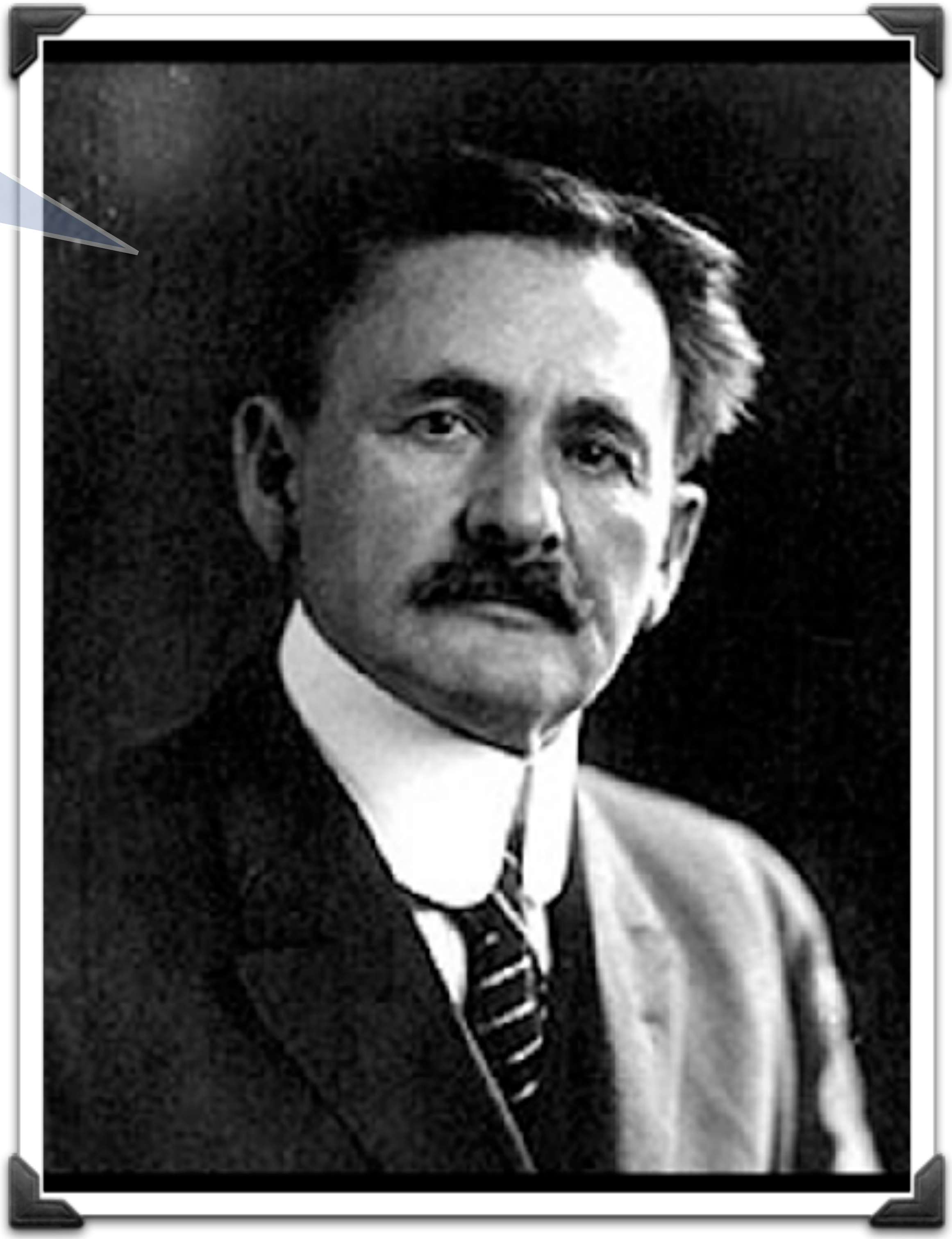
Welcome back to PHY 3305



Today's Lecture:

Michelson-Morley Experiment

Simultaneity

Albert A. Michelson
1852-1931

- Dr. Cooley's Office hours will be Mondays 10-11 am and Tuesdays 6 - 7 pm in FOSC 151 or by appointment.

- Mr. Thomas' Office hours will be Mondays 3-4 pm in FOSC 038A and Thursdays 2-3 pm in FOSC 060 or by appointment.

ANNOUNCEMENTS

-Dr. Cooley's Office hours will be Mondays 10-11 am and Tuesdays 6 - 7 pm in FOSC 151 or by appointment.

-Mr. Thomas' Office hours will be Mondays 3-4 pm in FOSC 038A and Thursdays 2-3 pm in FOSC 060 or by appointment.

-Reading Assignment for Tuesday, August 29: Chapter 2.3

-First homework assignment is due Tuesday, August 29th.

-Dr. Cooley will be out of town Friday August 25th.

-Extra Credit Opportunities throughout semester: Sign up as a student member to the American Physical Society (free 1-year membership) for your personal copy of Physics Today. https://www.aps.org/membership/student.cfm

TODAY

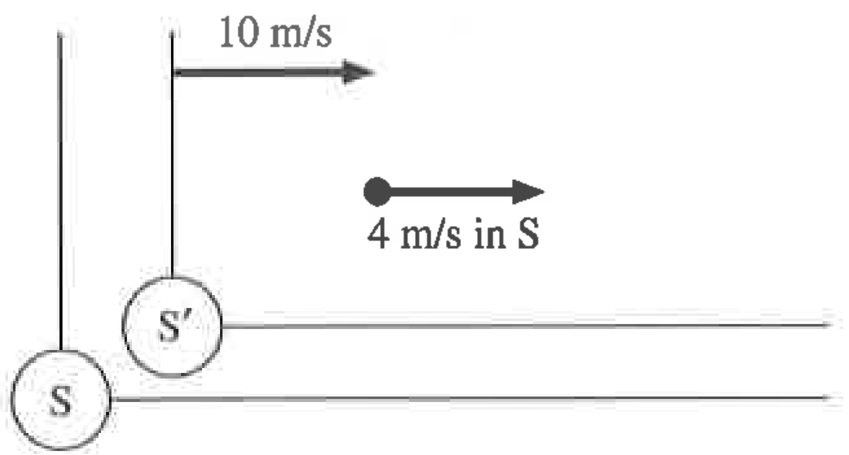
a) Review Galilean Relativity

b) Examine the Michelson-Morley Experiment

c) Explore Simultaneity

GALILEAN RELATIVITY

In which reference frame, S or S′ does the ball move faster?



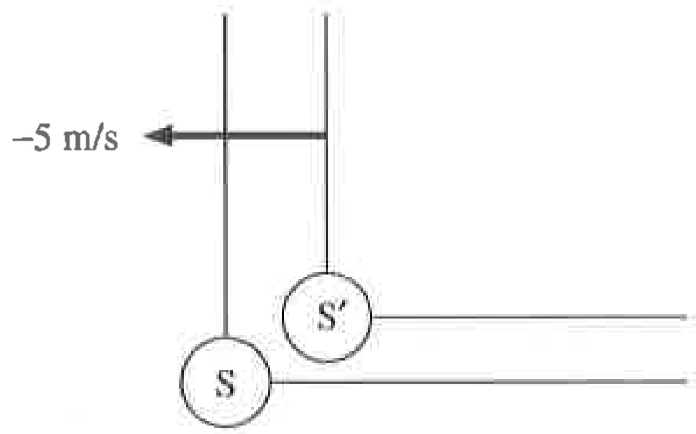
Answer: S′

Recall: $u' = u - v \;\; = 4\,\frac{m}{s} - 10\,\frac{m}{s} \;\; = -6\,\frac{m}{s}$

Moves faster —> speed and 6 > 4.

GALILEAN RELATIVITY

Frame S′ moves relative to frame S as shown.



a) A ball is at rest in frame S′. What are the speed and direction of the ball in frame S?

Ans: 5 m/s to the left

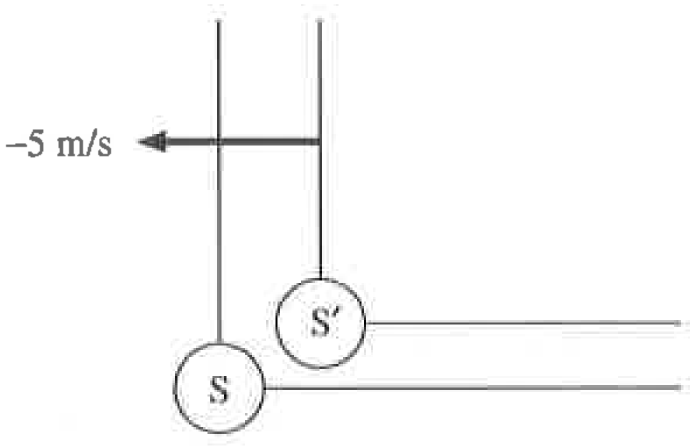
Start with:

$$u' = u - v$$

$$u = u' + v = 0\,\frac{m}{s} - 5\frac{m}{s} = -5\frac{m}{s}$$

GALILEAN RELATIVITY

Frame S′ moves relative to frame S as shown.



b) A ball is at rest in frame S. What are the speed and direction of the ball in frame S′?

