General Physics I

Lecture 17: The Speed of Light and the Principles of Relativity

Outline

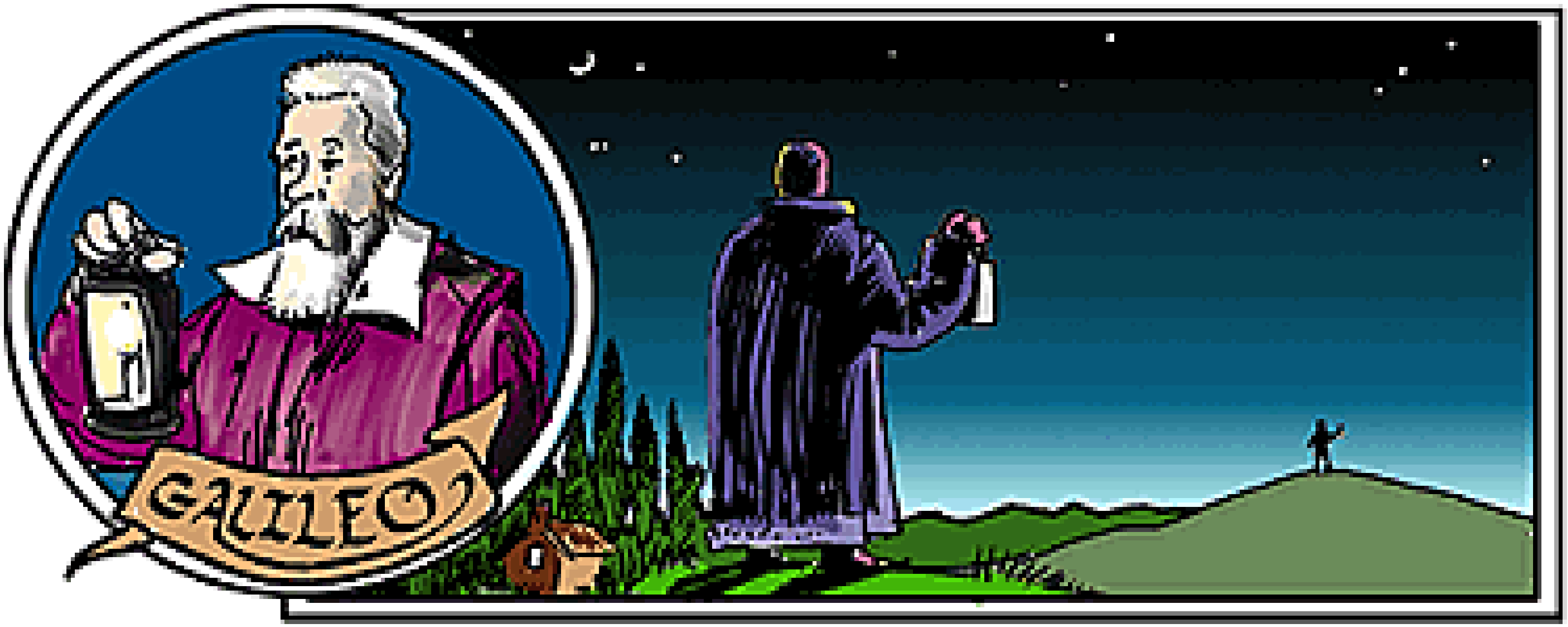
- **Early measurements of the speed of light**
  - **Galileo's attempt**
  - **Ole Roemer and the speed of light**
  - **James Bradley and the aberration of light**
- *** Maxwell and Hertz**
- **Does the speed of light depend on the motion of the light source?**
- **The two principles of relativity**

Measuring the Speed of Light

$$\text{Speed of light} = \frac{\text{Distance from the flashlight to Frank}}{\text{Time for the light to arrive at Frank}}$$

Galileo's Attempt

(Genesis 1:3) And God said, "Let there be light," and there was light.



Do you think if Galileo and his assistant successfully measured the speed of light in this way? Why?

Planet Jupiter and Its Moon Io

Jupiter orbital period ~ 12 years

Galileo spacecraft true-color image of Io.

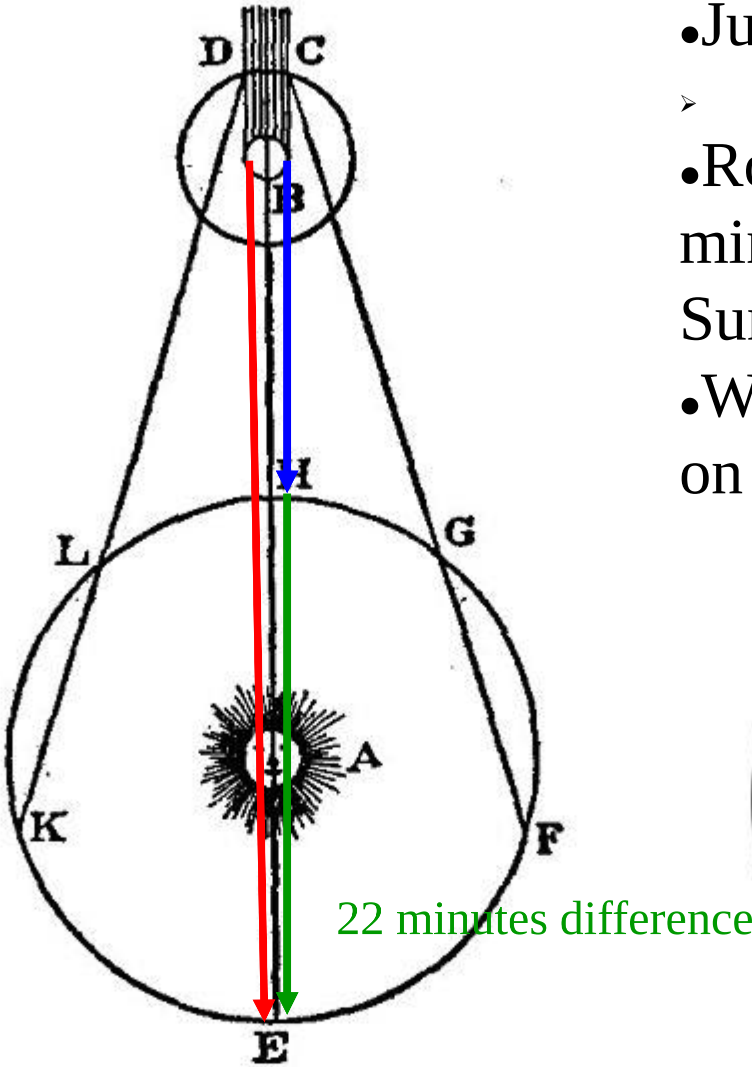
Io is the innermost of the four Galilean moons of the planet Jupiter. Orbital period ~ 42 hours

Galileo was an unmanned spacecraft launched on October 18, 1989 by Space Shuttle Atlantis. Galileo arrived at Jupiter on December 7, 1995.

Jupiter and Io

Juno discovering Jupiter with Io © National Gallery, London
1618, Pieter Lastman

Ole Roemer and the Speed of Light



- Jupiter is stationary.
  - 12 years >> 42 hours
- Roemer found that it takes 11 minutes for light to travel from the Sun to Earth.
- What is the speed of light based on this observation?

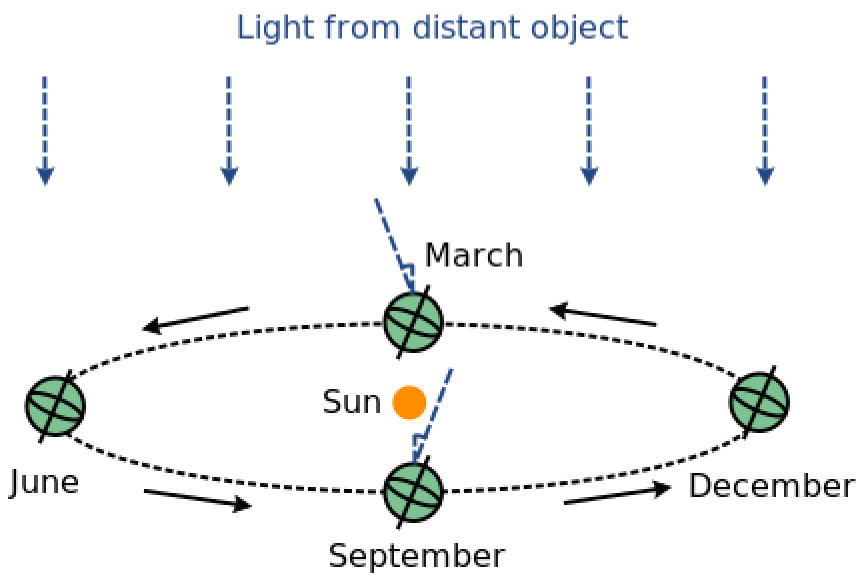
Ole Roemer
(1644–1710)

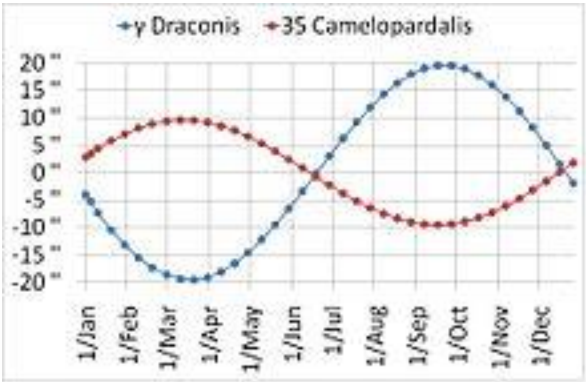
$R=1.496\times10^{11}$ m;

T= 16 min 24 sec;

