your reference frame.



Coordinate System Jargon

S is a frame with origin *O* for coordinate *x* and time *t*.

S' is another frame with origin *O'* for coordinate *x'* and time *t'*.

S' is moving with velocity *u* in the *x*-direction as seen from *S*.

For arithmetical convenience, we assume that the origins of *O* and *O'* overlap at $t = t' = 0$, meaning $x = x' = 0$ at $t = t' = 0$.

When we get to 3 dimensions, we assume that *y* and *y'* are parallel, and *z* and *z'* are parallel, and the velocity *u* is still in the *x* direction.

Gallilean Transformations

The Gallilean Transformations are what you are used to from PHYS 170:

$$x' = x - ut \qquad t' = t$$

To find velocity in *S'*, we take the time-derivative using *x'* and *t'*

$$\frac{dx'}{dt'} = \frac{dx'}{dt} = \frac{d}{dt}\left(x - ut\right) = \frac{dx}{dt} - u$$

So velocities are different in *S'*: we subtract u.

That would make the speed of light frame-dependent.
So these can't be the right coordinate transformations.

First Guess

The thought experiment suggests that time is transformed too.

Positive position went to negative time
and negative position went to positive time.

Let's keep the x transform,
but try a time transformation that depends on position and velocity.

$$x' = x - ut$$
$$t' = t - ux/c^2$$

The units match, it does nothing when $u = 0$
and gets the signs of the time shift signs right.

Let's see if it makes the speed of light constant.

Transformed Speed of Light

A light pulse is created in S at $t_1 = x_1 = 0$, and absorbed at $t_2 = T$, $x_2 = cT$.

Plug in to $\begin{aligned} x' &= x - ut \\ t' &= t - ux/c^2 \end{aligned}$ to find the S' frame values:

$$x_1' = 0 \qquad x_2' = x_2 - ut_2 = cT - uT = (c-u)T$$
$$t_1' = 0 \qquad t_2' = t_2 - ux_2/c^2 = T - u\cdot(cT)/c^2 = (1-u/c)T$$

Find the velocity of light in S' frame:

$$V' = \frac{x_2' - x_1'}{t_2' - t_1'} = \frac{(c-u)T - 0}{(1-u/c)T - 0} = \frac{c-u}{1-u/c}\cdot\frac{c}{c} = \frac{c-u}{c-u}\cdot c = c$$

Hey, it worked ! The speed of light is the same !

Transformed Speed of Light 2

Actually, we would find that the speed of light is the same in *S'* and *S* if we multiplied the transformation laws by any function of velocity u, as long as we use the same function for both:

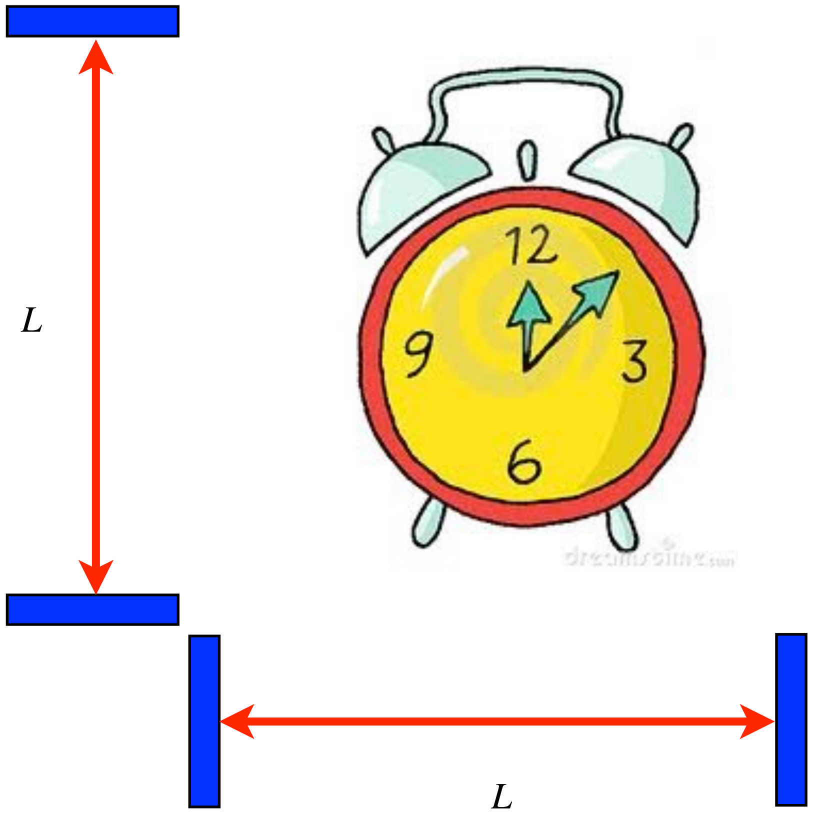
$$x' = (x - ut) \cdot f(u)$$
$$t' = (t - ux/c^2) \cdot f(u)$$