Ans: 5 m/s to the right

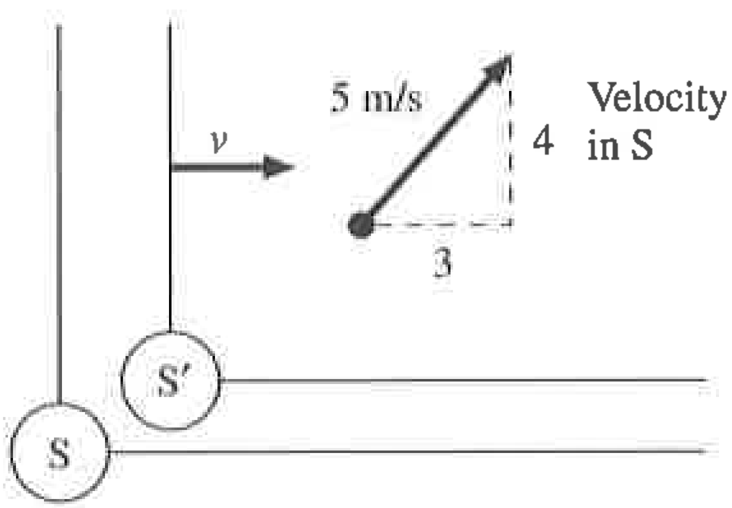
Start with:

$$u' = u - v$$

$$= 0\,\frac{m}{s} + 5\,\frac{m}{s} = 5\,\frac{m}{s}$$

GALILEAN RELATIVITY

Frame S′ moves parallel to the x-axis of frame S.

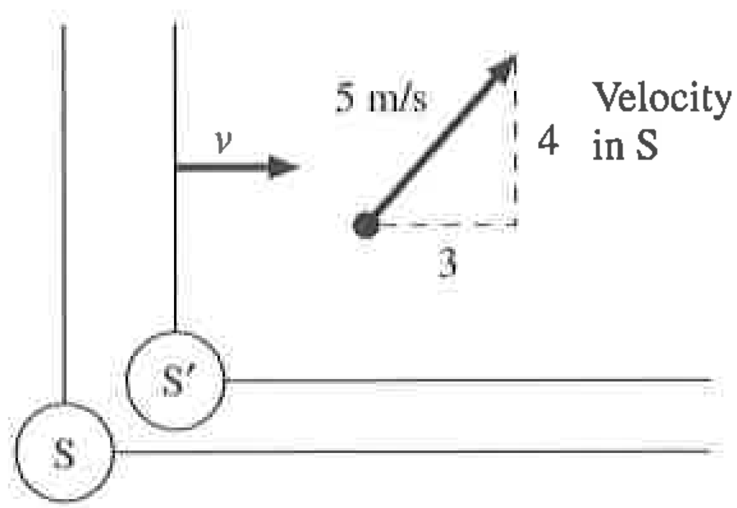


a) Is there a value of v for which the ball is at rest in S′? If so, what is v? If not, why not?

Ans: No, the ball will always have a y-component.

GALILEAN RELATIVITY

Frame S' moves parallel to the x-axis of frame S.



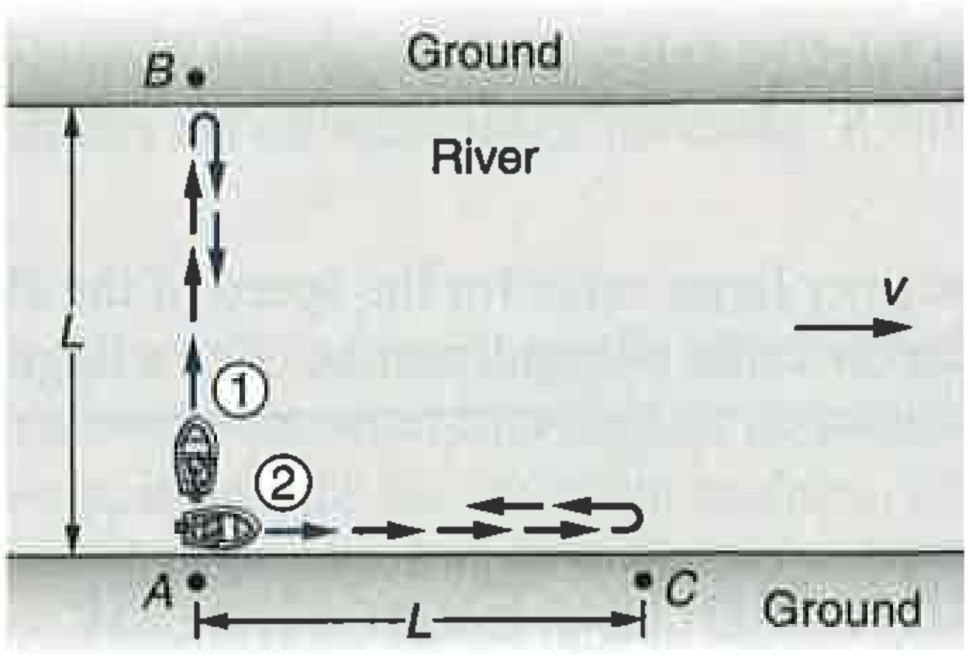
b) Is there a value of v for which the ball has a minimum speed in S'? If so, what is v? If not, why not?

Ans: Yes, when the x-component of the velocity vector is zero, the velocity will be at a minimum value of 4 m/s in the y-direction.

MICHELSON-MORLEY EXPERIMENT

- The speed of waves depends on the properties of the medium.
  - We can measure the speed of sound waves in air (the absolute motion of the waves relative to still air)

Example: A Boat Race

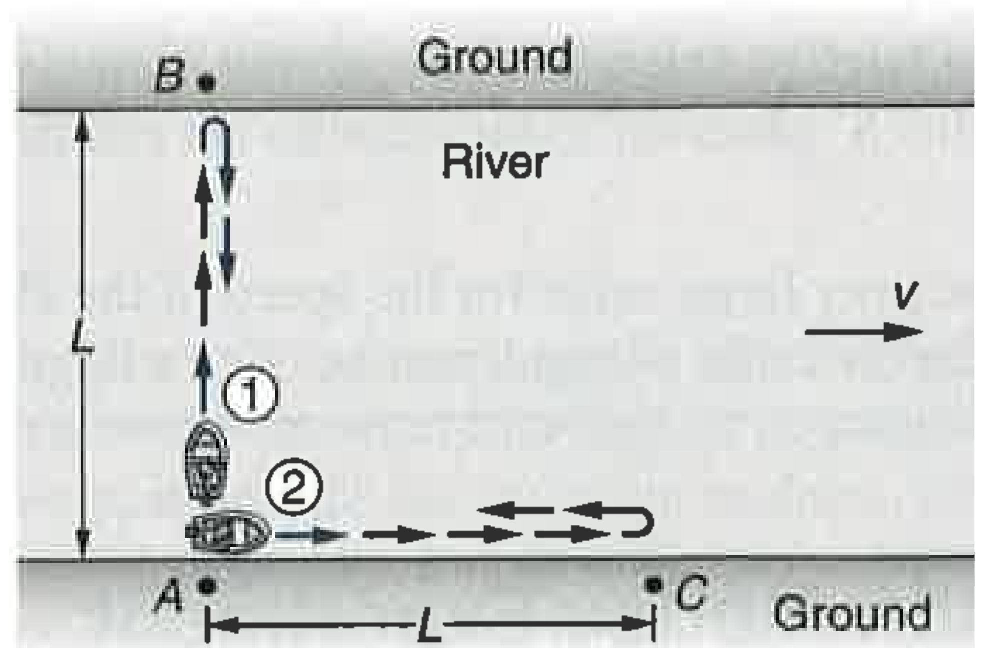


Two equally matched rowers race each other over courses as shown. Each oarsman rows at speed C in still water; the current of the river is v. Boat 1 goes from A to B, a distance L, and back. Boat 2 goes from A to C, a distance L, and back. A, B and C are marks on the riverbank. Which boat wins the race or is it a tie? Assume $c > v$.

MICHELSON-MORLEY EXPERIMENT

Example: A Boat Race

The winner will be the boat who completes the course in the least amount of time.

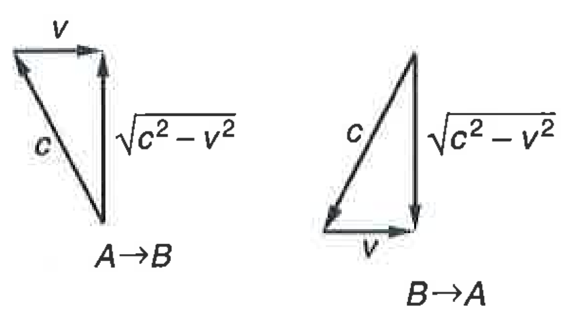


Boat 2:

$$t = \frac{L}{c+v} + \frac{L}{c-v} = \frac{L(c-v)}{c^2-v^2} + \frac{L(c+v)}{c^2-v^2} = \frac{2Lc}{c^2-v^2}$$

How to compare?

