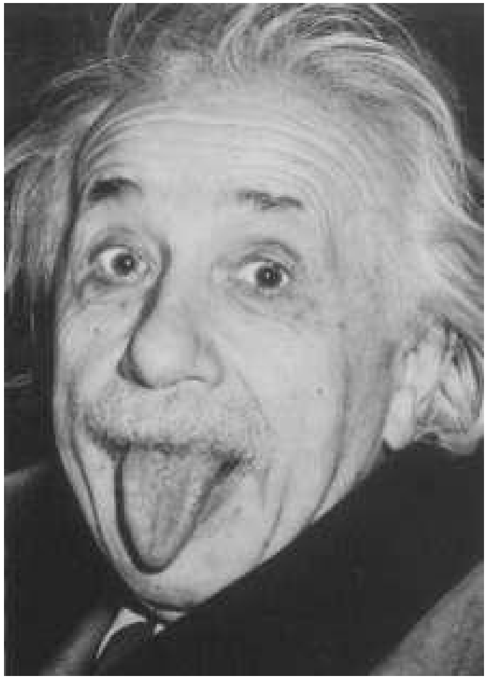
Einstein's theory of special relativity

Announcements:

- First homework assignment is online.
- You will need to read about time dilation (1.8) to answer problem #3 and for the definition of γ for problem #4.
- First problem solving session will be Tuesday 3-4 and 5-6.
- Homework is due Wednesday at 12:50pm in wood box in physics help room (G2B90).
- No class on Monday (MLK)



Albert Einstein (1879—1955):

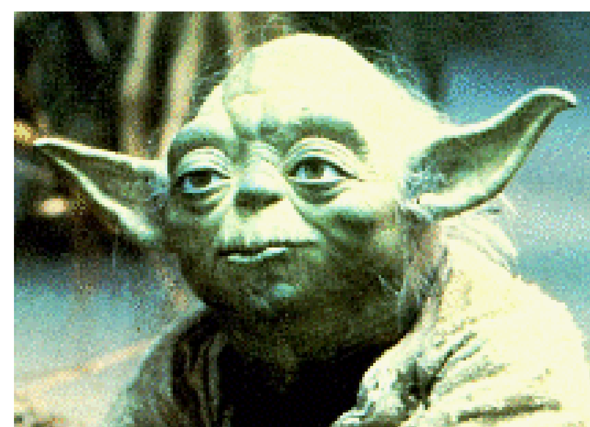
Today we will introduce the special relativity postulates and think about simultaneity.

From Maxwell's equations, light is an electromagnetic wave with speed:

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 299792458 \text{ m/s}$$

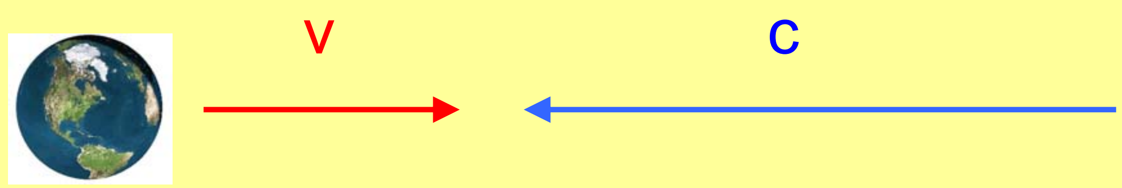
Conventional wisdom: Waves must have a medium to travel in – sound in air, tsunami in water, etc.

Therefore it was believed light traveled in stationary ether where the speed was 299792458 m/s.



If the ether exists, it is an incompressible, invisible, and non-viscous medium which permeates the universe (like The Force).

The ether



Clicker question 1

Set frequency to DA

Suppose the earth moves through the fixed ether with speed *v*. A light wave traveling at speed *c* with respect to the ether is heading in the opposite direction. According to *Galilean relativity*, what is the speed of the light wave as viewed from the earth?

