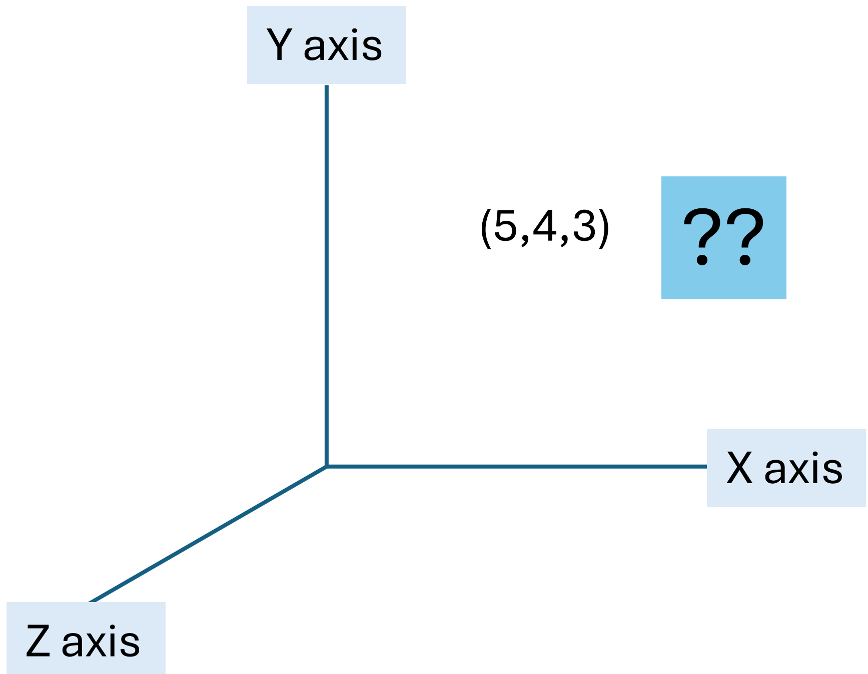
Learning Objectives

- Frame of reference
- Rest and motion
- Inertial and non-inertial frame of references
- Michelson Morley experiment
- Postulates of Special theory of relativity
- Time dilation

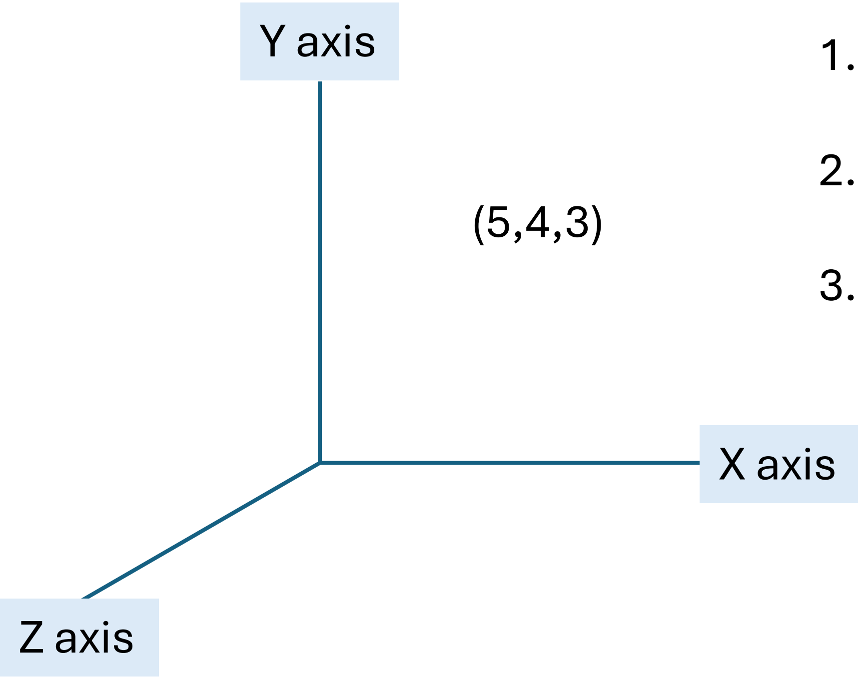
Ref. Modern Physics by Arthur Beiser

Frame of reference



Relativity

Frame of reference



1. Define length scale (5,4,3) m, nm or what?

2. To know about rest or motion ???

3. Time scale..

   3.1 when position changes with time-motion

   3.2 when position do not changes with time-rest

Are the definitions of rest or motion universal ? OR DEPENDENT ON SOME THING??

Relativity

Are the definitions of rest or motion universal ? OR DEPENDENT ON SOME THING??

Yes, dependent on frame of reference.
HOW??

Relativity

Yes, dependent on frame of reference. HOW??

Suppose travelling from Durg to Delhi

1. Standing on a platform
How far is Delhi?

2. Travelling in a train
How far is Delhi?

Your response will change as your frame of reference change.

Two types of frame of references

Inertial
Newton's first law is applicable

Non-Inertial
Newton's first law is not applicable

Newton's first law: If F=0, then a=0; every object will remain at rest or in uniform motion in a straight line unless compelled to change its state by the action of an external force.