Boat 1:



$$t = \frac{L}{\sqrt{c^2-v^2}} + \frac{L}{\sqrt{c^2-v^2}} = \frac{2L}{\sqrt{c^2-v^2}}$$

Binomial Expansions:

aside

For x << a, you can use this:

$$f(x) = (a+x)^n = a^n + na^{n-1}x + \frac{n(n-1)}{2!}a^{n-2}x^2 + \frac{n(n-1)(n-2)}{3!}a^{n-3}x^3 + ...$$

$$\frac{1}{(1-x^2)} = 1 + x^2 + x^4 + x^6 + ...$$

$$\sqrt{\frac{1}{(1-x^2)}} = 1 + \frac{1}{2}x^2 + \frac{1}{8}x^4 + \frac{1}{16}x^6 + ...$$

$$\sqrt{(1-x^2)} = 1 - \frac{1}{2}x^2 - \frac{1}{8}x^4 - ...$$

MICHELSON-MORLEY EXPERIMENT

Boat 2:

$$t_{AC+CA} = \frac{2Lc}{c^2 - v^2} = \frac{2L}{c}\frac{1}{(1-\frac{v^2}{c^2})}$$

$$= \frac{2L}{c}(1+\frac{v^2}{c^2}+...)$$

Boat 1:

$$t_{AB+BA} = \frac{2L}{\sqrt{c^2-v^2}} = \frac{2L}{c}(1-\frac{v^2}{c^2})^{-1/2}$$

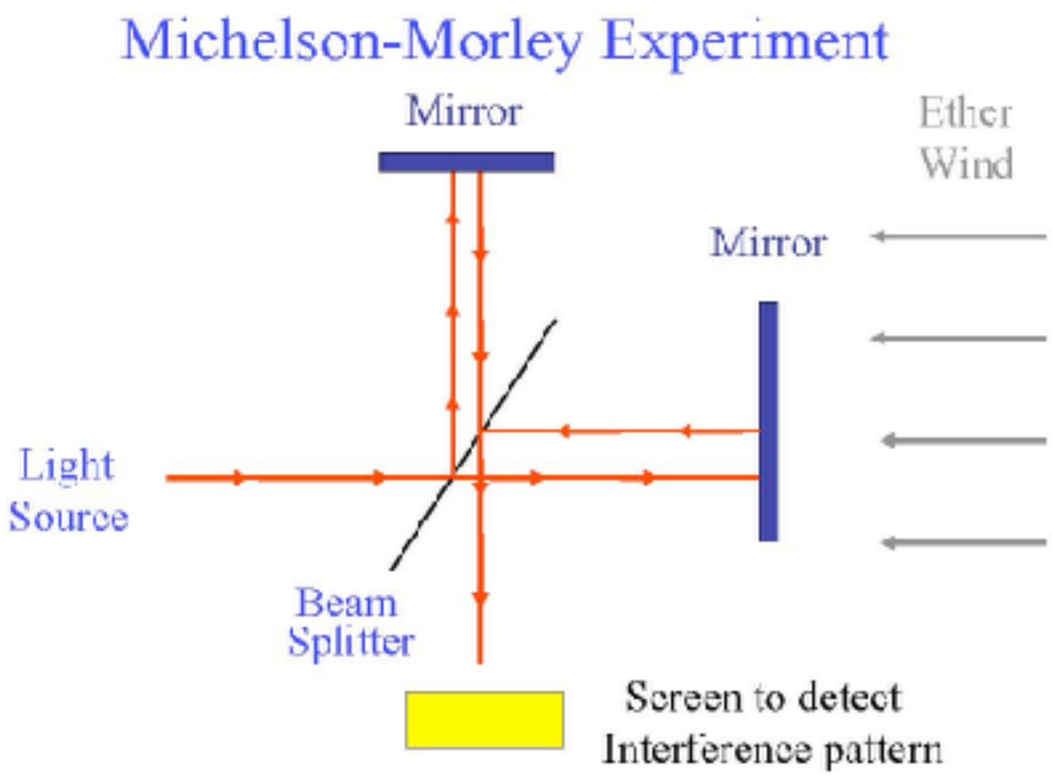
$$= \frac{2L}{c}(1+\frac{1}{2}\frac{v^2}{c^2}+...)$$

$$\Delta t = t_2 - t_1 \approx \frac{2L}{c}(1+\frac{v^2}{c^2}) - \frac{2L}{c}(1+\frac{1}{2}\frac{v^2}{c^2}) = \frac{Lv^2}{c^3}$$

So, since $t_2 > t_1$, Boat 1 has the faster average speed and wins the race.

MICHELSON-MORLEY EXPERIMENT

If the two beams are moving at different speeds, there will be a fast arm and a slow arm. Deduce Δt from observed # fringes.



$$N_{fringes} = \frac{\Delta t}{T}$$

T = period of light wave.

$$N_{fringes} = \frac{2L(c - \sqrt{c^2 - v_{ether}^2})}{T(c^2 - v_{ether}^2)}$$

Observation: No fringe.

Outcomes of Michelson-Morley Experiment

a) The speed of light was shown to be independent of the motion of the observer.

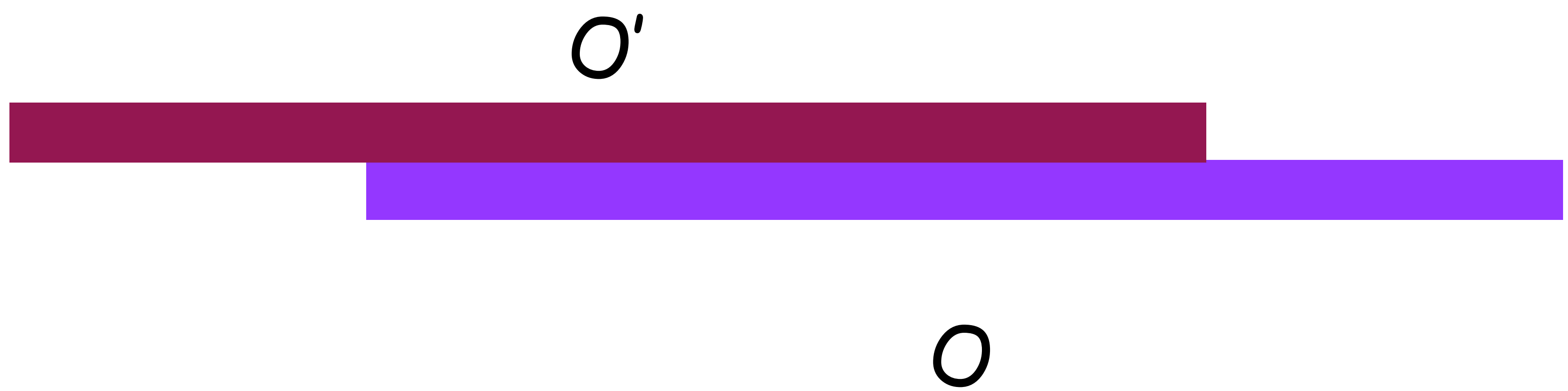
b) Helped cast away the ether hypothesis

c) E&M explained the origin of light, but did not require a medium for its wave propagation

d) 1907 Nobel Prize awarded to Michelson (1st American Physicist)

EVENTS IN DIFFERENT FRAMES

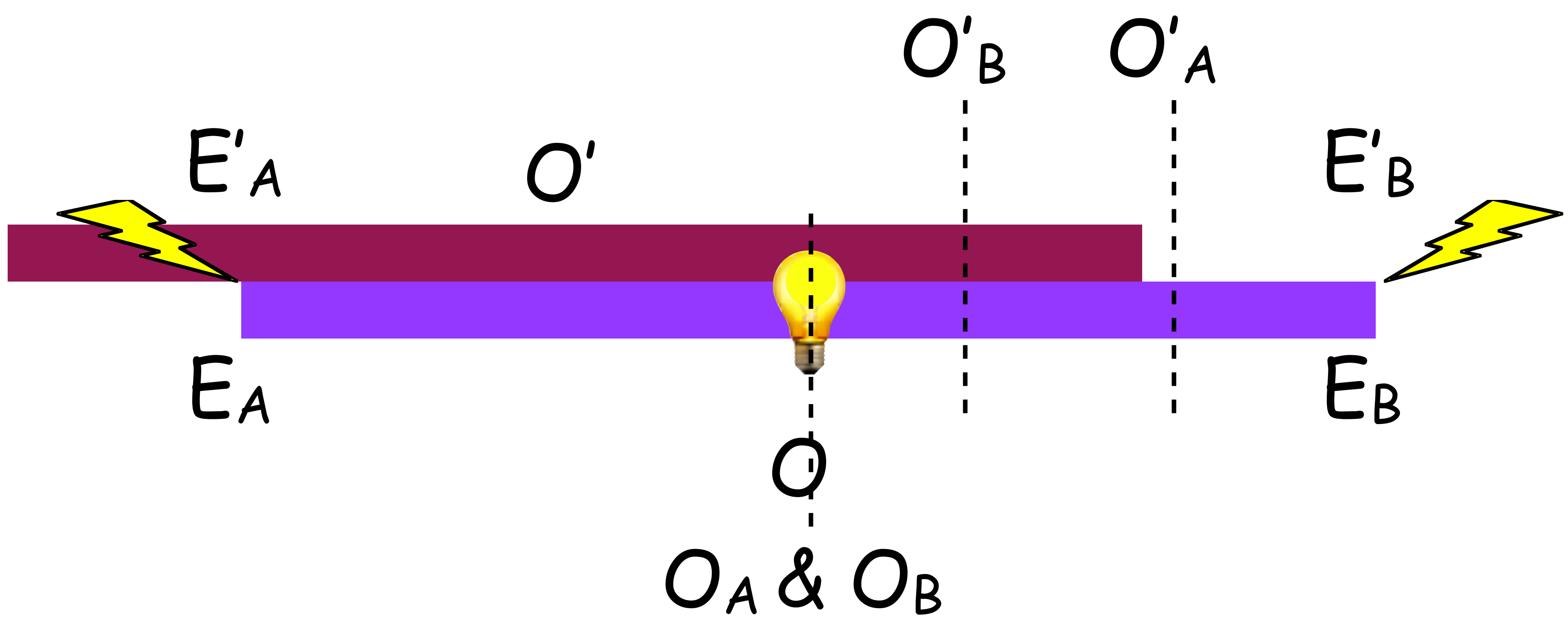
- Anna is an observer in the S' reference frame.
- She is on a high speed train traveling westward at the speed of light.
- O' is her origin.



Anna = S'
Bob = S

EVENTS IN DIFFERENT FRAMES

At the instant Anna and Bob pass each other, lightening strikes both ends of the train. Do Anna and Bob agree on the ordering of the lightening strikes?



(Anna) O' sees E'_B
(Bob) O sees E_B and E_A
(Anna) O' sees E'_A

Anna = S'
Bob = S

SIMULTANEITY

Two trees are 600 m apart. You are standing exactly half way between them and your lab partner is at the base of tree 1. Lightening strikes both trees.

a) Your lab partner, based on measurement he or she makes, determines that the two lightening strikes were simultaneous. What did you see? Did you see the lightening hit tree 1 first, hit tree 2 first or where the hits simultaneous? Explain.

