

# Modern Physics (Phys. IV): 2704

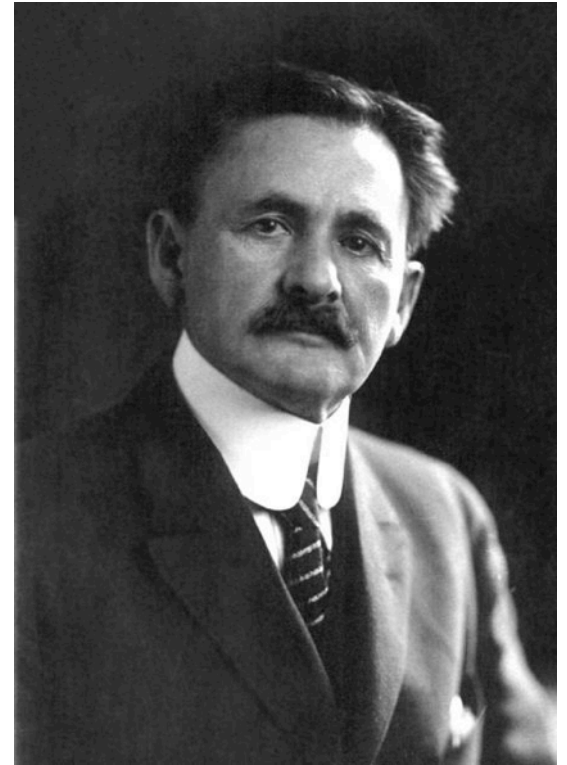
Professor Jasper Halekas  
Van Allen 70  
MWF 12:30-1:20 Lecture

# Announcements

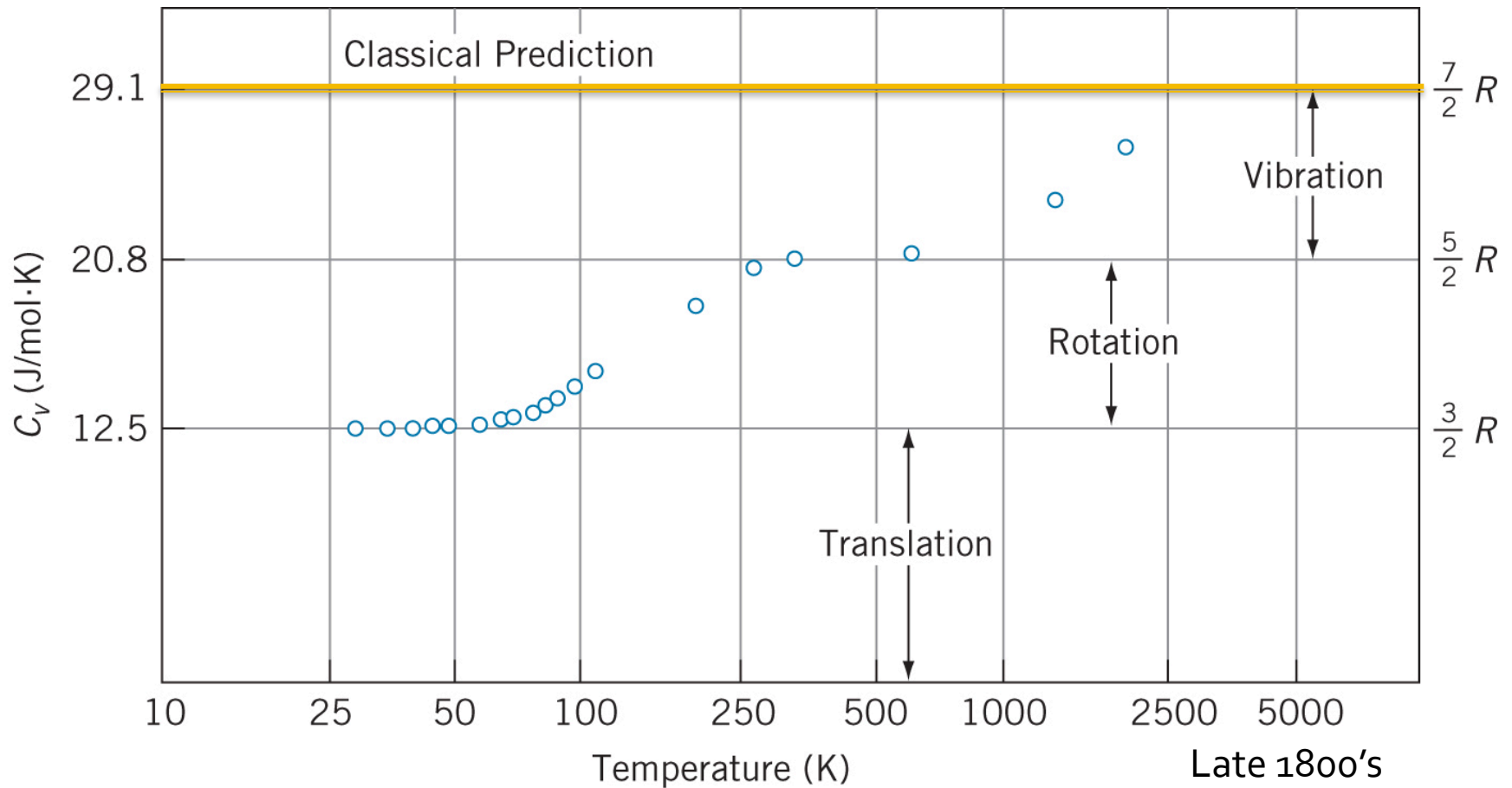
- First homework assigned – due next Friday
  - Go to “Assignments” tab on main web page
- Remember we will start using Turning Point this coming Monday

# Smug Physicists

- *While it is never safe to affirm that the future of Physical Science has no marvels in store even more astonishing than those of the past, it seems **probable that most of the grand underlying principles have been firmly established** and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice.*
  - Albert Michelson - 1907



