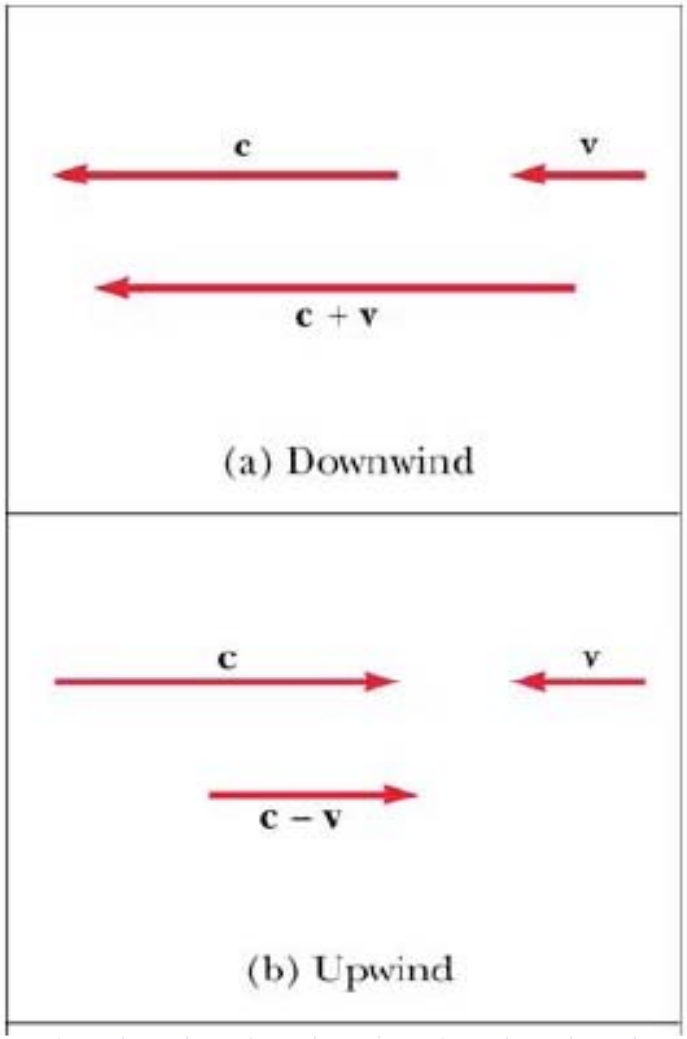
Michelson-Morley

- Developed an experiment to measure the speed of light in different directions
  - Ether was the assumed medium in which light waves traveled
    - The ether needs to have high restoring force and/or low density to support a velocity $v=c$
  - Ether was needed to support Galilean invariance of Maxwell's equations
    - We will come back to this point later but consider that the speed of sound has a characteristic value relative to the rest frame of the air ($v = 331\ m/s$)
    - c in Maxwell's equations was assumed to be relative to the ether