Ans: I saw the hits simultaneous. We are both in the same stationary frame of reference. The speed of light is the same in both reference frames. I am half way between the trees. From the definition of velocity, I must have seen the strikes at the same time.

SIMULTANEITY

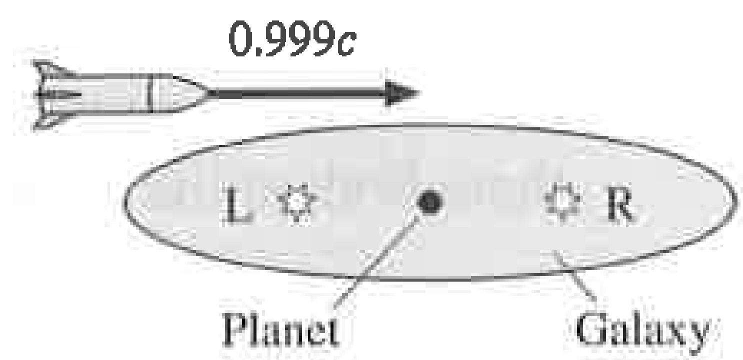
Two trees are 600 m apart. You are standing exactly half way between them and your lab partner is at the base of tree 1. Lightening strikes both trees.

b) This time your lab partner sees both flashes at the same instant of time. What did you see? Did you see the lightening hit tree 1 first, hit tree 2 first or hit them both at the same time?

Ans: I saw the hit from tree 2 first. The distance from tree 2 to my lab partner is greater than the distance of tree 1 to my lab partner. In order for my lab partner to see the flashes simultaneously, tree 2 must have been struck first. Since I am equidistant from both trees, I would light from tree 2 first.

SIMULTANEITY

Two supernovas, labeled L and R, occur on opposites sides of a galaxy. The two supernovas are seen at the same instant on a planet at rest in the center of the galaxy. A spaceship is entering the galaxy from the left at a speed of 0.999c relative to the galaxy.

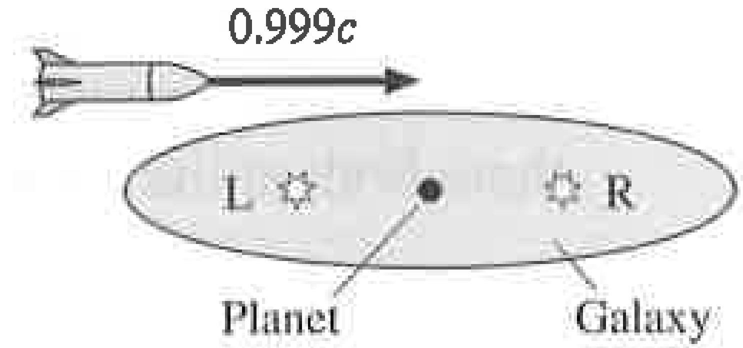


a) According to astronomers on the planet, were the two explosions simultaneous? Explain why.

Ans: Yes. Since the planet is equidistant from both supernova and the light was seen at the same time, the events must have occurred simultaneously.

SIMULTANEITY

Two supernovas, labeled L and R, occur on opposites sides of a galaxy. The two supernovas are seen at the same instant on a planet at rest in the center of the galaxy. A spaceship is entering the galaxy from the left at a speed of 0.999c relative to the galaxy.

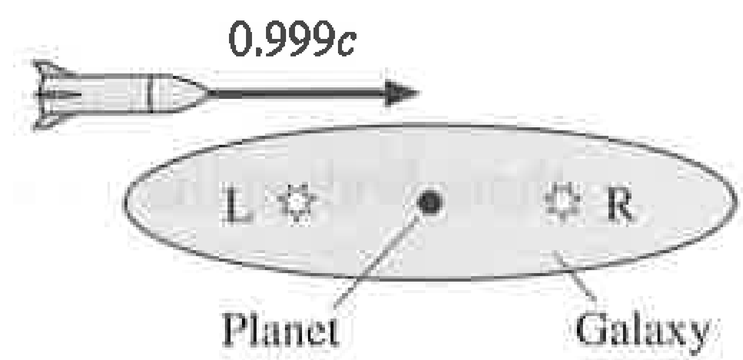


b) Which supernova does the spaceship crew see first?

Ans: The crew will see supernova L first.

SIMULTANEITY

Two supernovas, labeled L and R, occur on opposites sides of a galaxy. The two supernovas are seen at the same instant on a planet at rest in the center of the galaxy. A spaceship is entering the galaxy from the left at a speed of 0.999c relative to the galaxy.



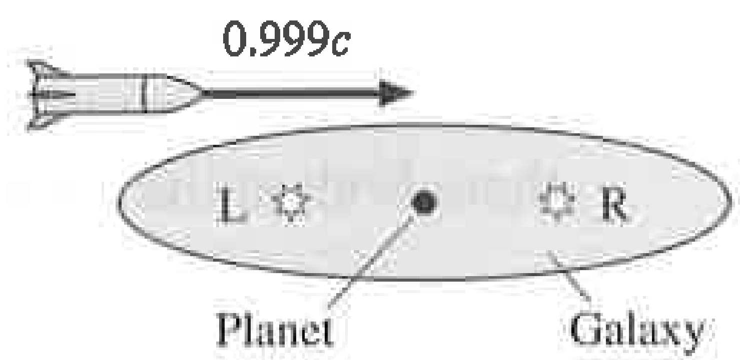
c) Did the supernova that was seen first necessarily happen first in the spaceships' frame? Explain why.

Ans: Yes. The crew is in a reference frame that is moving with respect to the planet and supernova.

SIMULTANEITY

Two supernovas, labeled L and R, occur on opposites sides of a galaxy. The two supernovas are seen at the same instant on a planet at rest in the center of the galaxy. A spaceship is entering the galaxy from the left at a speed of 0.999c relative to the galaxy.

d) Is “two light flashed reach the planet at the same instant” an event? Hint: Can you arrange for something to happen only if two flashes of light from opposite direction arrive at the same time.

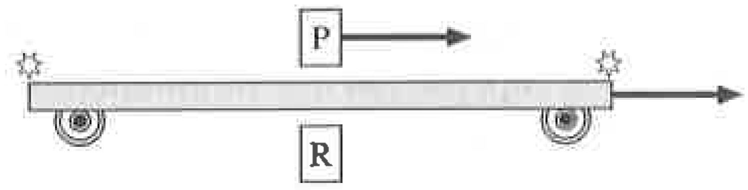


Ans: Yes. As a result, the crew on the spaceship will also determine that the light flashes reach the planet at the same time. Experimenters in different reference frames may disagree about when and where an event occurs, but they all agree that it does occur!

SIMULTANEITY

Peggy is standing at the center of her railroad car as it passes Ryan on the ground. Firecrackers attached to the ends of the car explode. A short time later, the flashes from the two explosions arrive at Peggy at the same time.

a) Were the explosions simultaneous in Peggy's reference frame? If not, which exploded first? Explain.

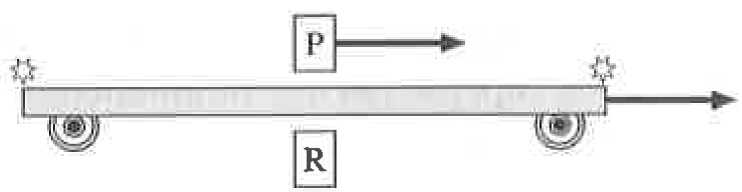


Ans: Yes. If the light arrives at Peggy at the same time, the events will be simultaneous in her frame of reference.

SIMULTANEITY

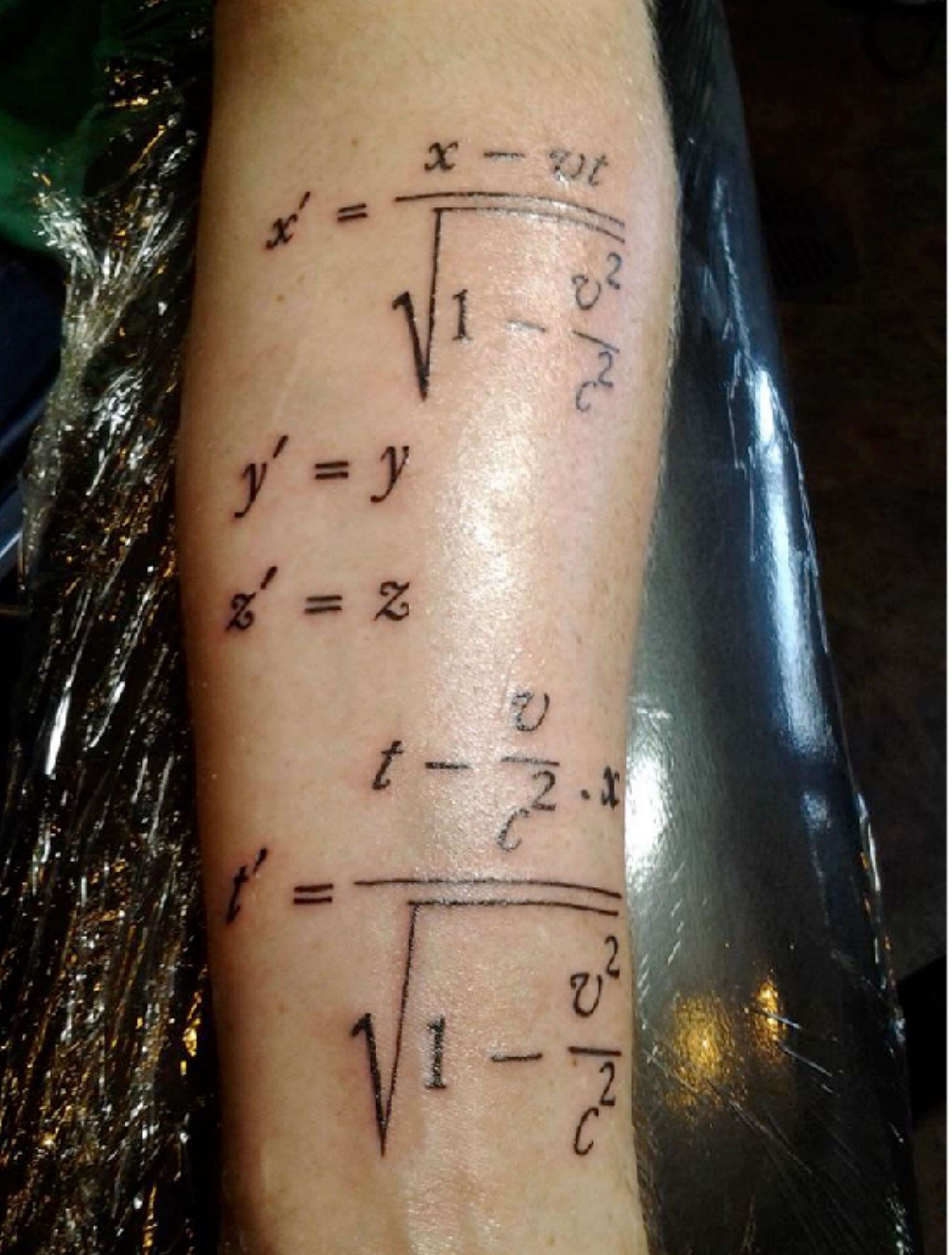
Peggy is standing at the center of her railroad car as it passes Ryan on the ground. Firecrackers attached to the ends of the car explode. A short time later, the flashes from the two explosions arrive at Peggy at the same time.

