Einstein's Two Postulates

With the belief that Maxwell's equations must be valid in all inertial frames, Einstein proposes the following postulates:

1) **The principle of relativity**: The laws of physics are the same in all inertial systems. There is no way to detect absolute motion, and no preferred inertial system exists.
2) **The constancy of the speed of light**: Observers in all inertial systems measure the same value for the speed of light in a vacuum.

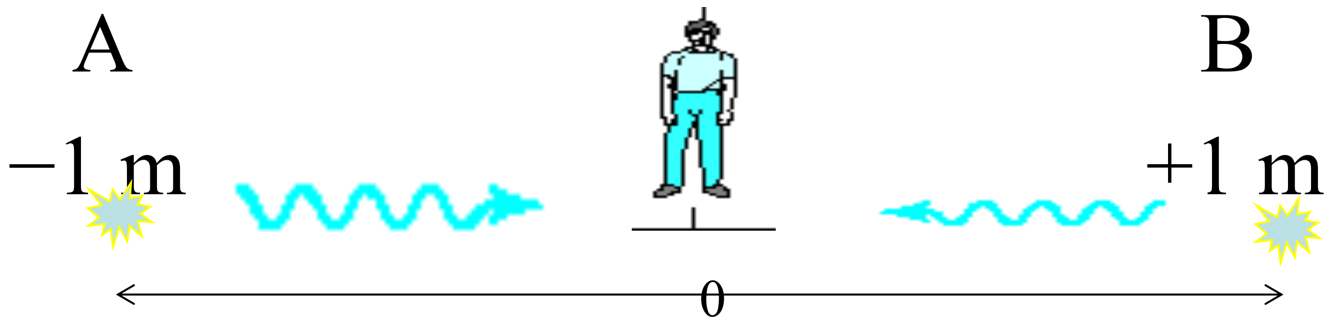
Einstein realized that Newton had not really defined "time" in a consistent way: it is not an "absolute" quantity, but must be defined in terms of observable quantities.

Re-evaluation of Time

- In Newtonian physics we previously assumed that $t = t'$
  - *Thus with "synchronized" clocks, events in K and K' can be considered simultaneous*
- Einstein realized that each system must have its own observers with their own clocks and meter sticks
  - Thus events considered simultaneous in K may not be in K'

The Problem of Simultaneity

Frank at rest is equidistant from events A and B:

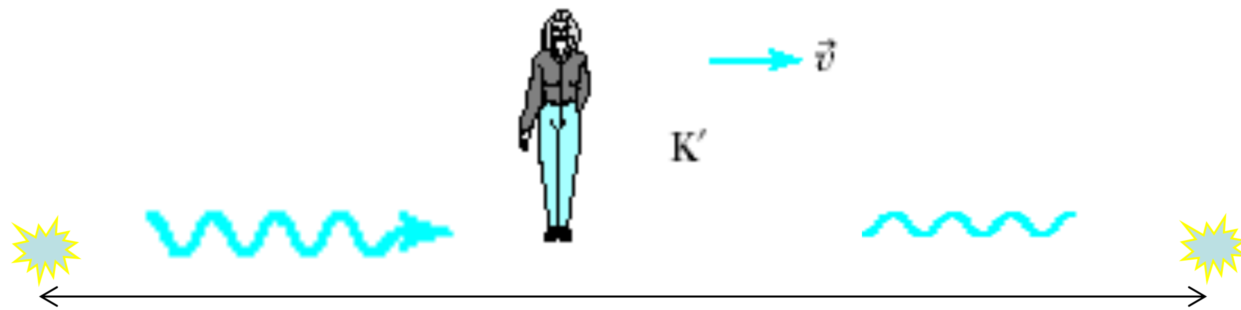


Frank "sees" both flashbulbs go off simultaneously.

Ok ✓

The Problem of Simultaneity

Mary, moving to the right with speed v, observes events A and B in different order:



−1 m 0 +1 m

A B

Mary "sees" event B, then A.

We thus observe…

- *Two events that are simultaneous in one reference frame (K) are not necessarily simultaneous in another reference frame (K') moving with respect to the first frame.*

- This suggests that each coordinate system has its own observers with their own "clocks".

