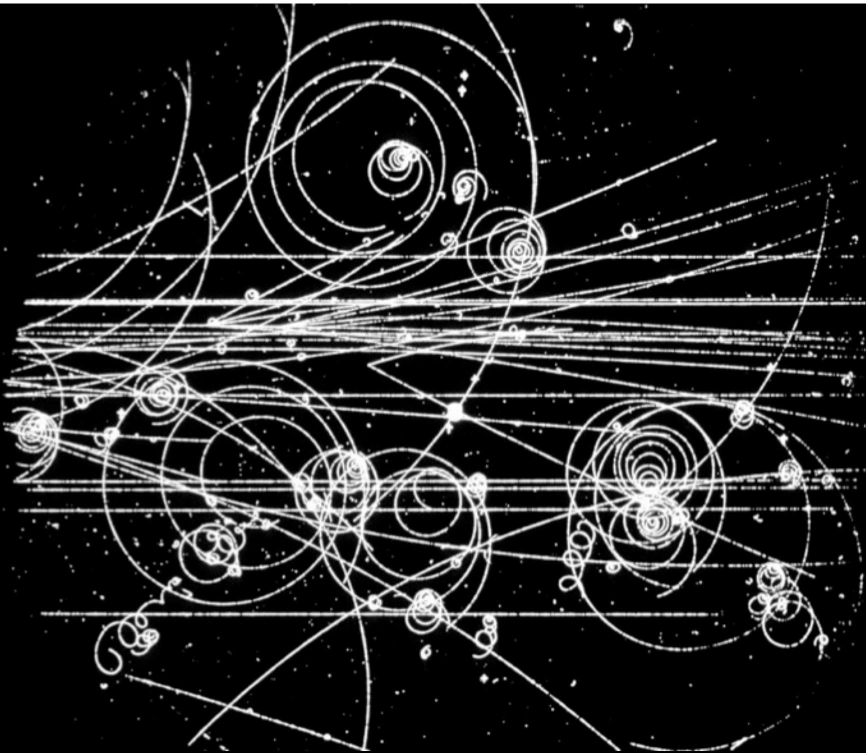
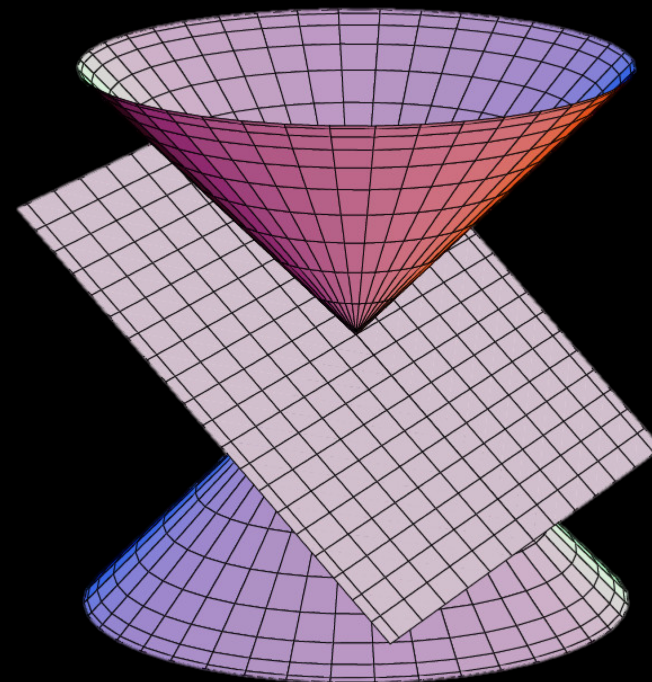




Modern Physics (Phys. IV): 2704

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

Clicker Practice

- First, open the web page (https://rwpoll.com or https://account.turningtechnologies.com) or the ResponseWare app
  - Enter the session ID on the board
- Wait until I open polling (arrow changes to square on my screen)
- Enter A, B, C, D, or E
  - Can change answer as long as polling still open
- After I close polling, we will see a histogram of the results

Background Question I

- What intro physics series did you take?

A. Physics I, II, & III here
B. Introductory Physics I & II here
C. An intro physics series at another institution
D. Did not take an intro physics series
E. Other

Background Question II

- When you graduate, do you want to:

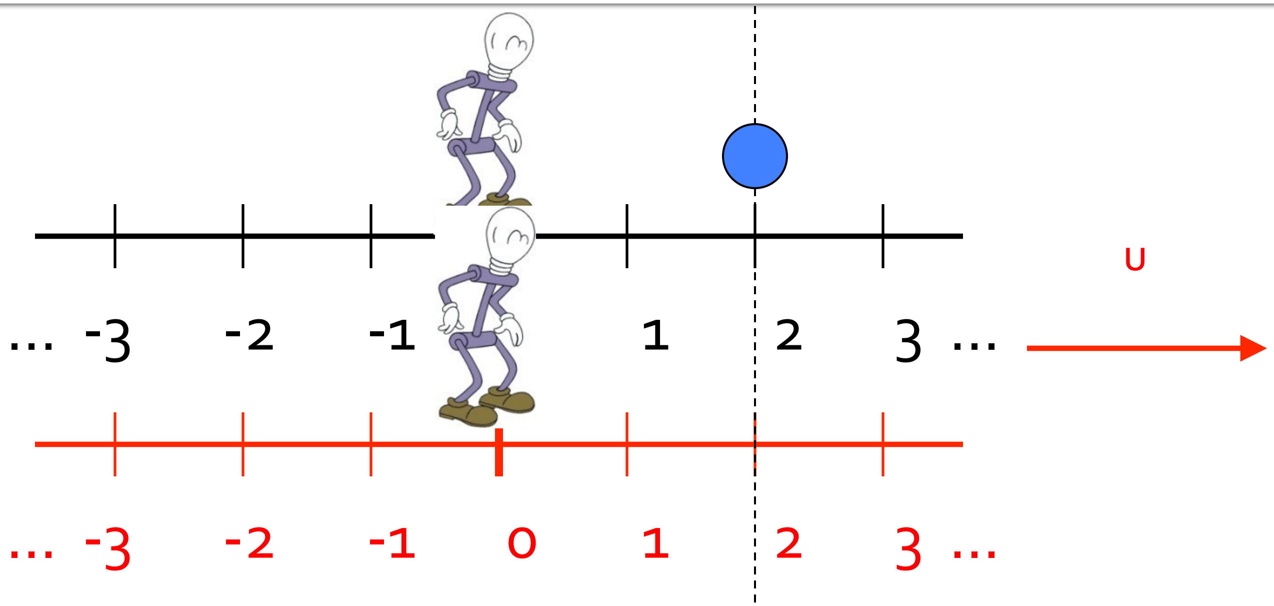
A. Get a higher degree in physics?
B. Get a higher degree in another subject?
C. Work in engineering, industry, computer science, data science, or other technical field?
D. Work in a non-technical field?
E. Flee the country?

Background Question III

- Are you looking forward to being able to explain quantum mechanics to your friends and/or significant other?

A. Yes, I enjoy demonstrating my intellectual acumen
B. No, I have better things to talk about
C. My significant other would leave me if I brought up quantum mechanics
D. Why the heck else would I be taking this class!!??

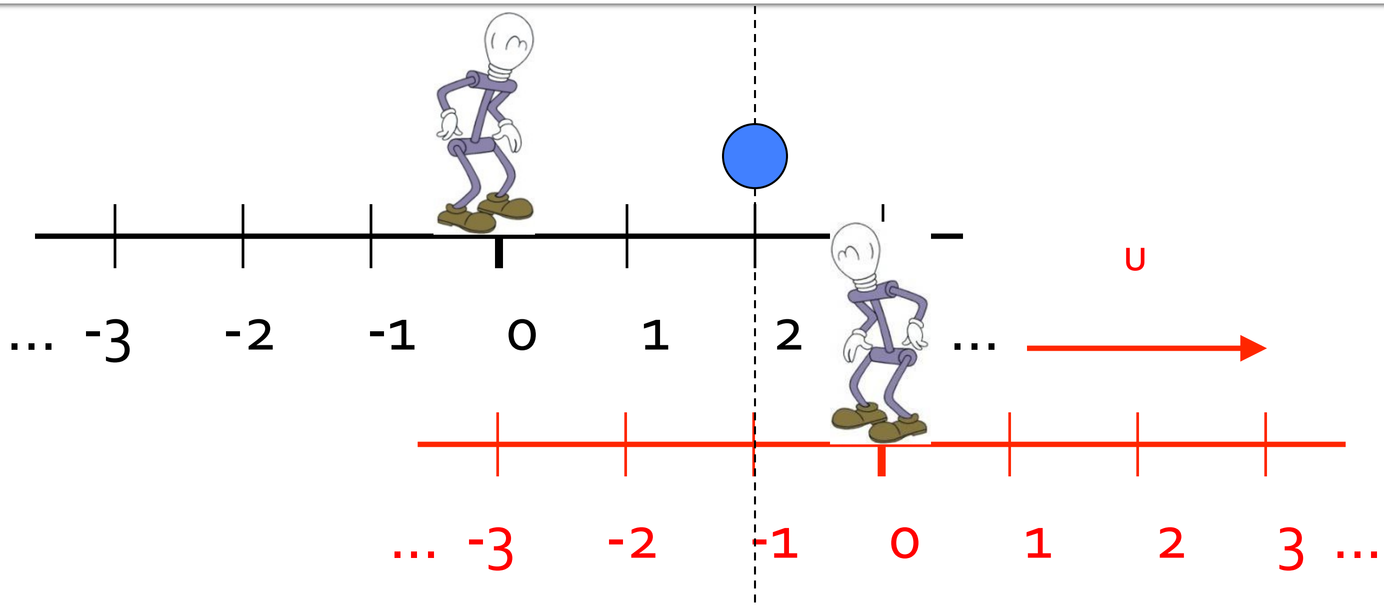
Comparing inertial frames



At time t = 0, the two frames coincide. A ball is at rest in frame S. Its position is