b) Were the explosions simultaneous in Ryan's reference frame? If not, which exploded first? Explain.



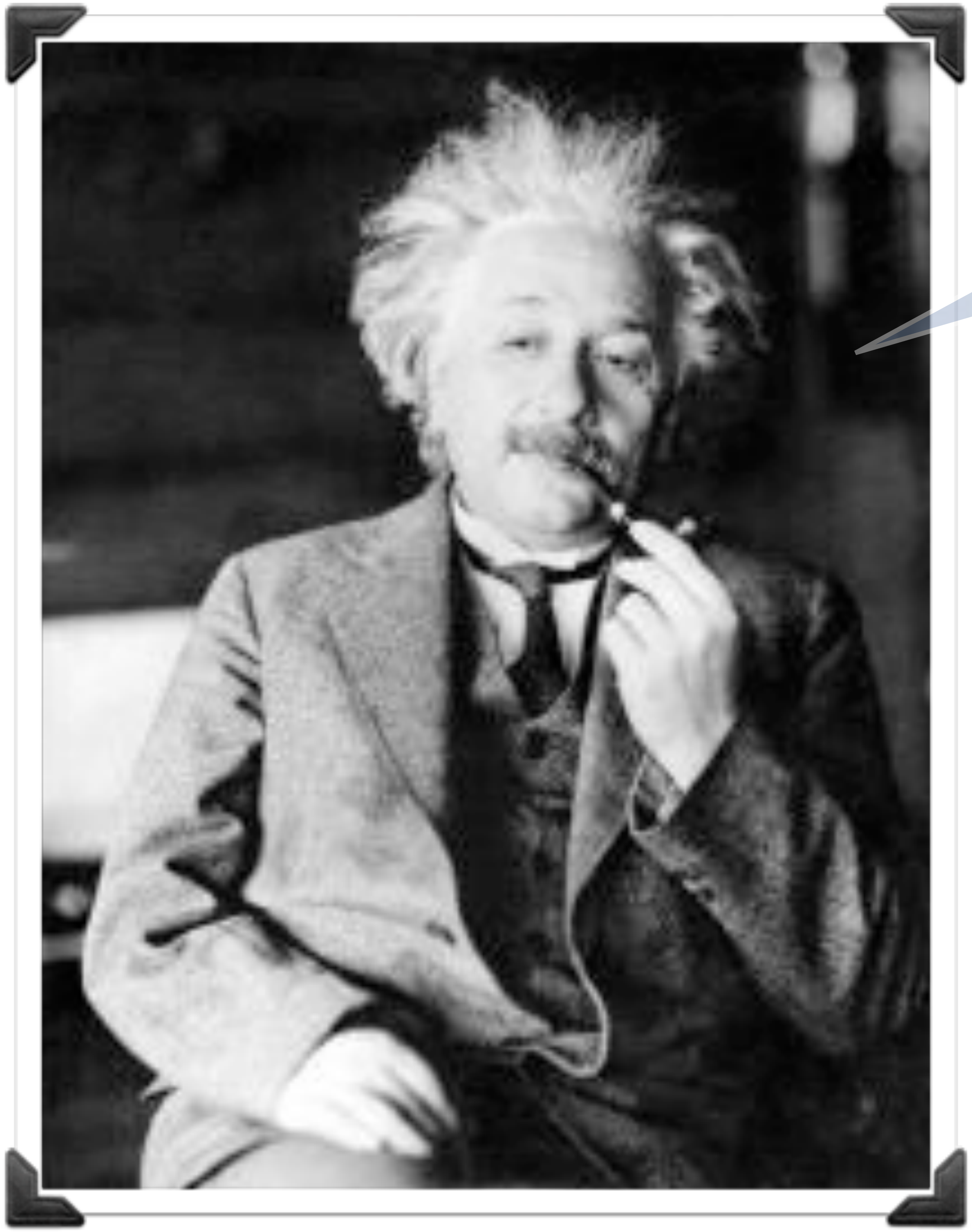
Ans: No. Ryan will see the firecracker on the left side explode before the firecracker on the right side. Ryan observes Peggy moving away from the left-side firecracker and towards the right-side firecracker. In order for the light from these firecrackers to arrive at Peggy at the same time, the left-side must have exploded first in Ryan's frame of reference.

Next Up: More Consequences of Einstein's Postulates and Lorentz Transformations!



THE END (FOR TODAY)

The ultimate “cheat sheet”?



Welcome back to PHY 3305

Today's Lecture:

General Relativity

Albert Einstein
1879-1955

ANNOUNCEMENTS

- There will be no lecture video (and hence no quiz) on Tuesday, September 13th. We will be doing an in class activity that will count towards your homework grade. We will meet in FOSC 026 that day.

- No reading assignment for Tuesday, September 13th.

- Homework assignment 3 is due Tuesday, September 13th at the beginning of class.

- Regrades for assignment 2 are due Tuesday, September 13th at the beginning of class.

- Dr. Cooley will be out of town September 8-12th. Mr. Thomas will cover office hours that day.

- Extra Credit Opportunity 1 will be due Thursday, September 29th.

REVIEW QUESTION 1

An electron moves through the lab at 99% the speed of light. The lab reference frame is S and the electron's reference frame is S'. In which reference frame is the electron's rest mass larger?

A) In frame S, the lab frame.
B) In frame S', the electron's frame.
C) It is the same in both frames.

rest mass ~ stationary energy

$m = E/c^2$

REVIEW QUESTION 2

Are the (a) kinetic energy and (b) the total energy of a 1 GeV electron more than, less than or equal to those of a 1 GeV proton?

The total energy of a 1 GeV electron equals the total energy of a 1 GeV proton. However, the rest energy of an electron is less than the rest energy of a proton. Thus, the kinetic energy of a 1 GeV electron is greater than that of the kinetic energy of a 1 GeV proton.

Lecture Video:

THE PRINCIPLE OF EQUIVALENCE

Einstein postulated:

A homogenous gravitational field is completely equivalent to a uniformly accelerated reference frame.