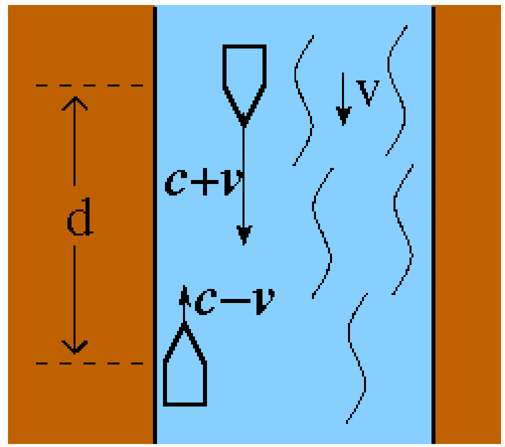
A) c B) $c + v$ C) $c - v$

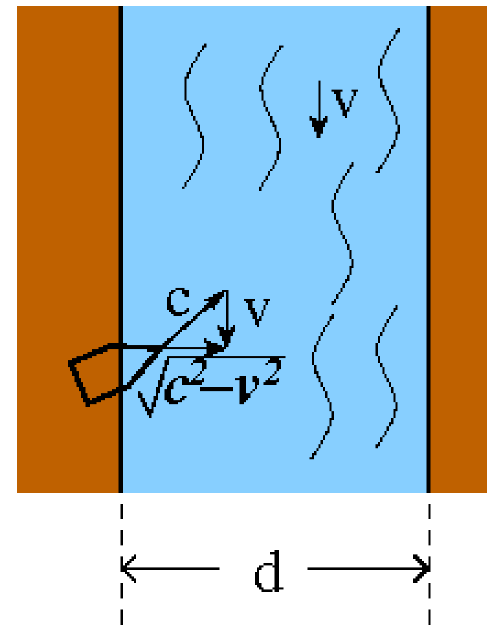
Boat travels at speed c on a river with current at velocity v

Boat travels up and down a river a distance of $2d$

Boat travels back and forth across river with width d

How long does it take to complete each trip?





Up & down river:

$$t_{up} = \frac{d}{c-v} \qquad t_{down} = \frac{d}{c+v}$$

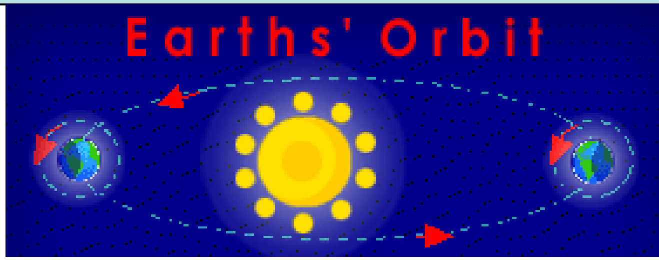
$$t_{up} + t_{down} = \frac{d(c+v)}{c^2-v^2} + \frac{d(c-v)}{c^2-v^2} = \frac{2dc}{c^2-v^2} = \frac{2d}{c\left(1-\frac{v^2}{c^2}\right)}$$

Across river: $t_{across} = \frac{d}{\sqrt{c^2-v^2}}$

$$t_{away} + t_{return} = \frac{2d}{\sqrt{c^2-v^2}} = \frac{2d}{c\sqrt{1-\frac{v^2}{c^2}}}$$

<u>You get different results depending on the route taken!</u>

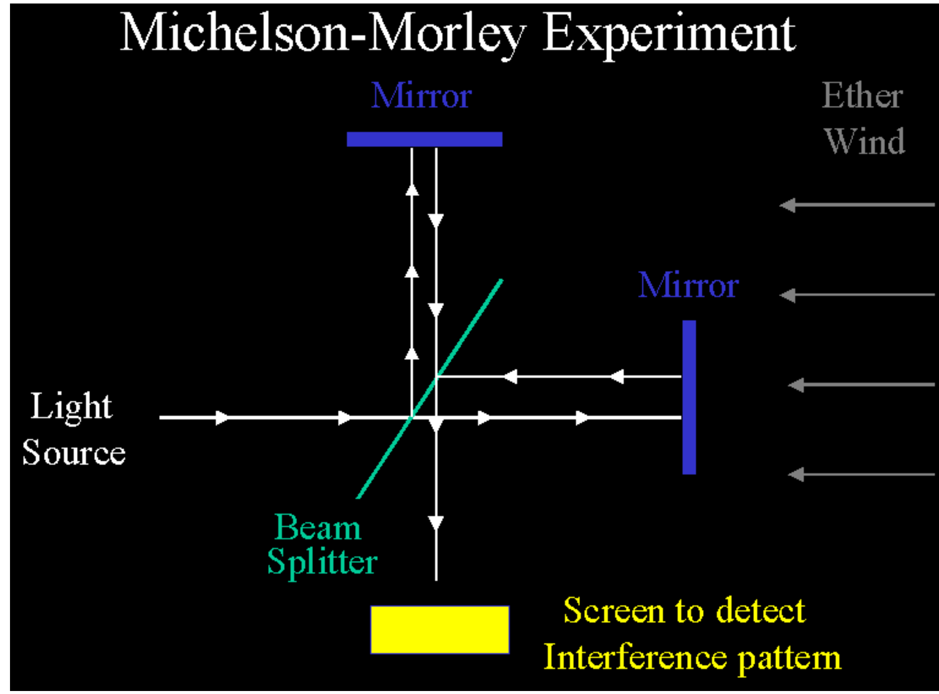
Michelson-Morley experiment in 1887 to see ether effect