Let us consider an example

Relativity

Inertial
Newton's first law is applicable

Non-Inertial
Newton's first law is not applicable

Let us consider an example

Inertial
Newton's first law is applicable

Books lying on the table
You are sitting on chairs

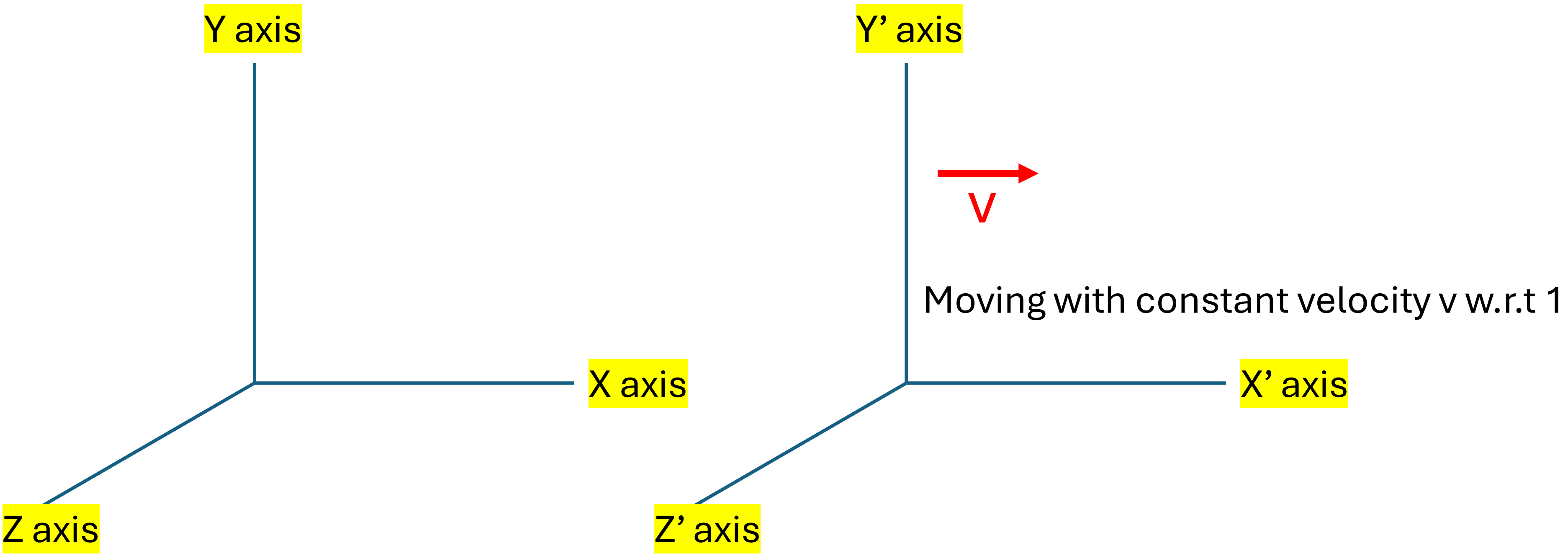
Non-Inertial
Newton's first law is not applicable

You are sitting inside a bus and then bus stops , you fall forward
No external force was applied to you and still your position of rest changes
Newton's first law is not applicable in this case

In order that we can use Newton's first law in such situations...we consider Pseudo forces..HOW?

Let's see an example

Galilean Transformation



Inertial frame 1 (at rest)

Inertial frame or not?

YES

Galilean Transformation

Y axis

An event occur at (x,y,z) and time t
In S frame

X axis

Z axis

Inertial frame 1 (at rest)

Transformation equation

$$x' = x - vt$$
$$y' = y$$
$$z' = z$$
$$t' = t$$

Y' axis

An event occur at (x',y',z') and time t'
In S' frame

V

Moving with constant velocity v w.r.t 1

X' axis

Z' axis

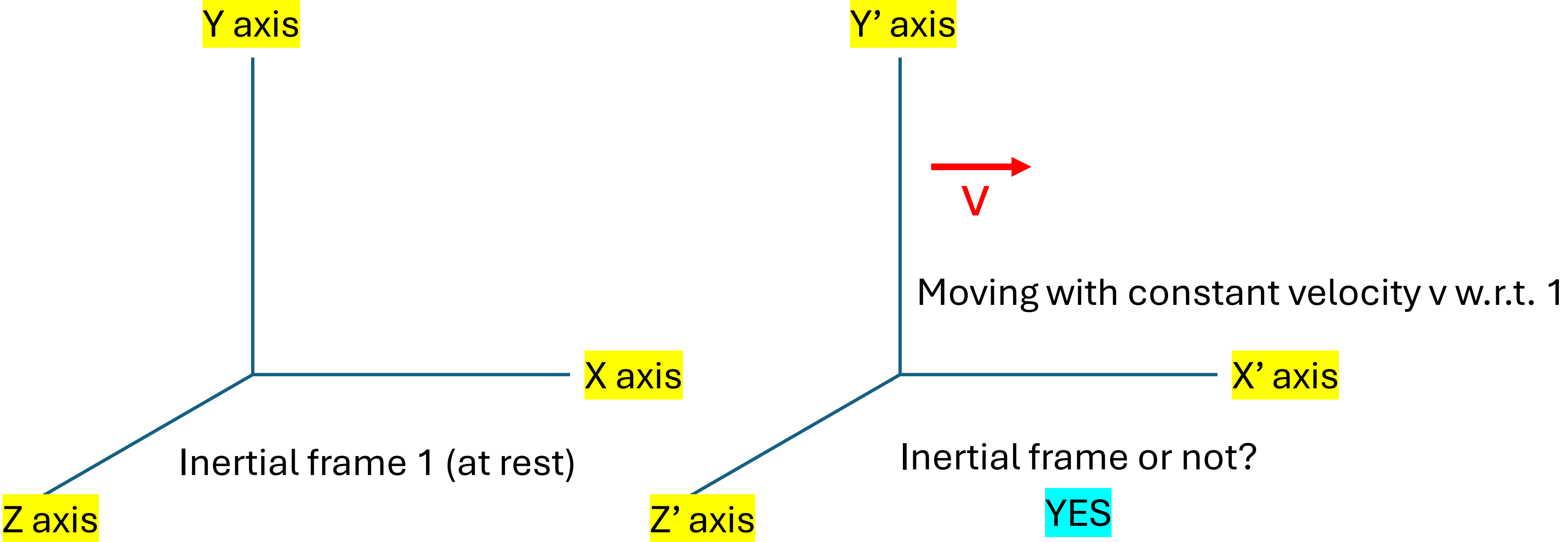
Inertial frame or not?

YES

$$v'_x = \frac{dx'}{dt'} = v_x - v$$
$$v'_y = v_y$$
$$v'_z = v_z$$
$$\boxed{c' = c - v}$$