Two stations are separated by several kilometers on earth. Bill is flying a rocket near the speed of light from station A to station B. At the instant Bill's rocket is halfway between A and B, both stations explode firecrackers simultaneously in their rest frame. If event A is "firecracker A explodes" and event B is "firecracker B explodes", which event will Bill see first?

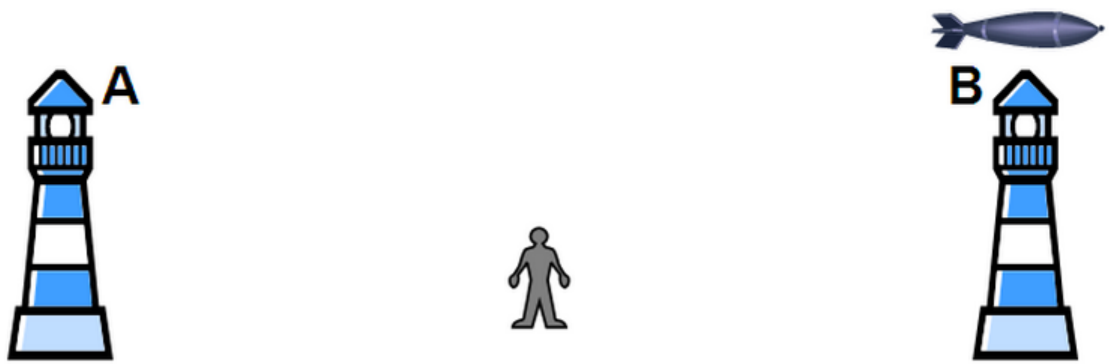
(1) Event A

(2) Event B

(3) Bill sees both events at the same instant

(4) Cannot be determined

Two stations separated by several kilometers on earth explode firecrackers. Bill is flying a rocket near the speed of light from station A to station B. At the instant Bill's rocket passes by station B, he sees firecrackers explode at both stations at the same instant of time. If you are standing at rest in the midpoint between the two stations, which event will you see first?



(1) Firecracker at station A

(2) Firecracker at station B

(3) Both firecrackers A & B at the same time instant

(4) Cannot be determined

1905 – Einstein published his first paper on the special theory of relativity. In it are 2 postulates:

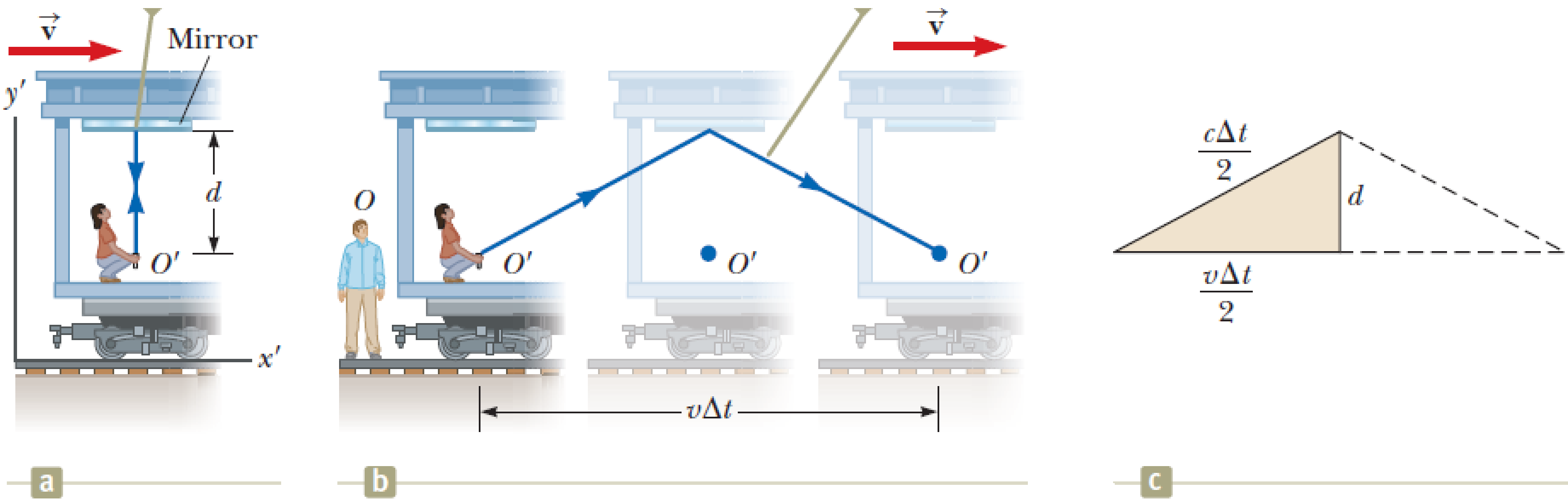
1. The speed of light in a vacuum is constant for all observers
2. Every observer derives the same physical laws

