Physics 280 Lecture One

Summer 2016

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Objectives

- Be able to identify where classical physics was going wrong regarding relativity

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- Be able to recognize the principles of relativity
- Be able to understand the radical truth of relativity
- Be able to apply the Lorentz transforms
- Be able to predict what a box will look like at relativistic speeds

Early evidence

- Electron acceleration

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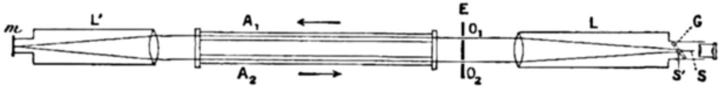
- The Experiments of Rayleigh and Brace (1902, 1904)

Fizeau experiment



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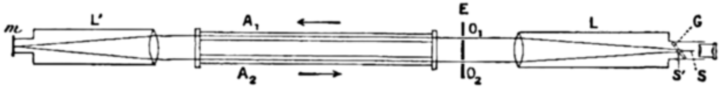

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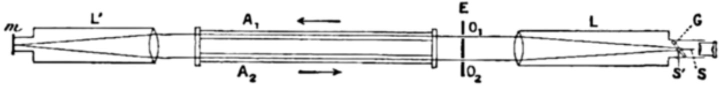

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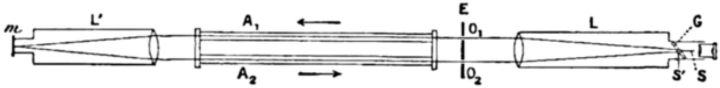

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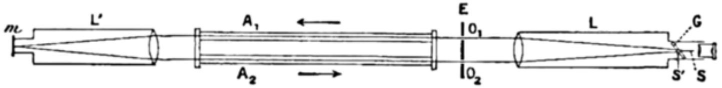

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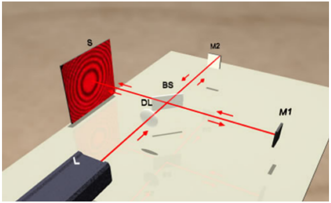
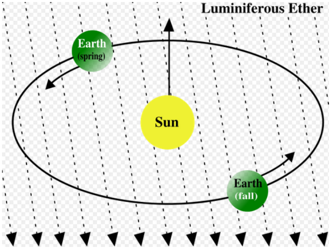
- If water flows with velocity v, light should travel at speed $w_{\pm} = \frac{c}{n} \pm v$.
- After reflecting at m, traveling back and recombining at S, interference patterns will reveal the speed difference between the two pipes.
- Actual finding: $w_{+} = \frac{c}{n} + v\left(1 - \frac{1}{n^2}\right)$

Michelson-Morley experiment





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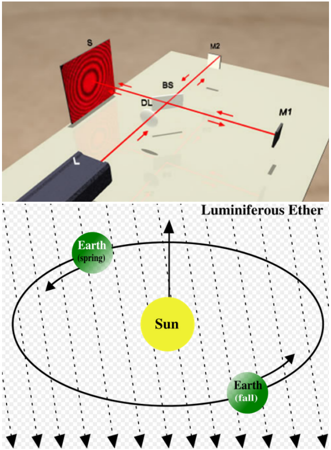

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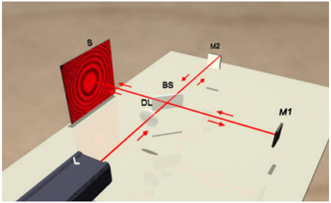

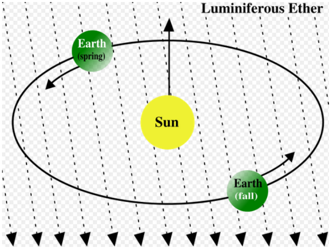

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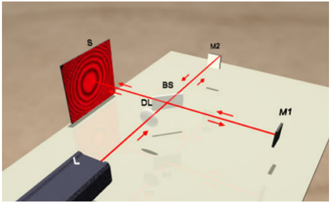

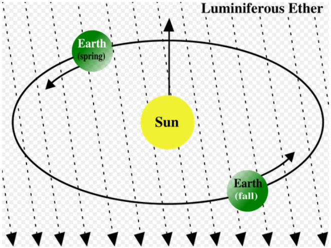

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- Earth is in motion through space, so there should be change in direction of motion
- A rotating interference apparatus sensitive enough to measure this speed difference failed to find any fringe shifts.
- “the most famous failed experiment in history”

Michelson-Morley experiment

“there is no such thing as a ”specially favoured” (unique) co-ordinate system to occasion the introduction of the ther-idea, and hence there can be no ther-drift, nor any experiment with which to demonstrate it.” – Einstein