Michelson-Morley

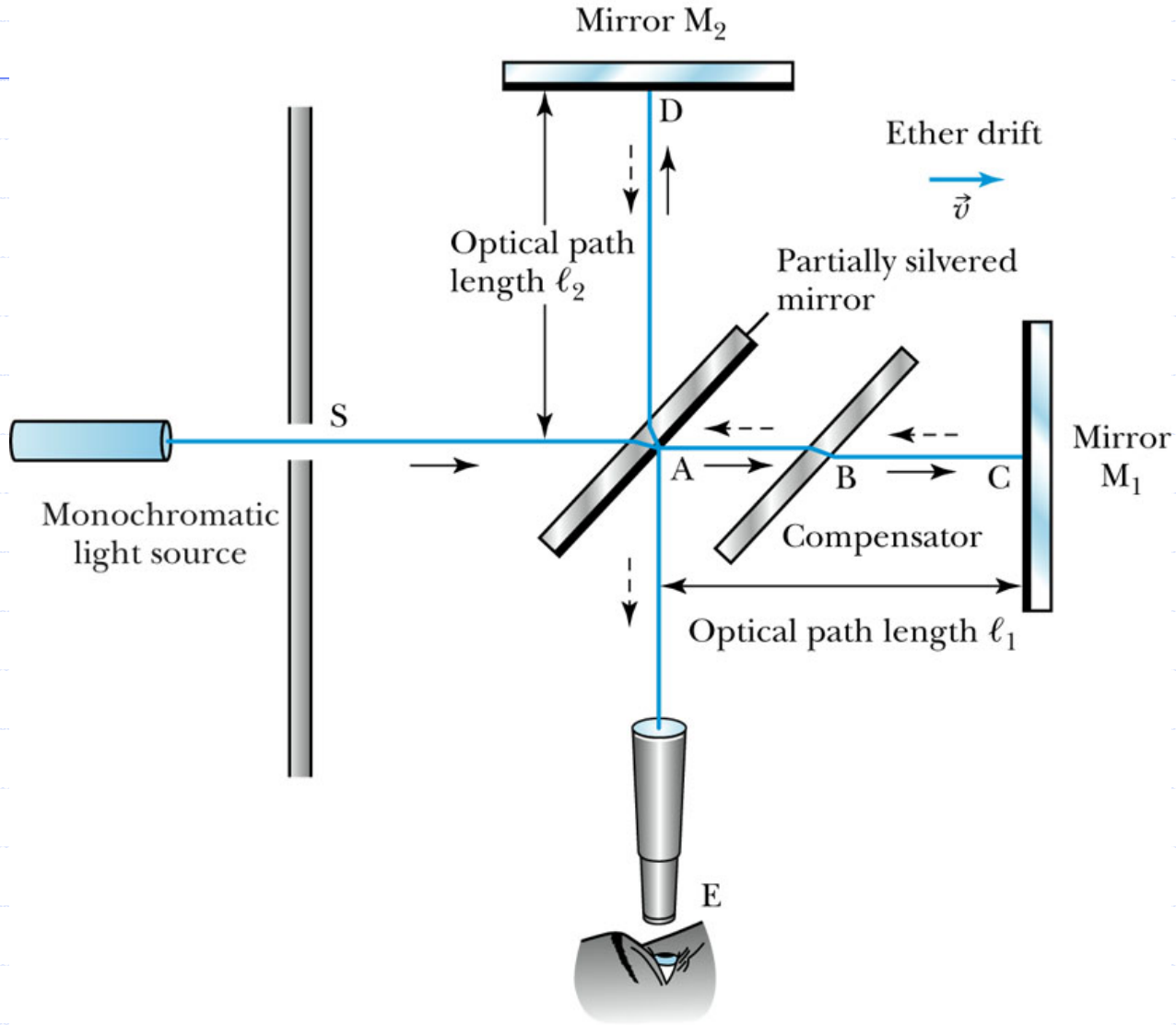
- c is the velocity of light relative to the ether
- v is the velocity of the ether relative to the earth