- x = 2 m in S
- x′ = 2 m in S′

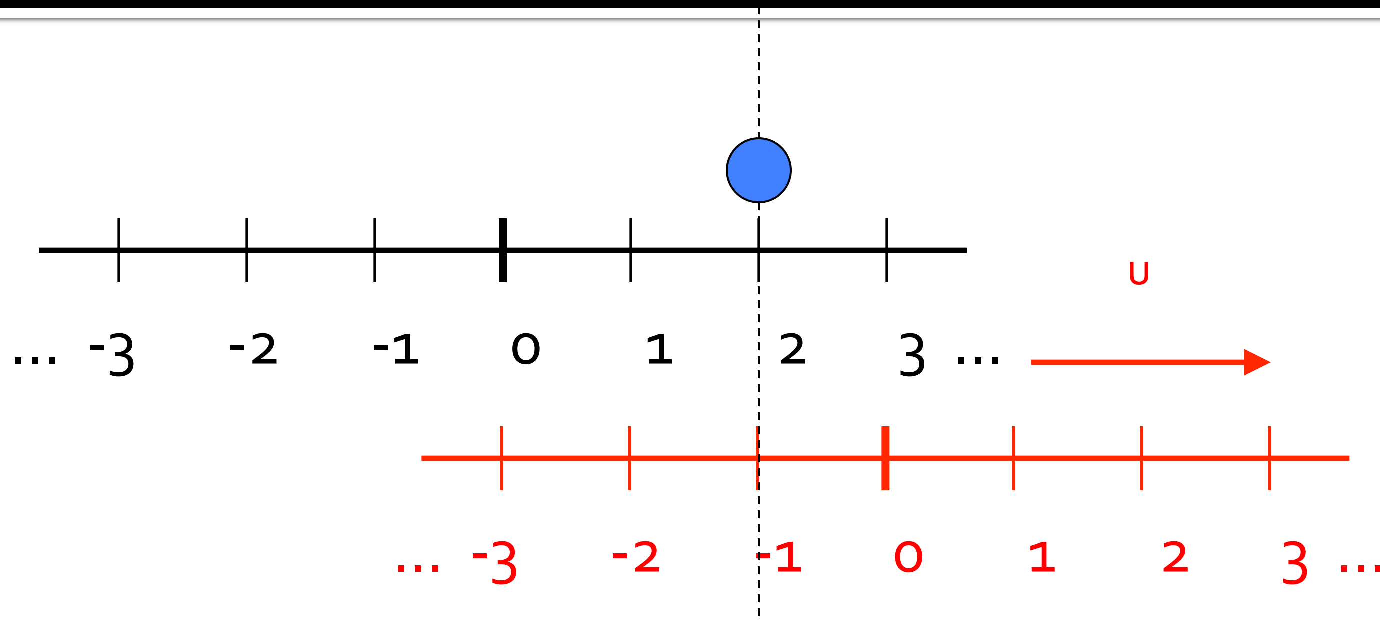
Comparing inertial frames



Frame S′ is moving to the right (relative to S) at u=1 m/s. At time t = 3 sec, the position of the ball is

- x = 2 m in S
- x′ = -1 m in S′

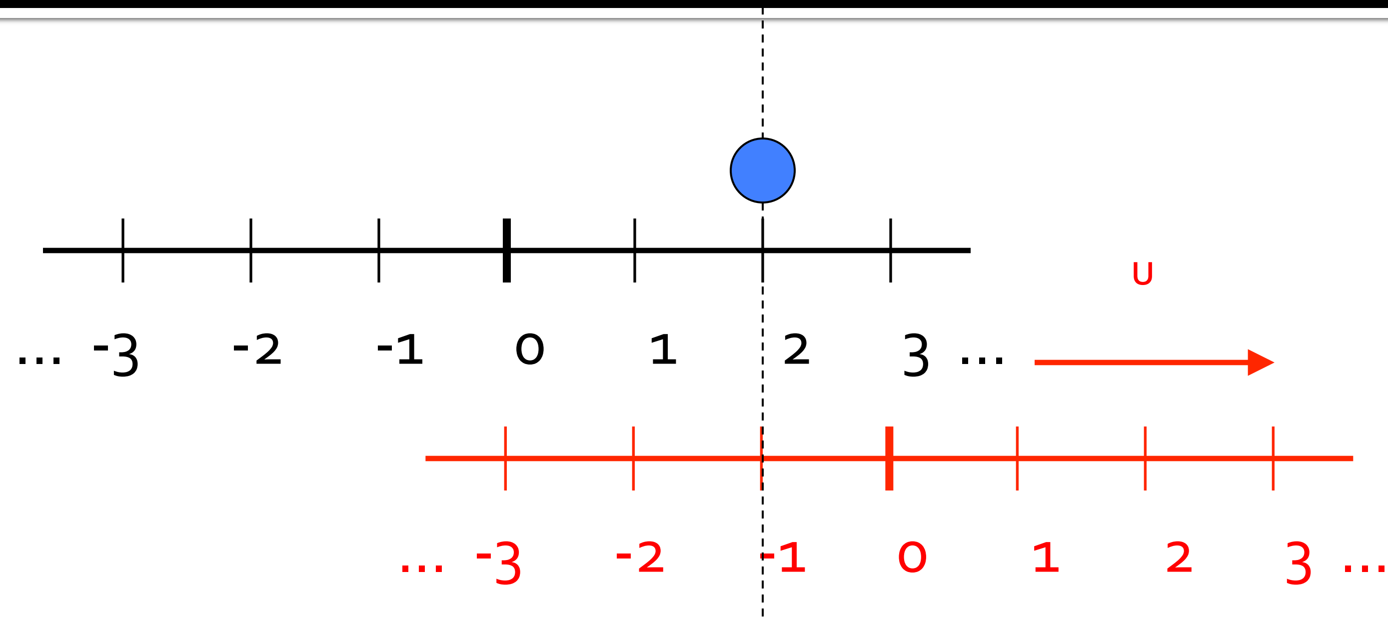
Concept Check: Comparing inertial frames



At time 0, the ball was at x = x′. At time t later, the ball is still at x in S but where is it in S′ at the same time t?

a) $x' = x$ b) $x' = x + ut$ c) $x' = x - ut$

Concept Check: Comparing inertial frames



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a) $x' = x$ b) $x' = x + ut$ $\boxed{\text{c) } x' = x - ut}$

Galilean Transformation

$$x' = x - ut$$

$$y' = y$$

$$z' = z$$

$$t' = t$$

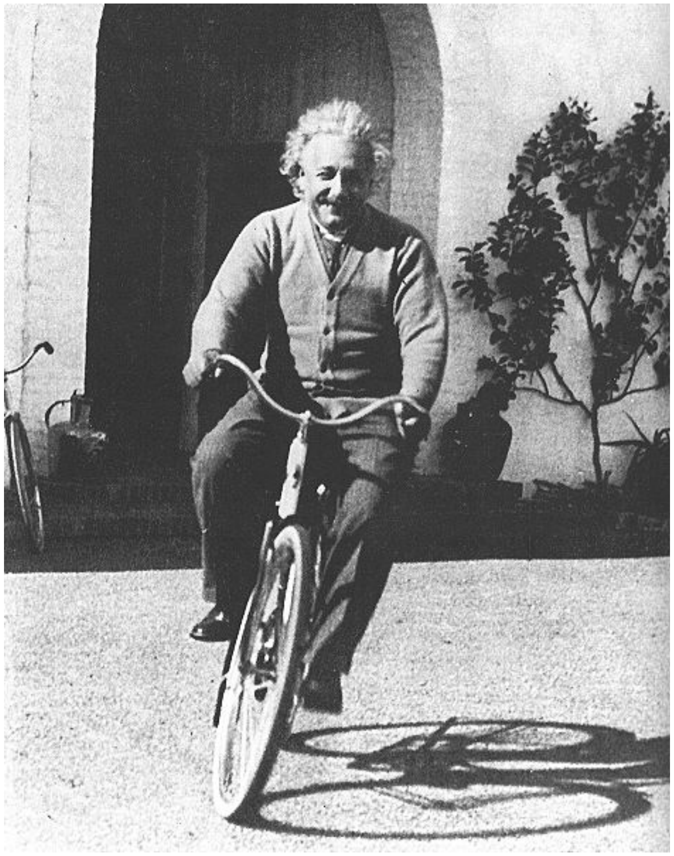
Note:
Assumes frames aligned at t = 0

$$v_x{}' = \frac{dx'(t)}{dt} = \frac{d}{dt}\left(x(t) - ut\right) = \frac{dx(t)}{dt} - u = v_x - u$$