$C= 3.0\times10^{8}$ m/s

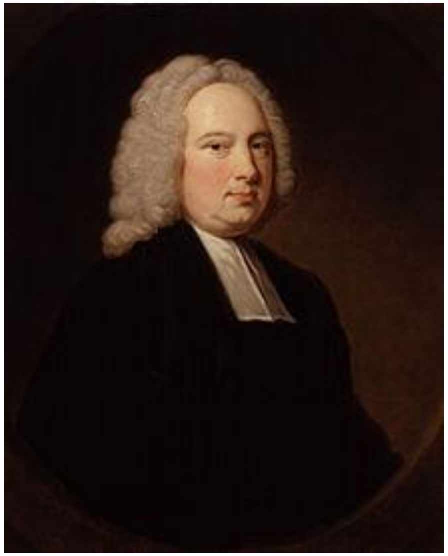
Aberration of Light





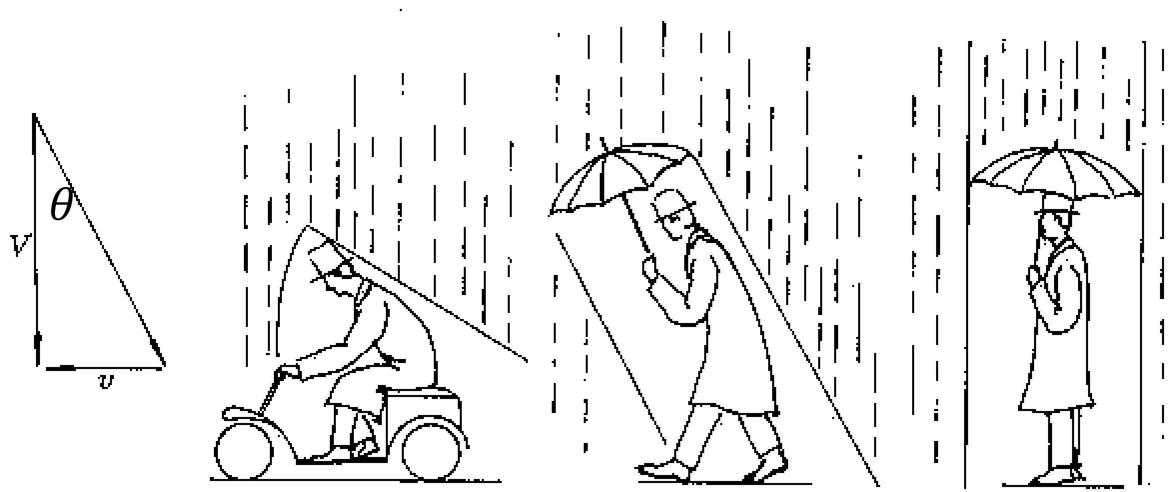
First direct experiment to suggest that the sun was a better inertial frame than the earth.

$$\tan(\phi) = \frac{u'_y}{u'_x} = \frac{u_y}{u_x + v} = \frac{\sin(\theta)}{v/c + \cos(\theta)} \xrightarrow[v/c \ll 1]{\theta = 90^\circ} \boxed{\theta - \phi = v/c.}$$



James Bradley (1693-1762)

Walking in the Rain



$$\tan\theta = \frac{v}{V}$$

At last, when he despaired of being able to account for the phenomena which he had observed, a satisfactory explanation of it occurred to him all at once, when he was not in search of it.

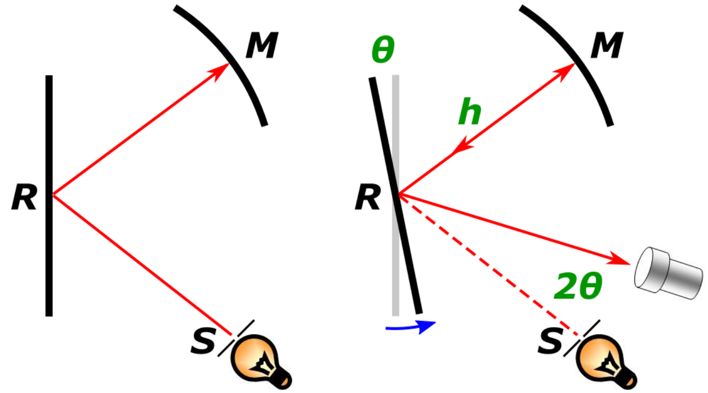
– T. Thomson, *History of the Royal Society*

Rotating-Mirror Method

Schematic of the Foucault apparatus.

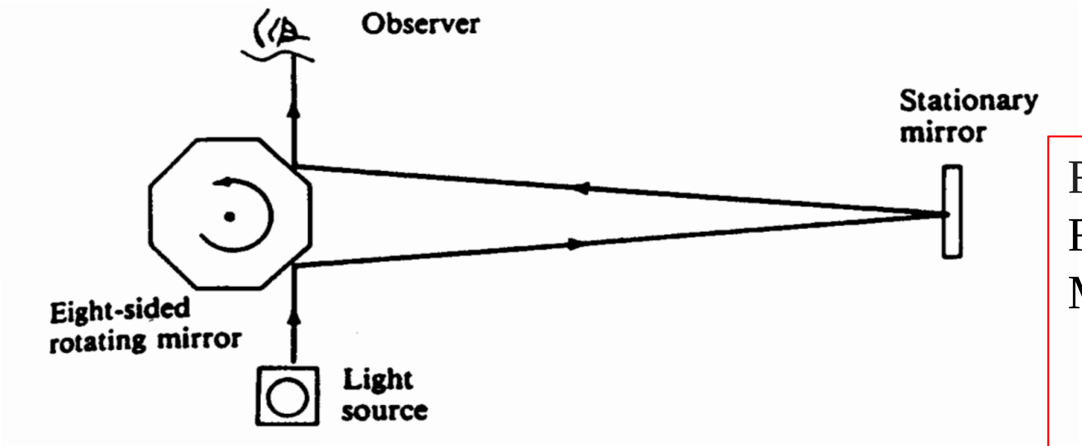
$$\theta = \frac{2h\omega}{c} = \omega t$$

$$c = \frac{2\omega h}{\theta}$$



A. A. Michelson
(1852 – 1931)

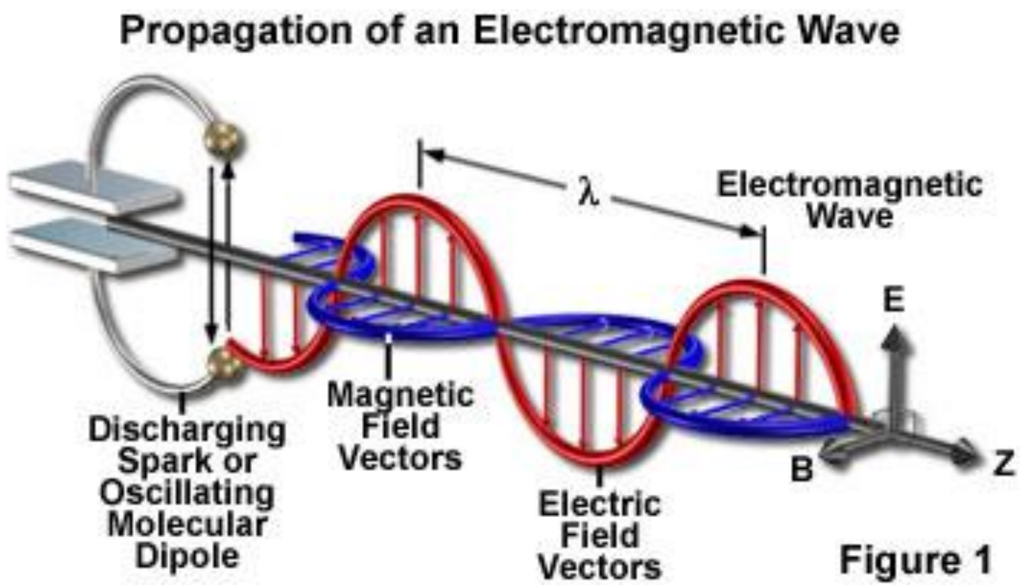
Michelson's Refinement



Fizeau, 1849: c=315000 km/s (5%);
Foucault,1862: c=298000 km/s (0.6%);
Michelson,
1879: c= 299944 km/s (0.05%);
1883: c = 299,853 ± 60 km/s;
1926: c = 299,796±4 km/s

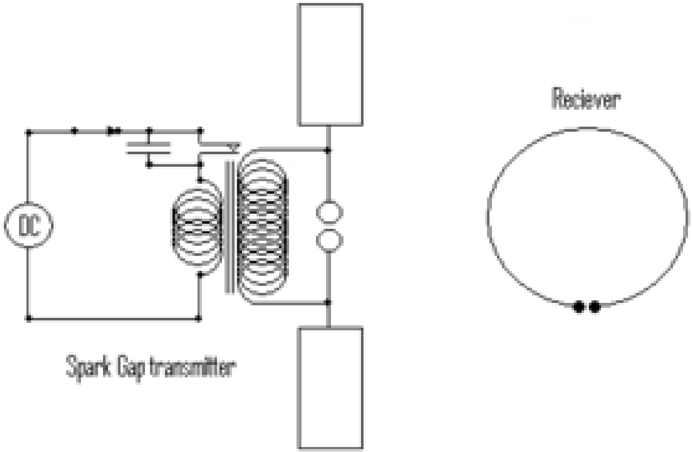
Maxwell's Theory

- Maxwell completed the unification of the laws of electricity and magnetism. His theory predicted the electromagnetic waves traveling at a speed of about 300,000,000 m/s, numerically indistinguishable from the speed of light.
- Maxwell's theory implied that the speed of the E&M waves does not depends on the speed of the source of the radiation.



Maestro Maxwell Was Right

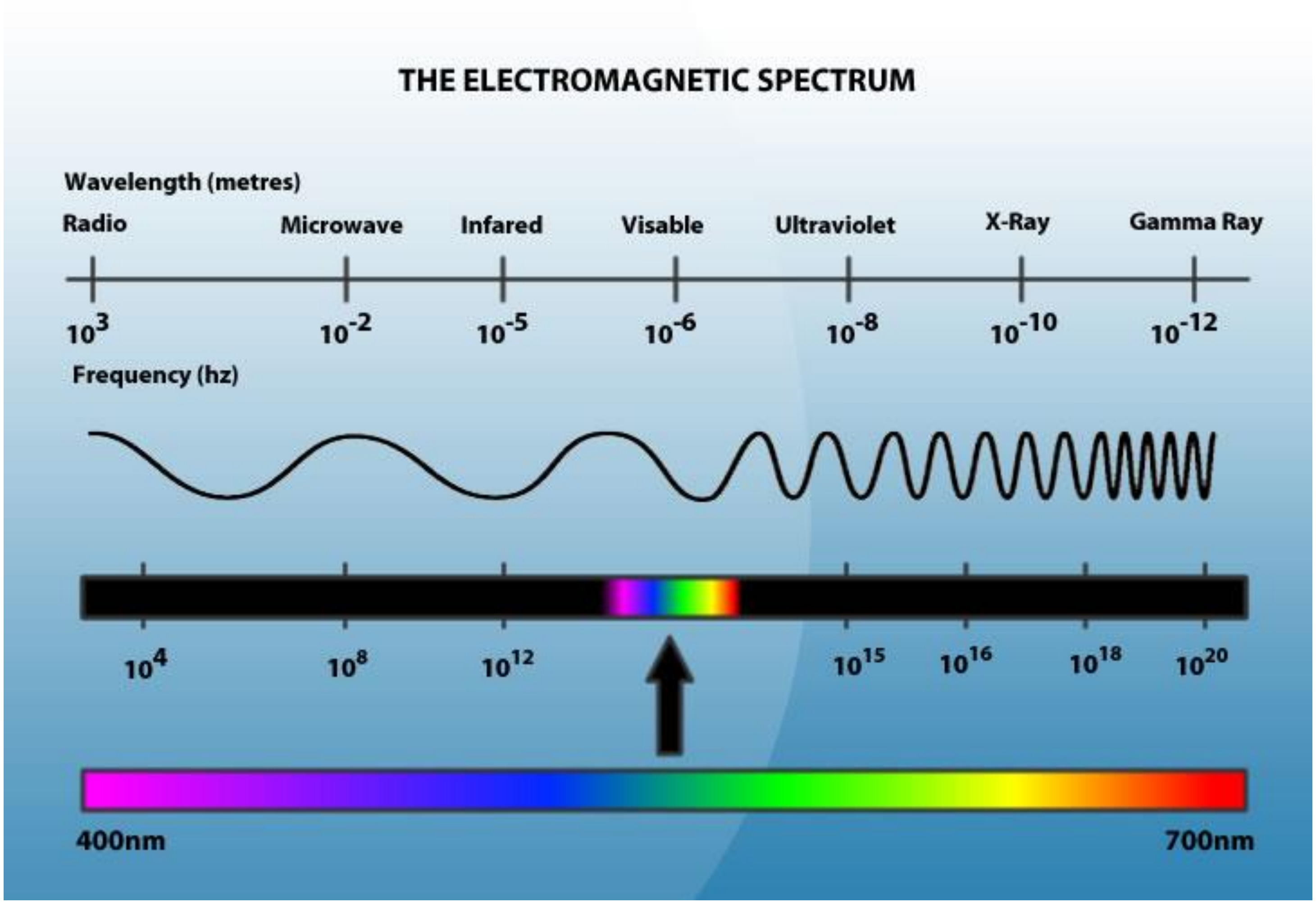
Heinrich Hertz (1857-1894) proved Maxwell's theory by engineering instruments to transmit and receive radio pulses (in the ultra high frequency range).