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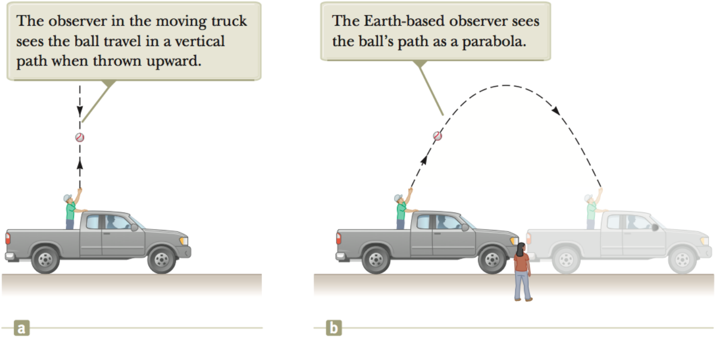
- We will learn about some other, even bigger problems later.
- Galilean Relativity must be wrong.

Galilean Relativity

"The laws of mechanics must be the same in all inertial frames of reference."

$$x' = x + vt$$

$$t' = t$$



Gregor throws a ball up at 5 m/s in a truck that is moving 20 m/s relative to Mei who is standing on the ground. How fast is the ball going according to Mei when it is first launched?

Galilean Relativity

Gregor throws a ball up at 5 m/s in a truck that is moving 20 m/s relative to Mei who is standing on the ground. What is the velocity of the ball according to Mei when it is first launched?

$$x' = x + v_x t \;\rightarrow\; \frac{dx'}{dt} = \frac{dx}{dt} + v_x = 0 + 20m/s = 20m/s$$

$$y' = y + v_y t \;\rightarrow\; \frac{dy'}{dt} = \frac{dy}{dt} + v_y = 5m/s + 0 = 5m/s$$

So according to Mei,

$$\vec{V} = 20m/s\hat{\mathbf{i}} + 5m/s\hat{\mathbf{j}}$$

whereas according to Gregor,

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Both are right according to Galilean relativity, but the truth is much more interesting.


ON THE ELECTRODYNAMICS OF MOVING BODIES

By A. Einstein
June 30, 1905

I. KINEMATICAL PART

§ 1. Definition of Simultaneity

- The principle of relativity: The laws of physics must be the same in all inertial reference frames.

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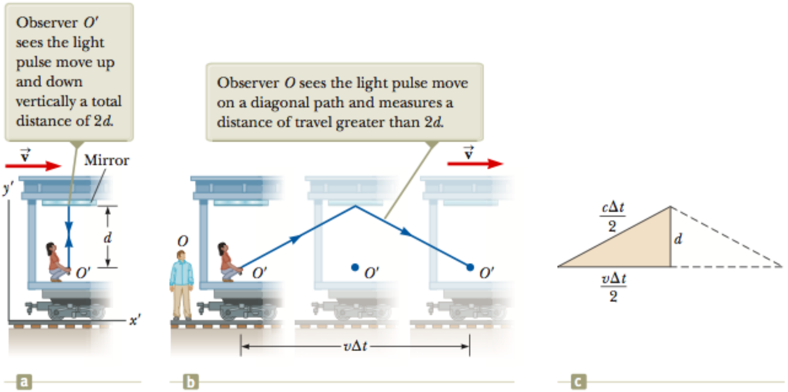
I. KINEMATICAL PART

§ 1. Definition of Simultaneity

- The principle of relativity: The laws of physics must be the same in all inertial reference frames.
- The constancy of the speed of light: The speed of light in vacuum has the same value, $(2.99 \times 10^8)\,\frac{\text{m}}{\text{s}}$, in all inertial frames, regardless of the velocity of the observer or the velocity of the source emitting the light.

Simple statement, Radical consequences



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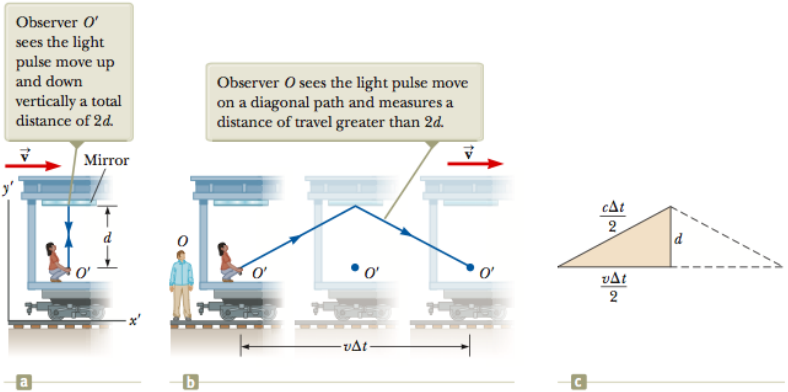

Both observers must absolutely measure the speed of light to be the same, $c = (2.99 \times 10^8)\,\frac{\mathrm{m}}{\mathrm{s}}$.