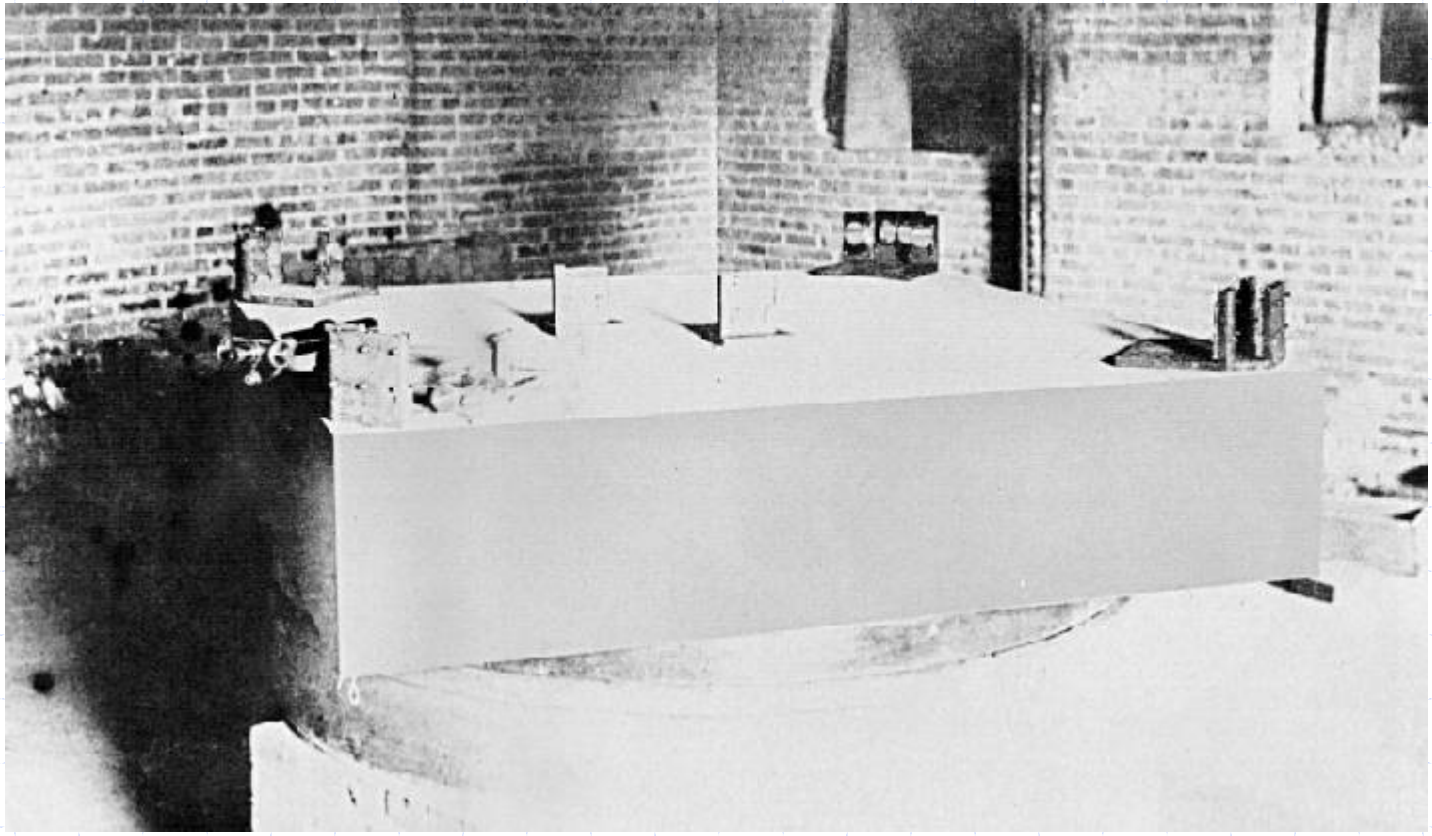
Michelson-Morley

- What is v_{earth}?
  - Earth spins on its axis
    - Rotation time = 24h x 60m/h x 60s/m = 86400 s
    - Rotation distance = 2 x pi x 6.4×10^6 m = 4.0×10^7 m
    - Rotation velocity = 465 m/s ~ $10^{-6}c$
  - Earth revolves around sun
    - Revolution time = 3.15×10^7 s
    - Revolution distance = 2 x pi x 1.5×10^{11} m =9.4×10^{11} m
    - Revolution velocity = 3×10^4 m/s ~ $10^{-4}c$
  - Earth/Sun moves wrt Milky Way galaxy center
    - Radial velocity = 2.5 x 10^5 m/s ~ $10^{-3}c$
- Measuring the round trip time for velocity c-v and c+v would require measuring a time difference to one part in 10^8 which is not feasible