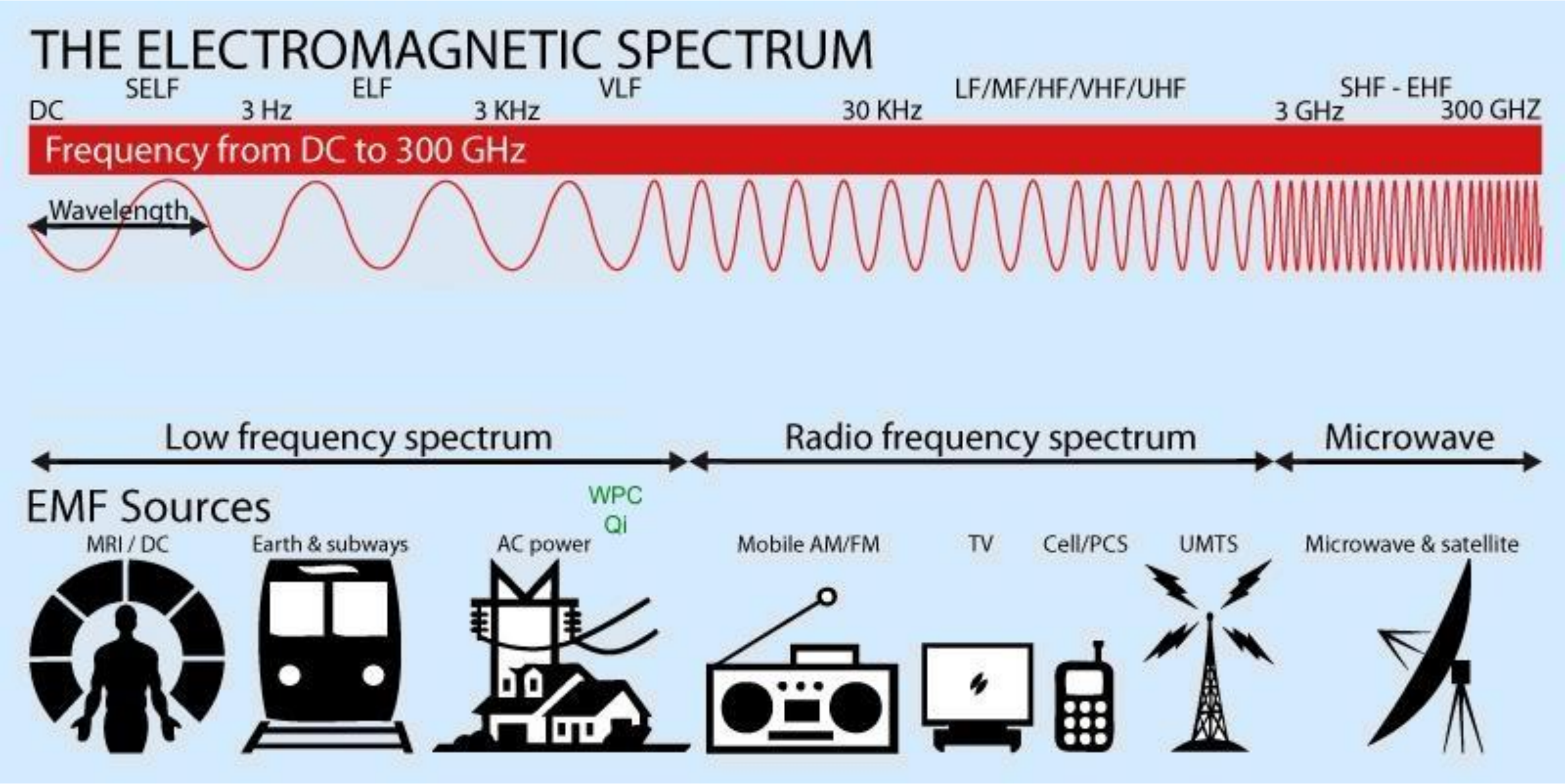
"It's of no use whatsoever[...] this is just an experiment that proves Maestro Maxwell was right—we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there."

Gee, he was completely wrong about its use!

The E&M Spectrum



Low-Frequency Spectrum



Can you hear the E&M wave with a frequency 1 kHz?

Speeds of Sound in Media

Gases	
Hydrogen (0°C)	1 286
Helium (0°C)	972
Air (20°C)	343
Air (0°C)	331
Oxygen (0°C)	317
Liquids at 25°C	
Glycerol	1 904
Sea water	1 533
Water	1 493
Mercury	1 450
Kerosene	1 324
Methyl alcohol	1 143
Carbon tetrachloride	926
Solids	
Diamond	12 000
Pyrex glass	5 640
Iron	5 130
Aluminum	5 100
Brass	4 700
Copper	3 560
Gold	3 240
Lucite	2 680
Lead	1 322
Rubber	1 600

with respect to the medium!

Does Light Have a Medium?

- **Physicists in the late 19th century believed**

  - **Surface water waves must have a supporting substance, i.e. a "medium", to move across (in this case water).**
  - **Audible sound requires a medium to transmit its wave motions (such as air or water).**
  - **So light must also require a medium, the "luminiferous ether", to transmit its wave motions in vacuum.**

- **Ether must have highly unusual properties**

  - **The speed of light is so great.**
  - **Material bodies pass through the ether without obvious friction or drag.**

With Respect to What?

- Light travels with a speed of 299,792,458 m/s in vacuum. The speed of light is then with respect to that ether.
- Light travels significant slower in transparent media like water or glass, and a little bit slower in air. So it appears that a medium moving through the stationary ether drags light propagating through it with only a fraction of the medium's speed (see Fizeau experiment).
- As Einstein later noted, “the introduction of a 'luminiferous ether' will prove to be superfluous” because there would be no way to determine the rest frame of the ether by any physical experiment involving electromagnetic phenomena (see Michelson-Morley exp.).

Fizeau Experiment (1851)

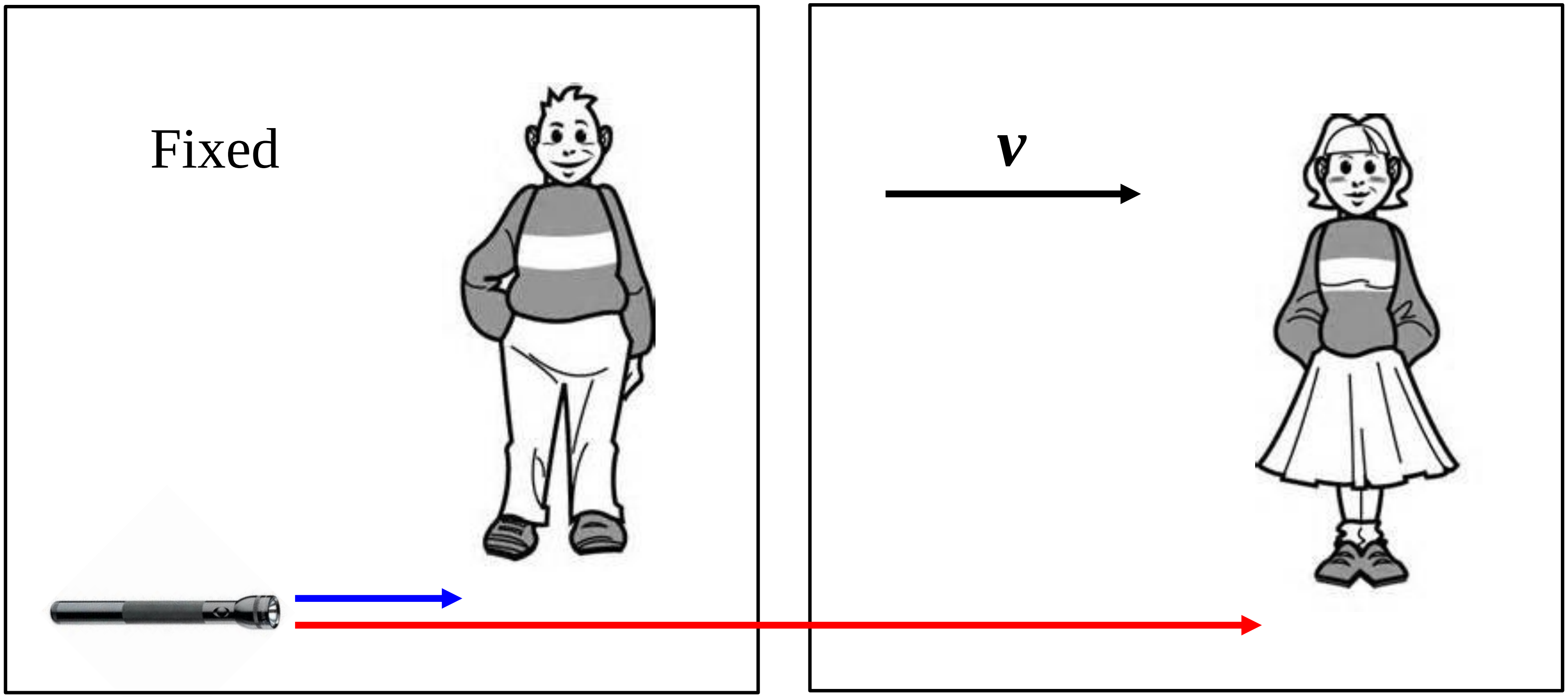
If n is the index of refraction of water, so that c/n is the velocity of light in stationary water. Now consider that water flows in the pipes at velocity v.