Of course we want $f(u=0)=1$ so the transformation does nothing when $u = 0$.

We will need to add an *f*-function to get something else right.

Light Clocks

Make a clock that measures time by bouncing a light pulse back and forth between mirrors. Make an identical clock but rotated by 90°. Put an ordinary mechanical clock next to them.

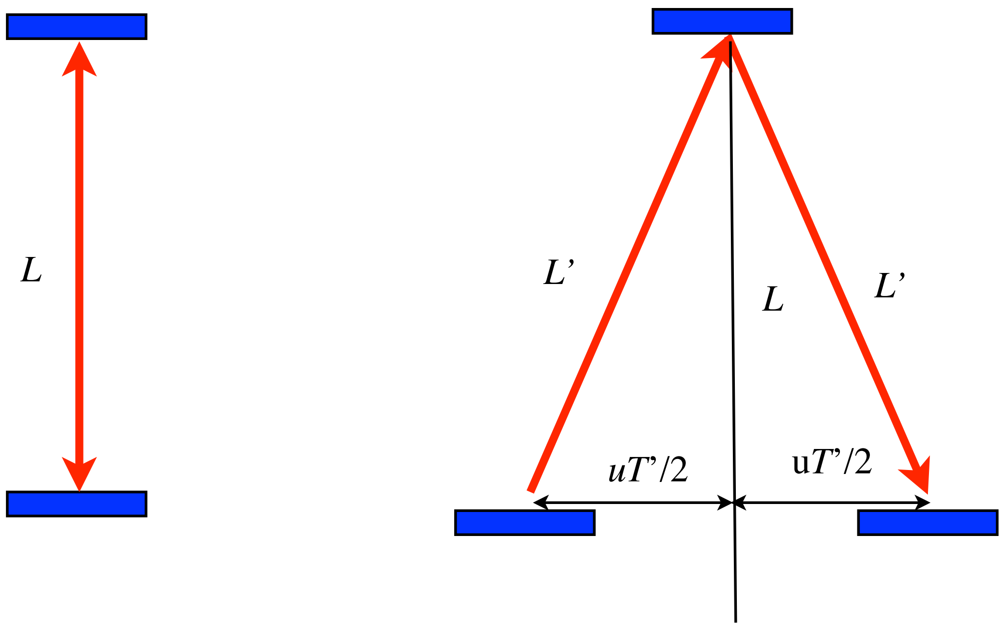


All 3 clocks tick at the same rate.

Now make 3 more identical clocks,
and put them in a spaceship moving with horizontal velocity u.

Transverse Clock

What does a stationary observer see for the moving transverse clock?



He says the light path in the moving clock is longer because it's diagonal.
But the speed of light is the same as for his own clock.