Michelson-Morley



Michelson-Morley



Michelson-Morley

- Parallel and anti-parallel propagation
  - Time t_1 from A to C and back

$$t_1 = \frac{l_1}{c+v} + \frac{l_2}{c-v} = \frac{2cl_1}{c^2 - v^2} = \frac{2l_1}{c}\left(\frac{1}{1-\frac{v^2}{c^2}}\right)$$

- Perpendicular propagation
  - Time t_2 from A to D and back

$$t_2 = \frac{2l_2}{\sqrt{c^2 - v^2}} = \frac{2l_2}{c}\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

- Difference

$$\Delta t = t_2 - t_1 = \frac{2}{c}\left(\frac{l_2}{\sqrt{1-\frac{v^2}{c^2}}} - \frac{l_1}{1-\frac{v^2}{c^2}}\right)$$

Michelson-Morley

- Now rotate the apparatus by π/2 (90°)

$$\Delta t' = t_2' - t_1' = \frac{2}{c}\left(\frac{l_2}{1-\frac{v^2}{c^2}} - \frac{l_1}{\sqrt{1-\frac{v^2}{c^2}}}\right)$$

- Take the difference

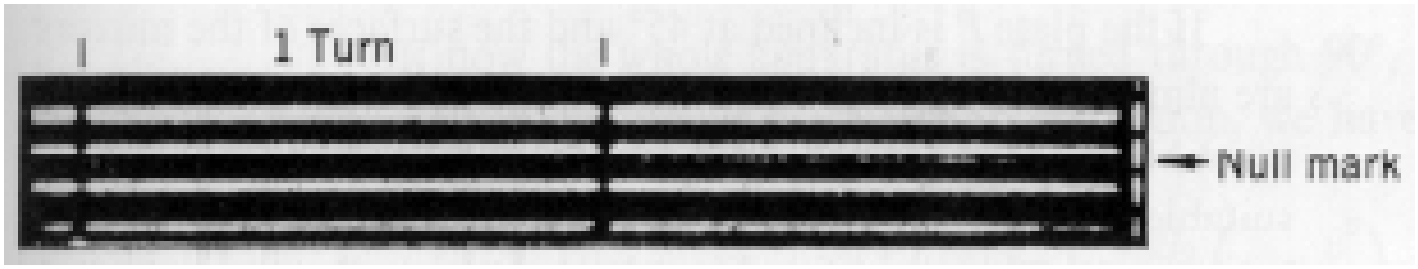
$$\Delta t' - \Delta t = \frac{2}{c}\left(\frac{l_1 + l_2}{1-\frac{v^2}{c^2}} - \frac{l_1 + l_2}{\sqrt{1-\frac{v^2}{c^2}}}\right)$$