Einstein realized that Newton had not really defined “time” in a consistent way: it is not an “absolute” quantity, but must be defined in terms of observable quantities.

Consequences of Relativity

Time Dilation

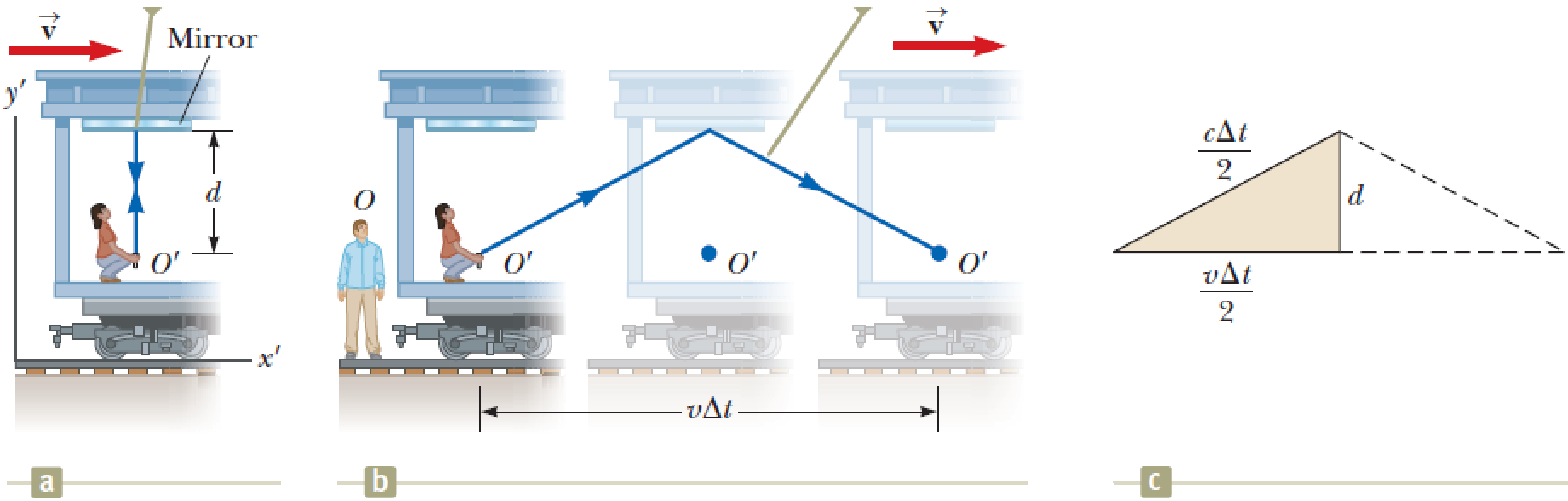
Suppose you ride a fast moving train parallel to a perfectly reflecting mirror, and shown a flashlight beam out the widow so that it came right back to the flashlight.



Time for light to hit mirror & return:

$$\Delta t_p = \frac{2d}{c}$$

The observer stationary on the ground sees:



$$\left(\frac{c\Delta t}{2}\right)^2 = \left(\frac{v\Delta t}{2}\right)^2 + d^2 \qquad \Delta t = \frac{2d}{\sqrt{c^2 - v^2}} = \frac{2d}{c\sqrt{1-\frac{v^2}{c^2}}}$$

$$\Delta t_p = \frac{2d}{c}$$

$$\Delta t = \frac{\Delta t_p}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma \Delta t_p \qquad \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \geq 1$$

Δt measured by O is longer than Δt_p measured by O'

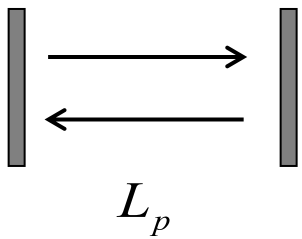
"Time dilation" –

Time in the moving frame passes more slowly when measured by an observer in the rest frame.