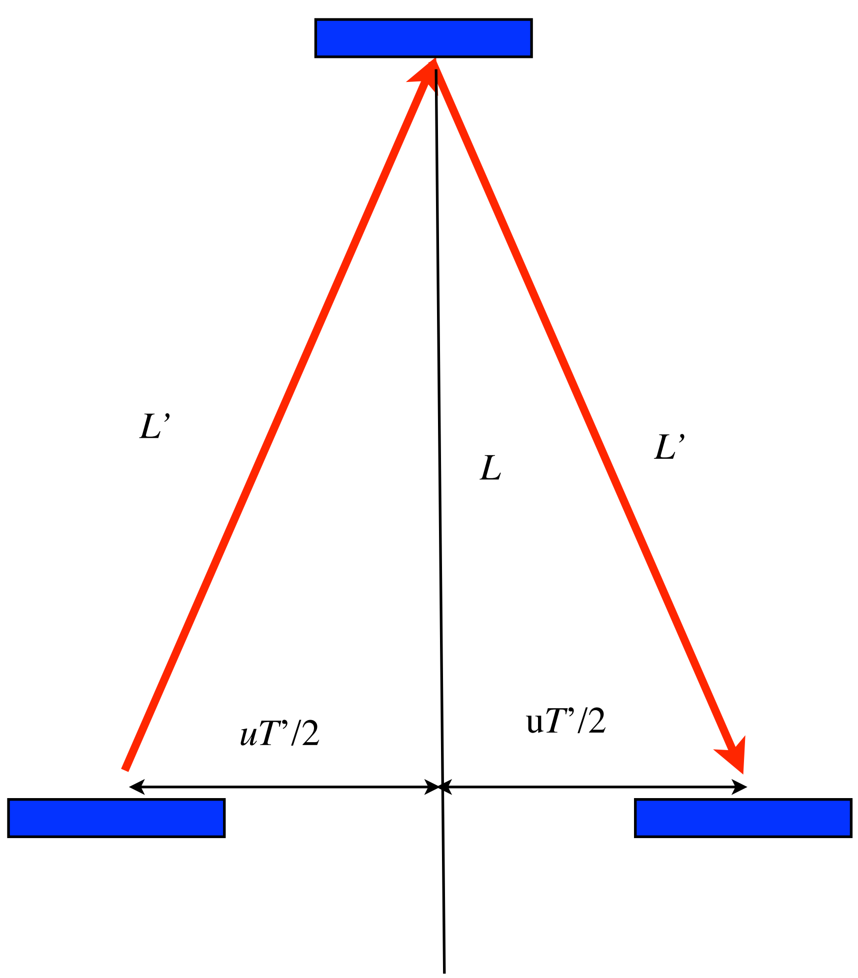
So he sees the vertical light-clock ticking more slowly than his own clock.

Period of Transverse Clock

The diagonal light path is $L' = \sqrt{L^2 + \left(uT'/2\right)^2}$

which depends on the period $T' = 2L'/c \rightarrow L' = cT'/2$.

Set these equal to get



$$\frac{cT'}{2} = \sqrt{L^2 + \left(uT'/2\right)^2}$$

$$\frac{c^2T'^2}{4} = L^2 + \frac{u^2T'^2}{4}$$

$$\frac{\left(c^2 - u^2\right)T'^2}{4} = L^2 \rightarrow T'^2 = \frac{4L^2}{c^2 - u^2}$$

$$T' = \frac{2L}{\sqrt{c^2 - u^2}} = \frac{2L}{c}\frac{1}{\sqrt{1 - \left(u/c\right)^2}}$$

The Correct Transformations

Time intervals are different in the *S'* frame by the factor $\frac{1}{\sqrt{1-(u/c)^2}}$.

So let's include that in the formula as an $f(u)$ factor.

We put the same factor into the *x* transform, to keep the speed of light constant.

$$x' = \frac{x - ut}{\sqrt{1-(u/c)^2}}$$

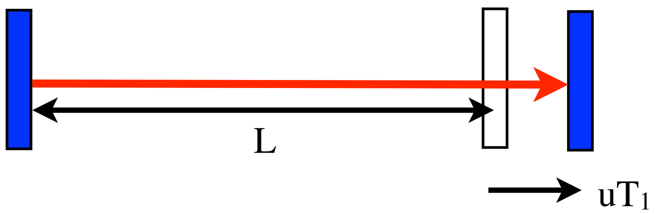
$$t' = \frac{t - ux/c^2}{\sqrt{1-(u/c)^2}}$$

These are now correct.

Longitudinal Light Clock

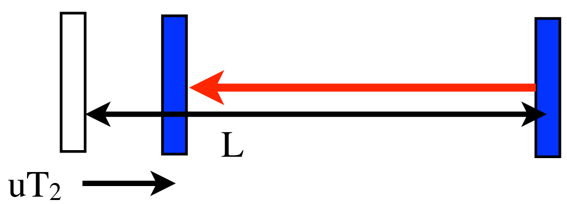
When the light is moving in the same direction as the mirrors, the light pulse has to travel length L, plus the distance the far mirror moves in the half-tick.