# Signs of Trouble: Heat Capacity



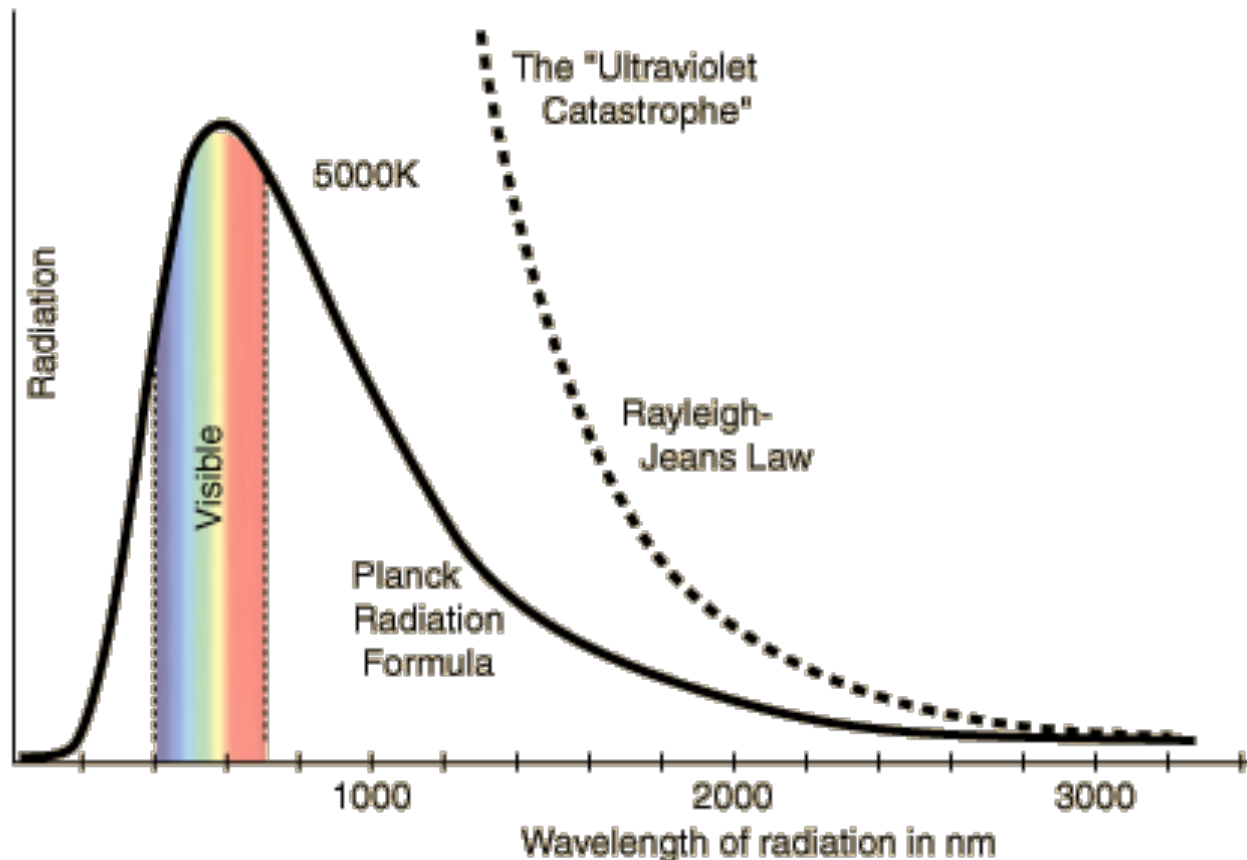


# The Root of the Issue: Equipartition

- Equipartition theorem says each degree of freedom for a particle has an average of  $1/2kT$  of energy
  - I.e.  $\langle E \rangle = \langle 1/2mv_x^2 + 1/2mv_y^2 + 1/2I\omega_x^2 + 1/2I\omega_y^2 \rangle = 4 * 1/2 kT = 2kT$  would be the average energy for a particle free to move or rotate in 2-d
- Implication for heat capacity
  - $C = \Delta E/n\Delta T = \text{constant}$  (does not match data!)