Speed of light is not constant

Galilean Transformation



OK to Newton Mechanics but not to equations of electricity and magnetism

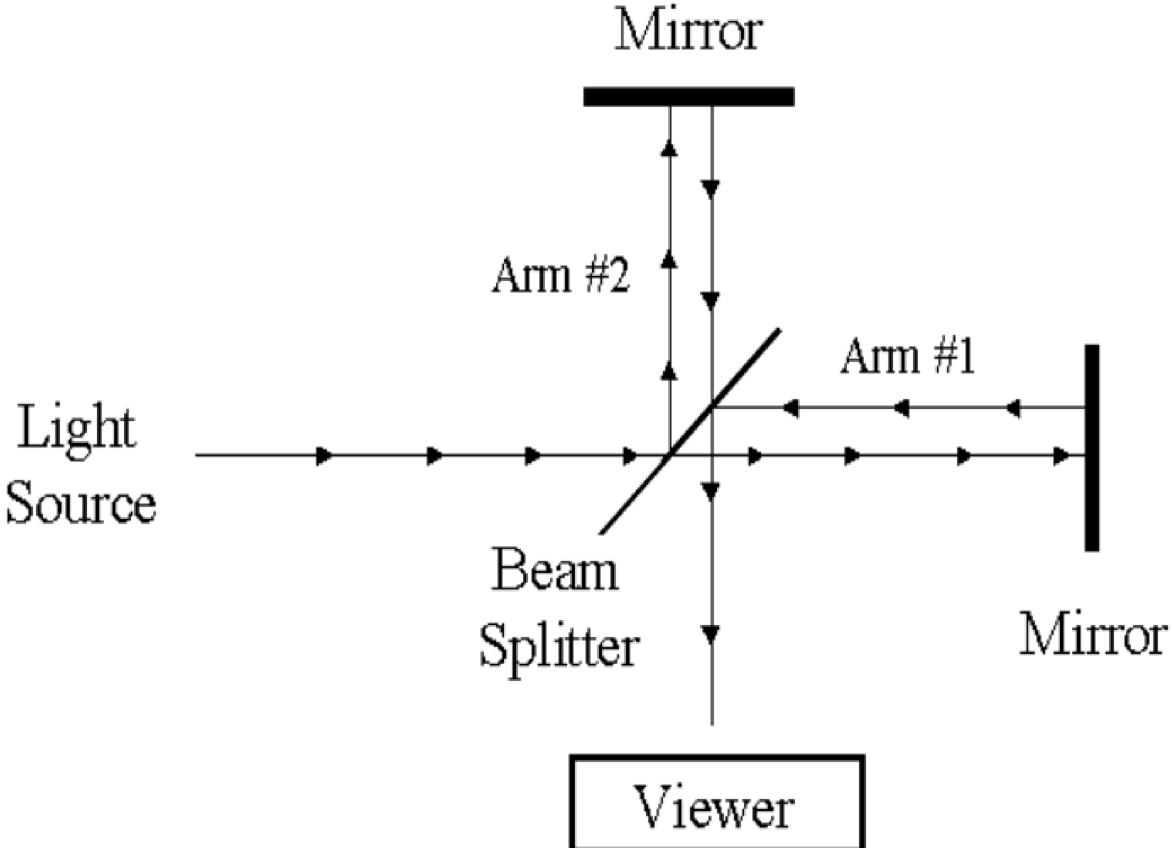
Michelson-Morley Experiment

Similar to other waves, light wave may also propagating through a medium ETHER (hypothetical medium).

Similar to gas in which sound waves propagate or water in which water waves propagate.

This ether was assumed to be everywhere and unaffected by matter. This ether could be used to determine an absolute reference frame (with the help of observing how light propagates through the ether).

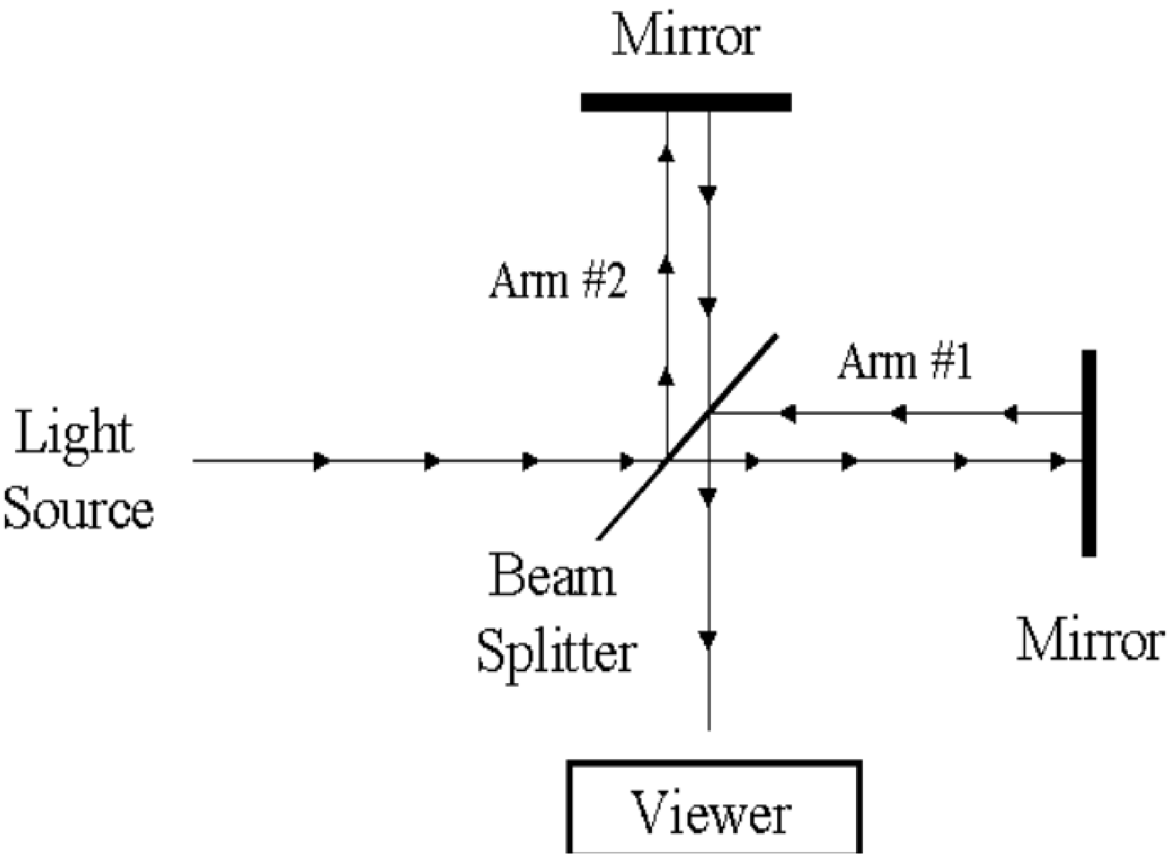
The Michelson-Morley experiment (1885) was performed to detect the Earth’s motion through the ether as follows:

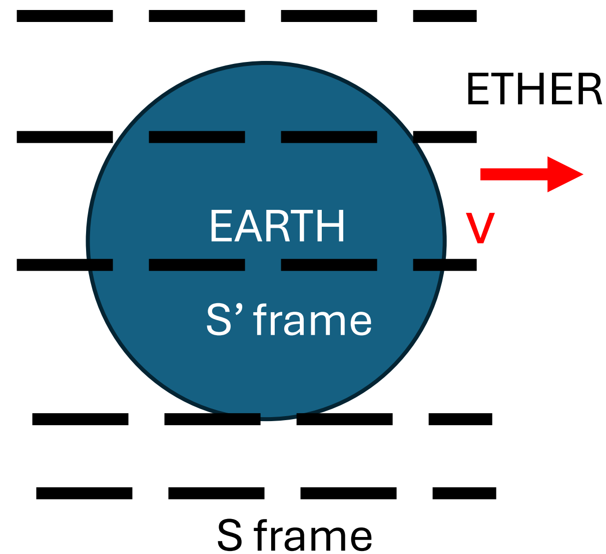


Michelson-Morley Experiment

The viewer will see the two beams of light which have traveled along different arms display some interference pattern. If the system is rotated, then the influence of the “ether wind” should change the time the beams of light take to travel along the arms and therefore should change the interference pattern. The experiment was performed at different times of the day and of the year.

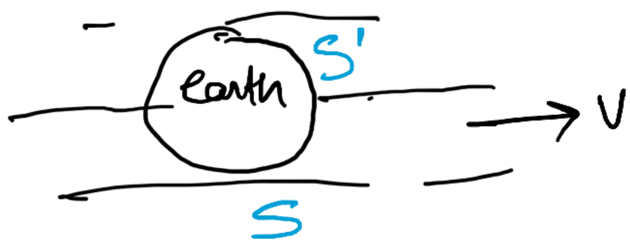
NO CHANGE IN THE INTERFERENCE PATTERN WAS OBSERVED!





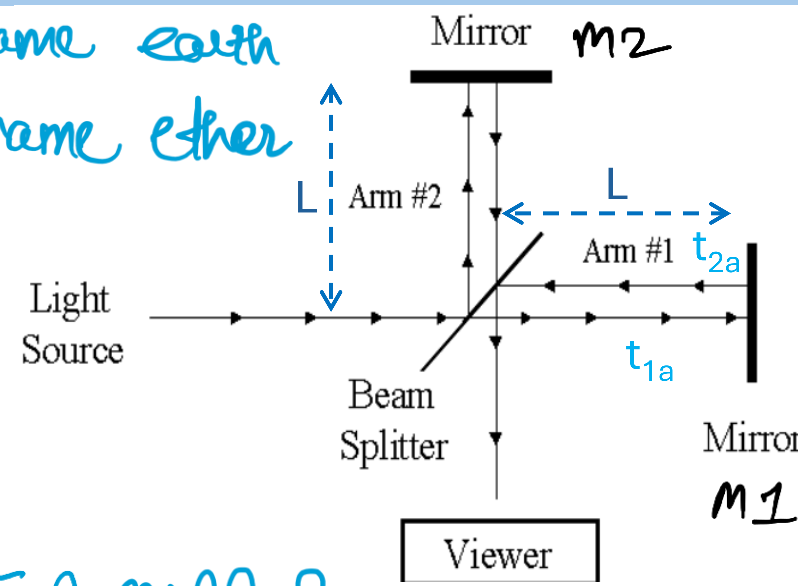
Speed of light in S frame is c

Michelson-Morley Experiment



S' frame earth

S frame ether



$$V_x' = V_x - V = c - V$$

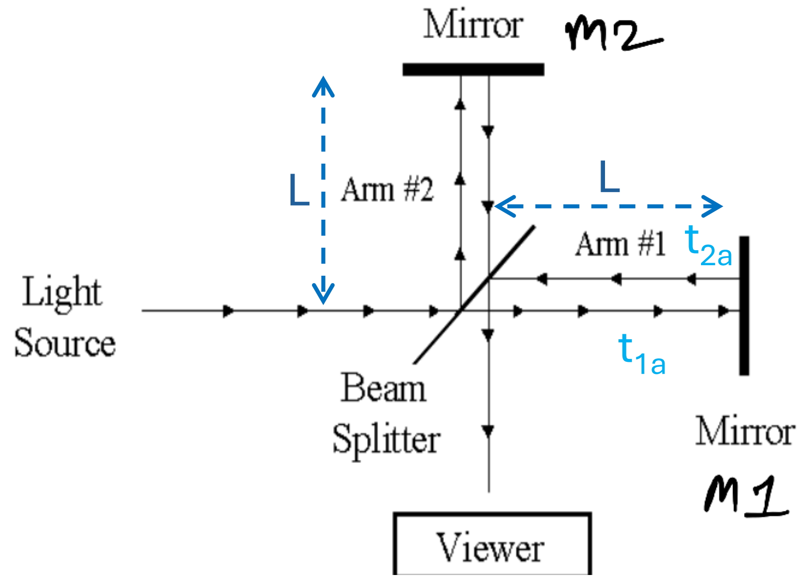
$$t_{1a} = \frac{L}{c-V} \qquad t_{2a} = \frac{L}{c+V}$$

FOR MIRROR m1

total time $t_1 = \frac{L}{c-V} + \frac{L}{c+V}$

$$\boxed{t_1 = \frac{2L}{c}\,\frac{1}{1-\frac{V^2}{c^2}}}$$

Michelson-Morley Experiment



$$v_x' = v_x - v = c - v$$

$$t_{1a} = \frac{L}{c-v} \qquad t_{2a} = \frac{L}{c+v}$$

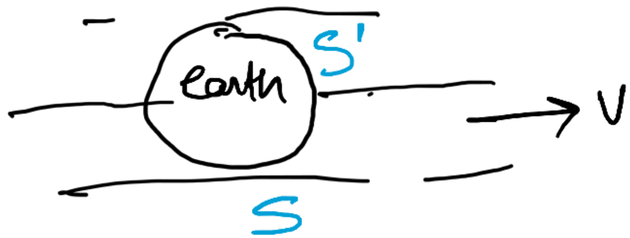
total time $t = \dfrac{L}{c-v} + \dfrac{L}{c+v}$