So the half-tick is the solution to $cT_1 = L + uT_1 \rightarrow T_1 = \dfrac{L}{c-u}$.



For the other half-tick, the light travels L minus the distance the mirrors travel,

so the half-tick is the solution to $cT_2 = L - uT_2 \rightarrow T_2 = \dfrac{L}{c+u}$.



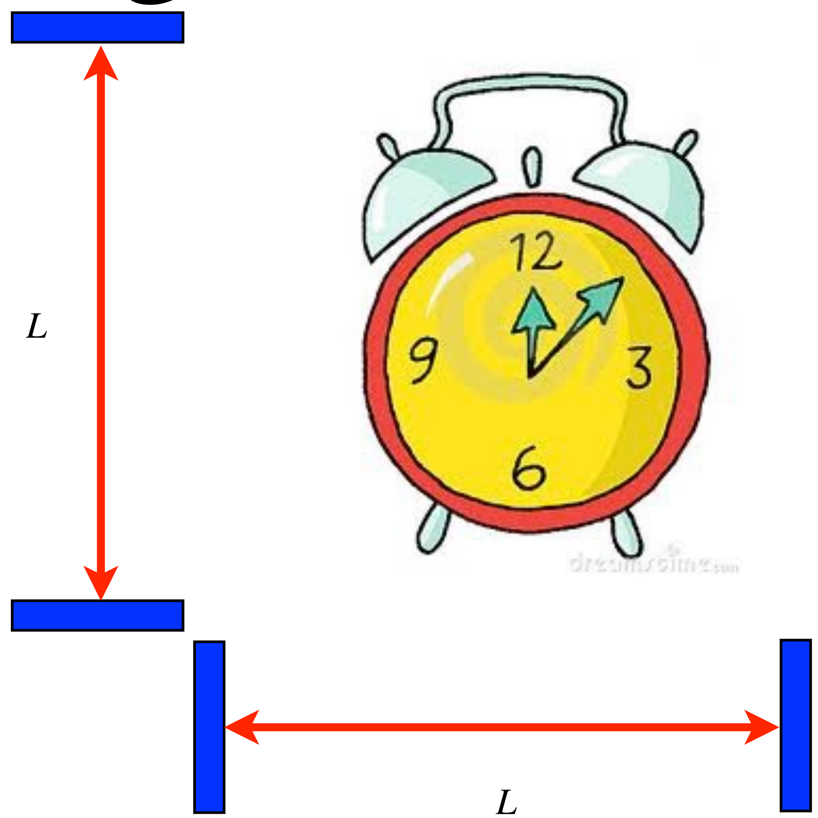
So the period is

$$T_1 + T_2 = \frac{L}{c-u} + \frac{L}{c+u} = \frac{L\cdot(c+u) + L\cdot(c-u)}{(c-u)(c+u)} = \frac{2Lc}{c^2 - u^2} = \frac{2L}{c}\frac{1}{1 - u^2/c^2}$$

Slower than the rate at rest, but <u>not</u> by the same factor as the transverse clock! The square-root is missing.

What Is Wrong?

The vertical and horizontal light clocks, and the mechanical clock, are all supposed to tick at the same rate.



The vertical light clock appears to slow down when moving. The horizontal light clock also slows down, but by a different amount ??

The resolution is that <u>moving objects appear shorter</u> by a factor that makes the horizontal light clock tick at the same rate as the vertical clock.

The right factor is already built into the Lorentz Transform equations.

But we have to define very carefully what we mean by the “length” of an object.

Length of a Moving Object

We measure the coordinates in frame S of both ends of a moving object at the same time $t = 0$ in the S frame, giving $x_1 = 0$ and $x_2 = L_{\text{lab}}$.