Simple statement, Radical consequences

The ground observer finds:

$$\left(\frac{c\Delta t}{2}\right)^2 = \left(\frac{v\Delta t}{2}\right)^2 + d^2$$

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Who is right?

Welcome to reality.

They are both right!

To distinguish their times, let us call the time measurement in the frame in which the event happens and is at rest the proper time (the clock here is at rest relative to the event) denoted t_p. Then relating the previous findings:

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WTF

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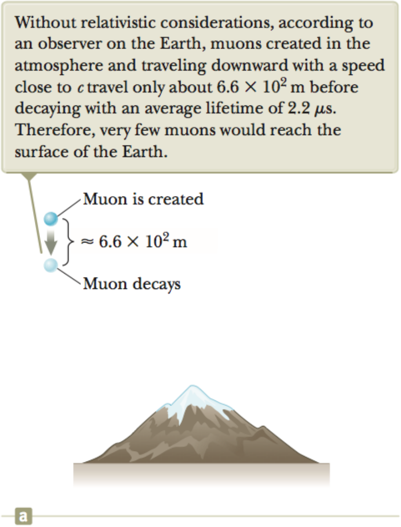
Proof: Muons.

Muon decays


Without relativistic considerations, according to an observer on the Earth, muons created in the atmosphere and traveling downward with a speed close to c travel only about 6.6×10^2 m before decaying with an average lifetime of 2.2 μs. Therefore, very few muons would reach the surface of the Earth.
Muon is created
$\approx 6.6 \times 10^2$ m
Muon decays
a
With relativistic considerations, the muon's lifetime is dilated according to an observer on the Earth. Hence, according to this observer, the muon can travel about 4.8×10^3 m before decaying. The result is many of them arriving at the surface.
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What will be the mean lifetime of a muon as measured in the laboratory if it is traveling at v = 0.60c with respect to the laboratory? Its mean lifetime at rest is 2.20 μs. How far does it travel in the lab before decaying?

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lab frame:

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Thus it will travel a distance:

$$d = v\Delta t = 0.60 \left(\left(2.99 \times 10^8 \right) \frac{\mathrm{m}}{\mathrm{s}} \right) \left(2.8 \times 10^{-6} s \right) = 500m$$

GPS!

GPS satellites move at about 4000 m/s. Show that a good GPS receiver needs to correct for time dilation if it produces results consistent with atomic clocks accurate to 1 part in 10^{13}. Hint, you will need the binomial expansion: $1/\sqrt{1-x} \approx 1 + \frac{1}{2}x$ when $x \ll 1$.

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That may seem small, but is actually large compared to the accuracy of the atomic clock. The inaccuracies pile up and eventually the signal would be way off.

One more thing...

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You both must measure the speed of light to be c.

Length Contraction

So let's consider one photon, sort of like we did with the baseball in the Galilean relativity example.

The position of that photon in the frame of a bystander on the ground should relate in some way to the position as measured by the person in the truck (whose speed is v):

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But, the speed will be the same:

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$$\sqrt{1 - \frac{v^2}{c^2}}\frac{dx'}{dt'} = \alpha\left(\frac{dx}{dt} - v\right) \rightarrow \sqrt{1 - \frac{v^2}{c^2}}c = \alpha(c - v)$$

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Multiplying the previous two equations together gives

$$c^2 = \alpha^2 \left(c^2 - v^2 \right) \quad \rightarrow \quad \alpha = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

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The Lorentz Factor:

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Say a 1 meter stick is measured in your rest frame to be 1 meter. Somebody running by at 0.9c will measure it how? To simplify, assume they measure the stick by watching where their ruler lands on either end at the same time. Then:

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$$\Delta x = \gamma\left(\Delta x' - v\Delta t\right) = \gamma\left(\Delta x'\right)$$

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$$\overbrace{\Delta x}^{\text{That being measured is at rest}} = \gamma \overbrace{\Delta x'}^{\text{That being measured is not at rest}}$$

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Objects are measured with longest length in their rest-frame.

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Implication: Not only do we have time dialation, but time and space are tied together. Implication: The definition of simultaneous differs between observers. If something is simultaneous in one frame, it may not be so in another frame.

In-Class practice

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In the astronaut's frame,

$$\Delta t = L/v = 5ly/0.8c = 5ly/(0.8ly/yr) = 6yr$$