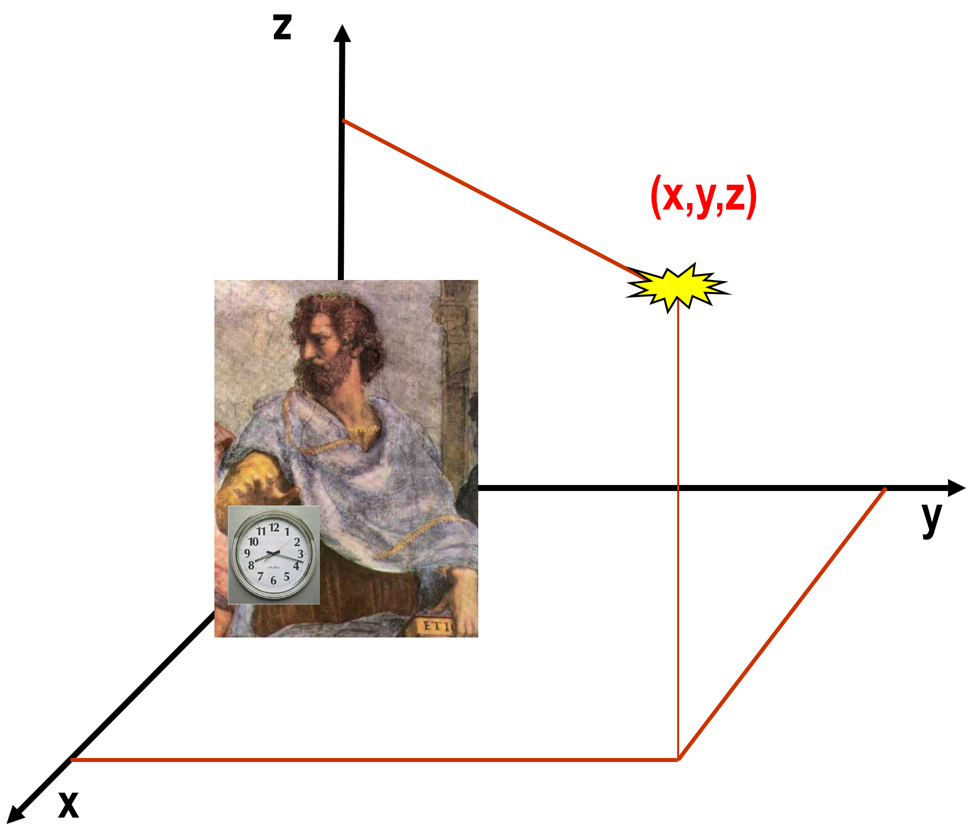
Lecture 38

Special Relativity

Einstein messes with space and time

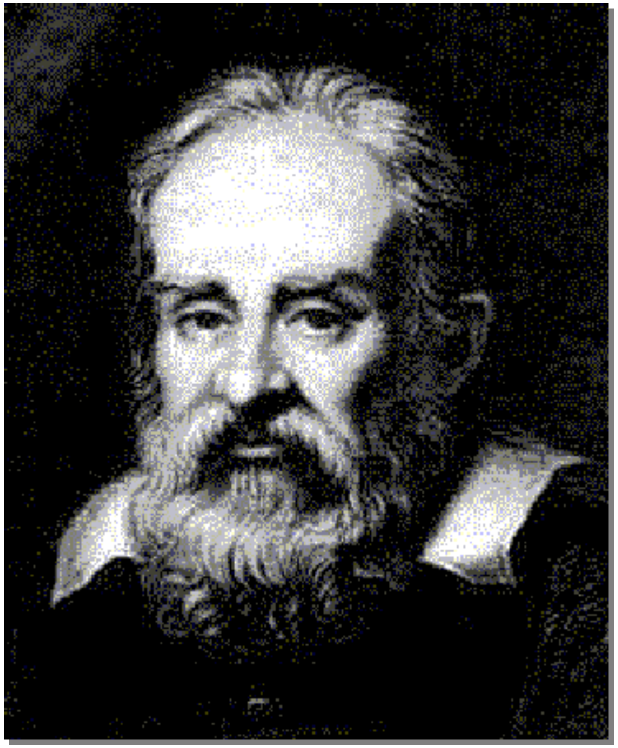
Aristotle's space and time



- There exists a Prime Mover, a privileged being in the state of Absolute Rest
- The position of everything else is measured with three numbers (x, y, z) with respect to the Prime Mover, who sits at (0,0,0).
- The time is measured by looking at the Prime Mover's clock