Naively, one expects $$v' = \frac{c}{n} + v$$

However, experiment found $$v' = \frac{c}{n} + v\left(1 - \frac{1}{n^2}\right)$$

Light appeared to be dragged by the water, but the magnitude of the dragging was much lower than expected. This appears to suggest that it cannot be with respect to water.

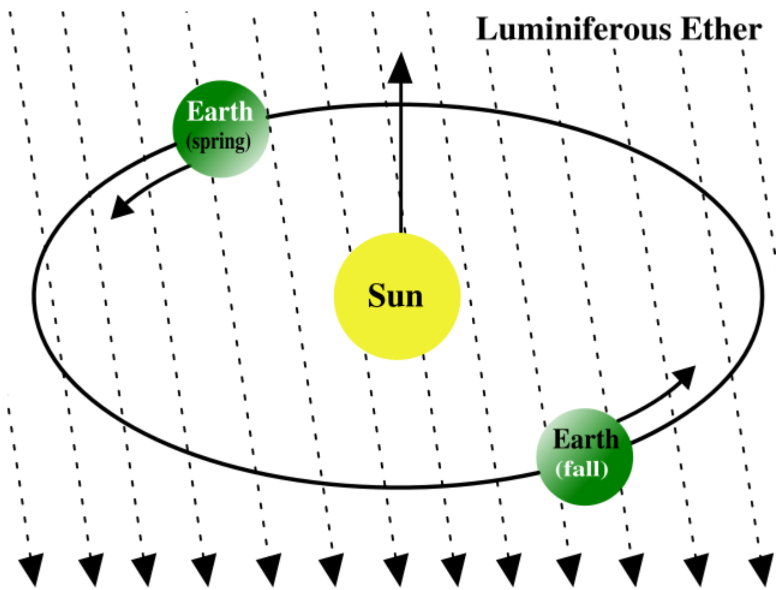
Moving vs Fixed Observer

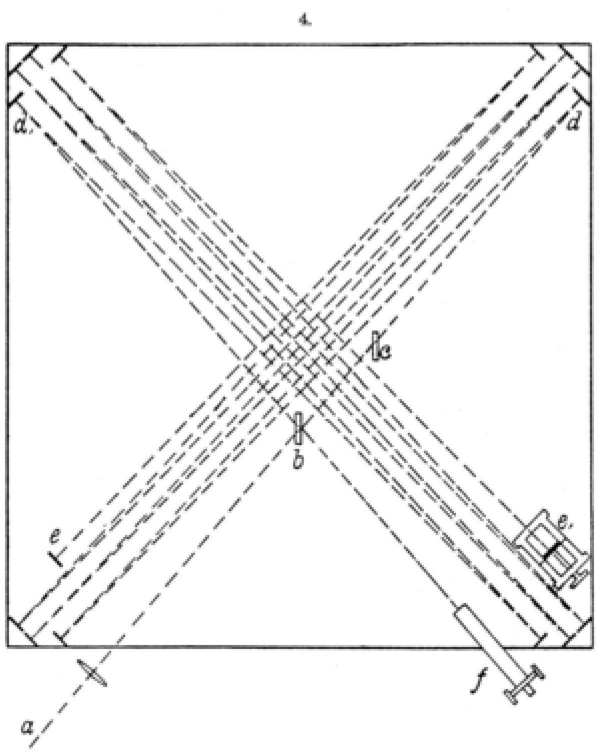


Assume Mary is moving with speed *v* with respect to the stationary ether. Does she observe a different speed of light?

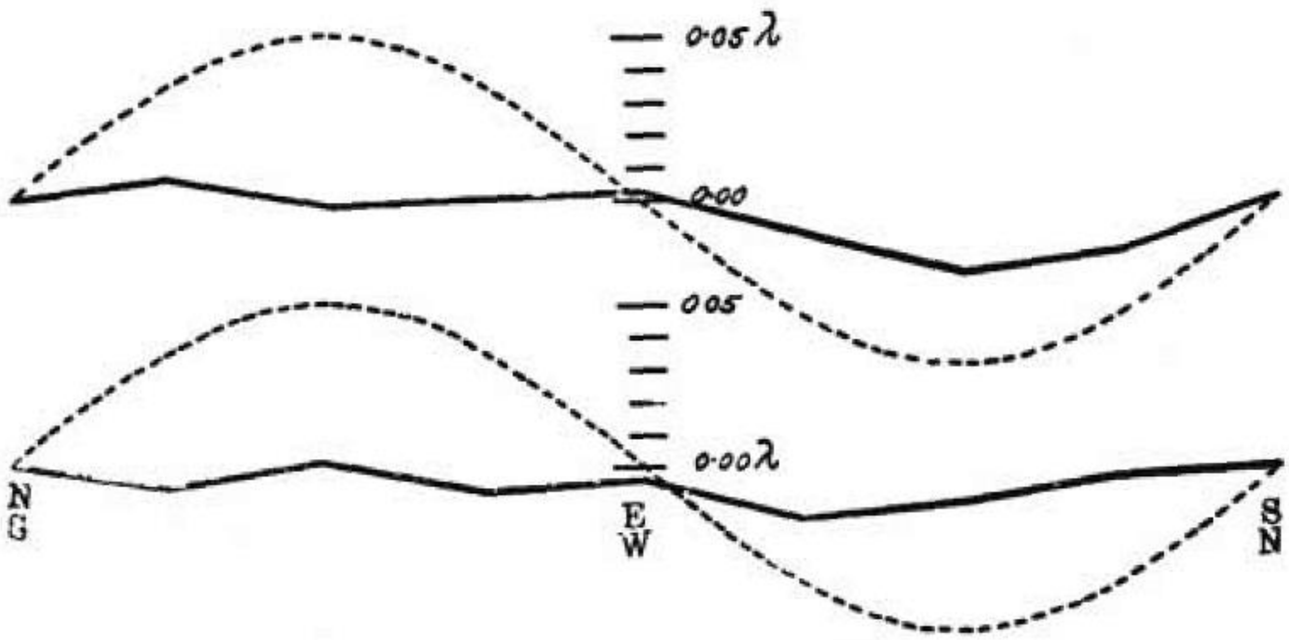
Michelson-Morley Experiment

- It was hypothesized that, generically, Earth and the ether are in relative motion, implying that a so-called "ether wind" should exist. At any given point on the Earth's surface, the magnitude and direction of the wind would vary with time of day and season.





Most Famous "Failed" Experiment

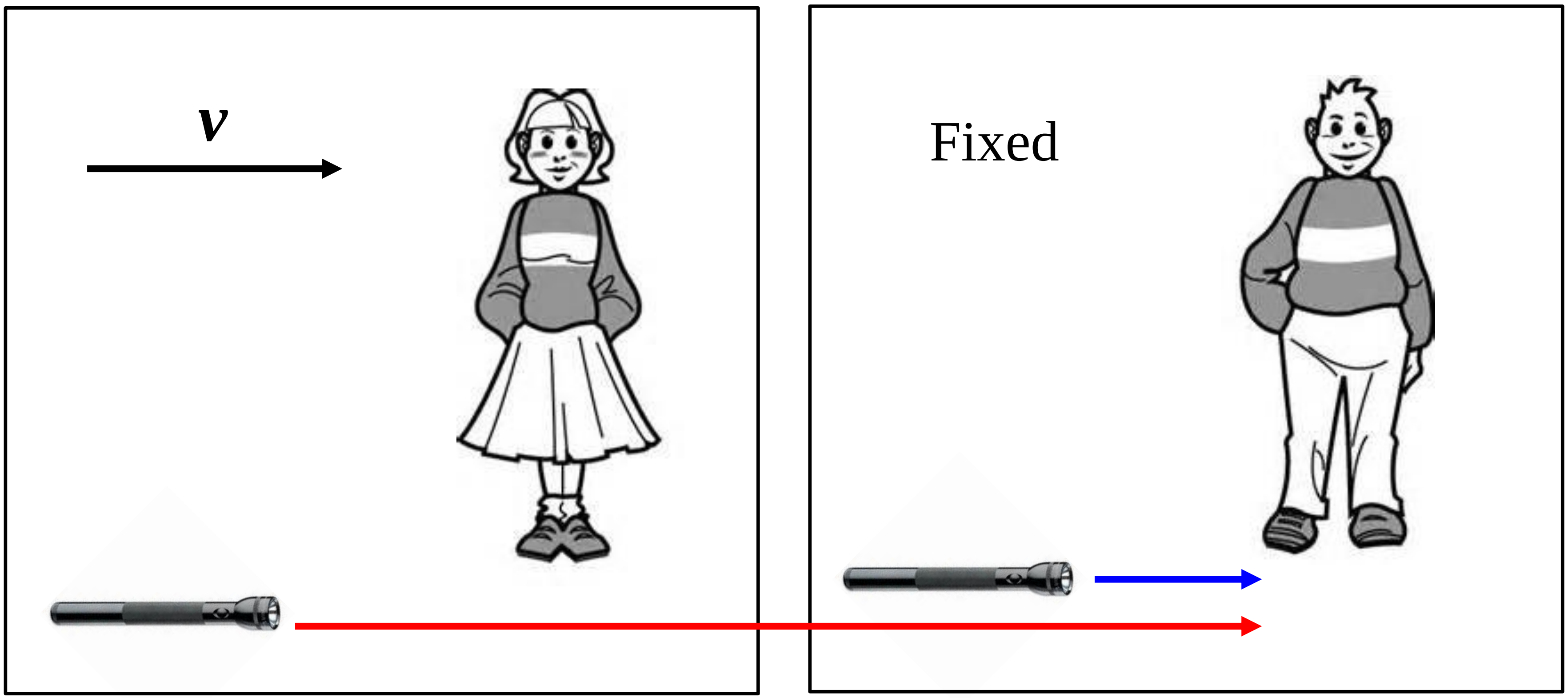


Note that the theoretical curves and the observed curves are not plotted at the same scale: the dashed curves, in fact, represent only one-eighth of the theoretical displacements.

The experiments on the relative motion of the earth and ether have been completed and the result decidedly negative.