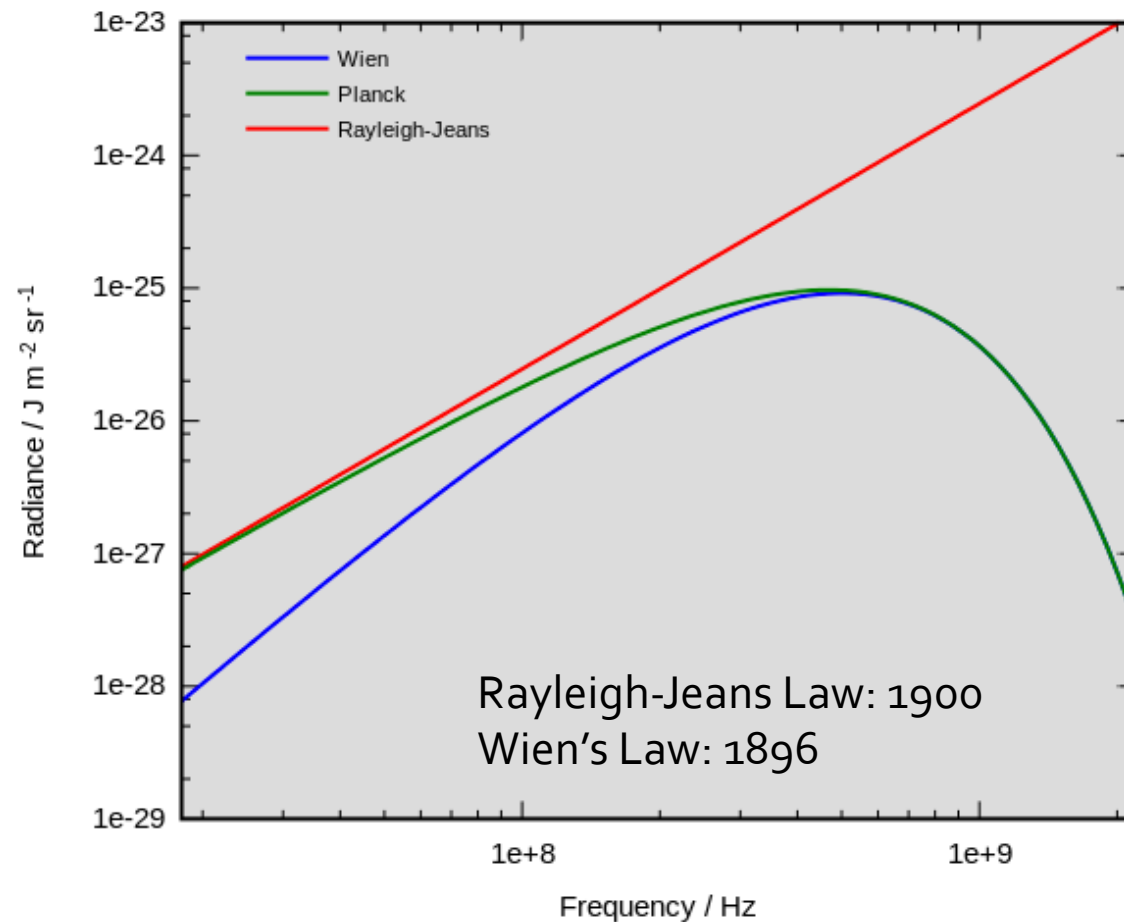
# Signs of Trouble: Blackbody Radiation

- Blackbody Radiation

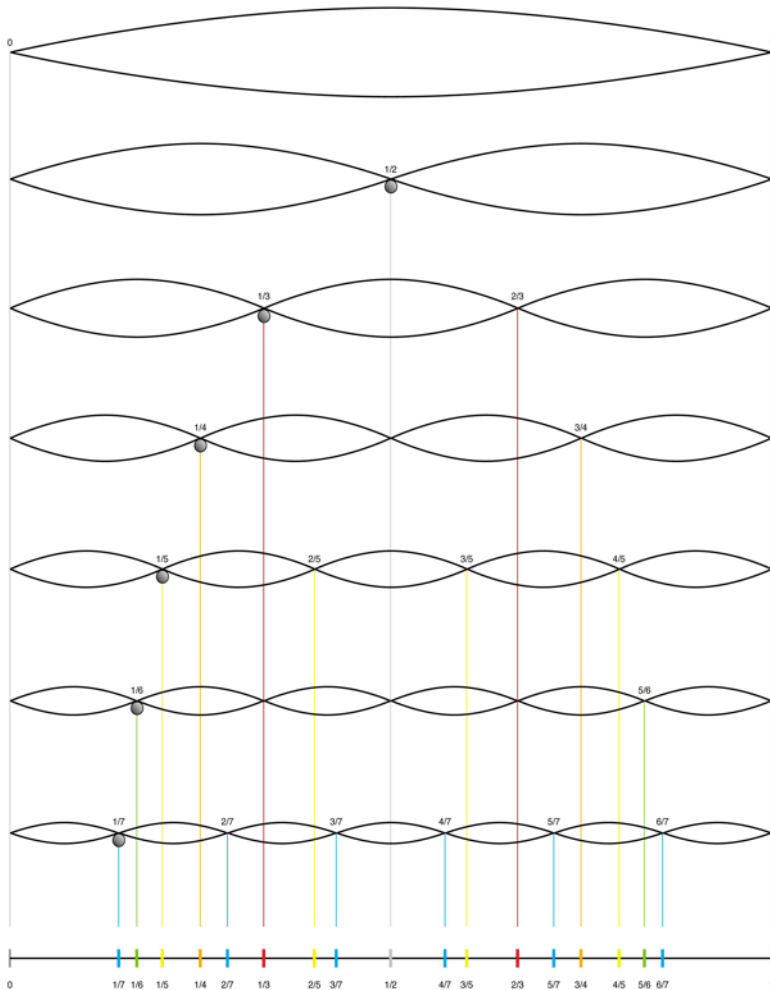


# Signs of Trouble: Blackbody Radiation

- Blackbody Radiation



# The Root of the Issue: Equipartition



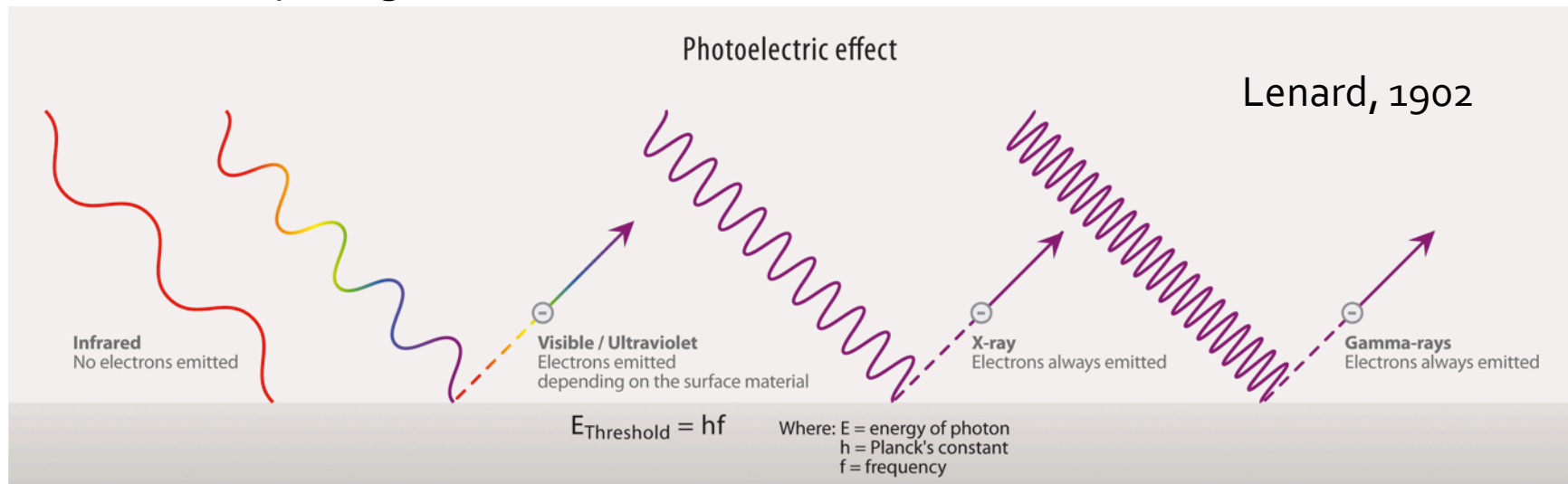
Equipartition says each mode of oscillation (standing wave) has  $\frac{1}{2}kT$  of energy on average

But... there are a huge number of standing waves at high frequency (small wavelength)

=> "The ultraviolet catastrophe"

# Signs of Trouble: Photoelectric Effect

**Classical Prediction:** Electrons should only be ejected if light is above some threshold intensity, and the energy of electrons ejected should depend on the intensity of light.



**Experimental Result:** Electrons only ejected for light above some threshold frequency. The energy of electrons ejected depends on frequency of light, and is independent of the intensity of the light.