In the frame of the object,

$$x_1' = \frac{x_1 - ut}{\sqrt{1-(u/c)^2}} = \frac{0 - u \cdot 0}{\sqrt{1-(u/c)^2}} = 0$$

$$x_2' = \frac{x_2 - ut}{\sqrt{1-(u/c)^2}} = \frac{L_{\text{lab}} - u \cdot 0}{\sqrt{1-(u/c)^2}} = \frac{L_{\text{lab}}}{\sqrt{1-(u/c)^2}}$$

The object length in its own frame is $L_{\text{own}} = x_2' - x_1' = \dfrac{L_{\text{lab}}}{\sqrt{1-(u/c)^2}} - 0$

So $L_{\text{lab}} = L_{\text{own}}\sqrt{1-(u/c)^2} < L_{\text{own}}$

Length Contraction Fixes It

The stationary observer sees the length of the horizontal moving clock divided by $1/\sqrt{1-u^2/c^2} > 1$, *i.e.* multiplied by a factor of $\sqrt{1-u^2/c^2} < 1$.

Then the period is

$$T_1 + T_2 = \frac{2\left(L_{\text{lab}}\right)}{c}\frac{1}{1-u^2/c^2} = \frac{2\left(L_{\text{rest}}\sqrt{1-u^2/c^2}\right)}{c}\frac{1}{1-u^2/c^2} = \frac{2L_{\text{rest}}}{c}\frac{1}{\sqrt{1-u^2/c^2}}$$

which is the same as we got for the moving vertical light clock.

Lorentz Contraction and Time Dilation

It's convenient to define $\beta \equiv \frac{u}{c}$ and $\gamma \equiv \frac{1}{\sqrt{1-u^2/c^2}} = \frac{1}{\sqrt{1-\beta^2}}$

Lorentz Contraction: Moving objects look shorter: $L_{\text{moving}} = \frac{L_{\text{rest}}}{\gamma}$

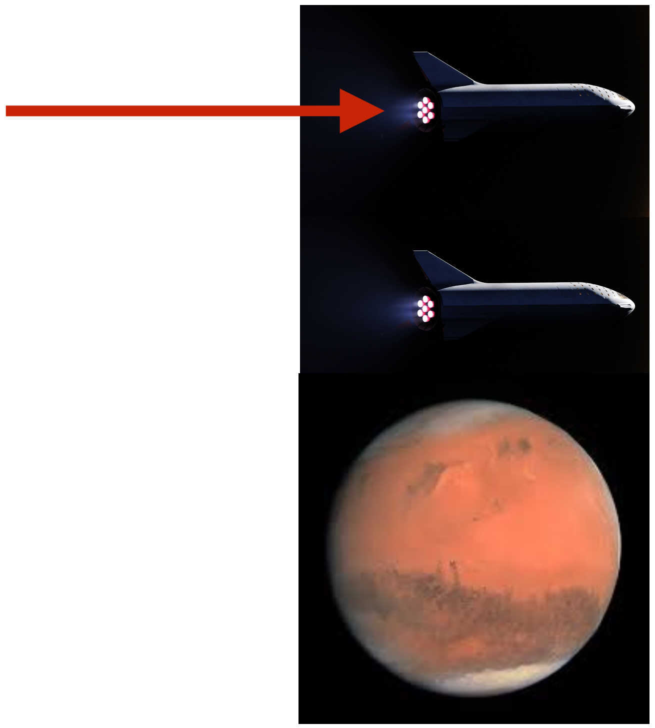
Time Dilation: Moving clocks tick slower: $T_{\text{moving}} = \gamma T_{\text{rest}} \leftrightarrow f_{\text{moving}} = \frac{f_{\text{rest}}}{\gamma}$

Elon-gth X

A SpaceX Starship with length 50 meters passes by Mars at $\beta = 0.2$.