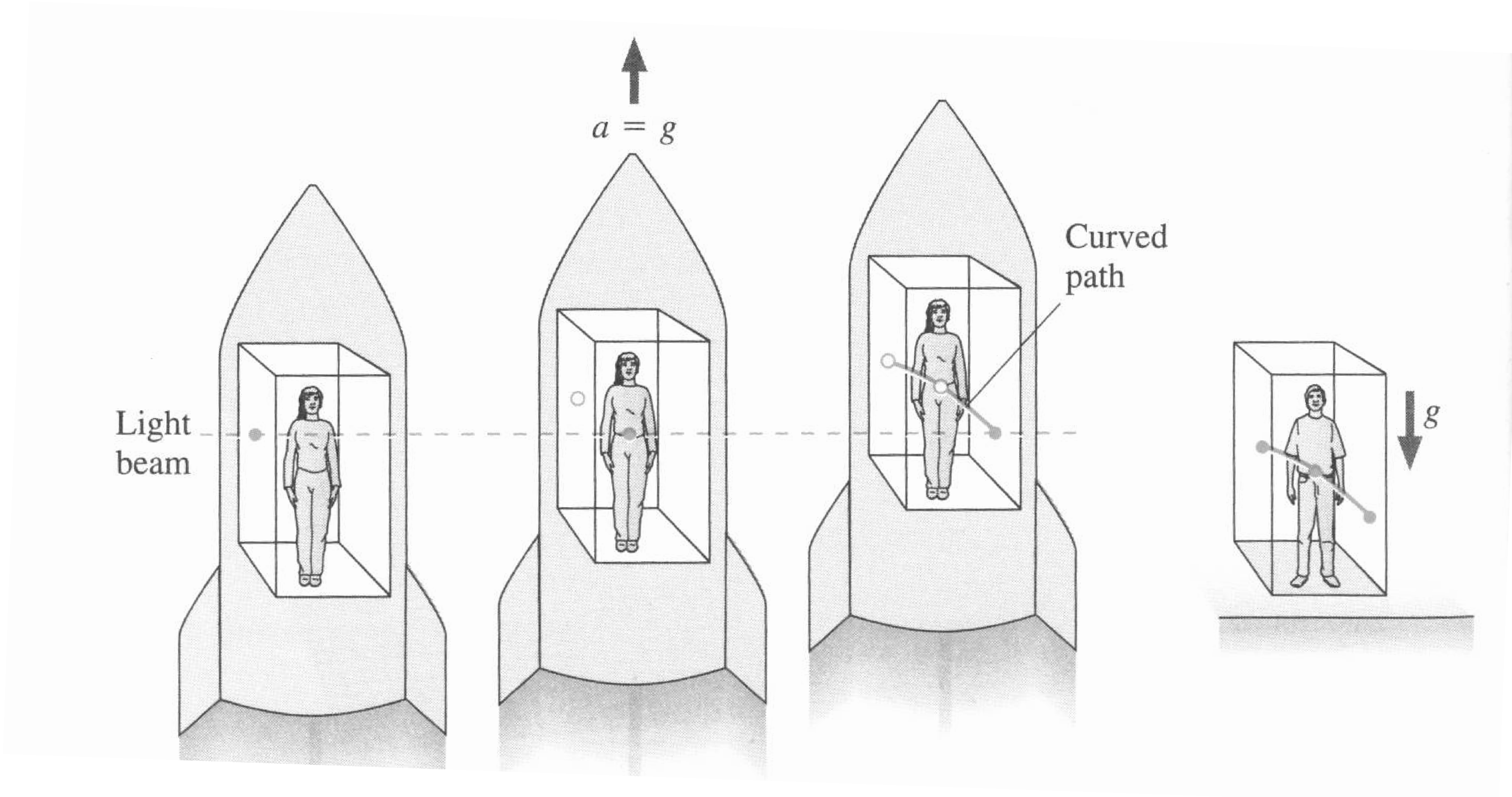
-or-

The form of each physical law is the same in all locally inertial frames.

Which of the following people will observe the same experimental results as someone who is standing on a solid lab floor on the moon?

a) An observer in a spaceship moving at constant velocity
b) An observer in an elevator on Earth moving upwards at constant velocity
c) An observer in an elevator on Earth with a broken cable (i.e. in free-fall)
d) An observer in an elevator on Earth moving downwards at constant velocity
e) An observer in a spaceship moving with constant acceleration

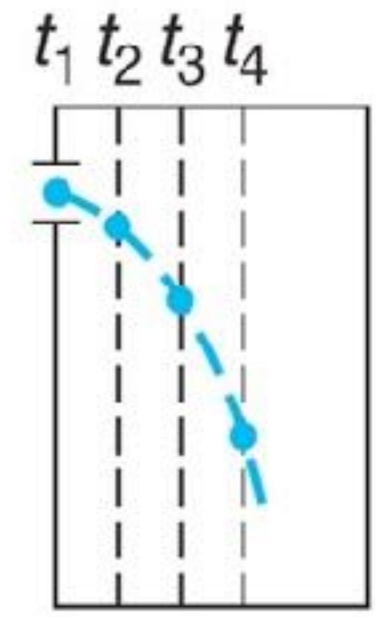
Deflection of Light in a Gravitational Field



Observing a beam of light in an accelerated reference frame.

DEFLECTION OF LIGHT IN A GRAVITATIONAL FIELD

- In an accelerating frame a light beams appears to be “falling down” in a parabolic arc

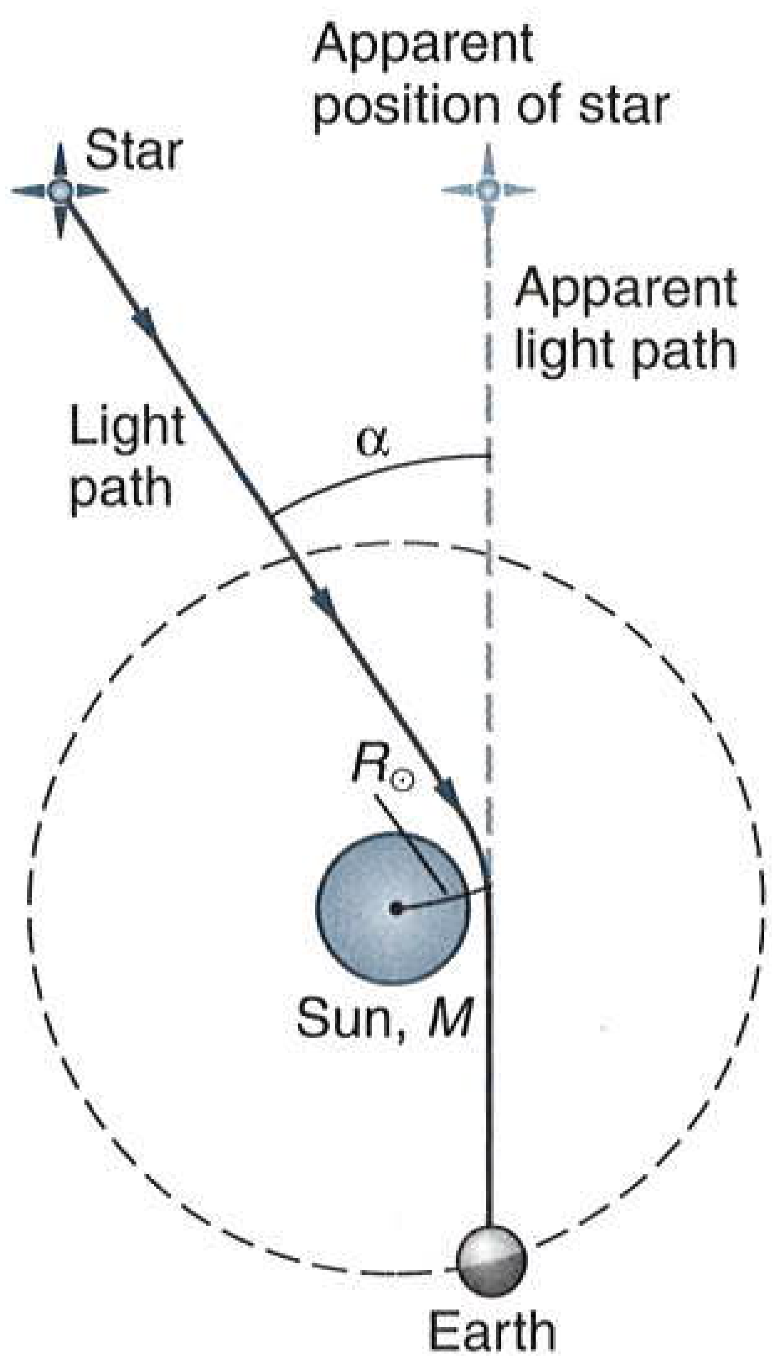


- According the the principle of equivalence: there is no physical difference between an accelerating frame and a gravitational field.

- Therefore a light beam will “fall down” in a gravitational field

Video Lecture:

Gravitational Lensing

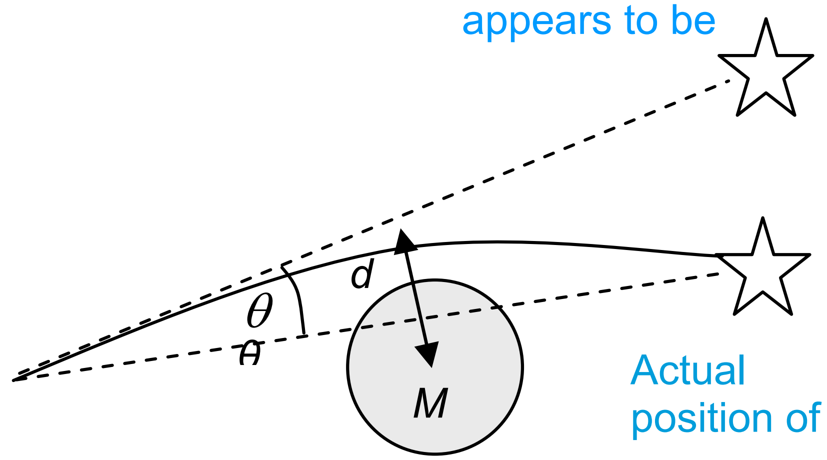


Note: This picture is an extreme exaggeration of the effect known as "Gravitational Lensing"

If you envision space-time as a fabric -- photons can not leave the fabric.

Demonstration!

Some of the best evidence that we have for the existence of dark matter comes from gravitational lensing.



$$\theta = \frac{4GM}{dc^2}$$

Calculate the deflection of light from a distant that approaches very close to the surface of the sun. The radius of the sun is 6.96×10^8 m.