# The Root of the Issue: Light is a Wave (Isn't it?)

*And it came to pass that...*

$$\oint \mathbf{E} \cdot d\mathbf{A} = q/\epsilon_0$$

Gauss' law for electricity

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

Gauss' law for magnetism

$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

Faraday's law

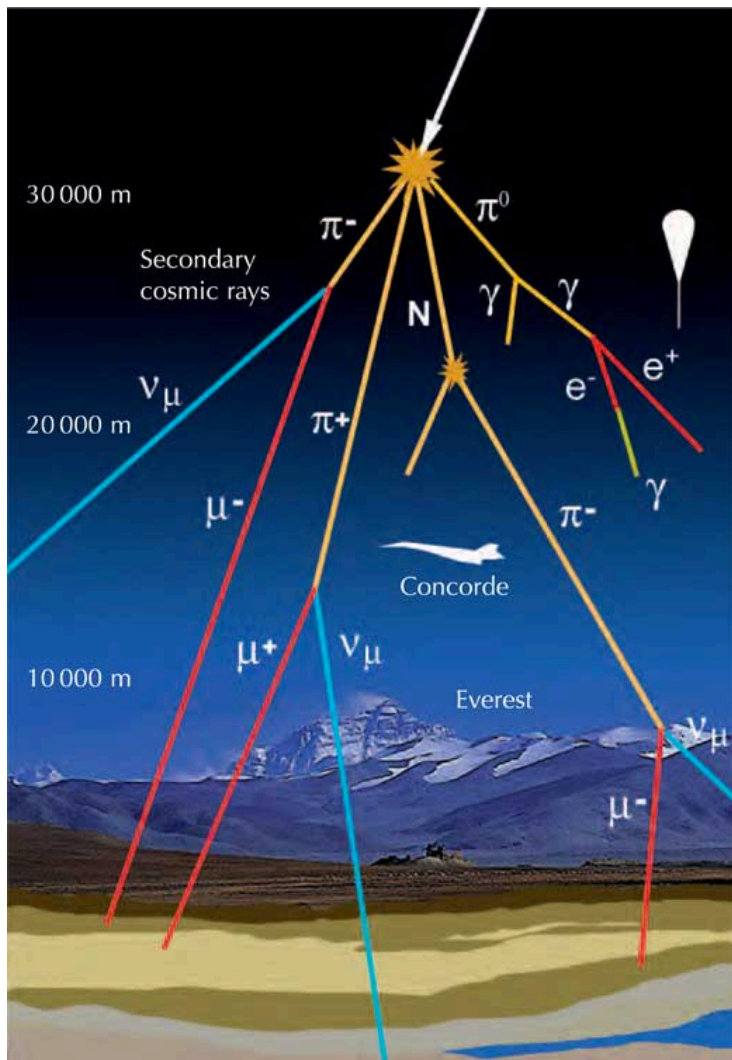
$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i$$

Ampere-Maxwell law

*and there was Light!*



# Signs of Trouble: Cosmic Rays



Cosmic rays strike the top of the atmosphere and produce a shower of secondary particles

Many muons reach sea level

But, according to laboratory experiments, muons have a lifetime of  $\sim 2.2 \mu\text{s}$ , only enough time to travel  $< 1 \text{ km}$  even at their maximum speed

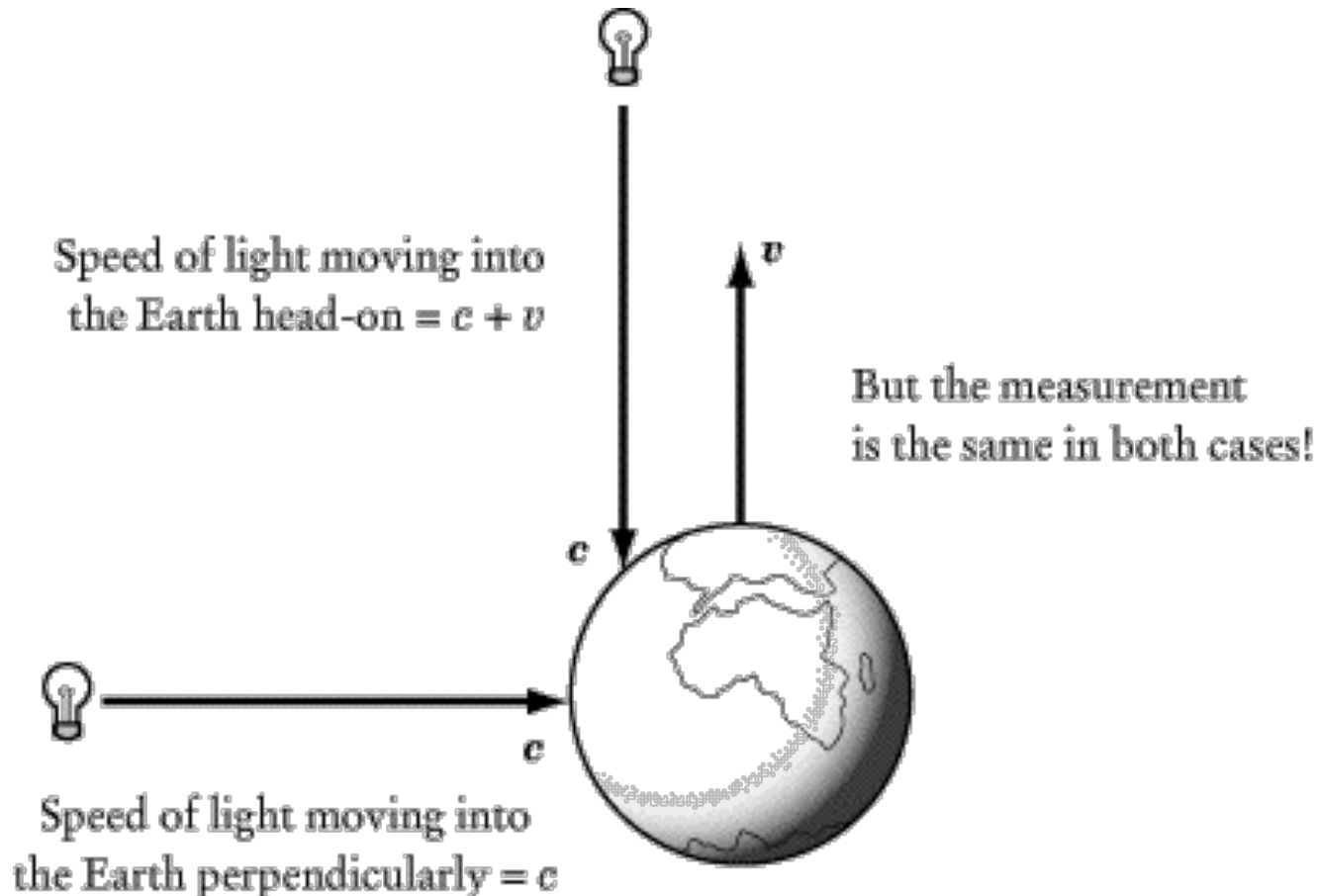
# The Root of the Problem: Time Invariance

- Everyone should agree on how long something takes (shouldn't they?)!