—Albert Abraham Michelson, 1887

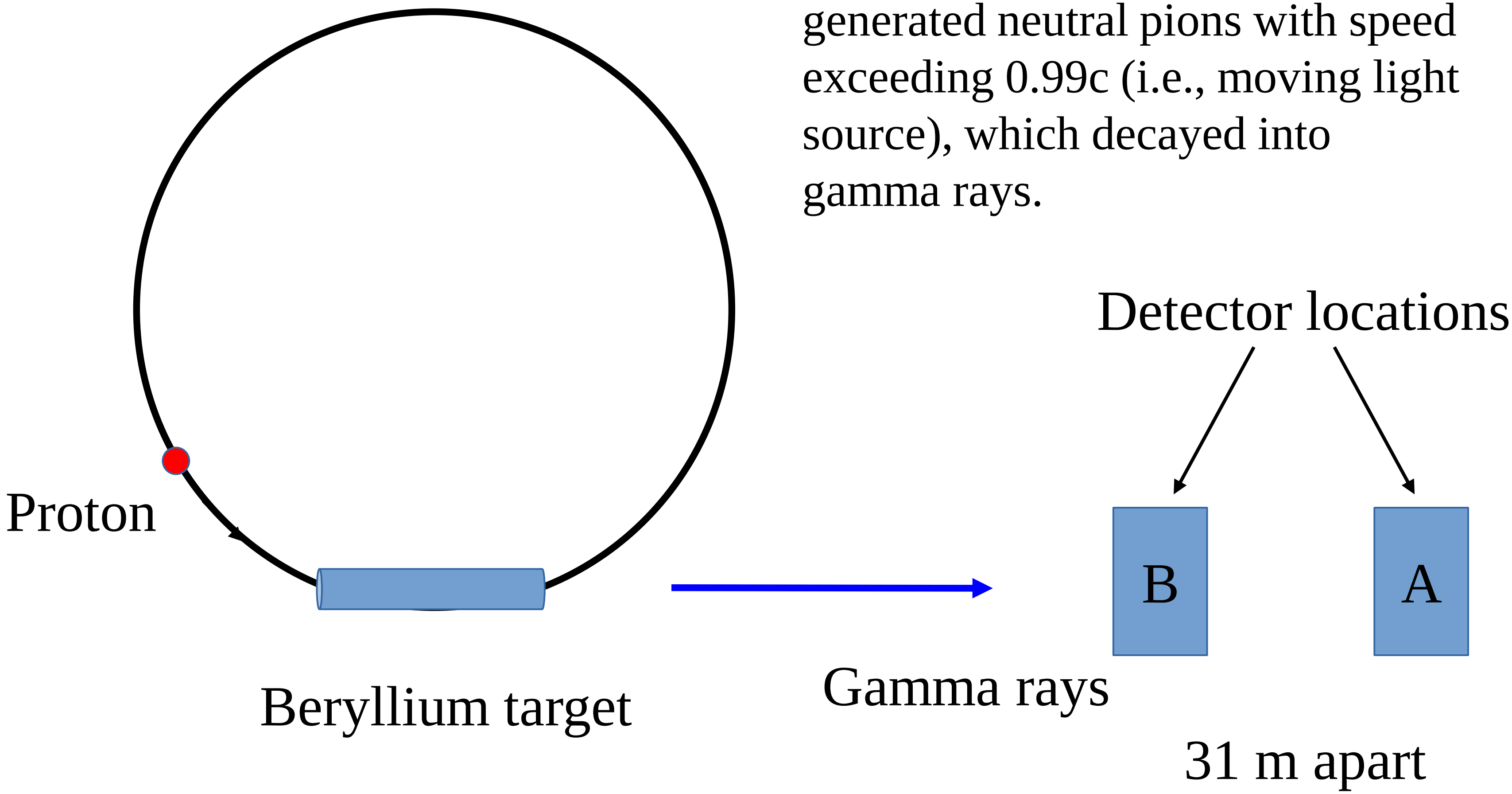
Moving vs Fixed Light Source



Mary's flashlight moves with speed *v*. Does Frank observe a different speed of light?

The 1964 Experiment

The proton-beryllium collisions generated neutral pions with speed exceeding 0.99c (i.e., moving light source), which decayed into gamma rays.



T. Alvaeger et al., Phys. Lett. 12, 260 (1964)

The Speed of Gamma Rays

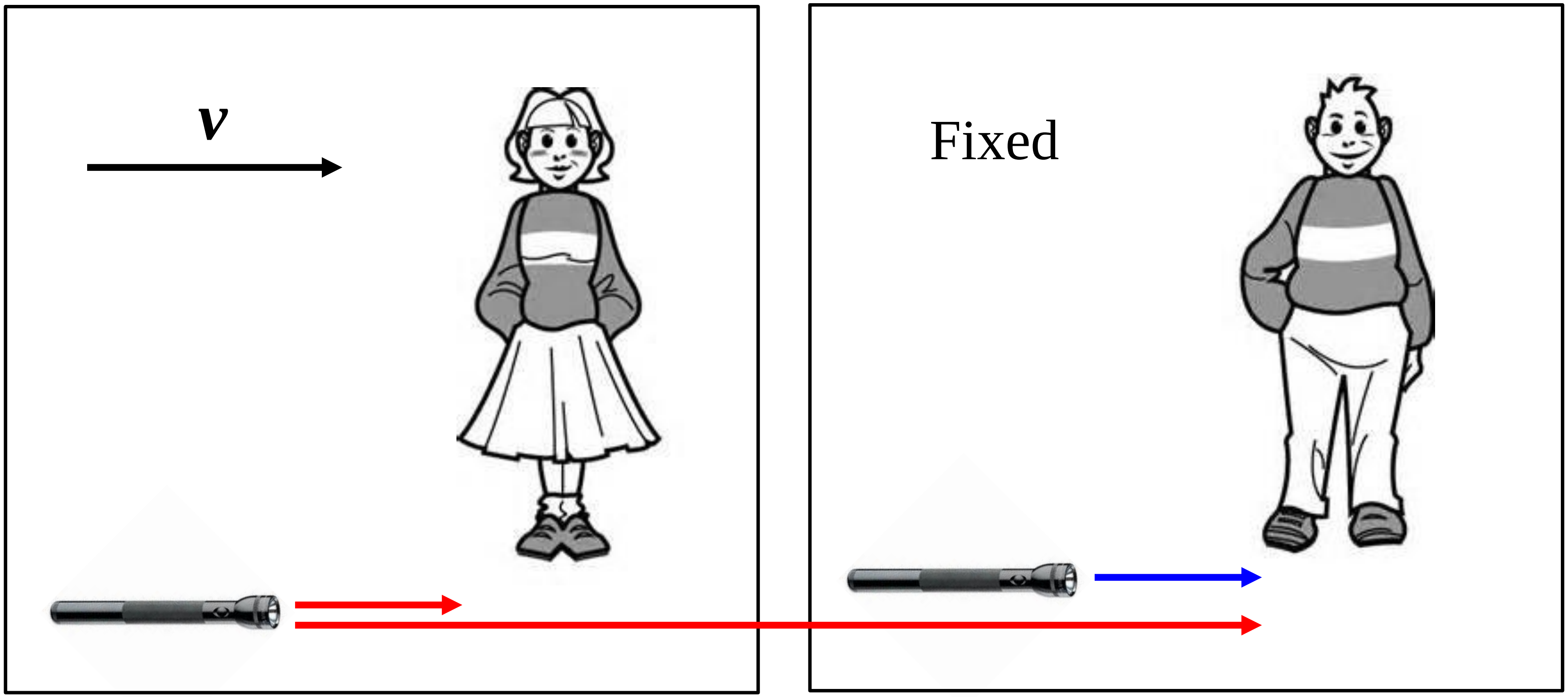
- **The speed of gamma rays from neutral pions**

$$\frac{\text{Separation of A and B}}{\text{t (production to A)} - \text{t (production to B)}}$$

$$= 2.9979 \times 10^{8} \text{ m/s}$$

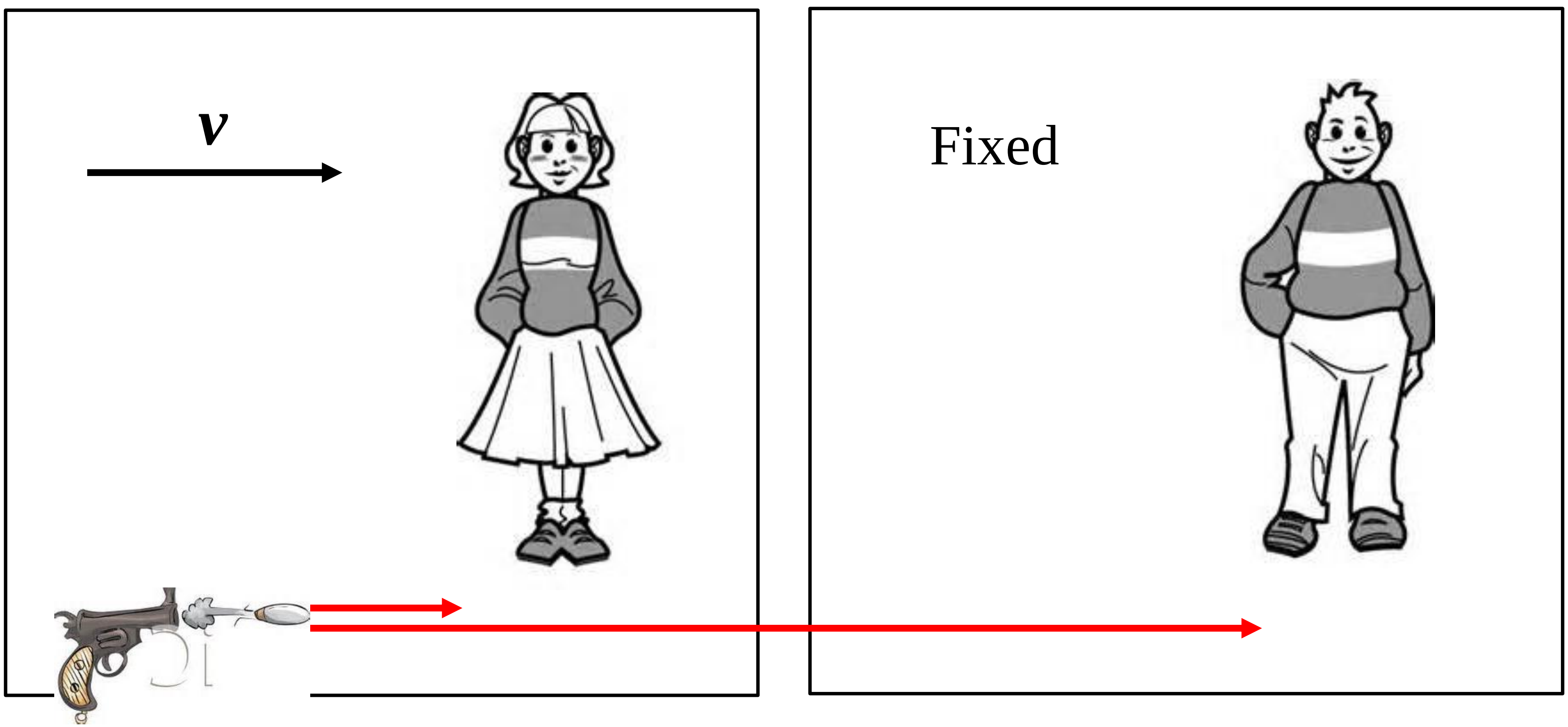
The same as that from a stationary source!