Space contraction

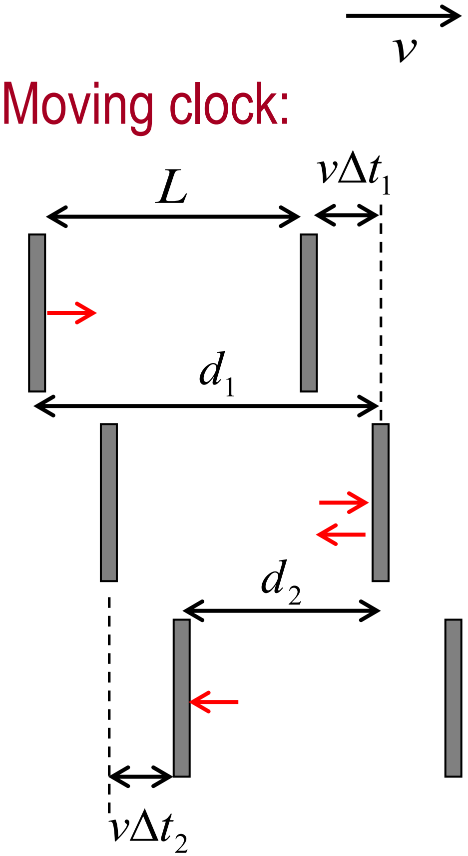
- Consider a "light clock" oriented parallel to the train's moving direction. To a person inside the train, the time to make a double pass between the mirrors is: $\Delta t_p = 2L_p / c$

Stationary clock:



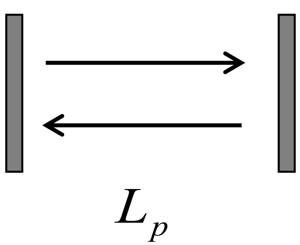
$$\Delta t_p = 2\frac{L_p}{c}$$

Moving clock:



- The outside observer also sees the mirrors constantly moving to the right.
- Let t_1 be the time for the photon to go from the left mirror to the right mirror. The right mirror then travels away a distance vt_1 before the photon hits it. Hence, the photon travels a distance $d_1 = c\Delta t_1 = v\Delta t_1 + L$. Thus, $\Delta t_1 = L/(c - v)$.
- On the return pass, let Δt_2 be the time for the photon to go from the right mirror to the left mirror. The left mirror then approaches a distance $v\Delta t_2$ before the photon hits it. Hence, the photon travels a distance $d_2 = c\Delta t_2 = L - v\Delta t_2$. Thus, $\Delta t_2 = L/(c + v)$.

Stationary clock:



$$\Delta t_p = 2\frac{L_p}{c}$$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \geq 1$$

The total time for a round trip

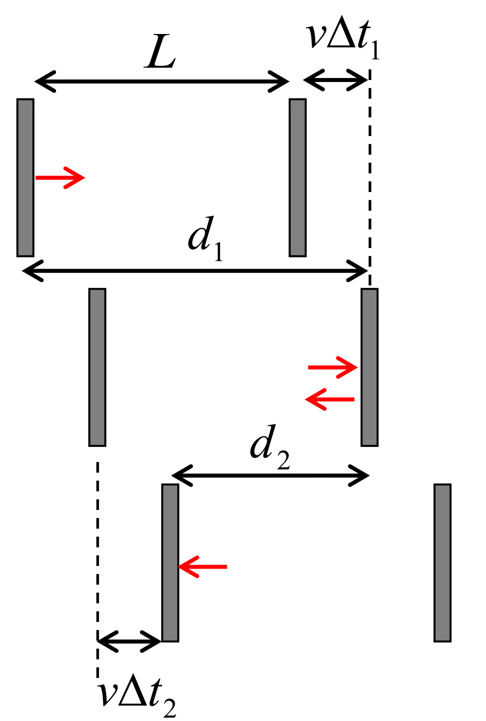
$$\Delta t = \frac{L}{c-v} + \frac{L}{c+v}$$