This point of view prevailed for almost 2,000 years

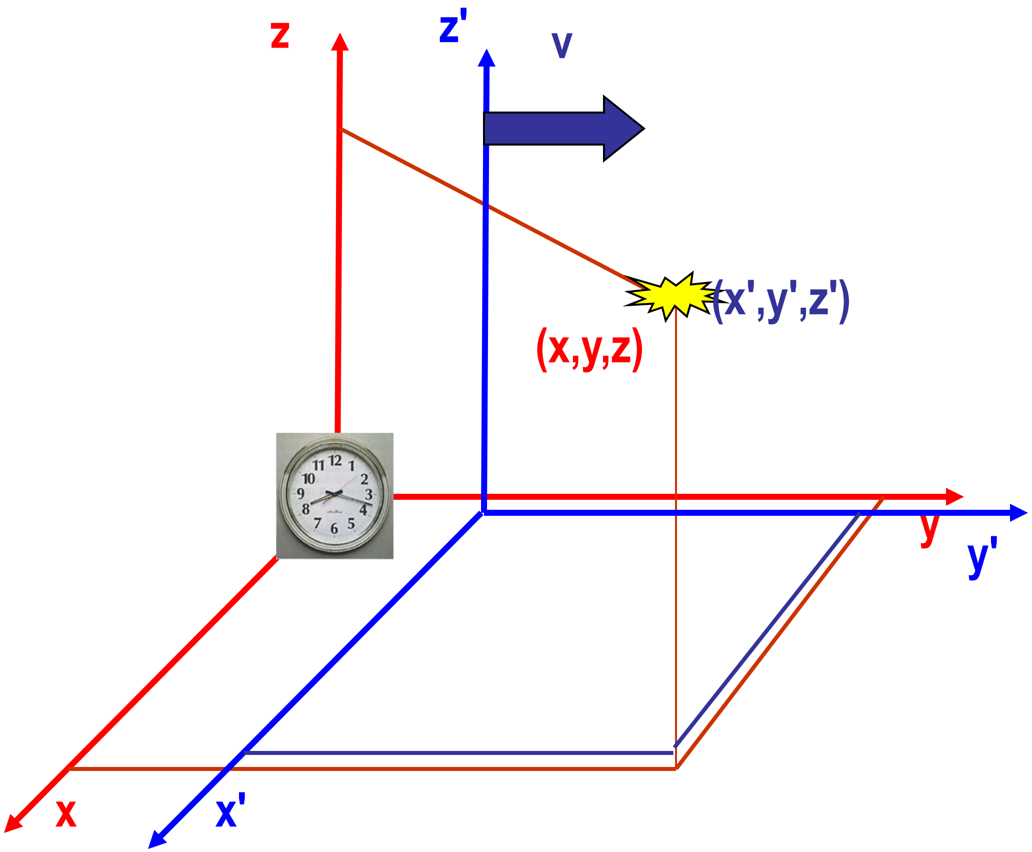
Galileo's challenge



Galileo Galilei
1564 -1642

- Galileo argued that there is no such thing as "Absolute Rest". In his view:
- The mechanical laws of physics are the same for every observer moving with a constant velocity along a straight line (this is called "inertial observer" for short).