Constancy of the Speed of Light



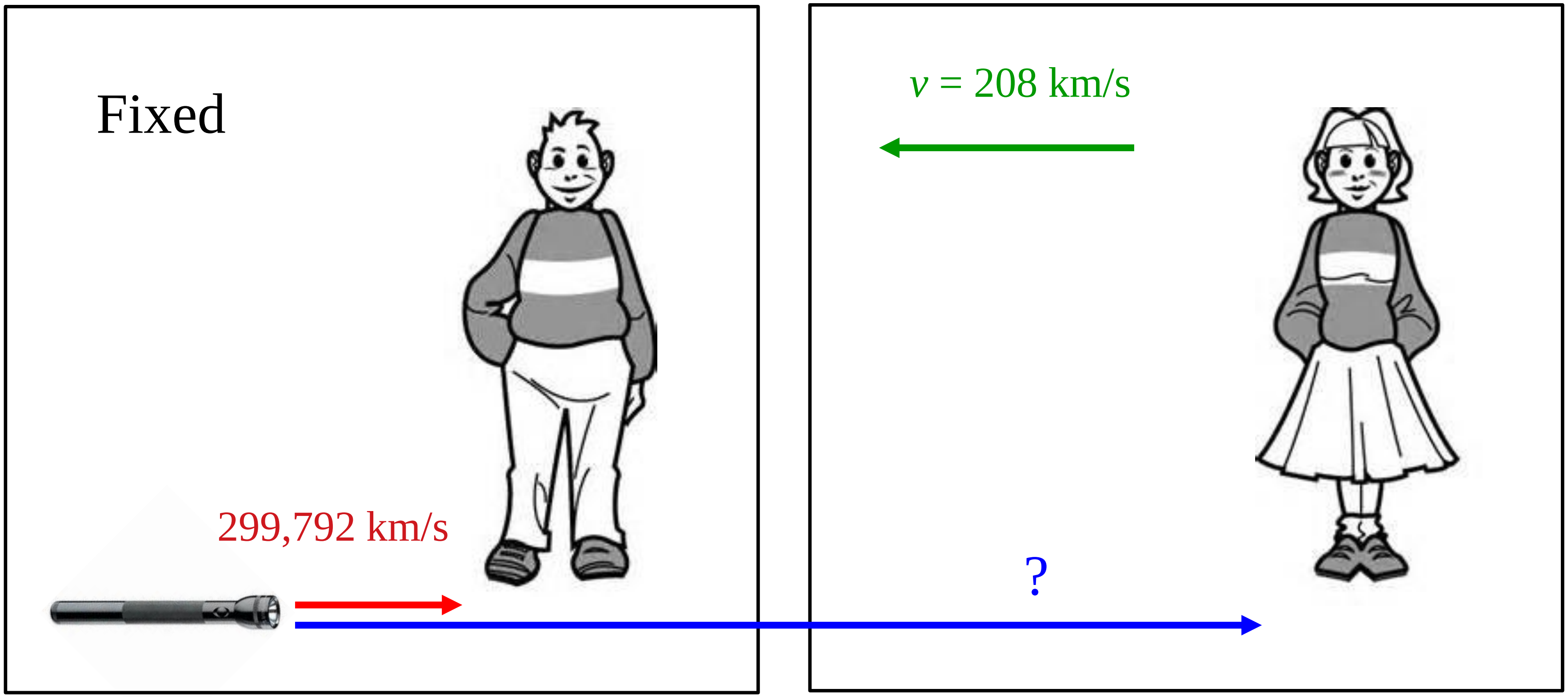
The speed of light is 299,792,458 m/s in vacuum, regardless of the motion of its source or observer.

The Contrast



Frank notes a larger speed of the bullet than Mary does.

Principle of the Constancy of Lightspeed



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The Principle of Relativity

- **In Einstein's words, "In electromagnetism as well as in mechanics, phenomena has no properties corresponding to the concept of absolute rest."**
- **The principle of relativity should now be a well-know feature of mechanics to you.**
- **In everyday language, this means that all other things being the same, it does not matter how fast you are going if you are moving with fixed speed along a straight line. (First enunciated by Galileo.)**

Newton's First Law of Motion

- **In the absence of external forces, an object at rest remains at rest and an object in motion continues in motion with a constant velocity (that is, with a constant speed In a straight line).**
- **In simpler terms, when no force acts on an object, the acceleration of the object is zero.**
- **Any isolated object (one that does not interact with its environment) is either at rest or moving with constant velocity.**

- concept of absolute rest

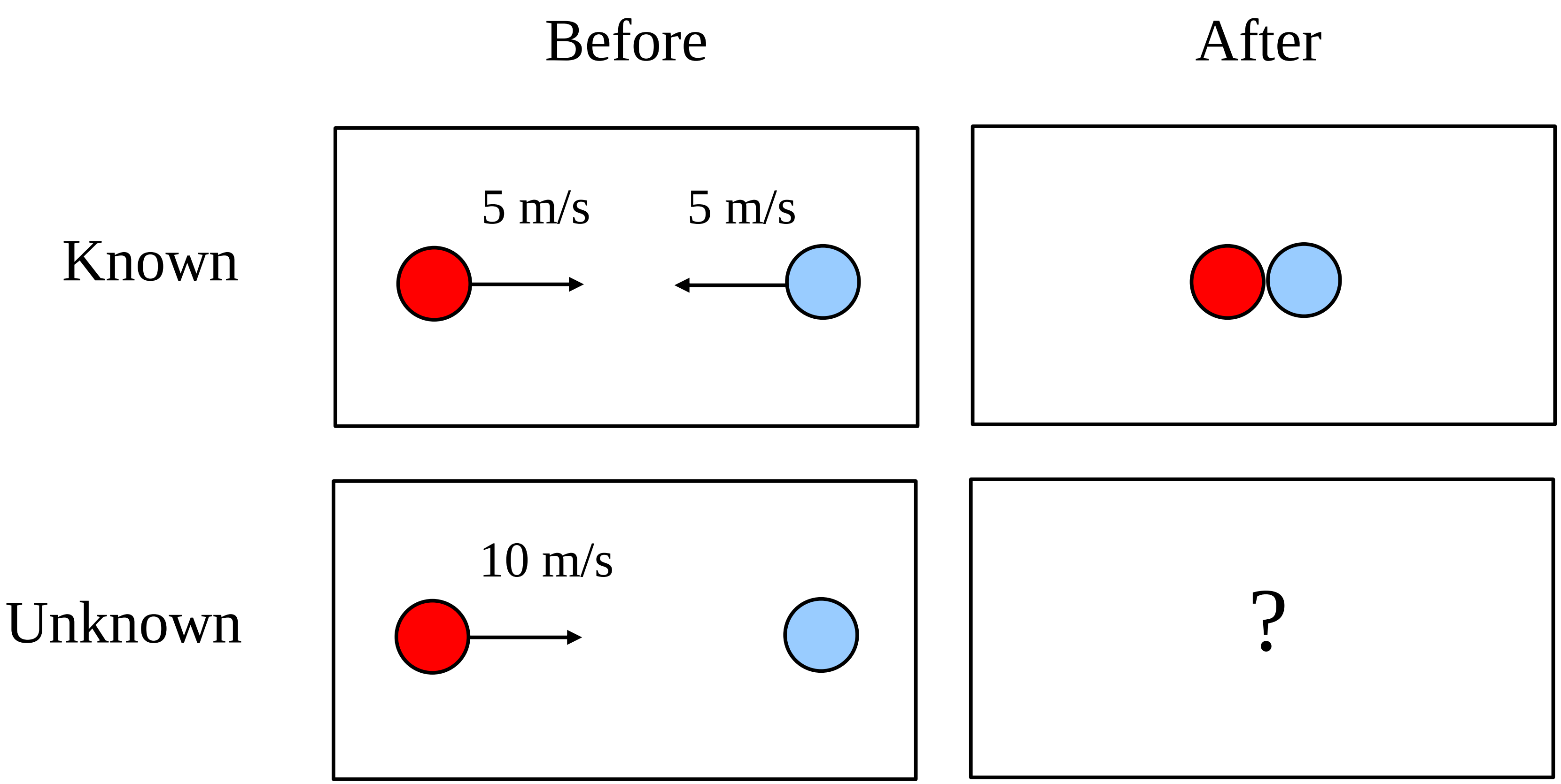
Significance of Newton's 1st Law

- Identifies a set of special reference frames in which we can apply the laws of classical mechanics.
- The tendency of an object to resist any attempt to change its velocity is called the inertia of the object.
- Newton's first law is often called the law of inertia. The reference frames to which it applies are called inertial frames.

The Application of the Principle

- Take a situation that you do not fully understand.
- Find a new frame of reference in which you do understand it.
- Examine it in the new frame of reference.
- Translate your understanding in the new frame back into the language of the old one.