$$= \frac{2L}{c(1-\frac{v^2}{c^2})} = \frac{2L}{c}\gamma^2$$

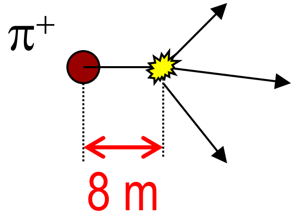
$$\Delta t_p \gamma = 2\frac{L}{c}\gamma^2 \qquad 2\frac{L_p}{c} = 2\frac{L}{c}\gamma$$

$$\boxed{\frac{L_p}{\gamma} = L}$$

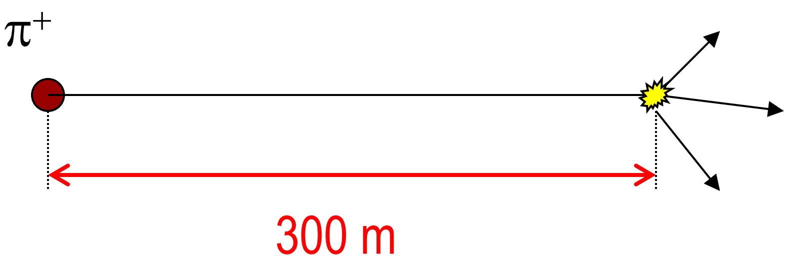
Moving clock: $\xrightarrow[v]{}$



What does this mean?