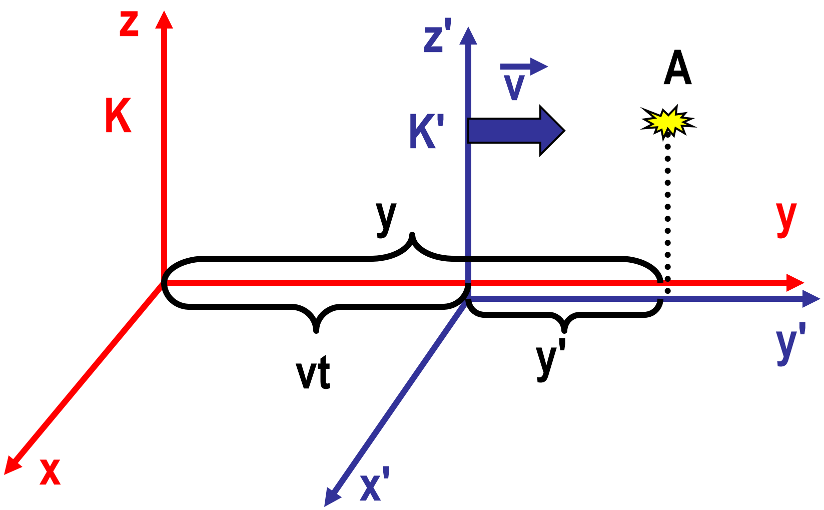
Galileo's space and time



- Every inertial observer could declare themselves "the Prime Mover", and measure the position of everything with respect to their own set of (x, y, z)

- The time is still measured by looking at the Prime Mover's clock!

Galileo's transformations



- We have two frames of reference, K and K', and K' is moving along axis y with some constant speed v.
- Something happened at point A.
- According to Galileo, there is no one special reference frame -- if we know where A happened in one frame, we are done! That's

$$y = y' + vt$$

$$x = x'$$

$$z = z'$$

$$t = t'$$

Galileo transformations:
know what happened in one frame, can tell what happened in another

Newton's laws of mechanics

Sir Isaac Newton
1642-1727

- Newton's laws of mechanics are in agreement with Galileo's relativity

1. A body, not acted upon by any force, stays at rest or remains in uniform motion, whichever it was doing to begin with
2. To get an object to change its velocity, we need a force

Force = mass x acceleration
(acceleration = change in velocity)

$$\vec{F} = m\vec{a} \equiv m\frac{\Delta\vec{v}}{\Delta t}$$

Newton's laws are the same in all inertial frames

- We know how positions of an object transform when we go from one inertial frame of reference to another

$$\boxed{\begin{aligned} &y = y' + vt \\ &x = x'; z = z'; t = t' \end{aligned}}$$

- What about velocities?

$$\boxed{\begin{aligned} &u_y \equiv \frac{dy}{dt} = \frac{d(y'+vt)}{dt} = \frac{dy'}{dt} + \frac{d(vt)}{dt} \equiv u_y' + v \\ &u_x = u_x'; u_z = u_z' \end{aligned}}$$

⇒ velocity of an object in K is equal to its velocity in K', plus the velocity of K' with respect to K

- What about accelerations?

$$\boxed{a_y \equiv \frac{du_y}{dt} = \frac{d(u_y'+v)}{dt} = \frac{du_y'}{dt} + \underbrace{\frac{dv}{dt}}_{= 0 \text{ as } v = \text{const}} \equiv a_y'}$$