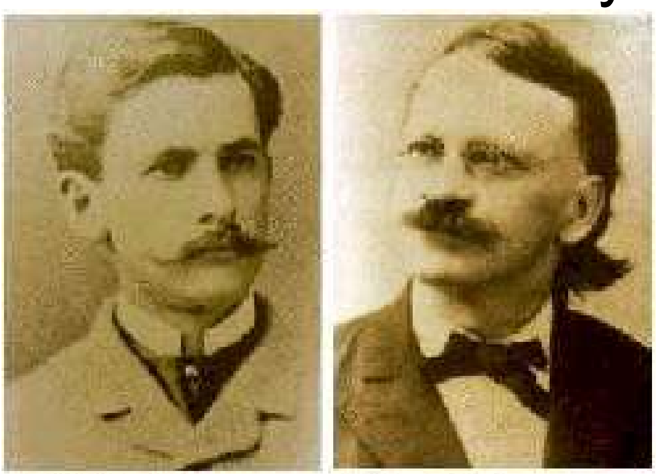


Earth goes around sun at 30 km/s – must be going through ether

Measure speed of light in 2 perpendicular directions

Floated in mercury so could rotate to see effect. Also took data at different times of year.

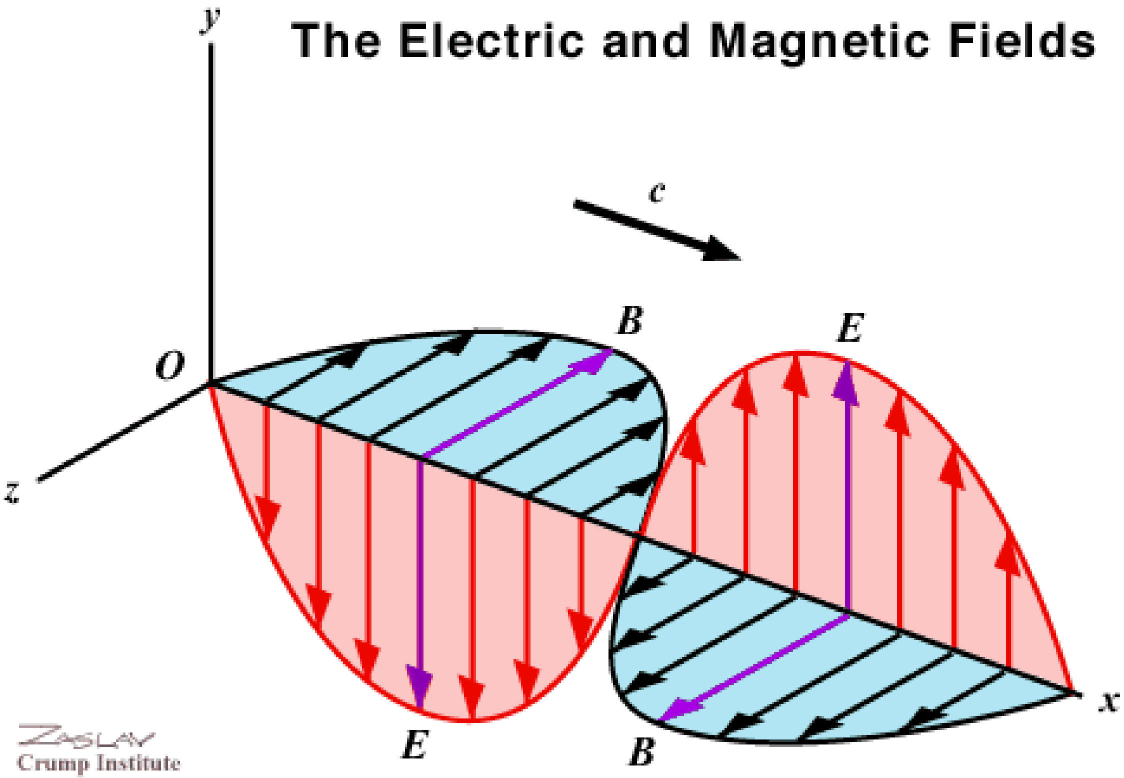




A.A. Michelson 1852 - 1931   E.W. Morley 1838 - 1923

Should see ether flow as small as 1 km/s and saw nothing!