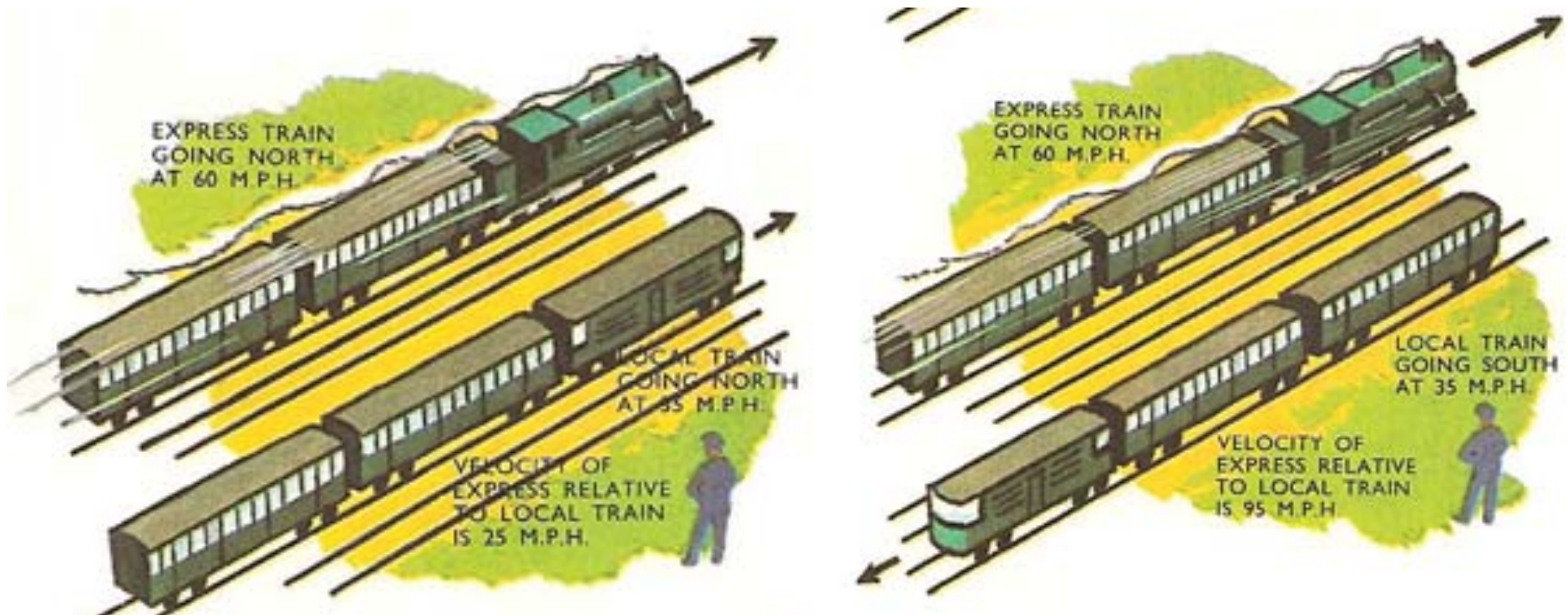
# Signs of Trouble: Speed of Light

- Michelson-Morley Experiment (1887)