⇒ **Accelerations are the same in both K and K' frames!**

So Newtonian forces will be the same in both frames

The clouds start to gather…

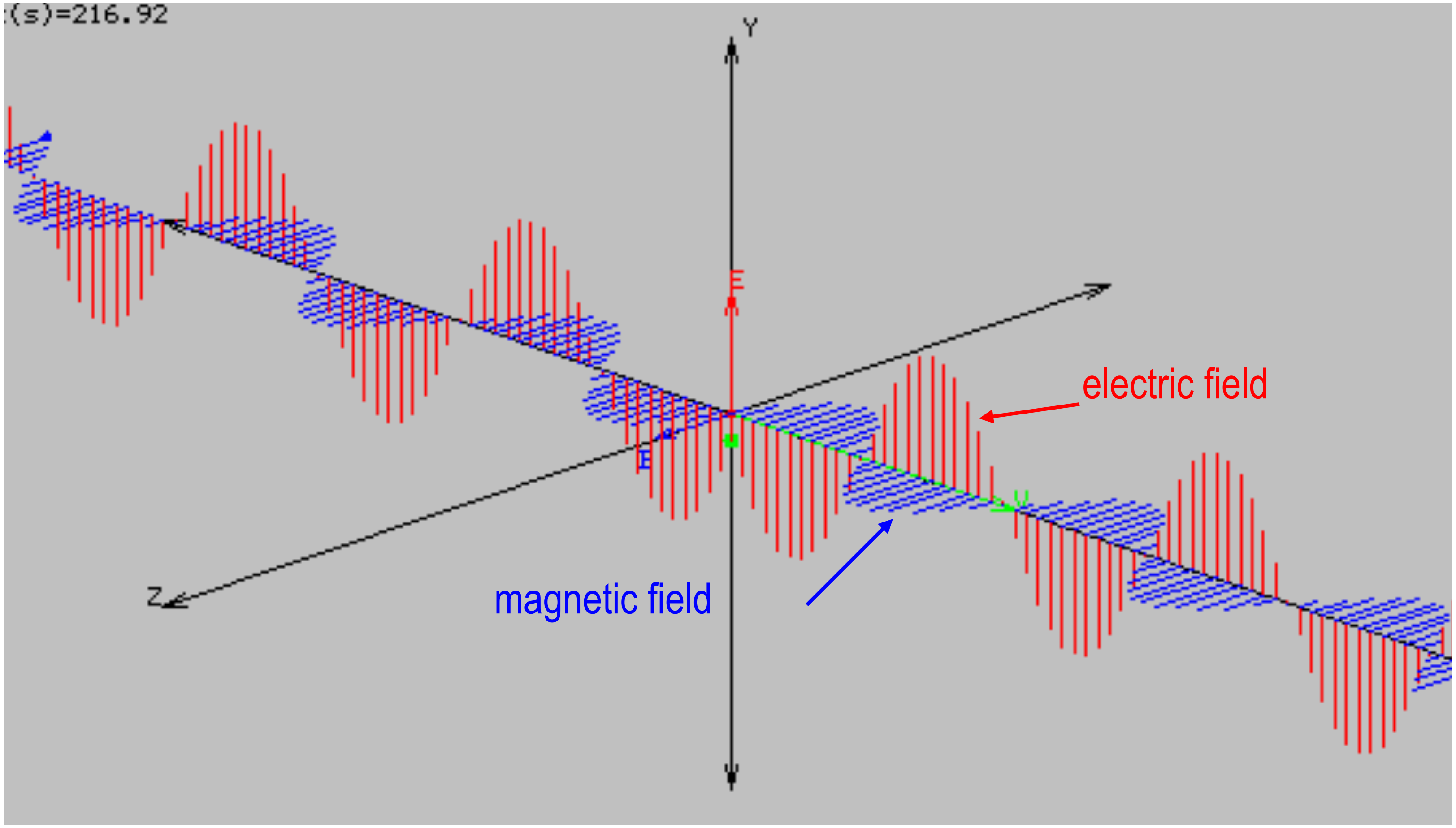
- For more than two centuries after its inception the Newtonian view of the world ruled supreme
- However, at the end of the 19th century problems started to appear
- The problematic issue can be reduced to these questions:
  - What is light? How does it propagate?

Here comes Maxwell

James C. Maxwell
1831-1879

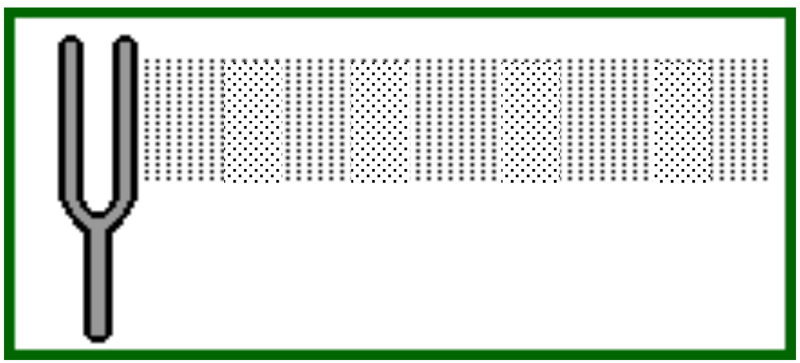
- Maxwell brought together the knowledge of electricity and magnetism known in his day in a set of four elegant equations known as **Maxwell's equations**
- In the process, he introduced a new concept: electromagnetic waves, and found that they traveled at the speed of light
  - Light is an electromagnetic phenomenon!

Electromagnetic waves



Waves in general

- The waves we are all familiar with require something to propagate in



Sound waves are compressions of air (water, etc.)

Spring compressions in a slinky

- What about light?
  – The most natural assumption would be that it requires a medium, too!

Ether

- This mysterious medium for light was called **ether**
- What would its properties be?
  - We see light from distant starts, so ether must permeate the whole universe
  - Must be very tenuous, or else the friction would have stopped the Earth long ago

→ **Ether would be like a ghostly wind blowing through the Universe!**

- Michelson and Morley attempted to detect ether by measuring the speed of light in two different directions: "upwind" and "downwind" with respect to ether.