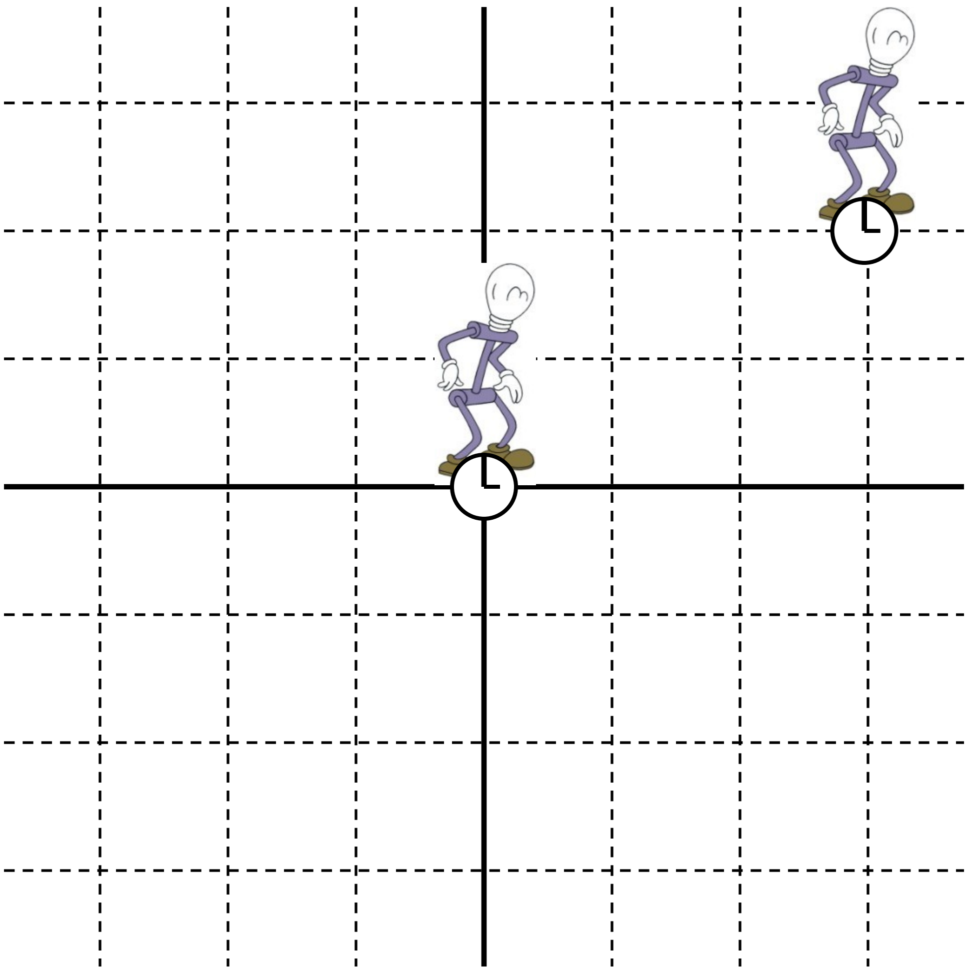
Einstein's Postulates

The laws of physics are the same in all inertial frames of reference.

The speed of light is the same in all inertial frames of reference.



'Events' in one reference frame

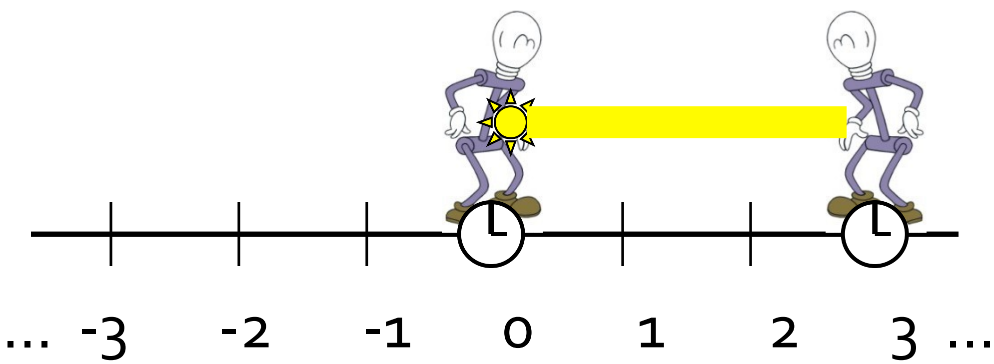


An observer at (0,0) has a clock; events there are covered.

An observer at (3m,2m) had better have a clock too, if we want to know about events there.

And, the two clocks had better show the same time.

Synchronizing Clocks in One Frame

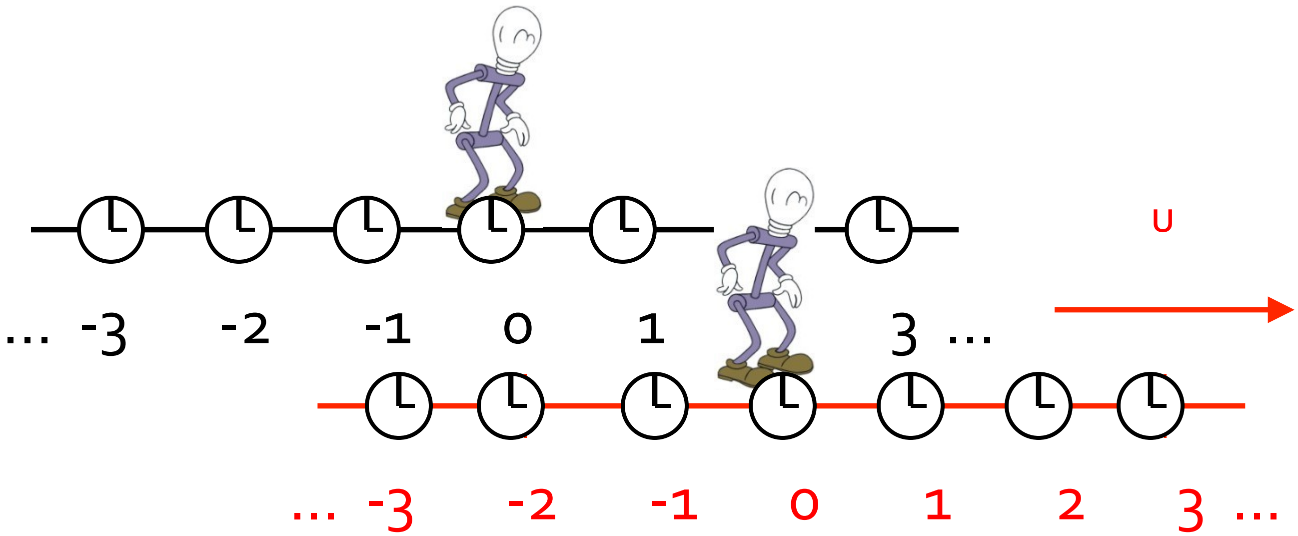


At the origin, at three o'clock, the clock sends out a light signal to tell everybody it's three o'clock.

Time passes as the signal gets to the clock at x = 3m.

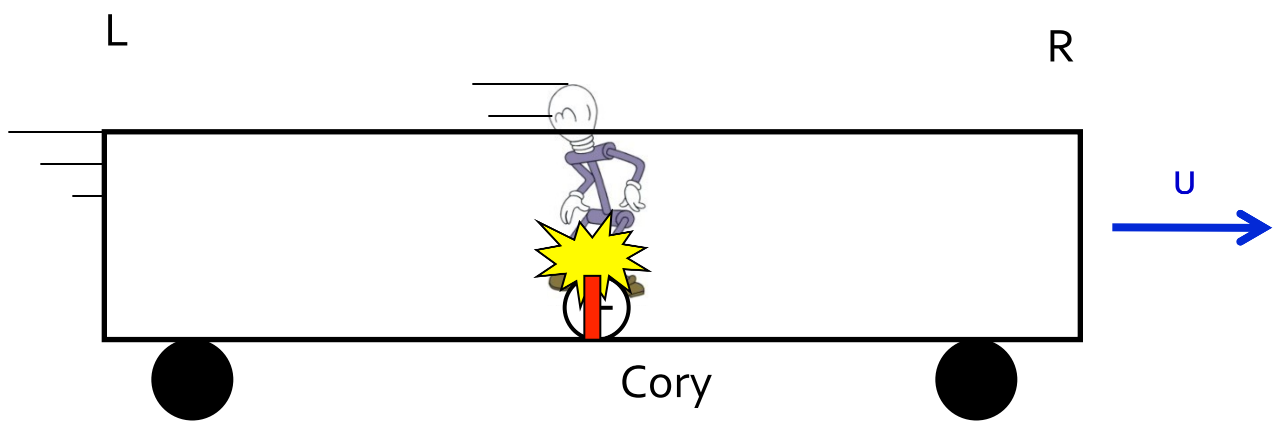
When the signal arrives, the clock at x=3m is set to 3:00 *plus the 10 ns delay (which is calculated by knowing the speed of light c)*.