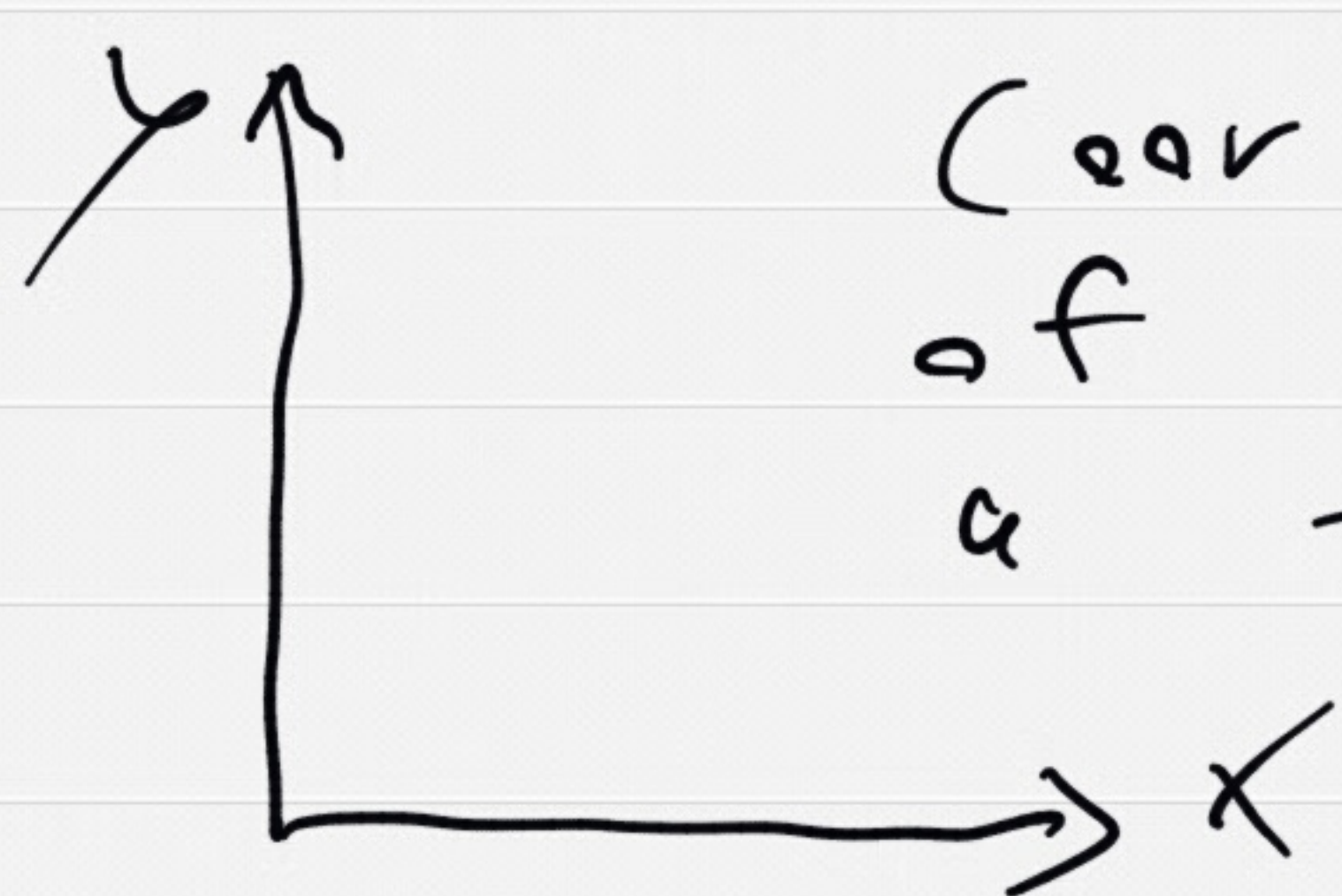


# The Root of the Issue: Velocity Addition





# Reference Frames

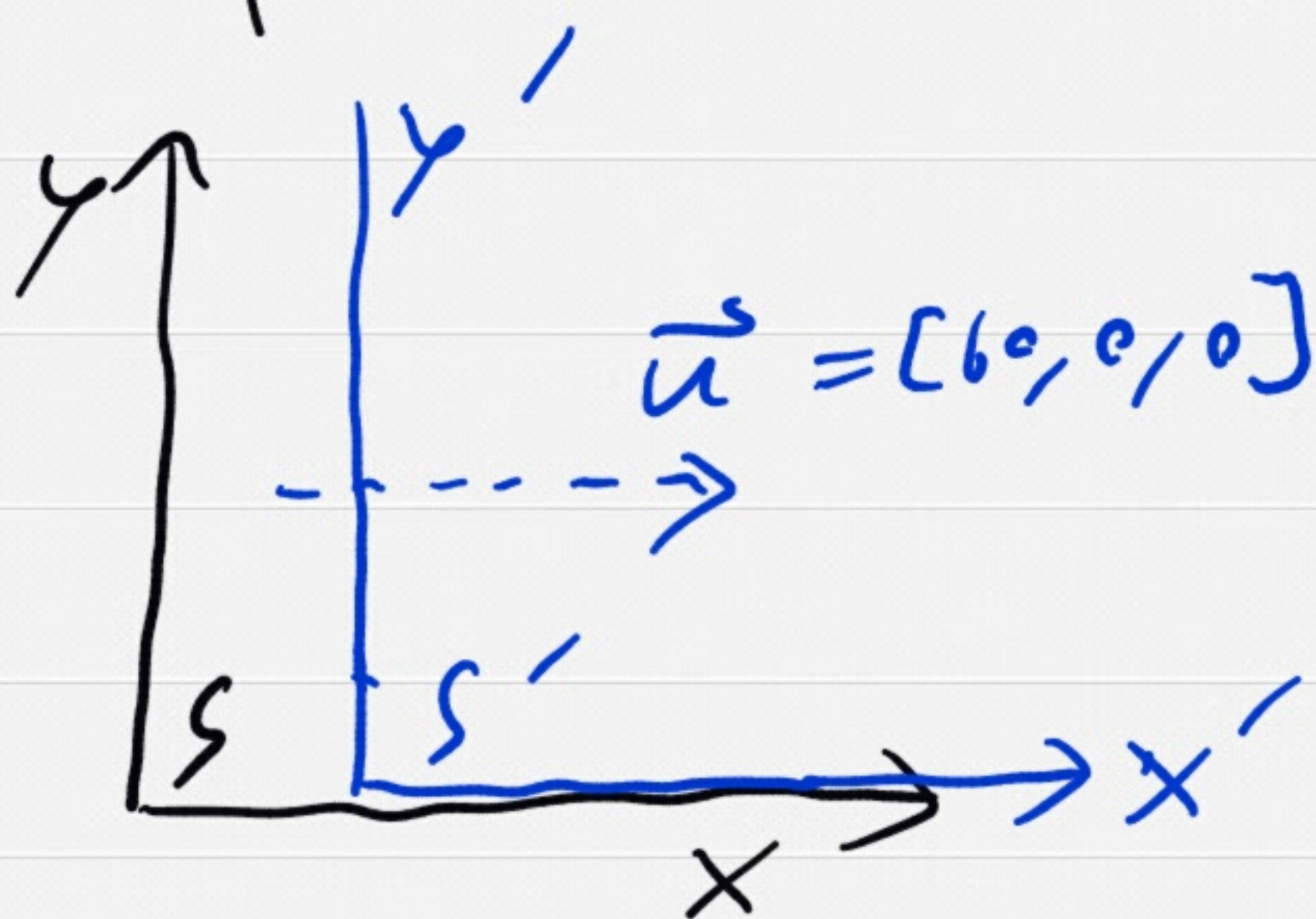


Coordinates of frame  $S$   
of observer not on  
a train

$$\vec{v}_{\text{express}} = [60, 0, 0]$$

$$\vec{v}_{\text{local}} = [25, 0, 0]$$

- But to a person on the  
express train



$$\begin{aligned} v'_{\text{exp}} &= [0, 0, 0] \\ v'_{\text{local}} &= [-35, 0, 0] \\ v'_{\text{obs}} &= [-60, 0, 0] \end{aligned}$$

Can write as 
$$\begin{aligned} \vec{v}' &= \vec{v} - [60, 0, 0] \\ &= \vec{v} - \vec{u} \\ &\text{w/ } \vec{u} = u\hat{i} \end{aligned}$$

$$\text{or } \left. \begin{aligned} v'_x &= v_x - u \\ v'_y &= v_y \\ v'_z &= v_z \end{aligned} \right\} \text{Galilean Transformation}$$



Integrate to find:

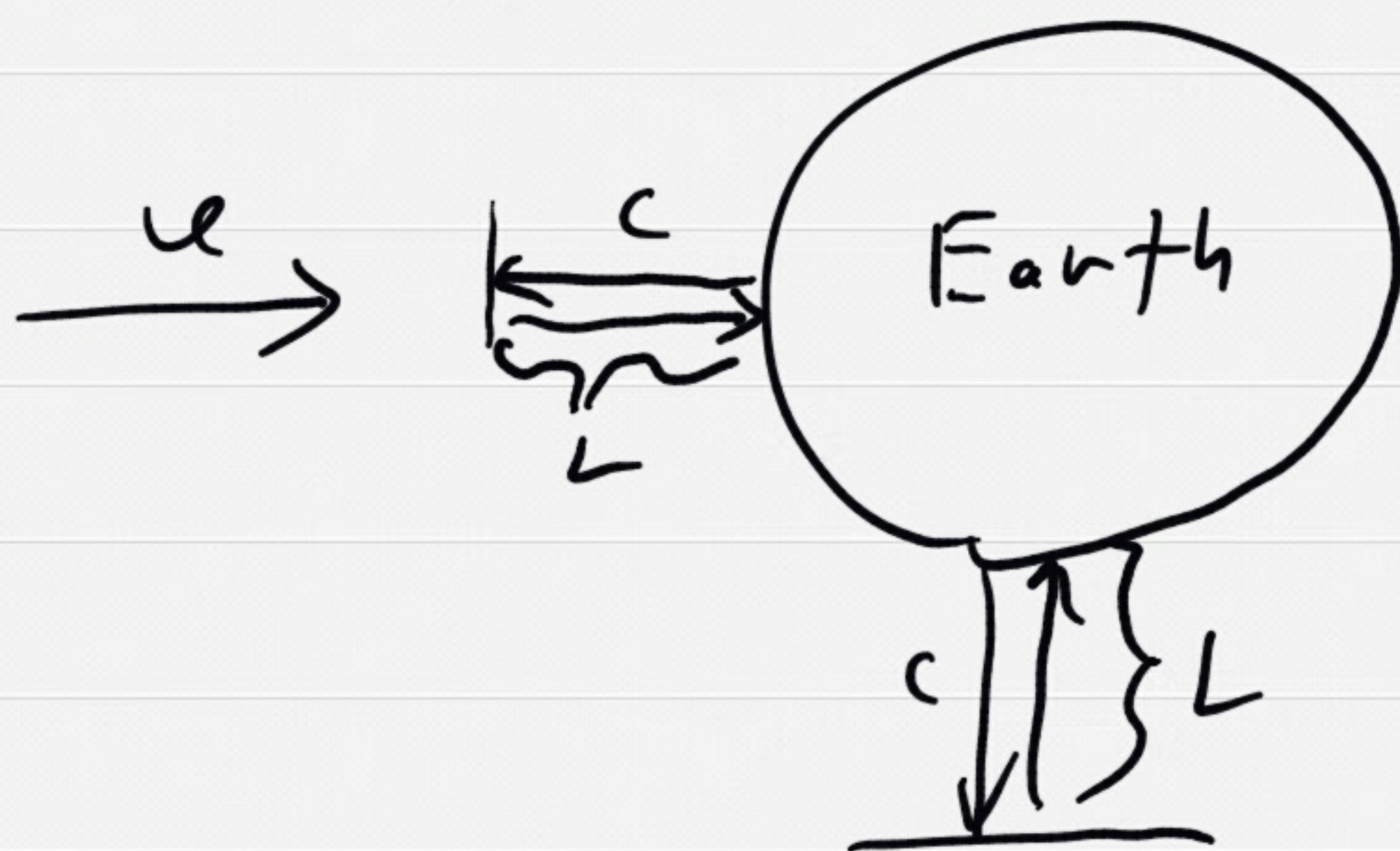
$$x' = x - ut + \text{const.}$$

$$y' = y + \text{const.}$$

$$z' = z + \text{const.}$$

## Michelson - Morley

Ether



- Look @ time to travel distance  $L$  for light moving at speed  $c$  w/ respect to ether (primed frame)