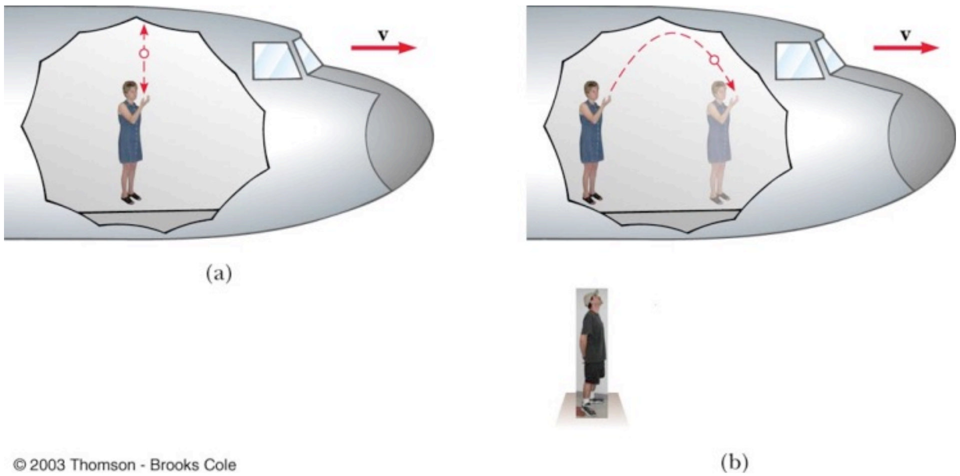
No time dilation



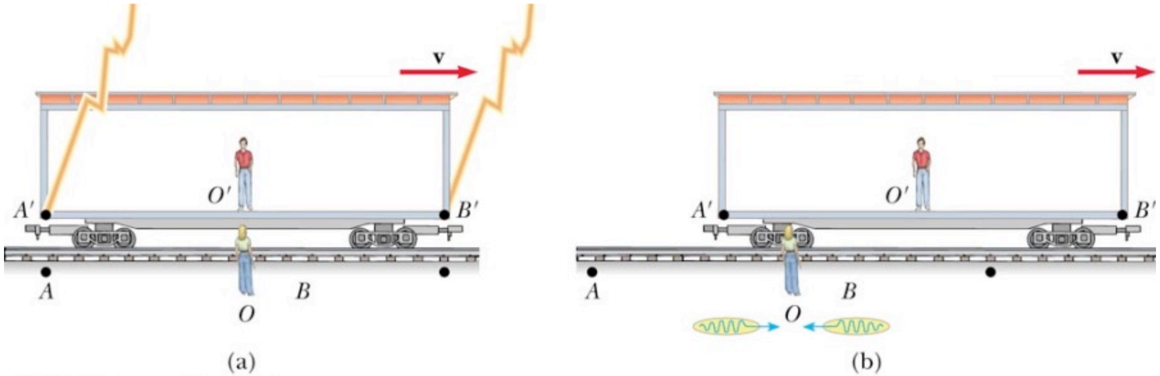
With time dilation

- **Time in a moving system slows down comparing to a stationary system!**
- E.g., charged pions have a lifetime of $t = 2.56 \times 10^{-8}$ s, so most of them would decay after traveling $ct = 8$ m.
- But we have no trouble transporting them by hundreds of meters!

If physical “laws” are universal, everyone should be able to derive the same sets of laws, even if they don’t see exactly the same thing.



“Events” that appear simultaneous in one frame of reference may not appear so in another.