The Michelson-Morley Experiment

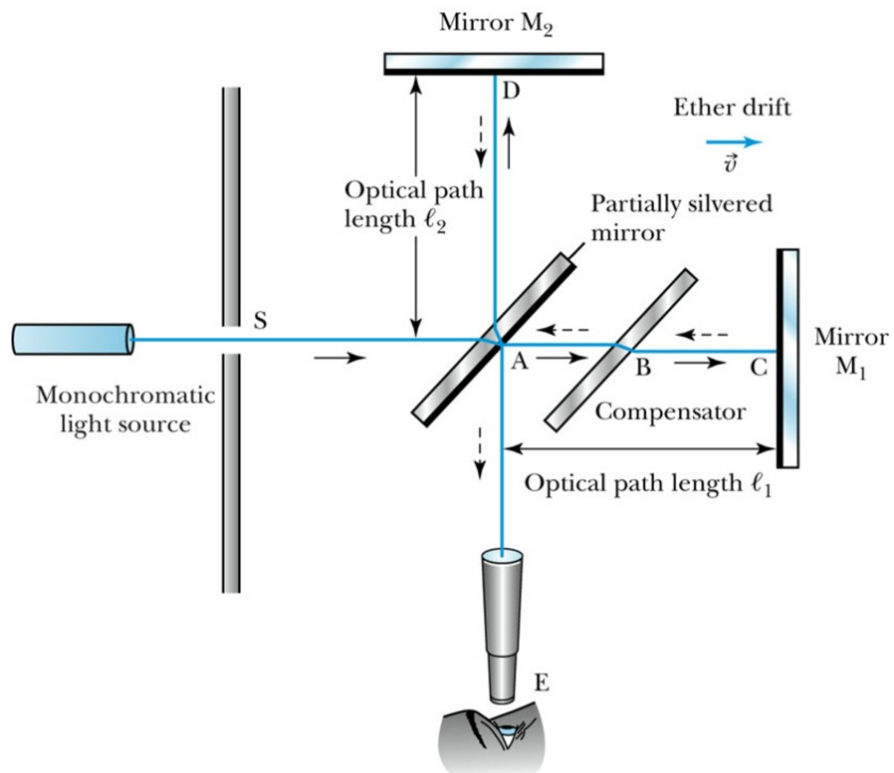
- Albert Michelson (1852–1931) was the first U.S. citizen to receive the Nobel Prize for Physics (1907), and built an extremely precise device called an *interferometer* to measure the minute phase difference between two light waves traveling in mutually orthogonal directions.

The Michelson Interferometer

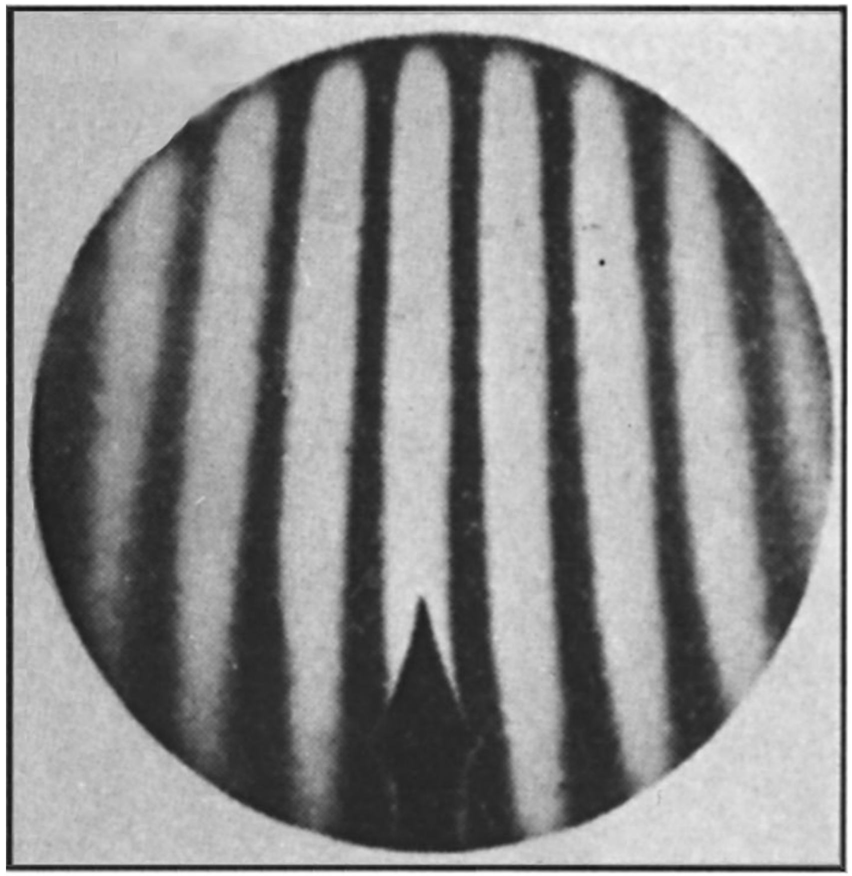
1. AC is parallel to the motion of the Earth inducing an “ether wind”