Simultaneity in *Two* Frames



A second frame has its own clocks, and moves past me.
What happens now?

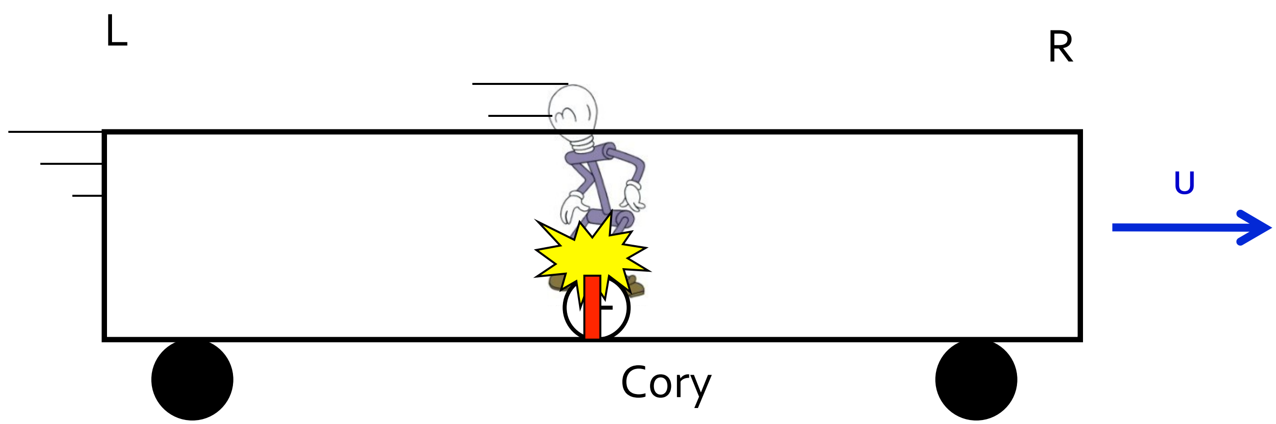
Concept Check: Cory's Frame



Cory is the middle of a railroad car, and sets off a firecracker. Light from the explosion travels to both ends of the car. Which end does it reach first according to Cory?

a) both ends at once
b) the left end, L
c) the right end, R

Concept Check: Cory's Frame



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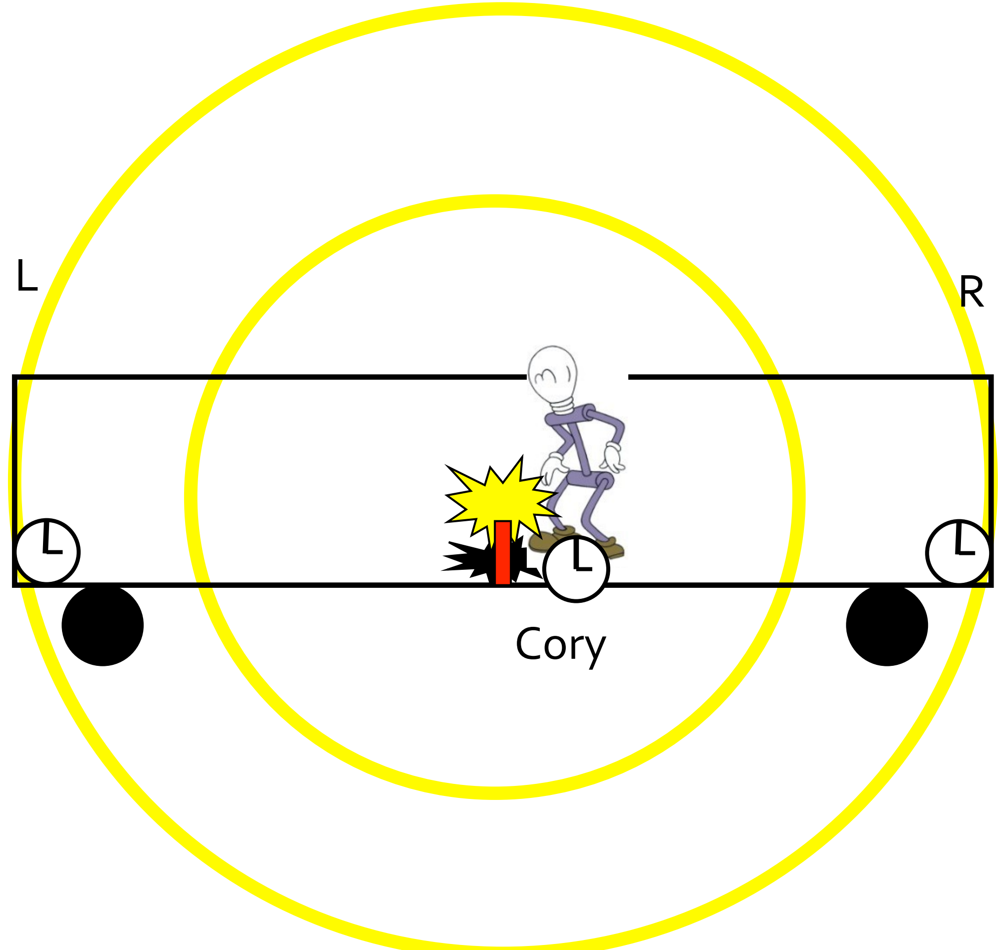
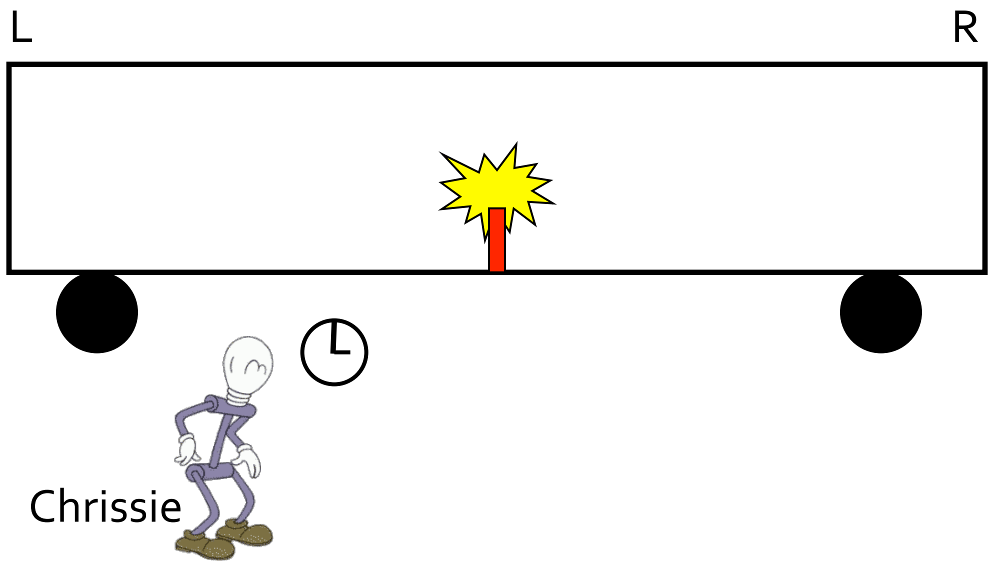
Cory's Frame



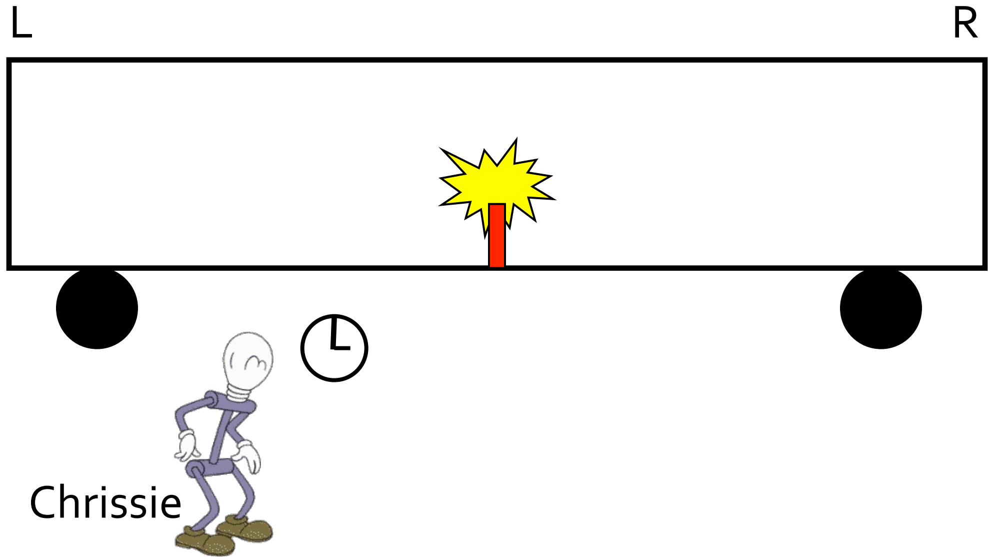
Concept Check: Chrissie's Frame



Chrissie is standing at rest next to the train tracks, watching the train move to the right. According to Chrissie, which end of the train car does the light reach first?