Ex. 1: Perfectly Inelastic Collision



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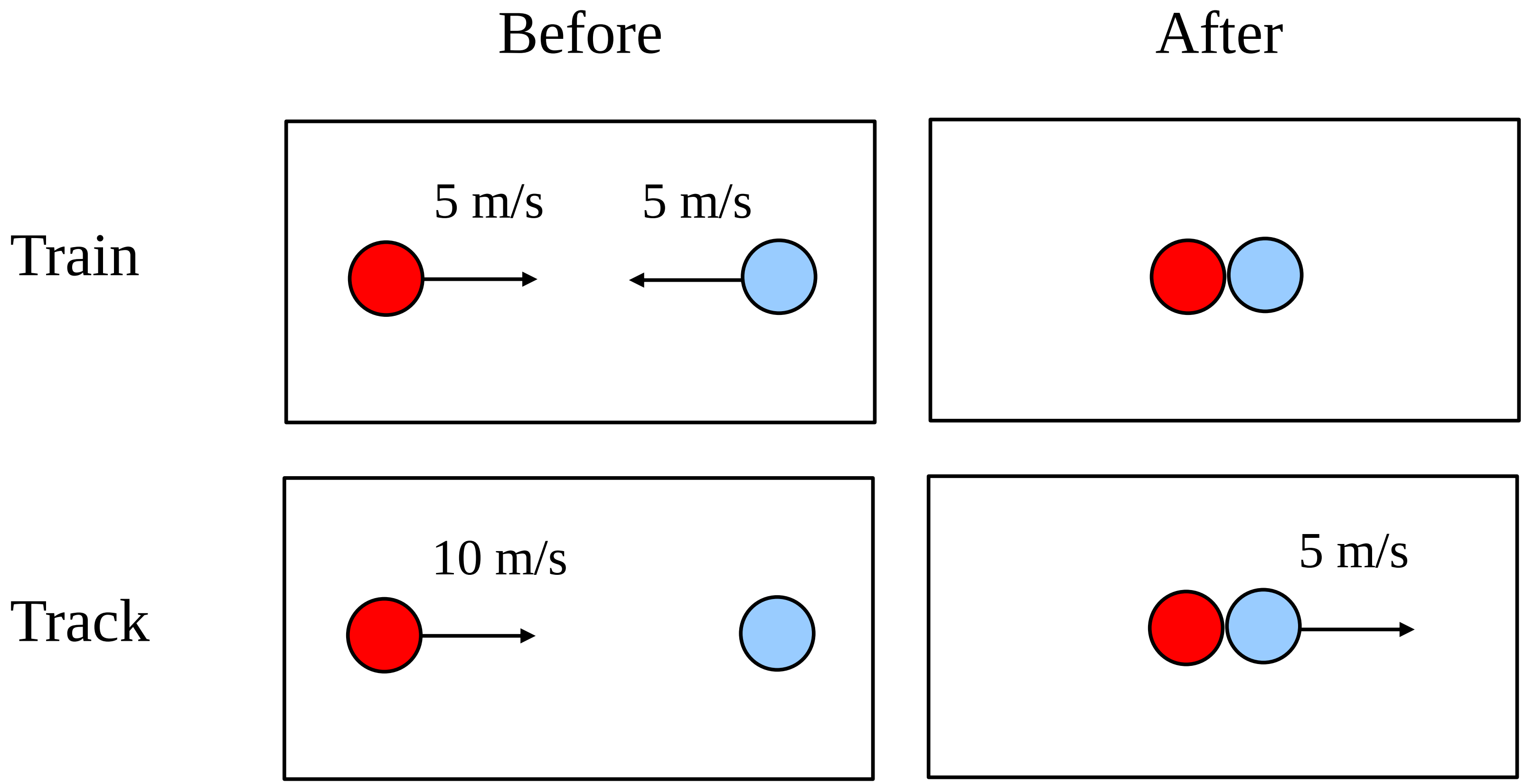


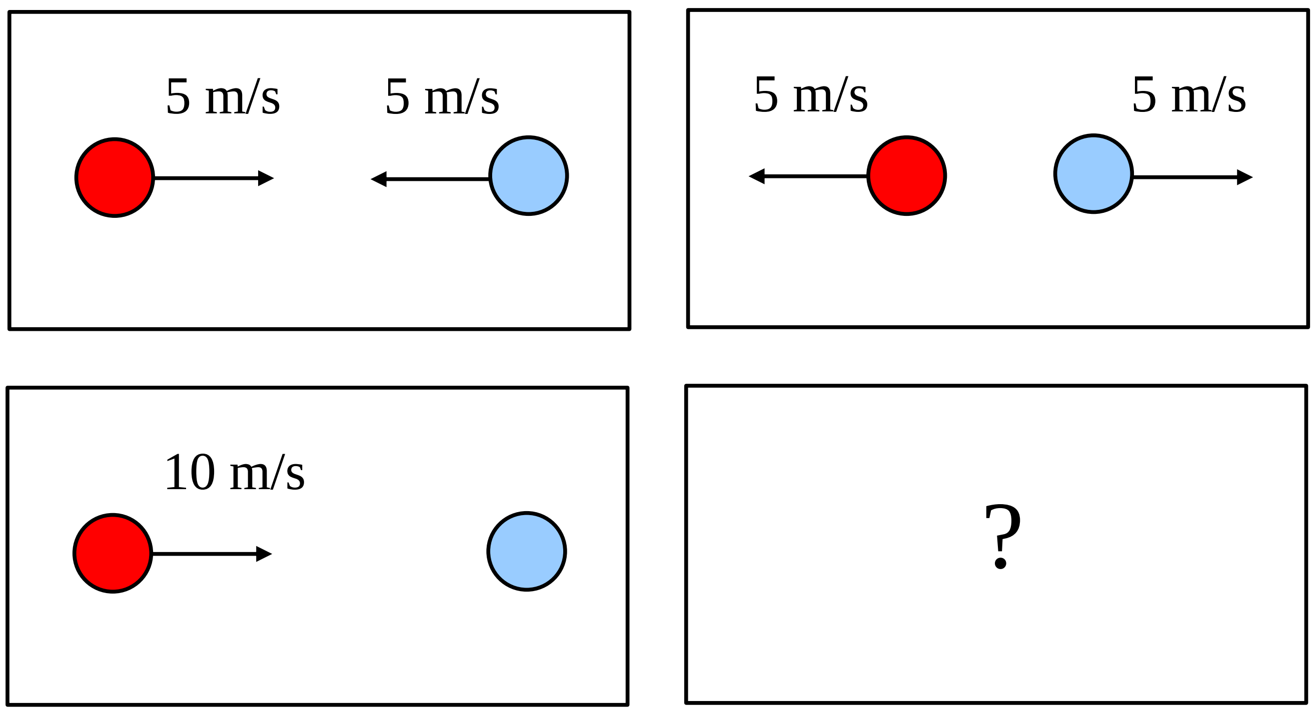
Assuming the train is moving at 5 m/s to the right.