Left

$$v_{x1} = v_{x1}' + u \quad (\text{Inverse Galilean})$$
$$= u - c$$

$$t_1 = L / |v_{x1}| = L / c - u$$

Right

$$v_{x2} = c + u$$

$$t_2 = L / |v_{x2}| = L / c + u$$

Round-trip

$$t_{1+2} = L / c - u + L / c + u$$
$$= [(c+u)L + (c-u)L] / (c^2 - u^2)$$
$$= 2Lc / (c^2 - u^2)$$



- Left-Right round-trip  
in Earth frame

$$t_{1+2} = \frac{2Lc}{c^2 - u^2}$$
$$= \frac{2L}{c} \cdot \frac{1}{1 - u^2/c^2}$$

- Travel time perpendicular to  
flow of ether



$$v_x' = -u$$

$$\Rightarrow v_x = v_x' + u = 0 //$$

$$v_y = v_y' = \sqrt{c^2 - u^2}$$

$$t_1 = t_2 = L/v_y = L/\sqrt{c^2 - u^2}$$

$$t_{1+2} = 2L/\sqrt{c^2 - u^2}$$

$$= 2L/c \cdot \frac{1}{\sqrt{1 - u^2/c^2}}$$

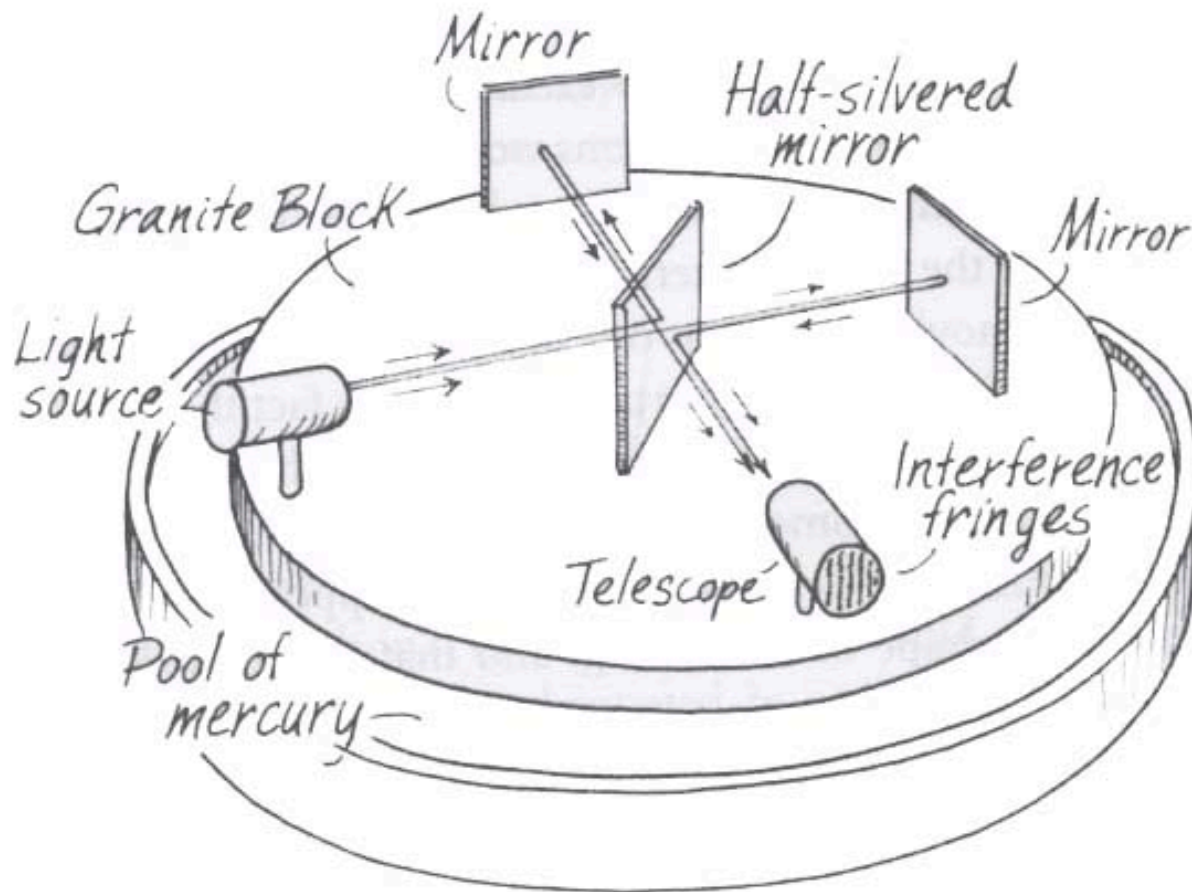
- Both tend to  $2L/c$  for  $u = 0$

- Not equal for  $u \neq 0$

- But M-M experiment  
shows they are exactly equal



# Michelson-Morley Experiment



# Michelson-Morley Experiment



# Michelson-Morley Results

- No time-difference detectable
  - Possible Implications:
    - Earth not moving
      - Inconsistent with known orbit around Sun!
    - No such thing as ether ✓
      - But then what is the medium that is “waving”?
    - Galilean transformation is incorrect ✓
      - But this must imply that time and/or space are not invariant...