a) both ends at once
b) the left end, L
c) the right end, R

Concept Check: Chrissie's Frame



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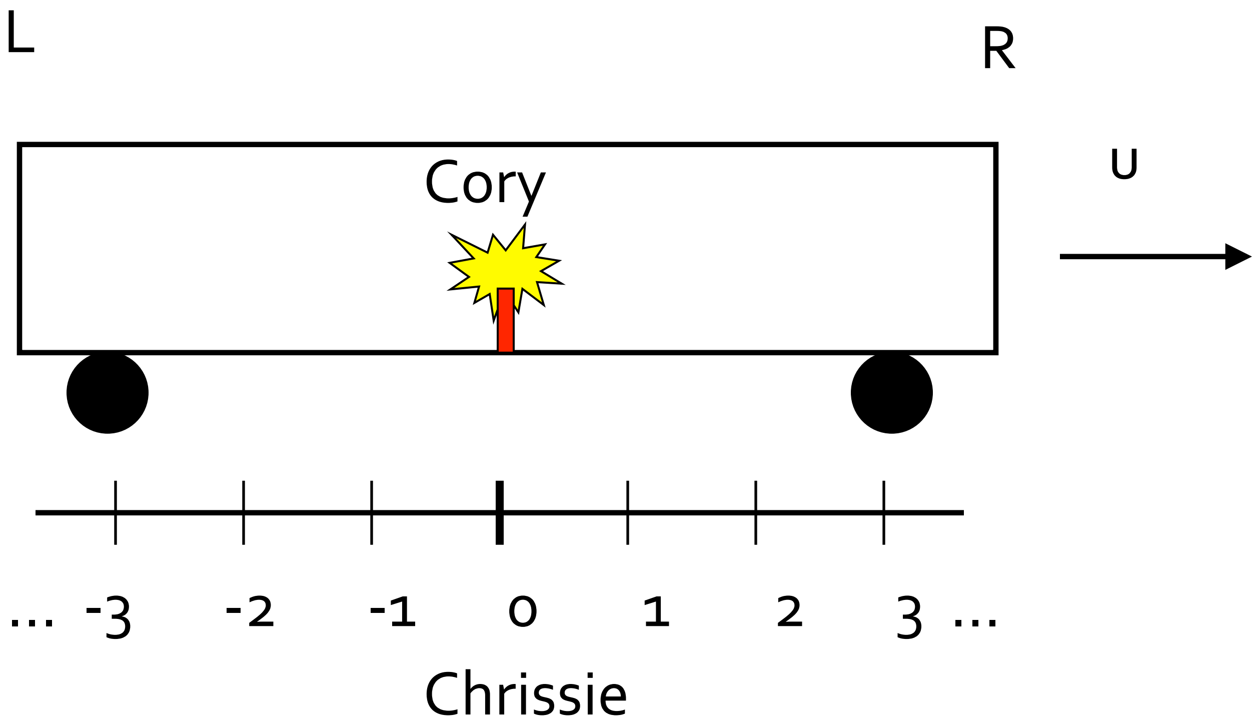
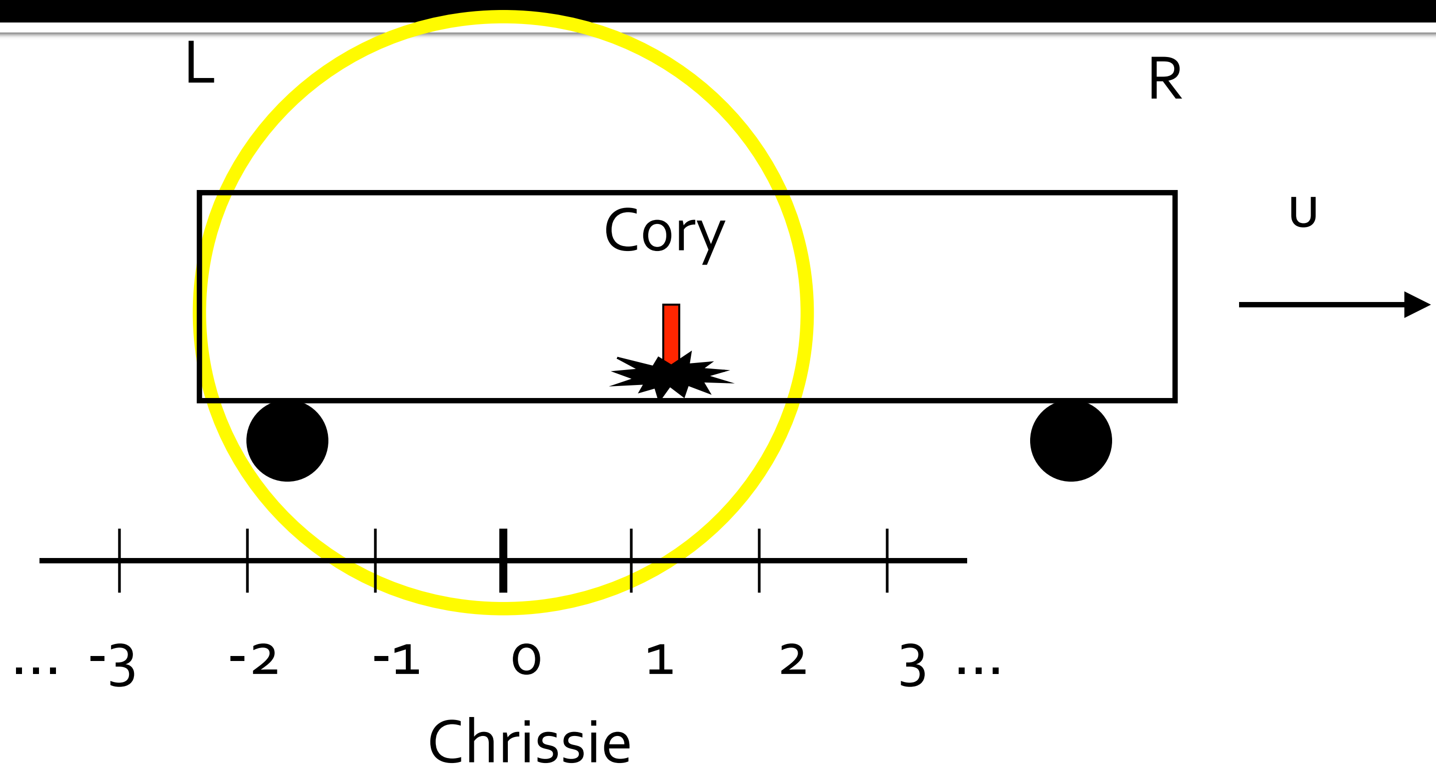
Chrissie's Frame