- And simplify using the binomial expansion

$$\Delta t' - \Delta t \approx \frac{v^2(l_1 + l_2)}{c^2}$$

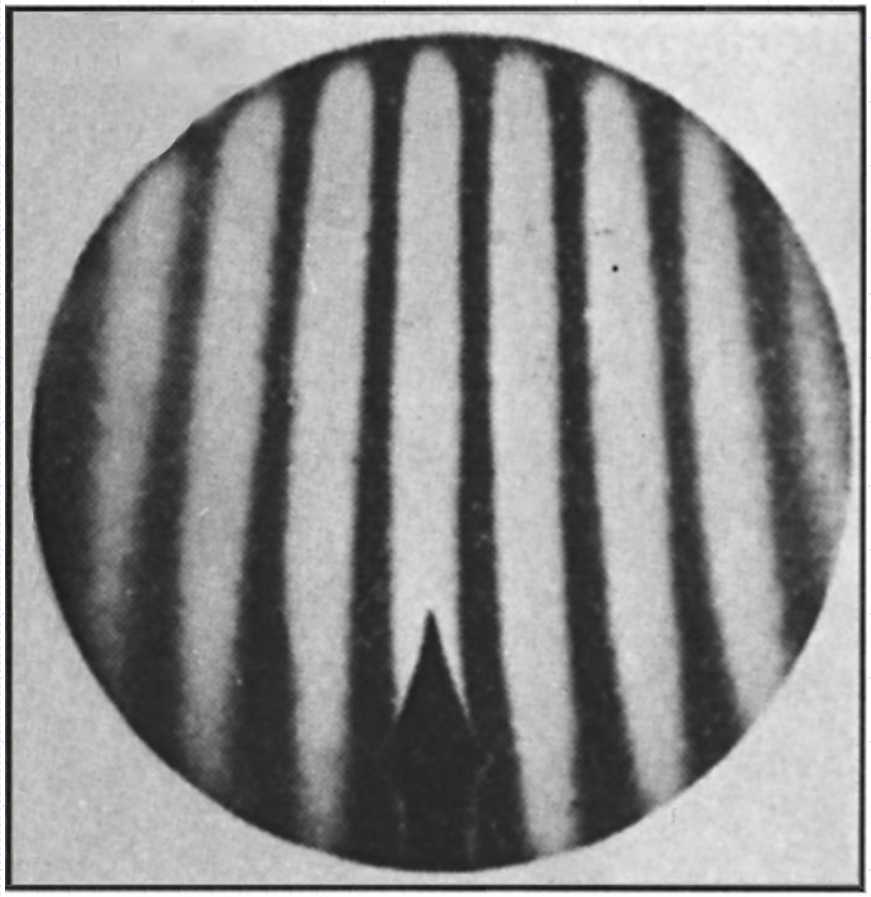
Michelson-Morley

- Expected result
  - For $L_1 = L_2 = 11$m and $v/c = 10^{-4}$
  - $\Delta t' - \Delta t \sim 0.3 \times 10^{-15}$ s
  - $\Delta\lambda = c/\Delta f = 90$ nm
  - $\Delta N = \Delta\lambda/\lambda \sim 100/590 \sim 0.4$ period shift
- Observed result
  - No fringe shift!



Michelson-Morley

- Typical interference pattern observed in the Michelson-Morley experiment



Michelson-Morley

- Even so, Michelson-Morley continued to believe in the ether
- Ether drag hypothesis held that the earth dragged the ether along, hence the $v_{earth} = 0$ with respect to ether
- This hypothesis was ruled out by observation of stellar aberration (apparent circular motion of star's position)

Special Theory of Relativity

- Postulate 1
  - Absolute, uniform motion cannot be detected
  - Or, the laws of physics are the same in all inertial frames
- Postulate 2
  - The speed of light in a vacuum is the same in all inertial frames
  - Or, the speed of light is independent of the motion of the source

Special Theory of Relativity

- Question
  - A spaceship is moving towards you with velocity 0.2*c*. The spaceship sends out a laser beam that you observe with photodetectors. What is the measured velocity of the laser light?
- Answer
  - A. 0.8*c*
  - B. 1.2*c*
  - C. 1.0*c*

Special Theory of Relativity

- Although the postulates are seemingly sensible, the consequences are not
  - Events measured to be simultaneous in one frame in general are not simultaneous in a second frame moving relative to the first
  - The distance between two objects is not absolute
  - The time interval between two events is not absolute
  - Velocities don't always add directly