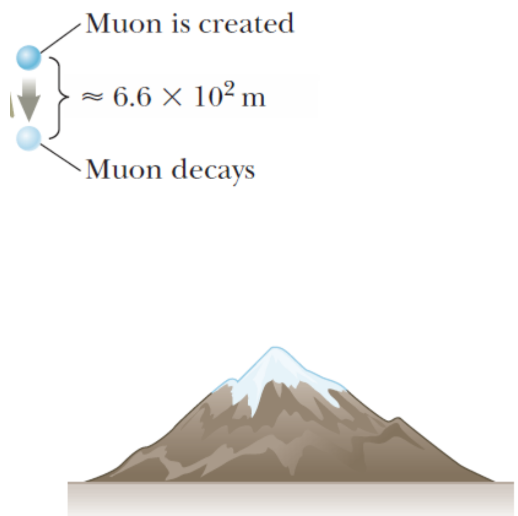
Muon Detection

$$v_\mu = 0.99c \approx 3.0\times10^{8}\, m/s$$

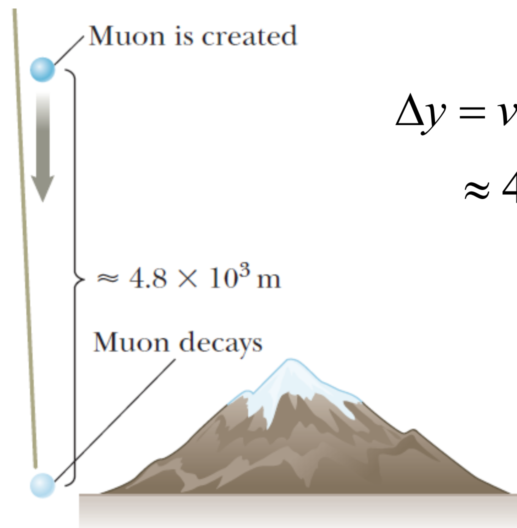
$$\Delta t_p = 2.2\times10^{-6}\, s$$

$$\gamma \approx 7.1$$

$$\Delta t = \gamma \Delta t_p \approx 16\times10^{-6}\, s$$



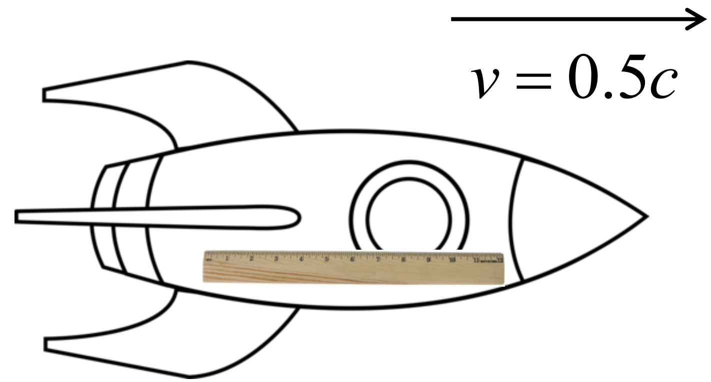
If calculated without time dilation



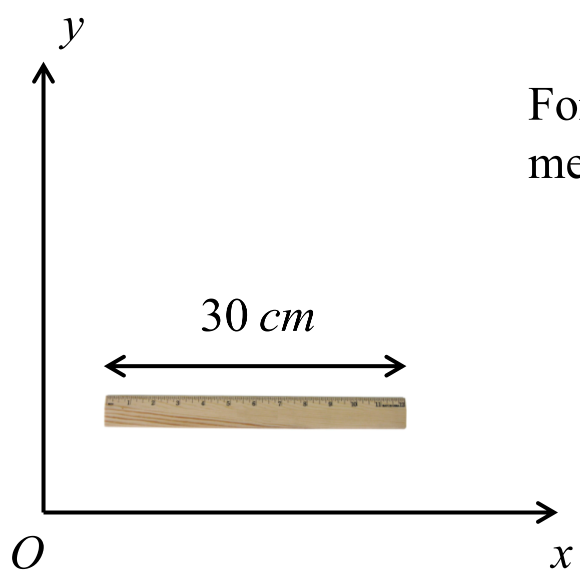
$$\Delta y = v\Delta t \approx 0.99c\times16\times10^{-6}$$
$$\approx 4.8\times10^{3}\, m$$

- Time in a moving system slows down comparing to a stationary system!

Two identical rulers of 30 cm in length. One is stationary in the rest frame O and the other is carried by a rocket moving at a velocity of 0.5c to the right.



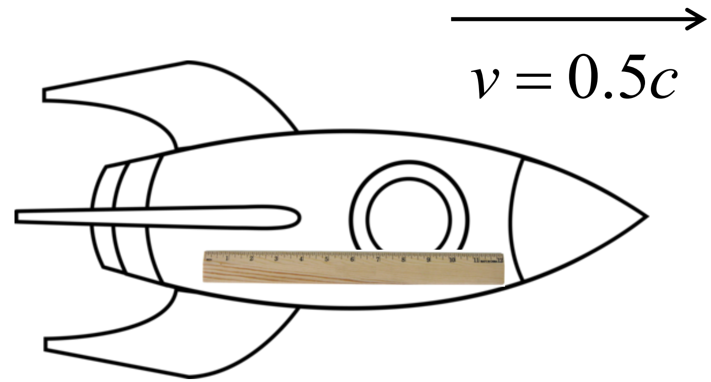
$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{1}{4}}} \approx 1.15$$



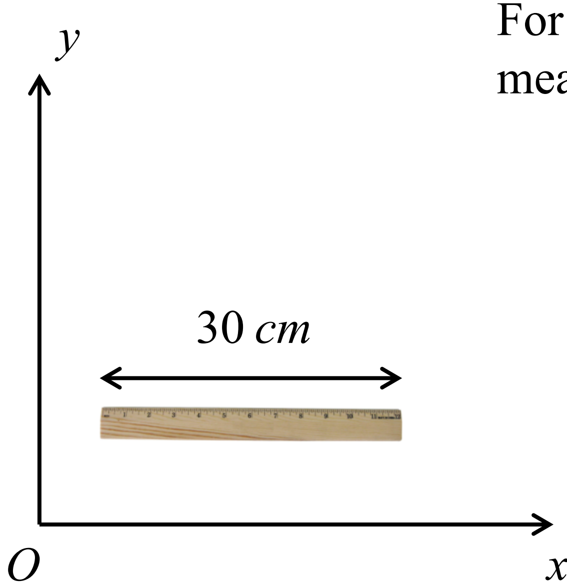
For the ruler on the rocket, what is its length measured by an observer in the rest frame O?

For the ruler on the ground, what is its length measured by an observer riding in the rocket?

Two identical rulers of 30 cm in length. One is stationary in the rest frame O and the other is carried by a rocket moving at a velocity of 0.5c to the right.



$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{1}{4}}} \approx 1.15$$



For the ruler on the rocket, what is its length measured by an observer in the rest frame O?

$$L = \frac{L_p}{\gamma} = \frac{30\ cm}{1.15} \approx 25\ cm$$

For the ruler on the ground, what is its length measured by an observer riding in the rocket?

$$L = \frac{L_p}{\gamma} = \frac{30\ cm}{1.15} \approx 25\ cm$$