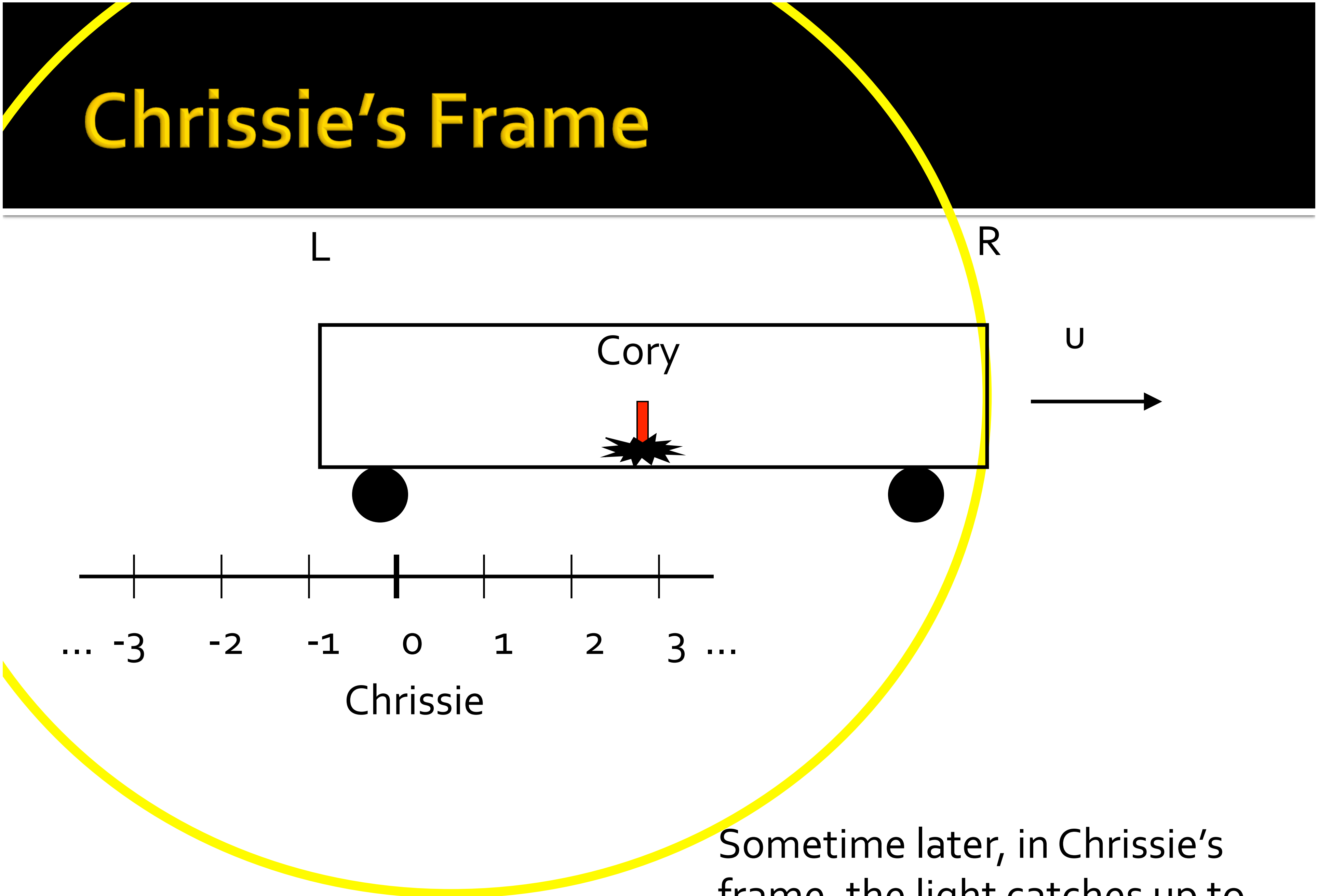
Suppose Cory's firecracker explodes at the origin of Chrissie's reference frame.

Chrissie's Frame



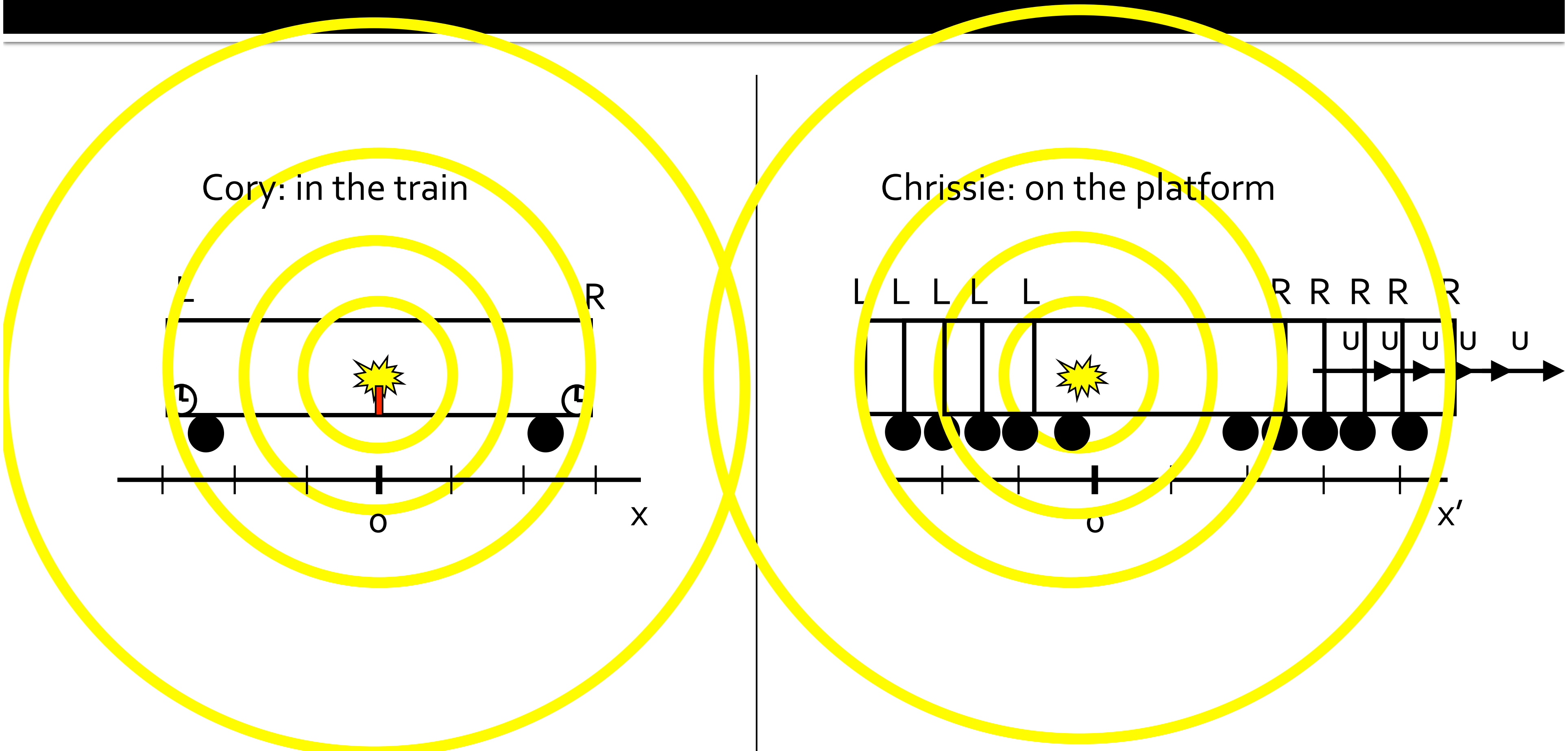
The light spreads out in Chrissie's frame from the point she saw it explode. Because the train car is moving, the light in Chrissie's frame arrives at the left end first.

Chrissie's Frame



Sometime later, in Chrissie's frame, the light catches up to the right end of the train.

Simultaneity is Relative



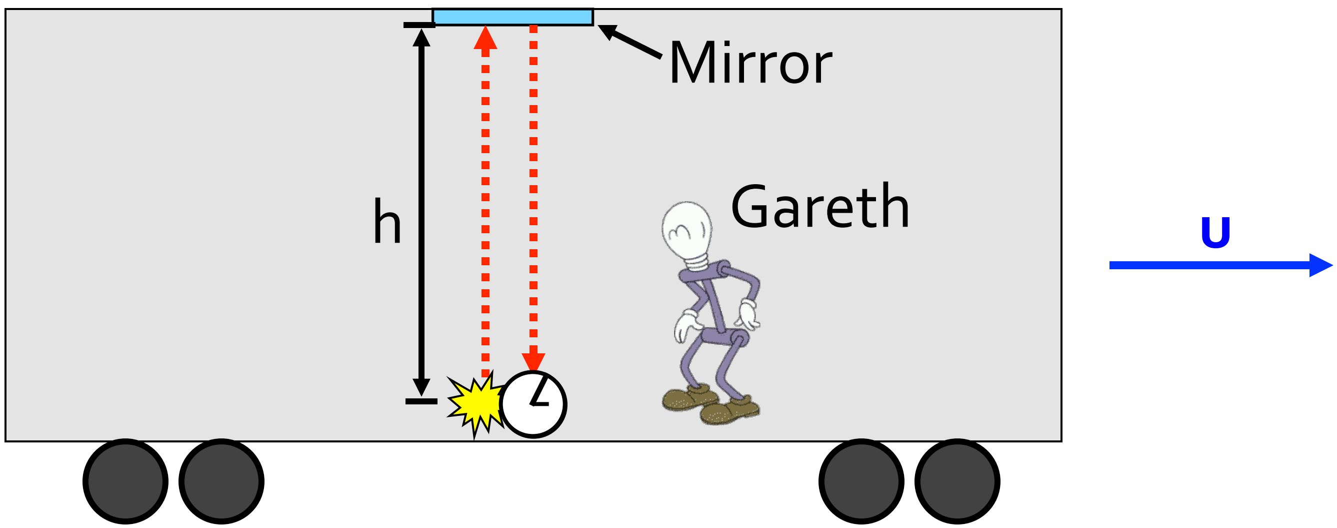
Event L: (x=-3, t=3s)	Event R: (x=+3, t=3s)

Cory says: ‘Simultaneous!’