# “Relativistic Speeds”

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 299,792,458 \text{ m/s} \sim 3 \times 10^8 \text{ m/s}$$

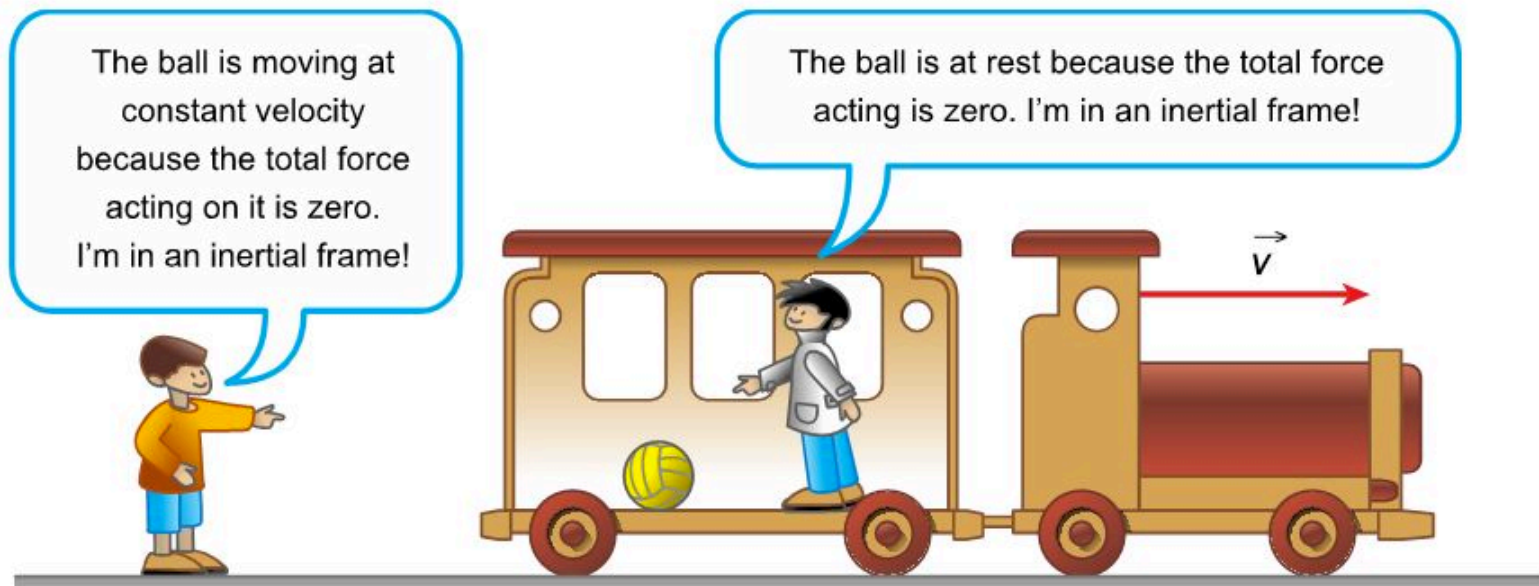
- Imagine accelerating a charged particle through a 500 V electrostatic potential (you'll do this in lab next week):
  - $\frac{1}{2}mv^2 = qV$  (non-relativistic expression)
    - Proton velocity =  $4.38 \times 10^5 \text{ m/s} \sim c/969$
    - Electron velocity =  $1.33 \times 10^7 \text{ m/s} \sim c/23$

# Inertial Reference Frames

- “Inertial reference frame” = A frame in which Newton’s laws hold
  - An object at rest stays at rest and an object in motion stays in motion with a constant velocity unless acted on by an unbalanced force

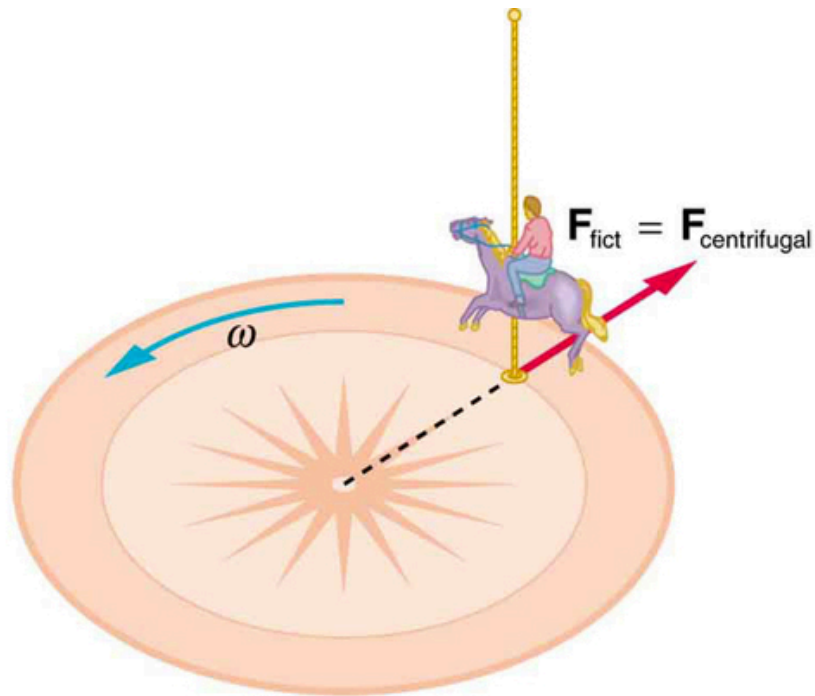


# Inertial Reference Frames

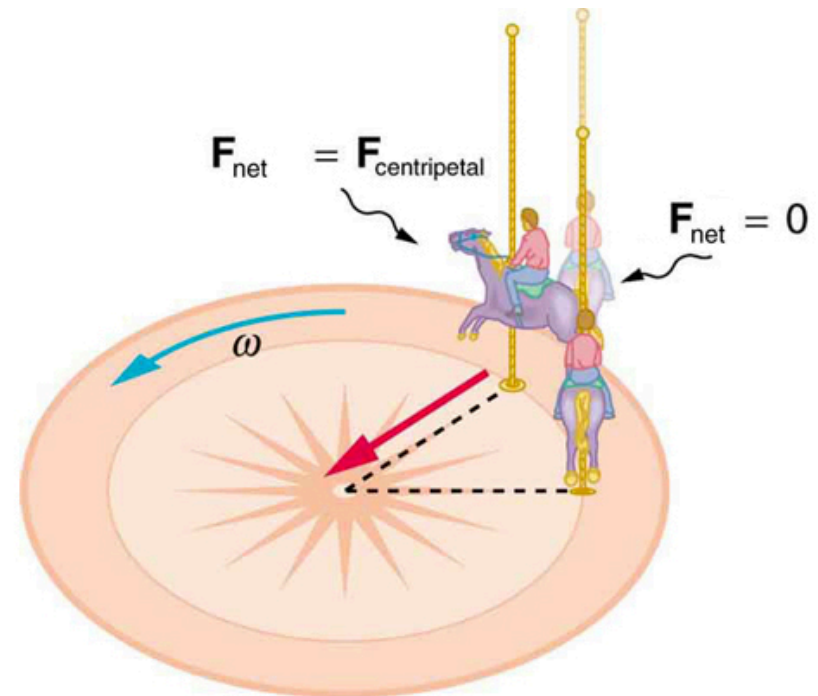


- Any inertial reference frame moving at constant velocity with respect to another is also an inertial reference frame

# Non-Inertial Reference Frames



Merry-go-round's rotating frame of reference



Inertial frame of reference

- Special relativity **only** applies to inertial reference frames
- General relativity is needed for non-inertial reference frames