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

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

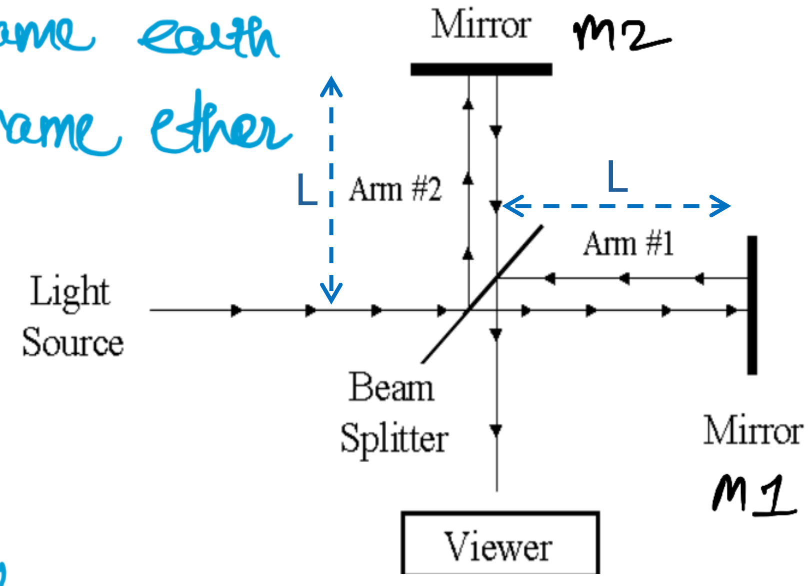
$$= \frac{2L}{c}\,\frac{1}{1-\frac{v^2}{c^2}}$$

Michelson-Morley Experiment



S' frame earth

S frame ether



FOR MIRROR 2

$$V'_x = V_x - V$$

$$0 = V_x - V \quad , \quad V_x = V$$

$$V'_y = V_y \quad , \quad V_y = V'_y$$

$$V_x^2 + V_y^2 = V^2 + V'^2_y$$

$$c^2 = V^2 + V'^2_y$$

$$c^2 - V^2 = V'^2_y$$

$$V'_y = \sqrt{c^2 - V^2}$$

time for mirror 2

$$t_2 = \frac{L}{\sqrt{c^2-V^2}} + \frac{L}{\sqrt{c^2-V^2}}$$

$$\boxed{t_2 = \frac{2L}{c}\frac{1}{\sqrt{1-V^2/c^2}}}$$

$$\Delta t = t_1 - t_2$$

$$= \frac{2L}{c}\left\{\frac{1}{1-\frac{v^2}{c^2}} - \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\right\}$$

This time difference will create interference fringes

The experiment was performed at different rotation, at different times of the day and of the year.

NO CHANGE IN THE INTERFERENCE PATTERN WAS OBSERVED!

plus	Minus
Ether is absolute reference frame	No experimental measurement has ever detected presence of ether.

It paved the way for Einstein's **special theory of relativity (1905)**, which postulates that the speed of light in a vacuum is the same for all observers, regardless of motion.

Einstein’s Special Theory of Relativity

Principle of relativity

All laws of physics are identical in all inertial reference frames.

Constant speed of light

Speed of light is same in all inertial frames (e.g. independent of velocity of observer)

These two postulates are the basis of the special theory of relativity

Simultaneity with sound

- Suppose you hear two loud shots about 0.5 s apart.
- Did they occur at the same time?
- Suppose you find out one of the shots was fired closer to you than the other.
- Sound travels at 340 m/s.
- If one gun were fired 170 m closer to you then they were fired at same time.

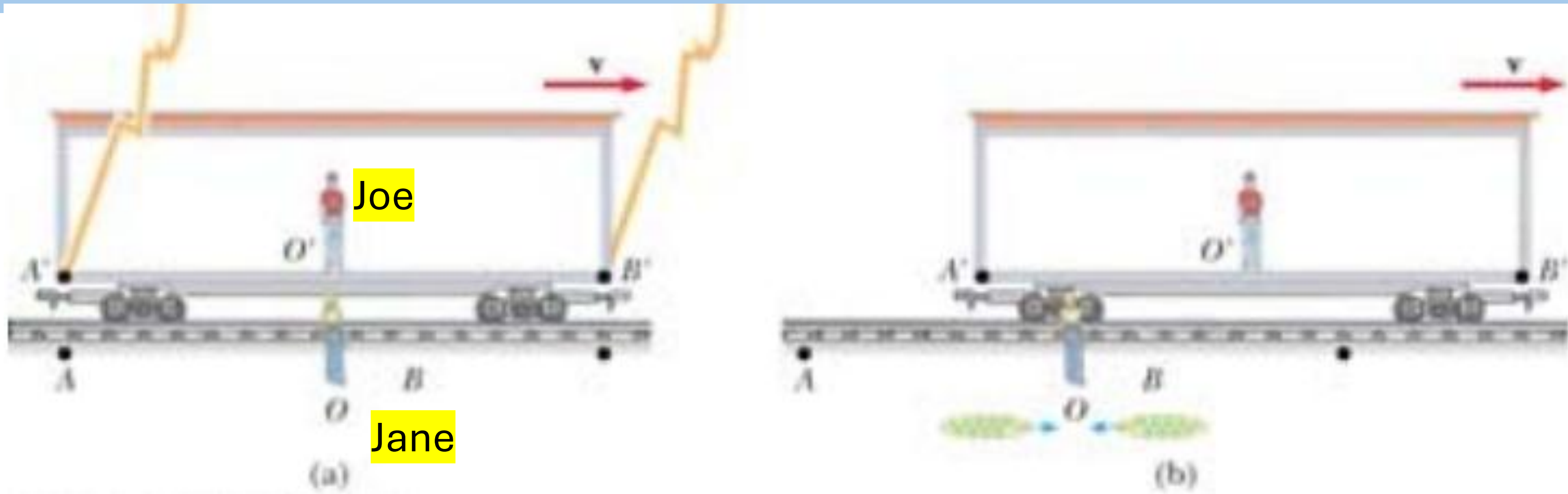
Simultaneity with sound

- If you know your distance from the shots, you can easily determine if they were simultaneous.
- And everyone will agree with you, after doing the same correction for distance.
- You might even come up with a definition

– Event ($x1$, $t1$) is simultaneous with event ($x2$, $t2$) if sound pulses emitted at $t1$ from $x1$ and at $t2$ from $x2$ arrive simultaneously at the midpoint between $x1$ and $x2$.