Compared to an identical Starship orbiting Mars, the moving spaceship appears

A. Longer
B. The same length
C. Shorter
D. I don't know how to do this



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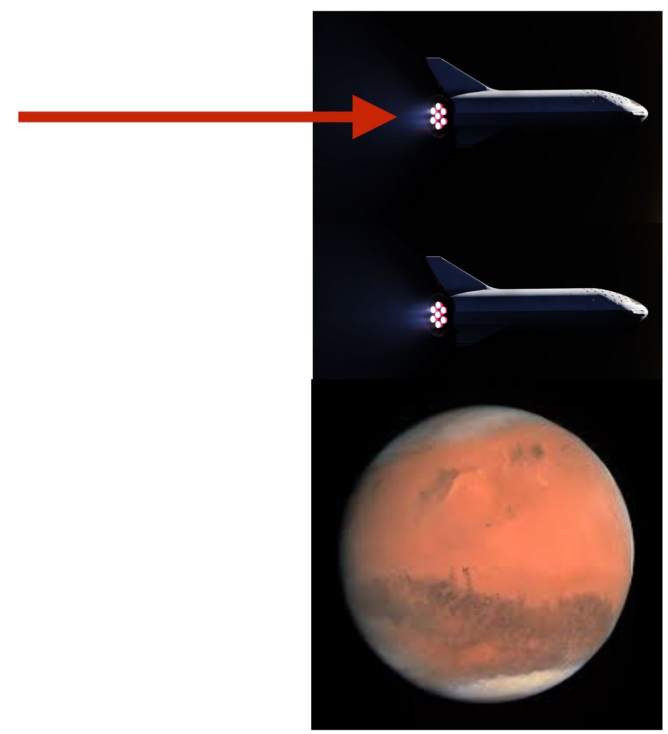
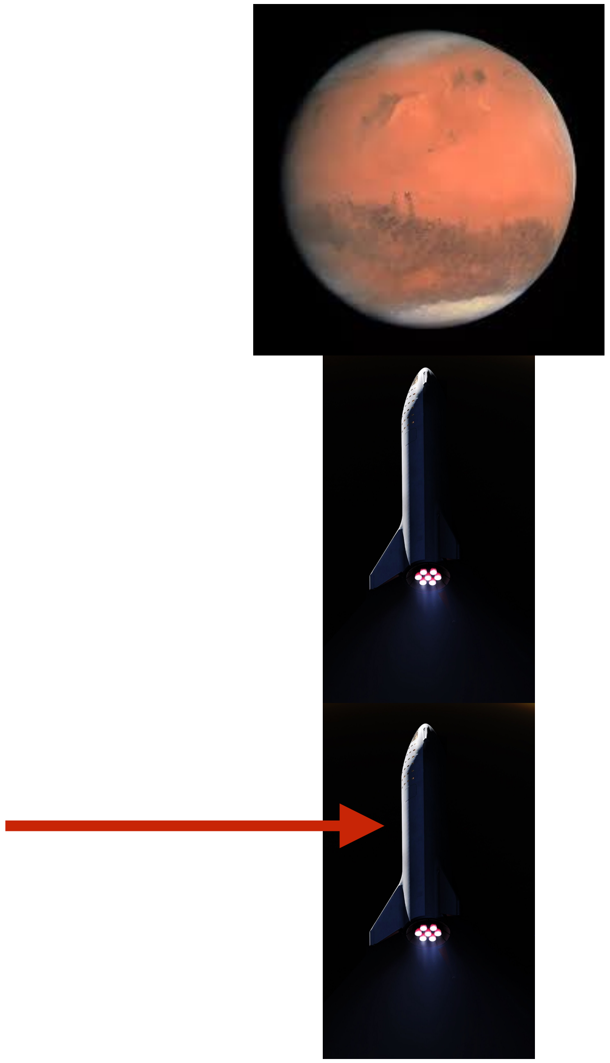


Although it's only 2% shorter
despite moving at 60,000 km per second !

Elon-gth Y

The same Starship at the same velocity $\beta = 0.2$ rotates 90° before passing Mars. Compared to an identical Starship orbiting Mars, the moving spaceship appears