2. Light from source S is split by mirror A and travels to mirrors C and D in mutually perpendicular directions

3. After reflection the beams recombine at A slightly out of phase due to the “ether wind” as viewed by telescope E.



Typical interferometer fringe pattern expected when the system is rotated by 90°



Michelson's Conclusion

- Michelson noted that he should be able to detect a phase shift of light due to the time difference between path lengths but found none.
- He thus concluded that the hypothesis of the stationary ether must be incorrect.
- After several repeats and refinements with assistance from Edward Morley (1893-1923), again *a null result*.
- ***Thus, ether does not seem to exist!***

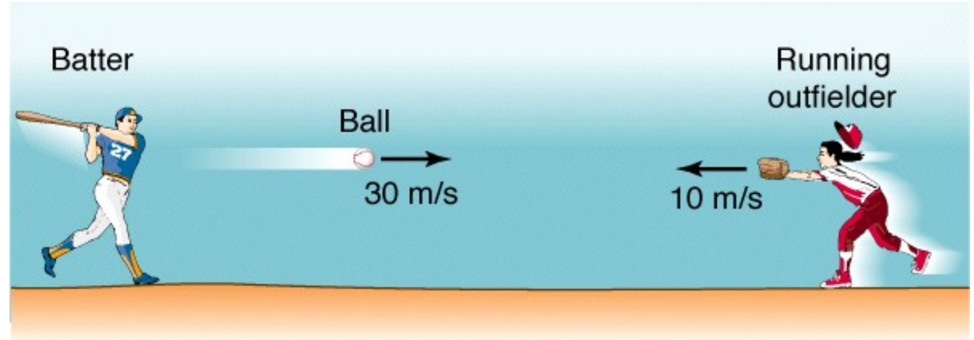
Einstein’s Two Postulates

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.

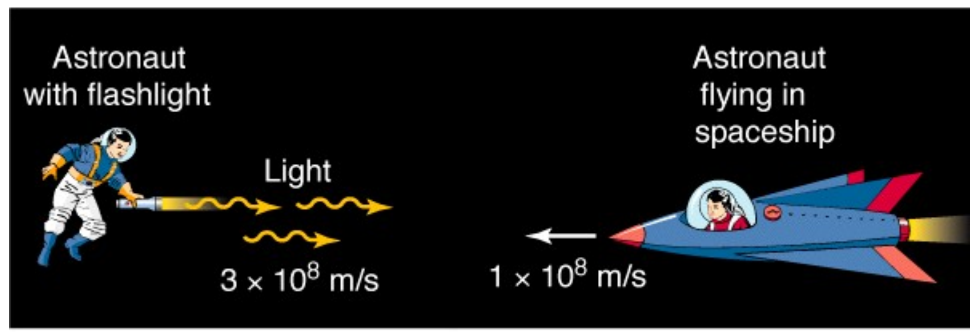
Although relative velocities add/subtract for most common objects,

THIS IS NOT TRUE FOR LIGHT! The speed of a light source coming toward you is the same as one going away from you.



As seen by outfielder, ball is approaching her at (30 m/s) + (10 m/s) = 40 m/s

a



Incorrect Newtonian description:

As seen by astronaut in spaceship, light is approaching her at $(3 \times 10^8 \text{ m/s}) + (1 \times 10^8 \text{ m/s}) = 4 \times 10^8 \text{ m/s}$

Correct Einsteinian description:

As seen by astronaut in spaceship, light is approaching her at 3×10^8 m/s

b