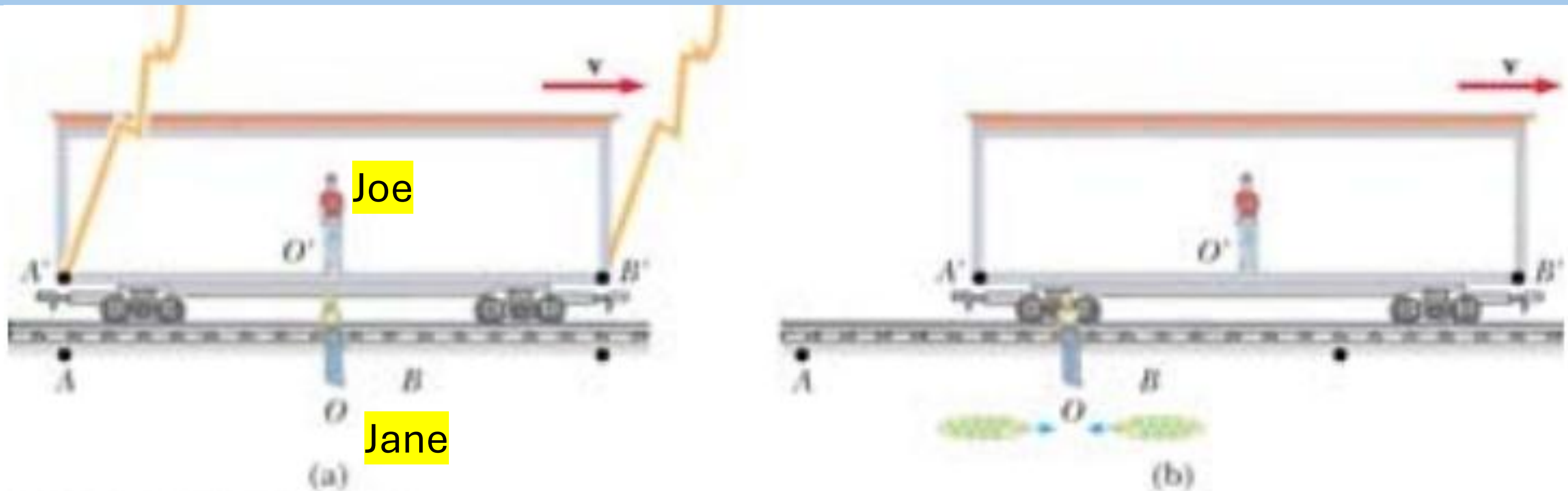
- Einstein came up with a similar definition for relativistic simultaneity.

Simultaneity with experiment



- A car moving with constant velocity v w.r.t. ground. Jane standing on the ground.
- Joe rides in the exact center of the car.
- Two lightning bolts strike the ends of the boxcar, leaving marks on the boxcar and the ground underneath.
- On the ground, Jane finds that she is halfway between the scorch marks.

Simultaneity with experiment



Jane (on the ground) observes that light waves from each lightning strike at the boxcar ends reach her at exactly the same time.

• Since each light wave traveled at c, and each traveled the same distance (since O is in the middle), the lightning strikes are simultaneous in the frame of ground observer.

When light from front flash reaches Joe, he has moved away from rear flash. — Front and rear flashes reach Joe at different times

• <u>*Since speed of light is always constant*</u>

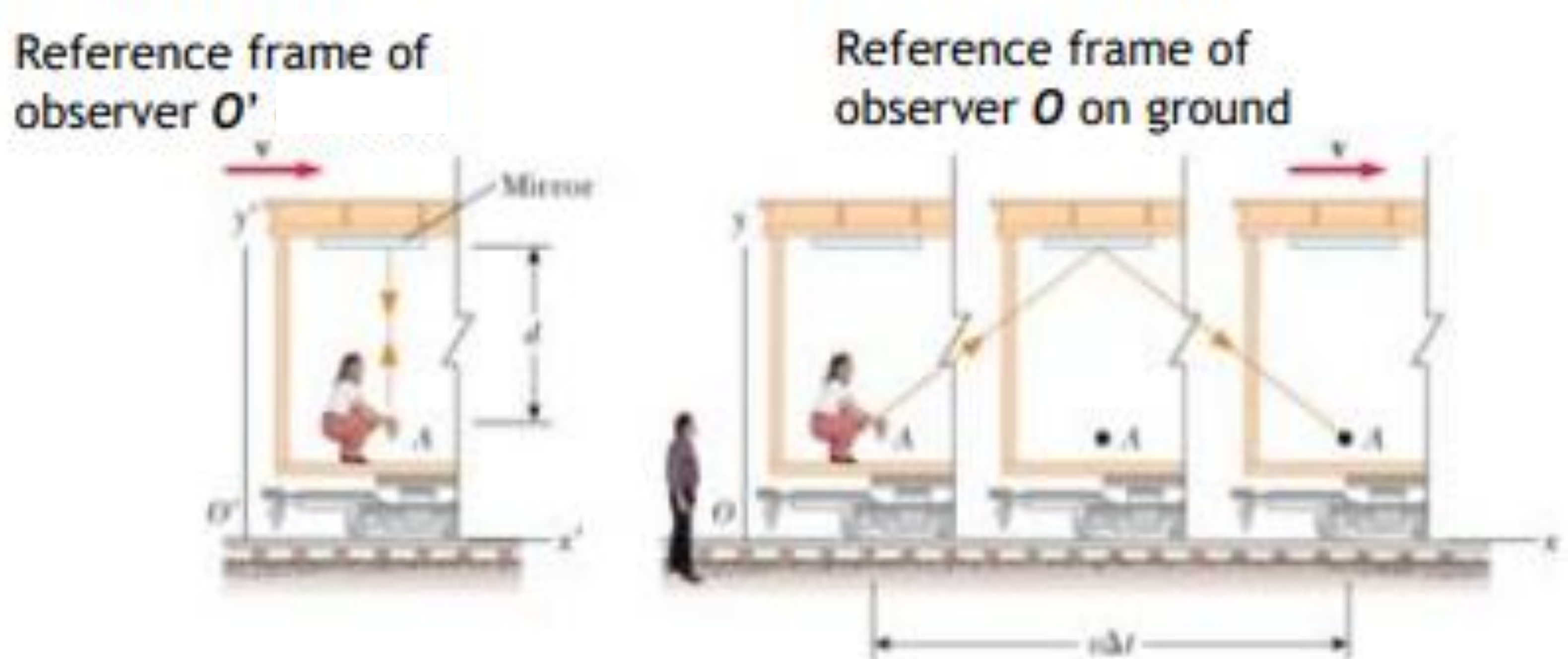
• Joe is equidistant from lightning strikes —Joe is equidistant from the lightning strikes —Light flashes arrive at different times —Both flashes travel at c