A. Longer
B. The same length
C. Shorter
D. I don't know how to do this



Elon-gth Y

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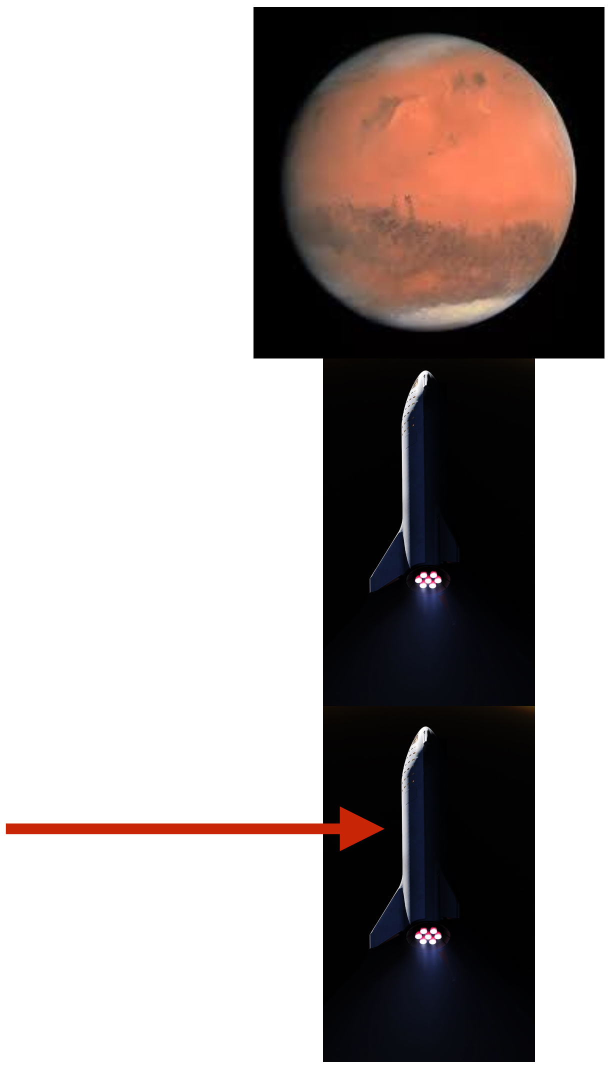

A. Longer
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C. Shorter
D. I don't know how to do this

We didn't talk yet about coordinates other than along the line of motion.

But we can derive the right rule.

Elon-gth Y

The same Starship at the same velocity $\beta = 0.2$ rotates 90° before passing Mars. Compared to an identical Starship orbiting Mars, the moving spaceship appears

A. Longer
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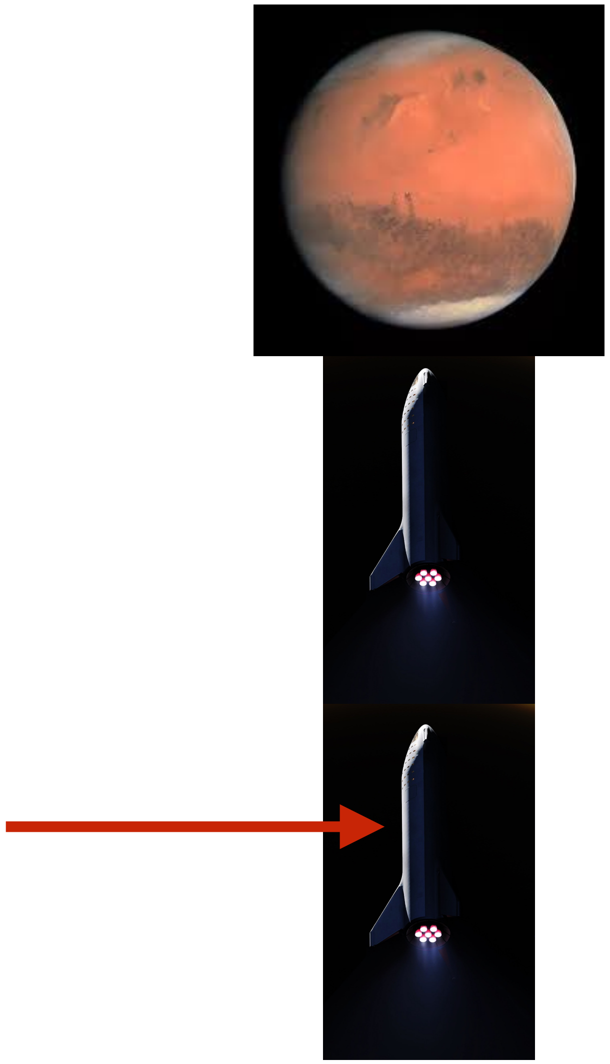

For Next Time

Get your iClicker account working.

“Acquire” Young & Freedman with Chapter 37, and skim it.

We’ll do relativistic Doppler effect.

We’ll introduce 4-vectors and relativistic invariants.

We’ll see how mass, momentum and energy are affected by relativity.

We’ll introduce the possibility of particles with zero mass: photons!

WeBWorK homework will be posted Wednesday evening