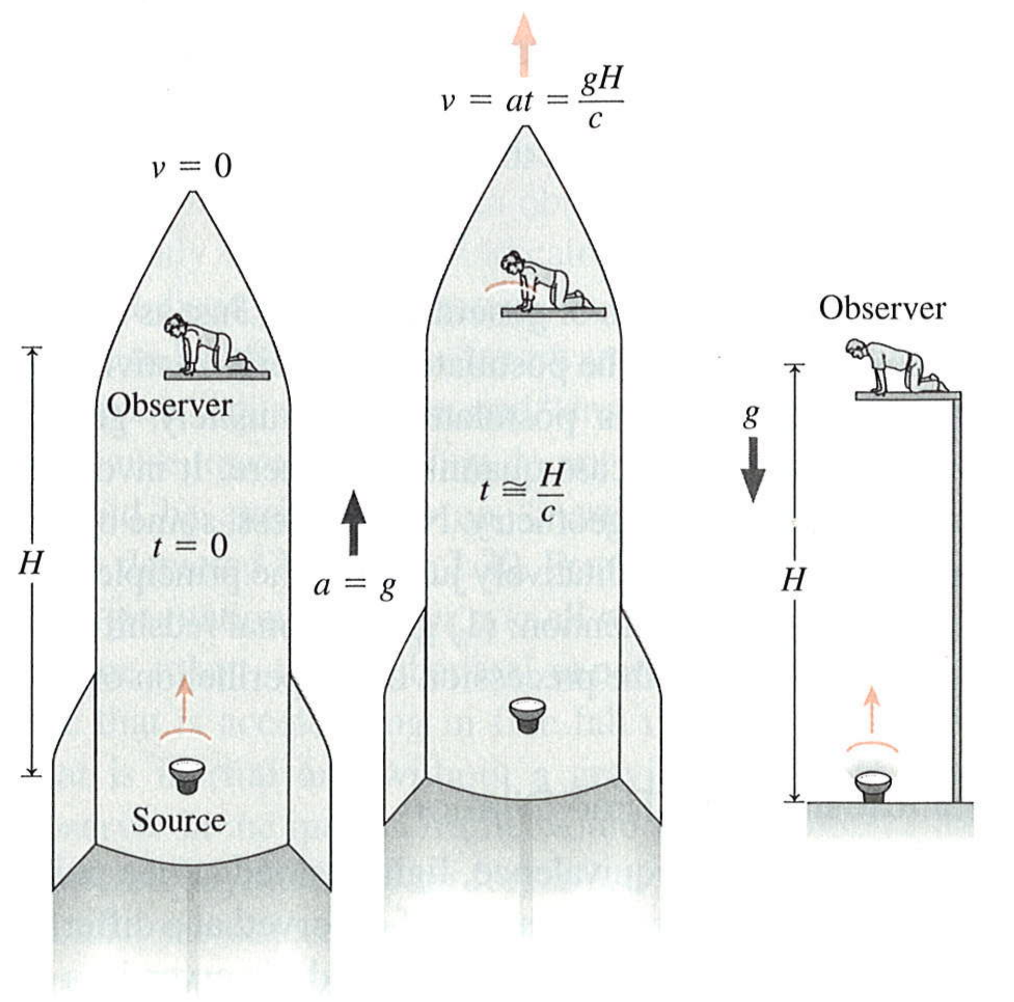
$$\theta = \frac{4(6.67 \times 10^{-11}\ N \cdot m^2/kg^2)(1.99 \times 10^{30}\ kg)}{(6.96 \times 10^8\ m)(3 \times 10^8\ m)^2} = 8.48 \times 10^{-6}\ rad$$

$$= 4.86 \times 10^{-4}\ degrees$$

Convert to degrees:

$$= 2.92 \times 10^{-2}\ arcmin$$

LAST TIME: Gravitational Redshift



(a) Accelerating frame **(b)** Equivalent frame

$$\Delta t_{lower} = \Delta t_{higher}(1 - \frac{gH}{c^2})$$

Relativity and GPS

$$\Delta t_{lower} = \Delta t_{higher}(1 - \frac{gH}{c^2})$$

General relativity tells us that a clock runs slower when it is deeper in a gravitational field (closer Earth). So, clocks on a satellite run faster than clocks at ground level. In Earth's non-uniform field ...

$$\Delta t_E = \Delta t_{sat}[1 - \frac{1}{c^2}(\frac{GM_E}{r_E} - \frac{GM_E}{r_{sat}})]$$

Apply the Physics

r = distance from center of Earth

A GPS satellite orbits at an altitude of 2.0×10^7 m and a speed of 3.0×10^3 m/s. The radius of Earth is 6.4×10^6 m. a) By what fraction must the time be adjusted to account for both regular speed dependent and gravitational time dilation?

$$\Delta t_E = \Delta t_{sat}[1 - \frac{1}{c^2}(\frac{GM_E}{r_E} - \frac{GM_E}{r_{sat}})]$$

Speed dependent time dilation is given by

$$\Delta t = \gamma \Delta t_0 \longrightarrow \Delta t_E = \frac{\Delta t_{sat}}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\Delta t_E = \frac{\Delta t_{sat}}{\sqrt{1 - \frac{(3.9\times 10^3 m/s)^2}{(3\times 10^8 m/s)^2}}} = (1 - 1.7 \times 10^{-10})^{-\frac{1}{2}} \Delta t_{sat}$$

Use Binomial Expansion: $\boxed{\Delta t_E \approx (1 + 8.5 \times 10^{-11}) \Delta t_{sat}}$

Gravitational time dilation of the satellite is given by

$$\Delta t_E = \Delta t_{sat}[1 - \frac{1}{(3 \times 10^8 m/s)^2}(\frac{(6.67 \times 10^{14} \frac{m^3}{s^2})5.98 \times 10^{24} kg}{6.4 \times 10^6 m} - \frac{(6.67 \times 10^{14} \frac{m^3}{s^2})5.98 \times 10^{24} kg}{2.64 \times 10^7 m})]$$

$$\boxed{\Delta t_E = (1 - 5.26 \times 10^{-10}) \Delta t_{sat}}$$

The gravitational effect makes the satellite's time larger. Its clock runs faster.
The speed-dependent effect makes the satellite's time smaller. Its clock run slower.

The fractional change is then:

$$\frac{\Delta t_E - \Delta t_{sat}}{\Delta t_{sat}} = (8.5 \times 10^{-11}) - (5.26 \times 10^{10})$$

$$\boxed{\frac{\Delta t_E - \Delta t_{sat}}{\Delta t_{sat}} = -4.4 \times 10^{-10}}$$

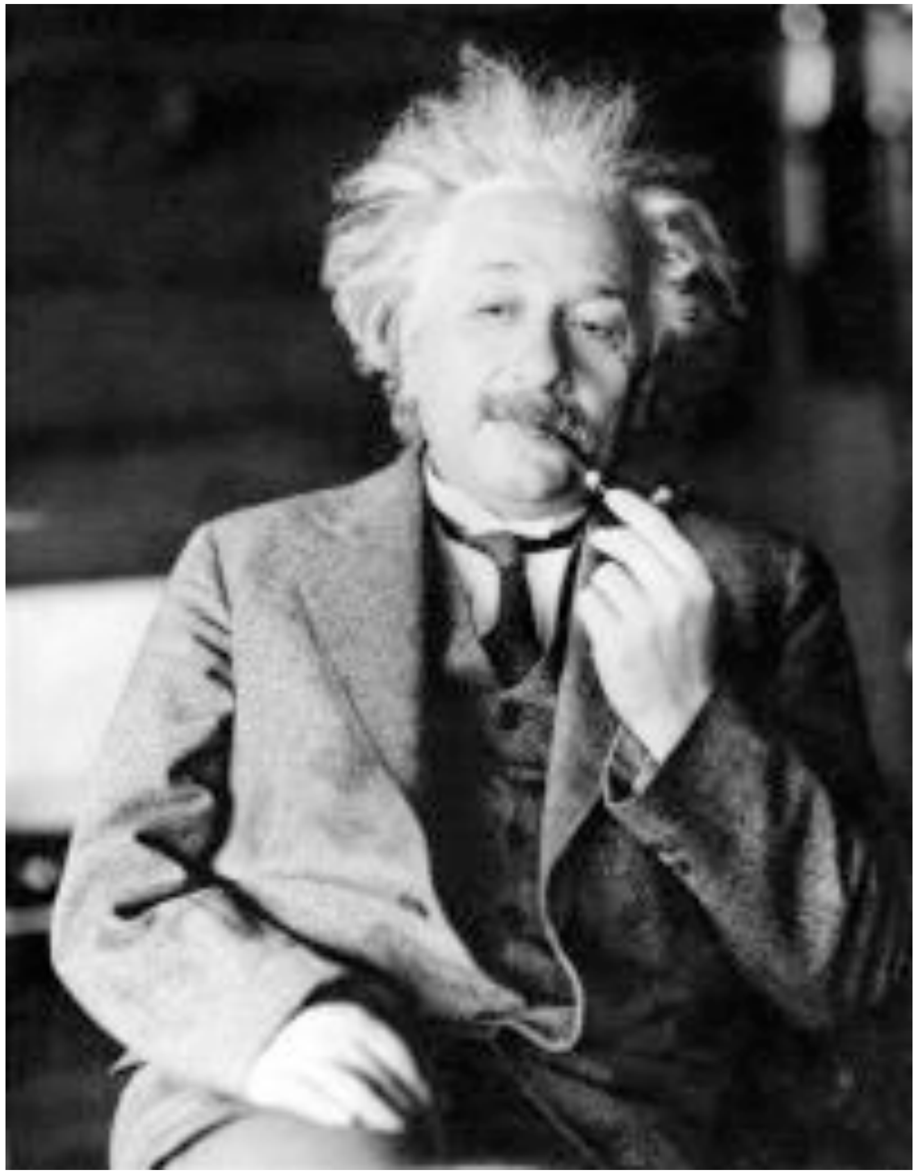
If this effect was not accounted for, how soon would the time be in error be 10 ns?

$$\frac{10 \times 10^{-9} s}{\Delta t_{sat}} = 4.4 \times 10^{-10}$$

$$\boxed{\Delta t_{sat} = 23\ s}$$

Clocks aboard GPS satellites account for the gravitational effect. Velocities and elevations of the receiver units are calculated in the receiving units.

Einstein's Postulates:



1. The laws of physics are invariant to observers in different inertial reference frames.
2. The speed of light is the same to all observers, regardless of their motion relative to the light source.

As a consequence of Einstein's Postulates, <u>no information travels faster than the speed of light</u>.

This claim is supported by the Lorentz Equations!

Events simultaneous in one reference frame occur in different orders in another reference frame.