Ex. 2: Elastic Collision

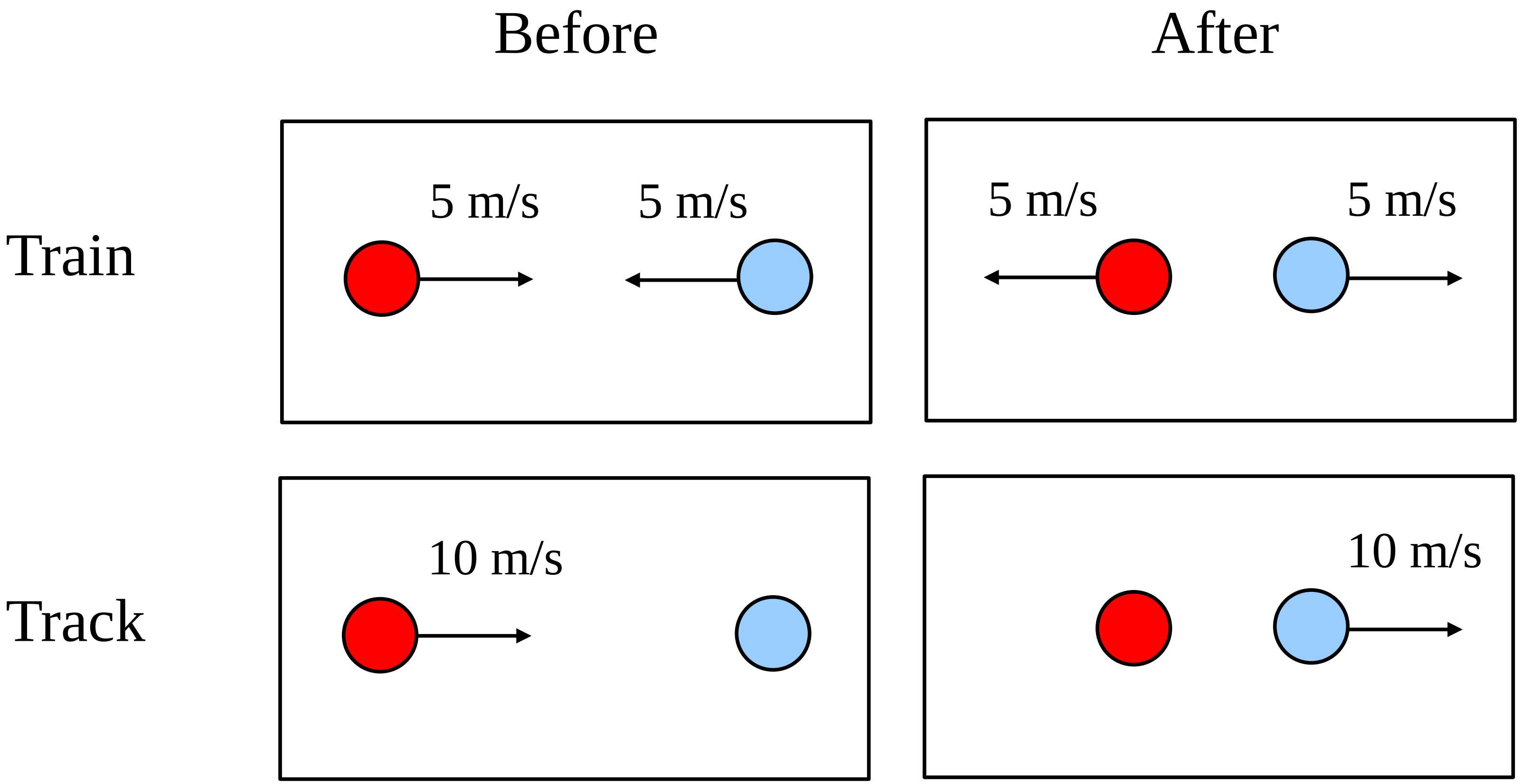
Before After

Known

Unknown

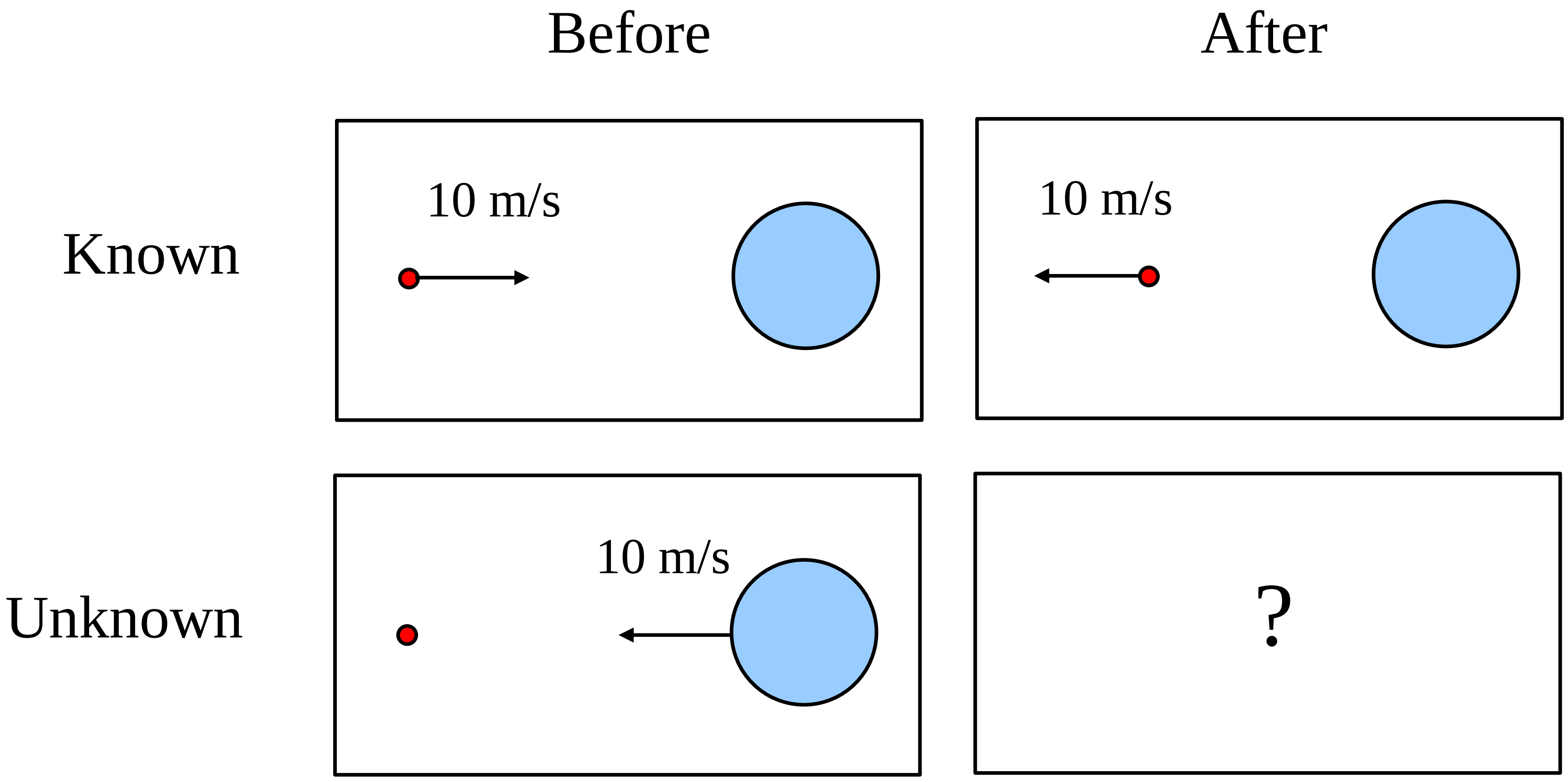


Ex. 2: Elastic Collision

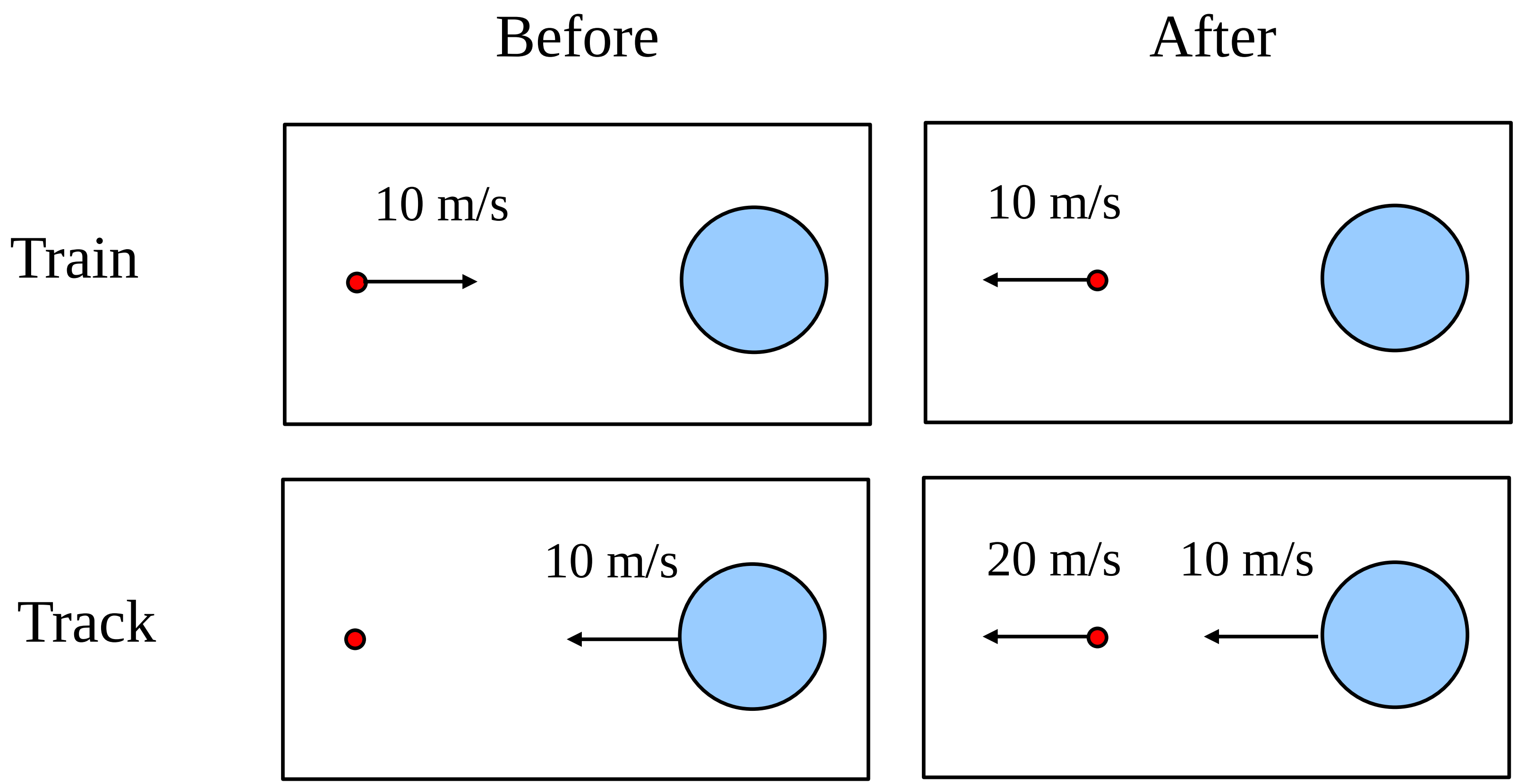


Assuming the train is moving at 5 m/s to the right.

Ex. 3: Very Small vs Very Big

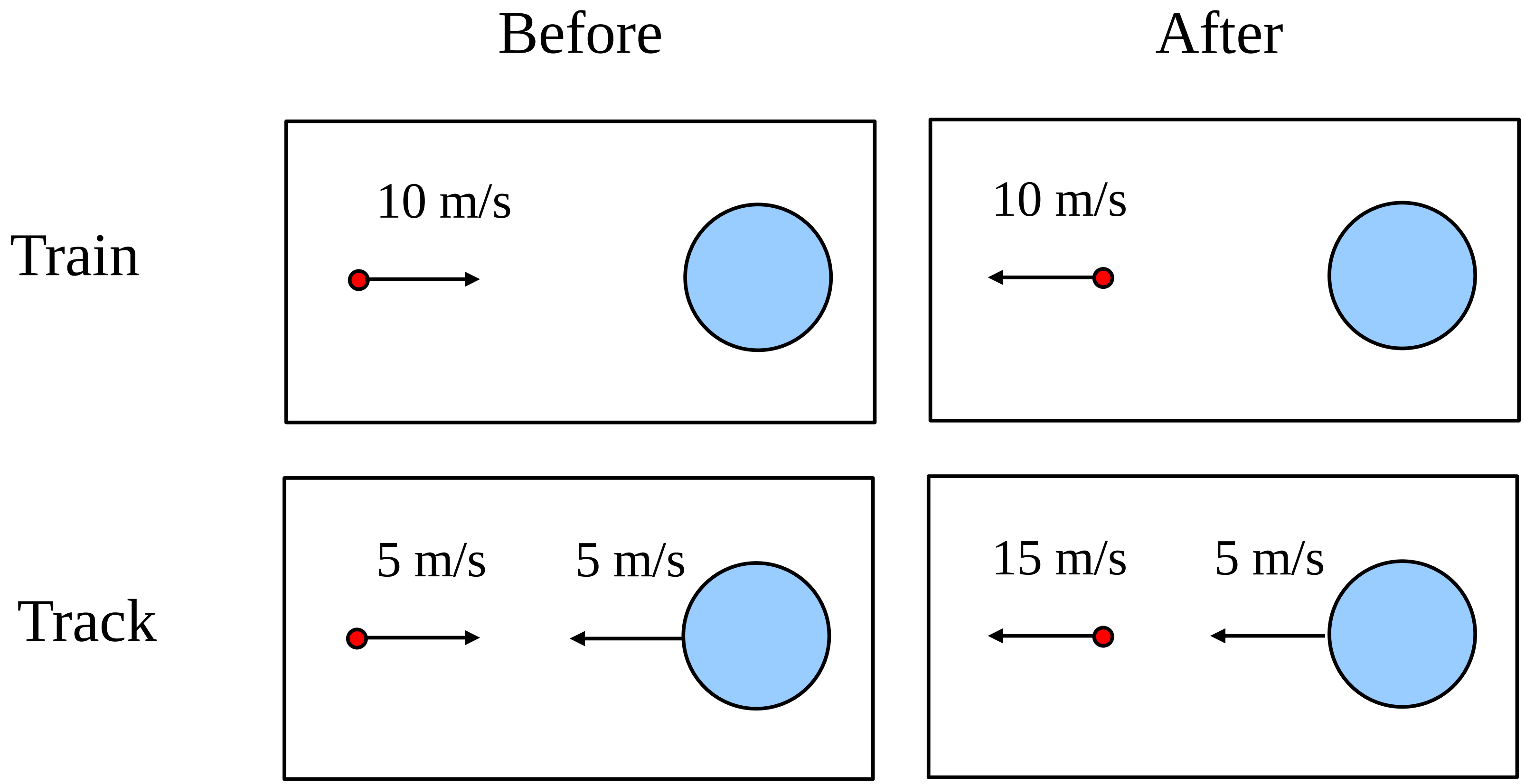


Ex. 3: Very Small vs Very Big



Assuming the train is moving at 10 m/s to the left.

Ex. 4: Slow Down the Train



Assuming the train is moving at 5 m/s to the left.

With Respect to What?

- **Light travels with a speed of 299,792,458 m/s in vacuum. With respect to what? The answer seems to be "with respect to any inertial frame you like."**

- **But how can this even be possible? It is highly counterintuitive. No, it seems impossible.**
  - **Frank notes in each second the light moves 299,792 km to his left, and Mary is moving 208 km (we assume this for simple illustration) to his right. Light is moving closer to Mary at 300,000 km/s, isn't it? But Mary should measure the light coming at her with a speed 299,792 km. Who is wrong?**

This appears to violate the principle of relativity!?

Now we need insight….

- We next march to the theory of relativity.