Event L′: (x′=-2, t′=2s)	Event R′: (x′=+5, t′=4s)

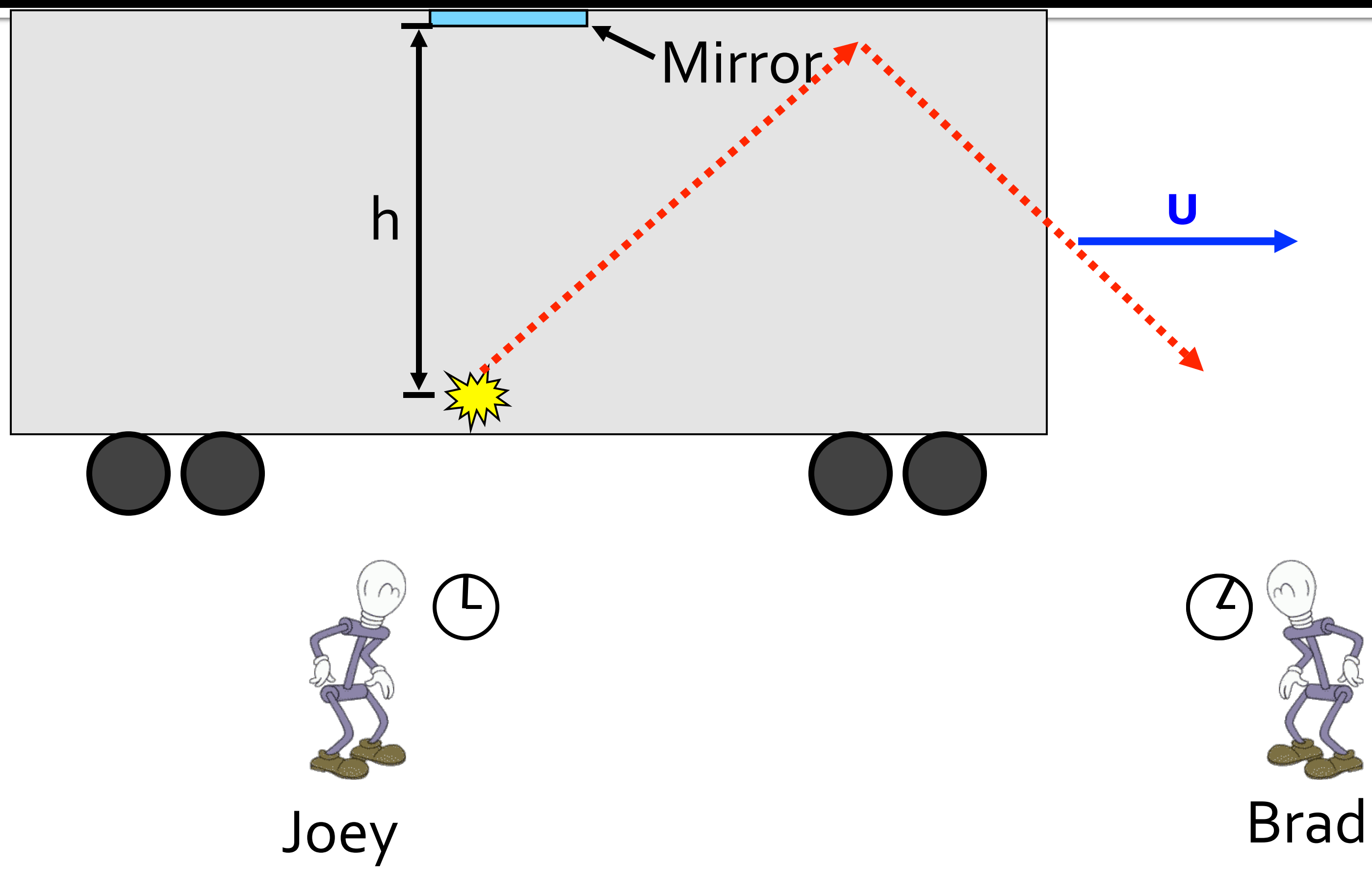
Chrissie says: ‘Not simultaneous!’

Time Dilation



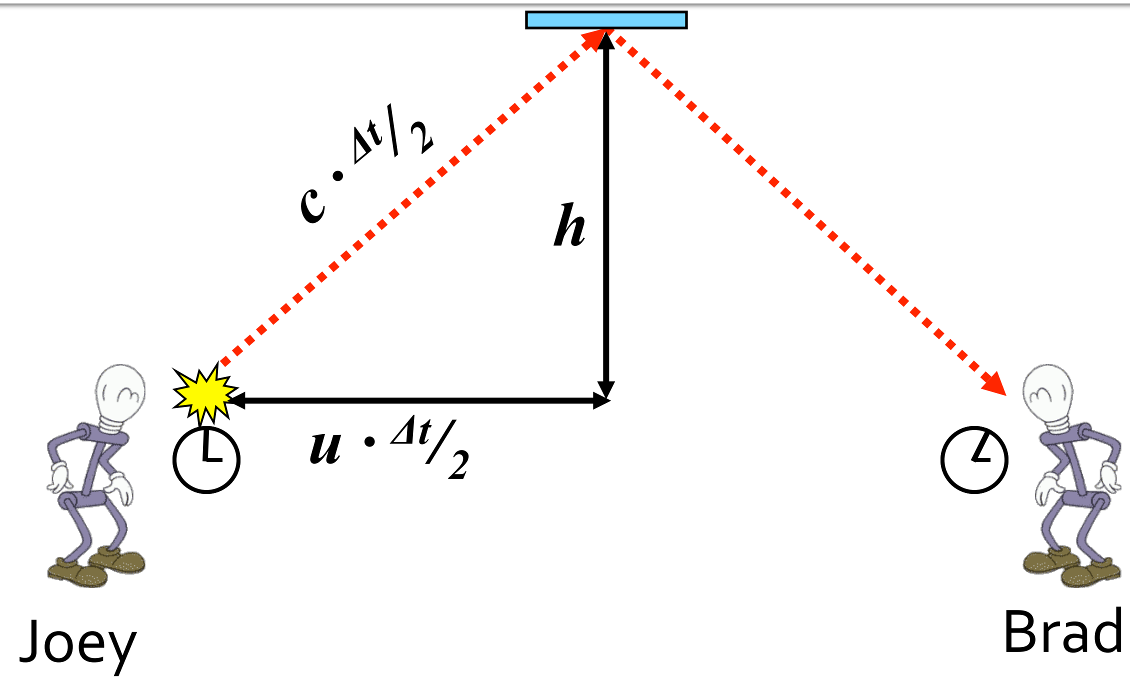
Gareth measures the time interval: $\Delta t' = \Delta t_0 = {}^{2h}/_{c}$

Time Dilation

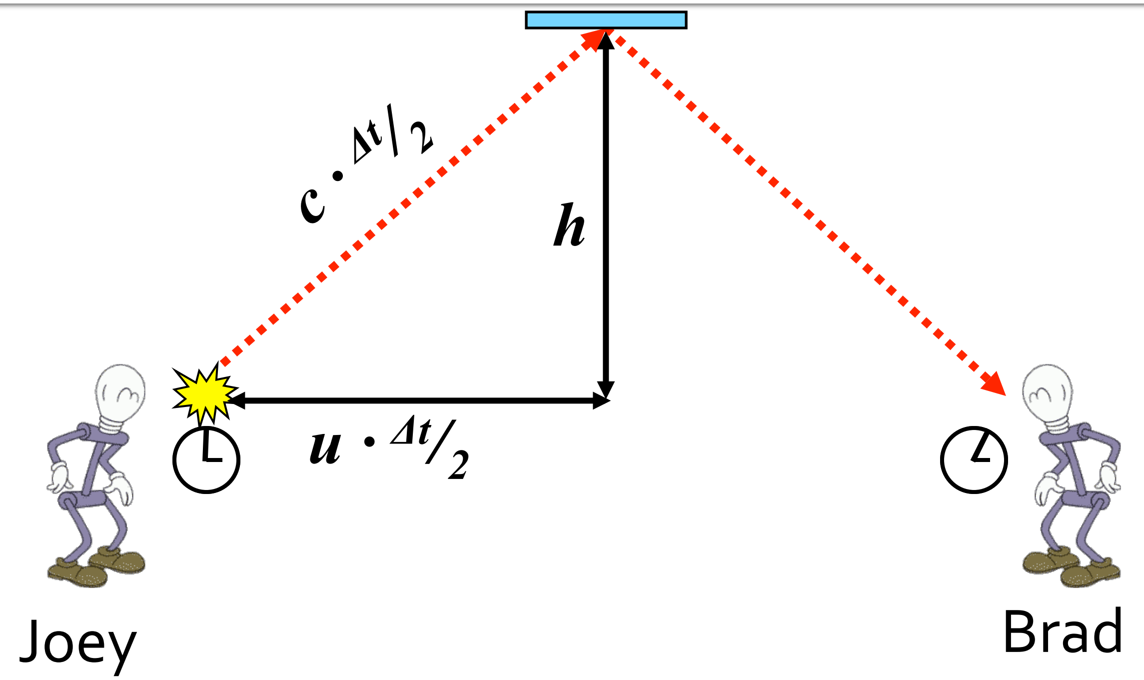


Note: This experiment requires two observers.