Is it possible that the effect can precede the cause?

NO!

The Lorentz transformations forbid it! Events can only be reversed if they are not causally related.

Event A occurs at space time coordinates (300 m, 2μs).

A) Event B occurs at spacetime coordinates (1200 m, 6 μs). Could A possible be the cause of B?

Yes

$$v = \frac{1200 - 300\ m}{6 \times 10^{-6} - 2 \times 10^{-6}\ s} = 2.3 \times 10^{-6}\ {}^{m}/_{s}$$

Intuitive example, think of how a shadow moves.

Project a shadow of your finger on a wall & wiggle it. The shadow travels faster than your finger. If you wiggle your finger at c, the shadow's speed will appear greater than c.

Is this a violation of cause and effect?

SHADOWS

Shadows on a wall.

The misconception is that the edge of a shadow "moves" along a wall, when in actuality the change in a shadow's motion is part of a new projection, which will propagate at the speed of light from the object of interference.

TELEVISION IN THE 'OLDEN' DAYS

In the 'olden' days televisions contained a picture tube, a beam of electrons sent from the back to the front (screen) by an electron gun. When the electrons strike the screen, it causes a phosphor to glow briefly. To produce an image across the entire screen, the glowing beam is electrically deflected up and down and right and left.

The beam may sweep from left to right at a speed greater than c. Why is this not a violation of the claim that no information may travel faster than the speed of light?

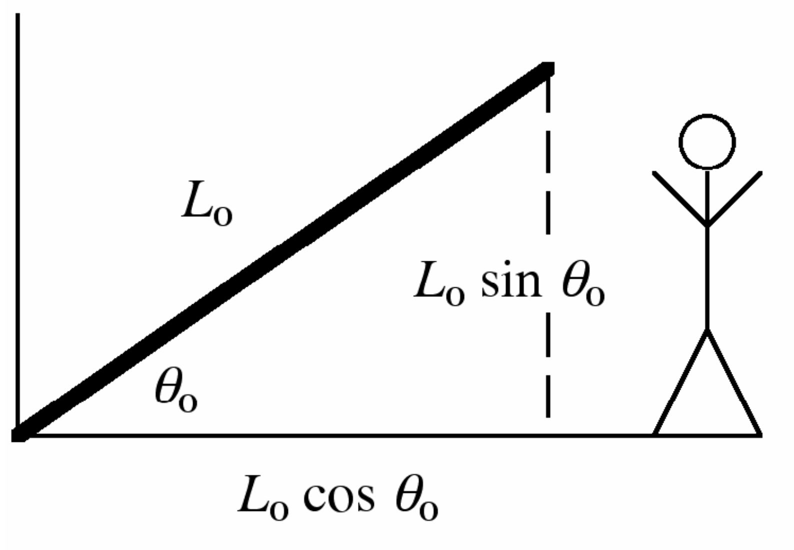
LIGHTSPOTS

The light spots are caused by electrons hitting the phosphors, not the electrons themselves. No electron travels from one side of the screen to the other. Nothing that can have information about the left-hand side of the screen moves to the right-hand side of the screen. The events (electrons hitting phosphors) are all planned ahead of time and have no effect upon on another. Thus, no information travels faster than c.

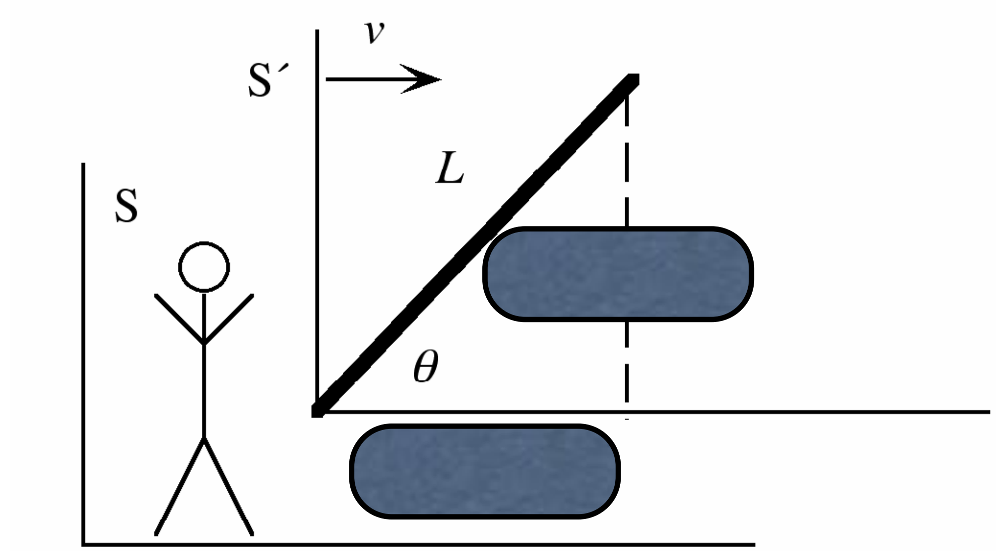
REVIEW PROBLEM

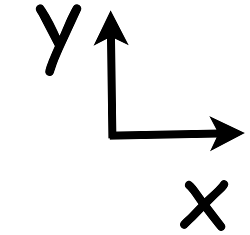
A plank, fixed to a sled at rest in frame S, is of length L_0 and makes an angle Θ_0 with the x-axis. Later, the sled zooms through frame S at a constant speed v parallel to the x-axis. Derive an expression for the length of the plank and the angle it makes with the x-axis according to an observer who remains at rest in frame S. Simplify so that your final expression for L is in terms of $\cos\Theta_0$ and your final expression for Θ is in terms of $\tan\Theta_0$.

Original:



Later:





What is the observed length along the y-axis?

$$L'_y = L_0 \sin \theta_0$$

What is the observed length along the x-axis?

$$L'_x = \frac{L_0 \cos \theta_0}{\gamma_\mu} = \sqrt{1 - \frac{v^2}{c^2}}(L_0 \cos \theta_0)$$

Use geometry to find total length L.

$$L = \sqrt{L_x'^2 + L_y'^2}$$

$$L = (L_0^2 \sin^2\theta_0 + (1 - \frac{v^2}{c^2})L_0^2 \cos^2\theta_0)^{\frac{1}{2}}$$

$$L = L_0(1 - \cos^2\theta_0 + \cos^2\theta_0 - \frac{v^2}{c^2}\cos^2\theta_0)^{\frac{1}{2}}$$

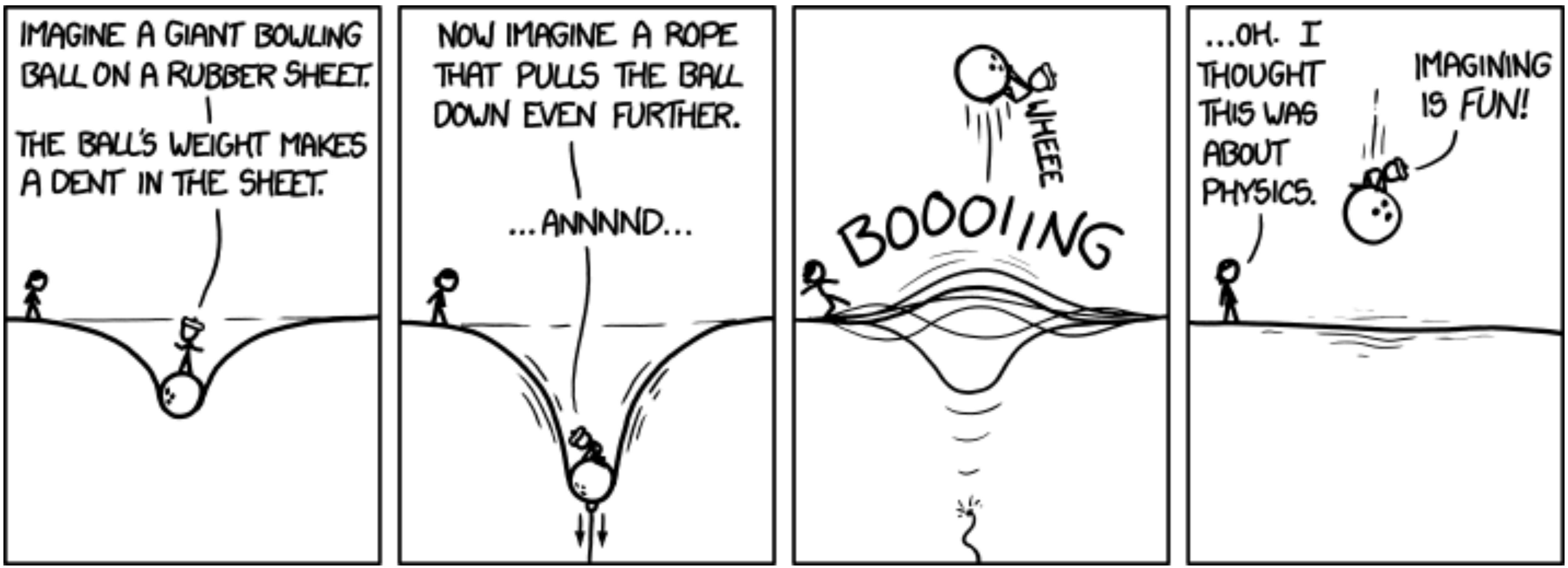
$$\boxed{L = L_0\sqrt{1 - \frac{v^2}{c^2}\cos^2\theta_0}}$$

Use geometry to find Θ.

$$\tan\theta = \frac{L_y'}{L_x'} = \frac{\gamma_\mu L_0 \sin\theta_0}{L_0 \cos\theta_0}$$

$$\boxed{\theta = tan^{-1}(\gamma_\mu \tan\theta_0)}$$

THE END (FOR TODAY)



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