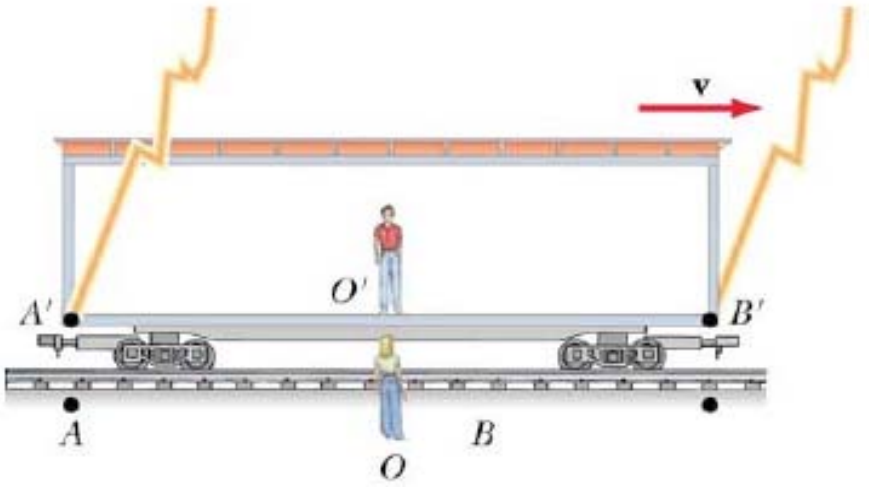
Synchronization

- Question
  - Suppose A and B are at rest in K a distance L apart. How should we synchronize their clocks?
- Answer
  - A. A looks at B's clock and sets his clock to the same value
  - B. A looks at B's clock and sets his clock to a time L/*c* ahead of B's clock
  - C. C, positioned midway between A and B, sends a light signal to A and B whereupon they each set their clocks to the same value

Simultaneity

- In special relativity we often consider reference frames K and K’ where K’ moves with velocity v wrt K
- One consequence of the special theory of relativity is that events that are simultaneous in one frame are in general not simultaneous in a second frame moving relative to the first

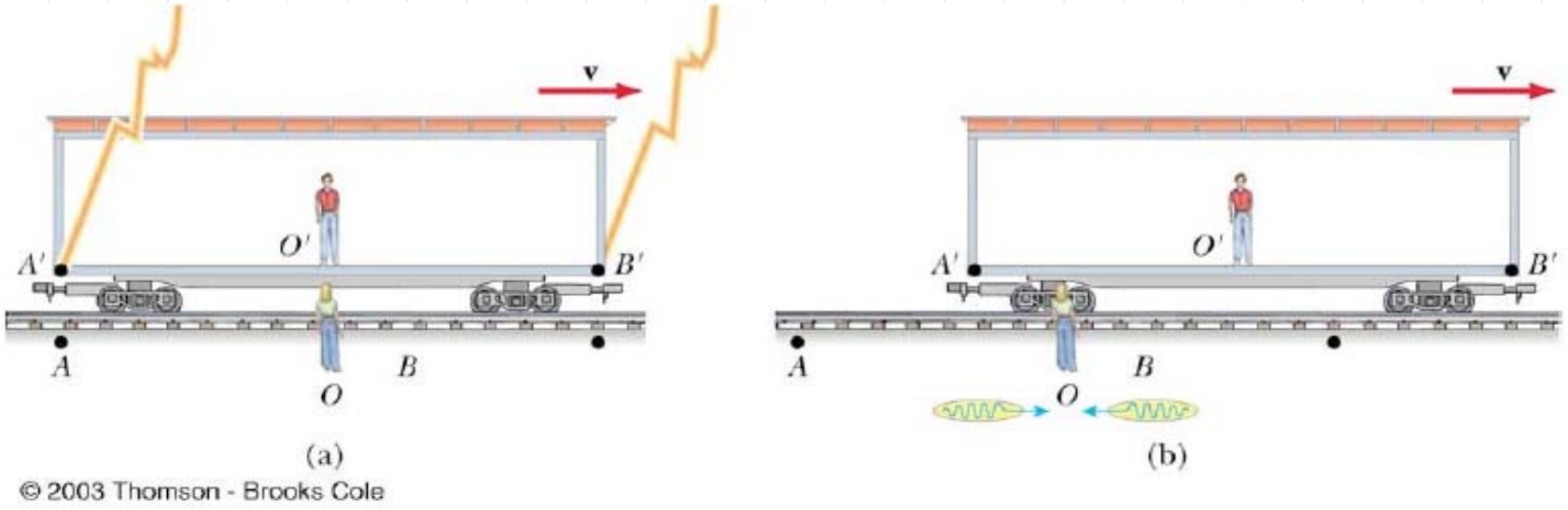
Simultaneity



(a)