Time Dilation



Time Dilation

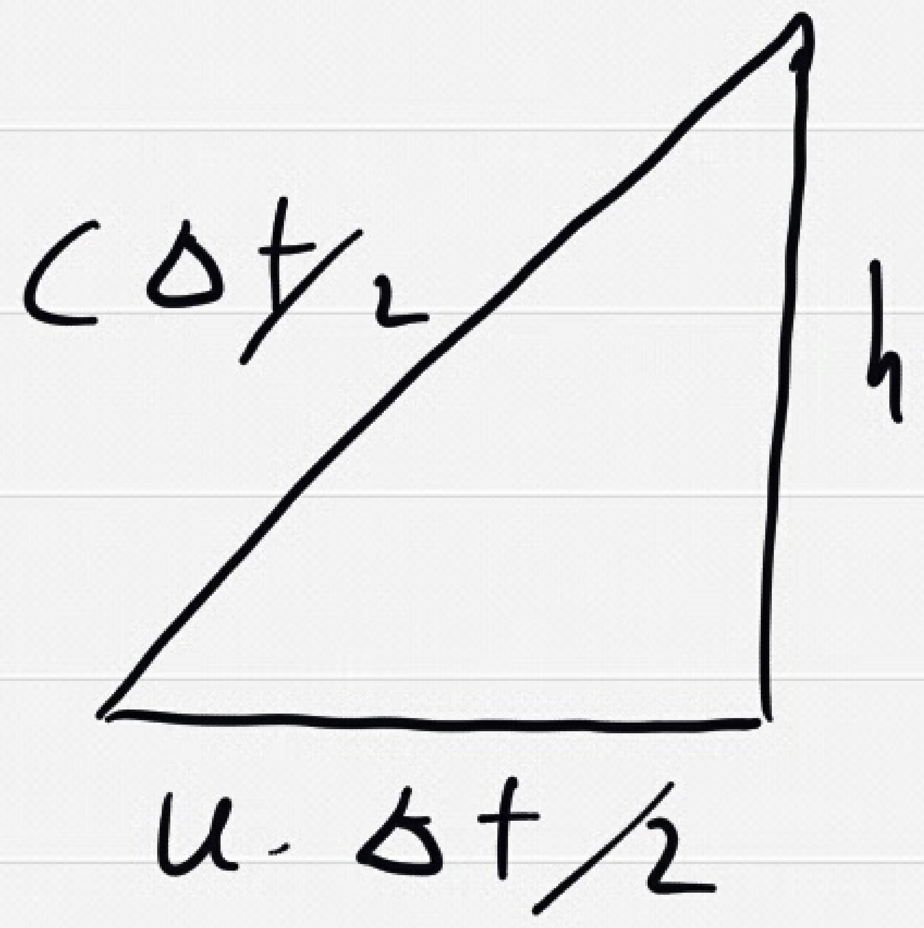


Joey and Brad measure the time interval:

$$\Delta t = \frac{2h}{c}\gamma, \quad \gamma = \frac{1}{\sqrt{1-\frac{u^2}{c^2}}}$$

But Gareth measured $\Delta t' = \Delta t_0 = 2h/c$!!

$\boxed{\text{Time Dilation}}$



Joey & Brad's frame

$$\left(c\,\Delta t/2\right)^2 = h^2 + \left(\frac{u\,\Delta t}{2}\right)^2$$

$$c^2/4\,\Delta t^2 = h^2 + \frac{u^2}{4}\Delta t^2$$

$$\frac{\Delta t^2}{4}\left(c^2-u^2\right) = h^2$$

$$\Delta t^2 = \frac{4h^2}{c^2-u^2}$$

$$\Delta t = 2h/\sqrt{c^2-u^2}$$

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

$$= \gamma\, 2h/c$$

$$= \gamma\,\Delta t' = \gamma\,\Delta t_0$$

$$\gamma = \frac{1}{\sqrt{1-u^2/c^2}} \geq 1$$

"Time Dilation"

Proper Time

- "Proper Time" = $\Delta\tau = \Delta t_o$
  - The time interval measured in a frame where the two events occur at the same spatial coordinate – i.e. the frame moving with your clock
- The time interval Δt measured in **any** other frame moving with respect to this frame will be longer
  - $\Delta t = \gamma \Delta t_o$

Concept Check: Muon Decay

- A muon lifetime is 2.2 μs in its rest frame, but it is observed to live for 220 μs in traveling from the upper atmosphere to the ground. Which is closest to its velocity according to the external observer?

A. $v = \sqrt{(0.9)}\ c$
B. $v = \sqrt{(0.99)}\ c$
C. $v = \sqrt{(0.999)}\ c$
D. $v = \sqrt{(0.9999)}\ c$

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C. $v = \sqrt{(0.999)}\ c$
D. $\boxed{v = \sqrt{(0.9999)}\ c}$

$\beta = v/c =$
$\sqrt{(0.9999)}$
$= 0.99995$

Muon Decay

$$\Delta t = \gamma \Delta t' = \gamma \Delta t_0 = \gamma \tau$$

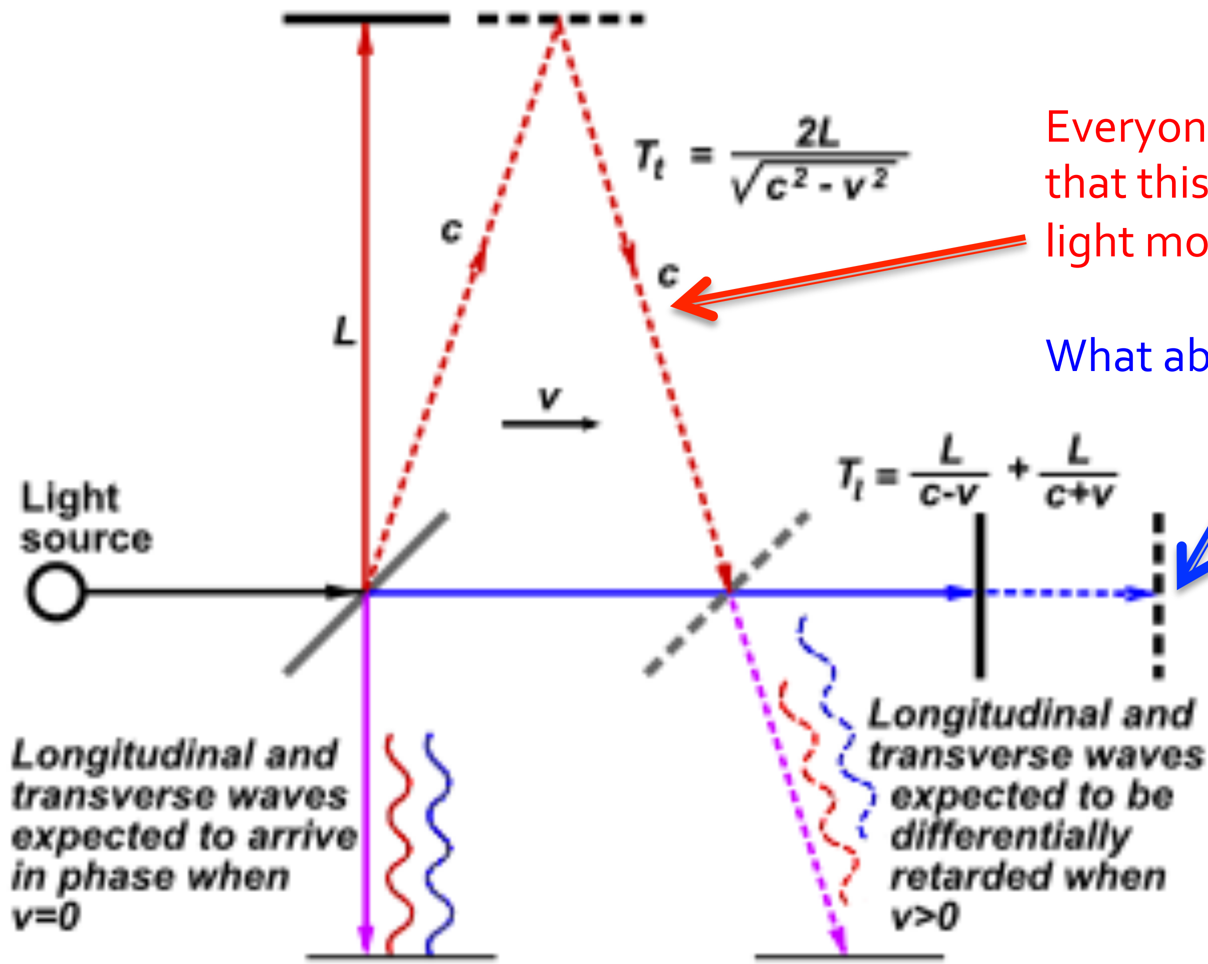
$$\gamma = 220/2.2 = 100$$

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

$$\Rightarrow 1 - u^2/c^2 = 0.0001$$

$$\Rightarrow u/c = \sqrt{0.9999}$$

Back to Michelson-Morley



Everyone now agrees that this half of the light moves at c

What about this half?