• Therefore for Joe, lightning strikes are not simultaneous

Simultaneity and relativity

- Means there is no universal, or absolute time.
- The time interval between events in one reference frame is generally different than the interval measured in a different frame.
- Events measured to be simultaneous in one frame are in general not simultaneous in a second frame moving relative to the first.
- Has other consequences for time

Time dilation

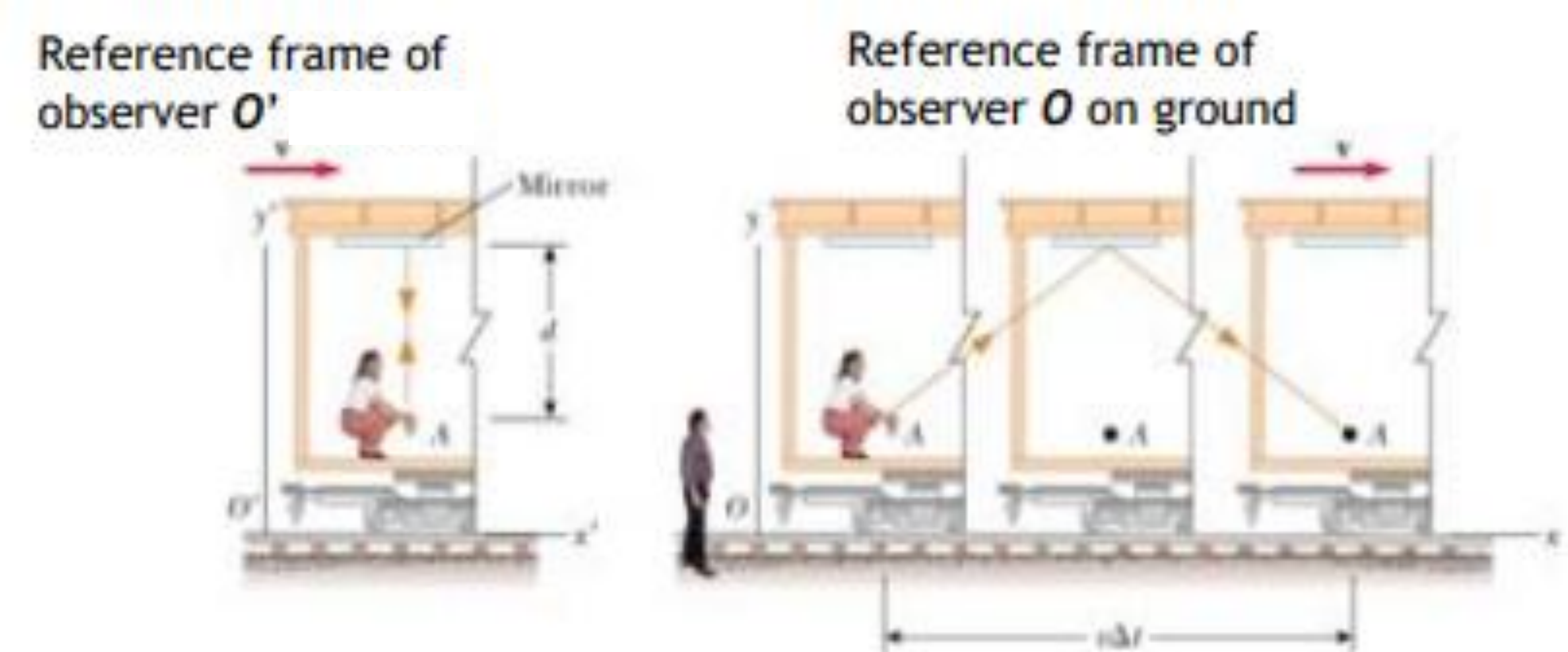


Observer O on ground

- Observer O’ on spaceship moving at v relative to O
- Pulse of light emitted from laser, reflected from mirror, arrives back at laser after some time interval.
- Let’s figure out what this time interval is for the two observers

1. Speed of light is constant. 2. In which frame is observer?

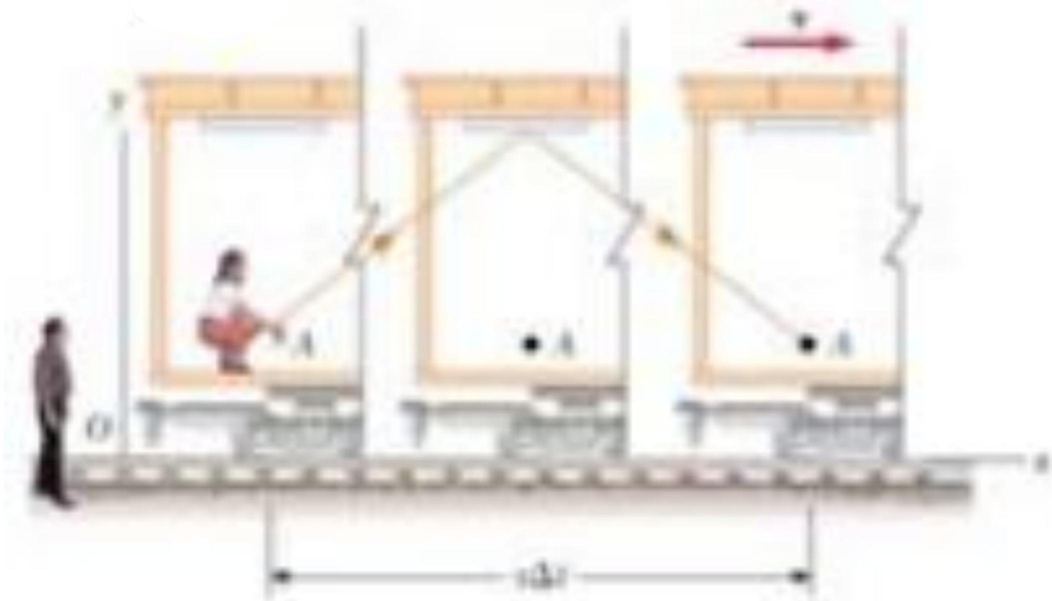
Time dilation

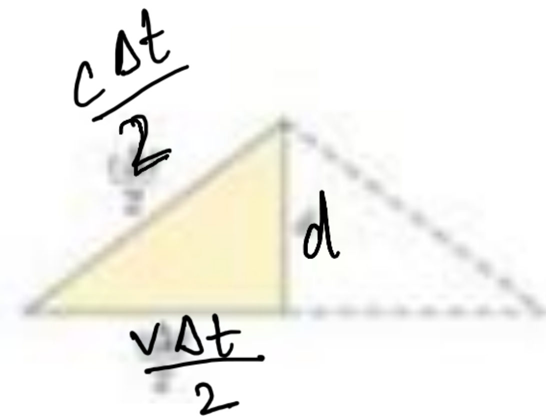


Observer O’ on spaceship: light pulse travels distance 2d.