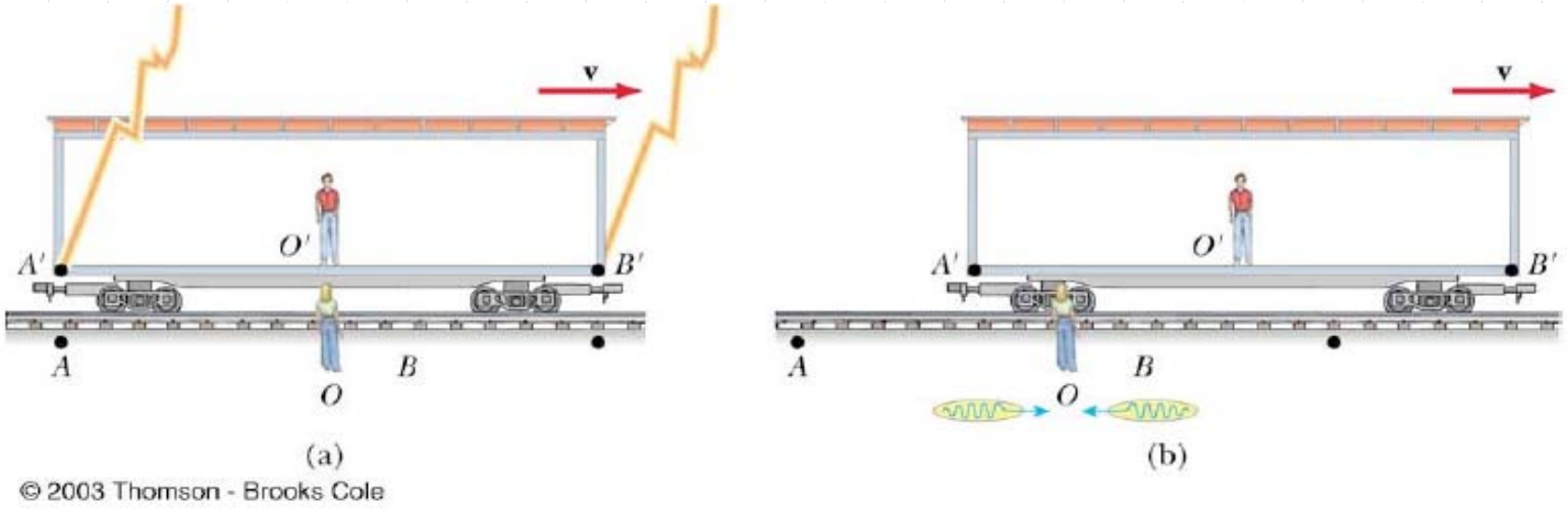
- O’ moves with constant velocity v wrt O
- O’ is in the middle of points A’ and B’
- O is in the middle of points A and B
- The lightning bolt leaves scorch marks on the train and the ground underneath

Simultaneity



- O observes the light from each lightning strike reach her at the same time
- Since O is equidistant between the two strikes, she observes the lightning strikes to be simultaneous

Simultaneity



- O′ observes the light from the front lightning strike reach him before the light from the back lighting strike
  - Even though the velocity of light is *c* for both strikes, the distance the light travels is smaller for the front strike
- Since O′ is equidistant between the two strikes, he observes the lightning strikes NOT to be simultaneous

Simultaneity

- Definition
  - Event (x_1,t_1) is simultaneous with event (x_2,t_2) if light signals emitted at t_1 from x_1 and at t_2 from x_2 arrive simultaneously at the midpoint between x_1 and x_2
- Events (and clocks) synchronous in one frame are not synchronous in another frame moving relative to the first