- Observer O on ground: light pulse travels farther
- Relativity: light travels at velocity c in both frames – Therefore time interval between the two events (pulse emission from laser & pulse return) is longer for stationary observer
- **This is time dilation**

How large an effect is time dilation?





t = time interval between events in frame O (observer on ground)

- **Δ*t* satisfies** $(c\Delta t/2)^2 = (v\Delta t/2)^2 + d^2,$

$$(\Delta t)^2(c^2 - v^2)^2 = (2d)^2$$

$$\Delta t = 2d/\sqrt{c^2 - v^2} = \frac{2d}{c}\frac{1}{\sqrt{1-(v/c)^2}} = \frac{\Delta t_0}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma\,\Delta t_0$$

$\Delta t_0 = \frac{2d}{c}$, $\Delta t_0 \rightarrow$ proper time

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

time dilation-consequences

TWIN PARADOX

1. Why don't we observe time dilation in daily life?
2. Two twins- one at earth while other in spaceship
3. After returning from spaceship…both still are twins?
4. Which one is older now?

The spaceship is accelerating so it's a non-inertial frame of reference

The earth is an inertial frame and thus relativity applies

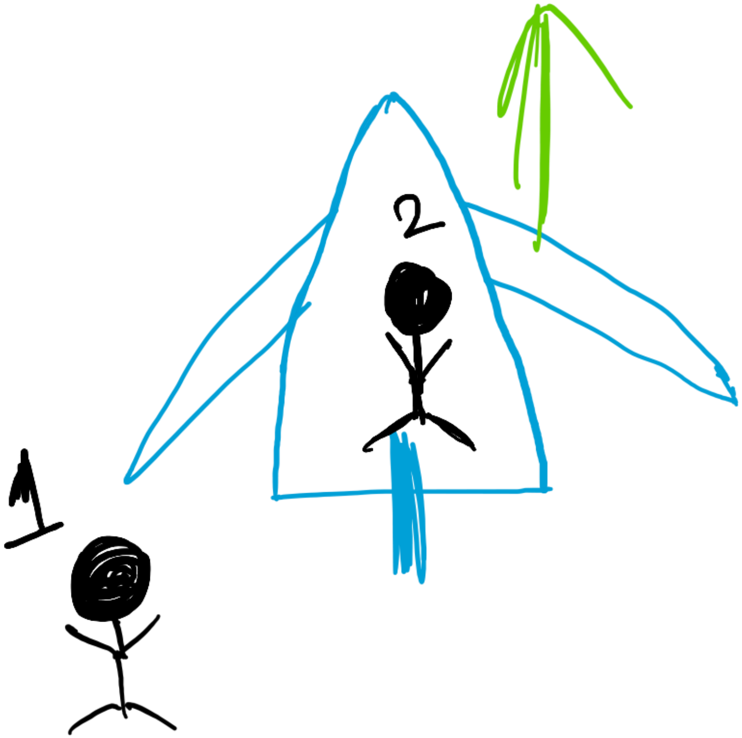
time dilation-consequences

reference

The earth is an inertial frame and thus relativity applies

4. Why we don't observe time dilation in daily life?

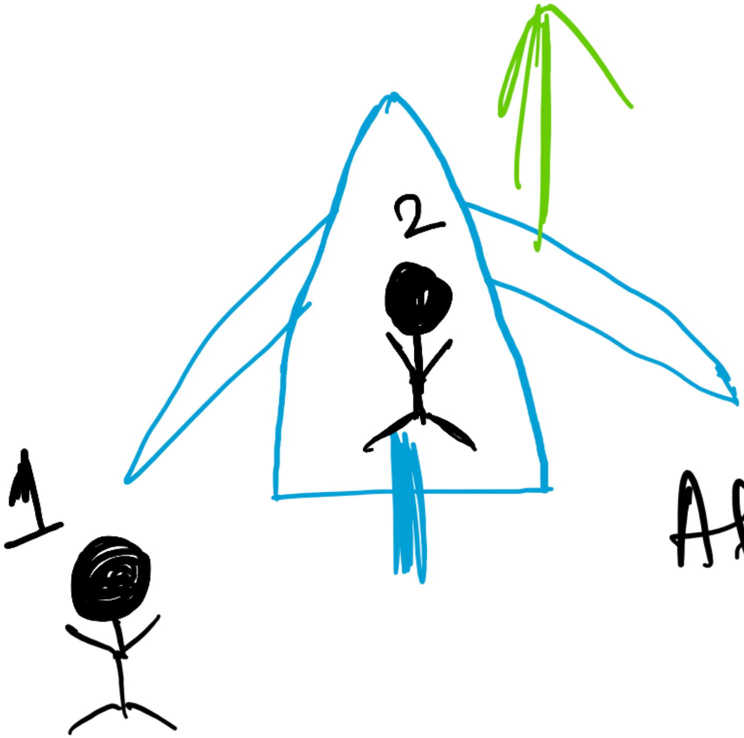
TWIN PARADOX



Ref.- https://www.nasa.gov/humans-in-space/twins-study/

time dilation-consequences

TWIN PARADOX



after 1 year passed on earth. Spaceship is travelling at 0.8c.

After 1 year, what is the age of 2?

$$= \frac{t_0}{\sqrt{1 - v^2/c^2}}$$

time dilation-consequences

TWIN PARADOX

after 1 year passed on earth. Spaceship is travelling at 0.8 c.
After 1 year, what is the age of 2 ?

$$t = \frac{t_0}{\sqrt{1 - v^2/c^2}}$$

$$1 = \frac{t_0}{\sqrt{1-(0.8)^2}} = 1 \times 0.6 = t_0$$

$$\boxed{0.6 = t_0}$$

age of 2 is only 0.6 years.

Special Relativity: GPS

- GPS satellites have atomic clocks accurate to 1 nanosecond (one billionth of a second)
- Positions computed by comparing time signals from several satellites.
- Satellites moving at 14,000km/hr

- Special Relativity:
  Clocks run slow by 7000ns per day!