Present View: There is no ether



Electromagnetic waves are special. A time-changing electric field induces a magnetic field, and vice-versa. A medium ("ether") is not necessary.

Einstein's relativity postulate #2

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

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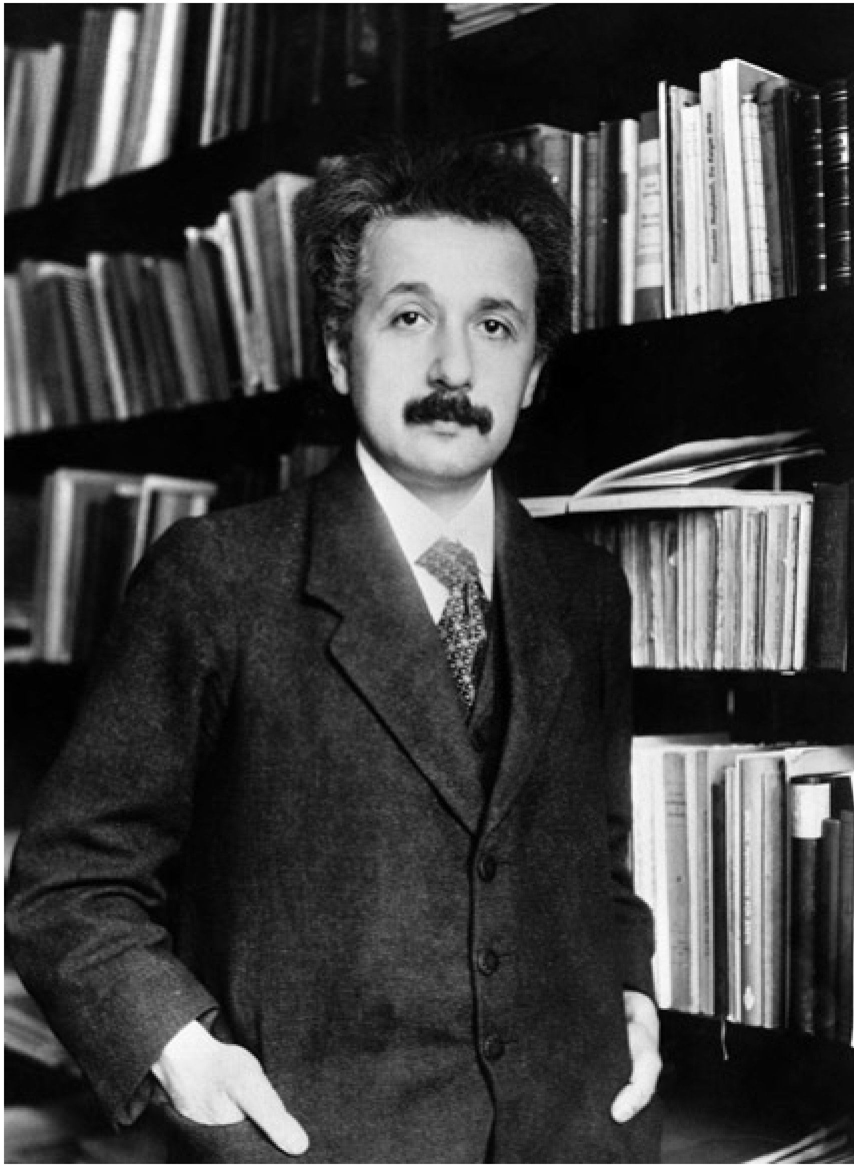
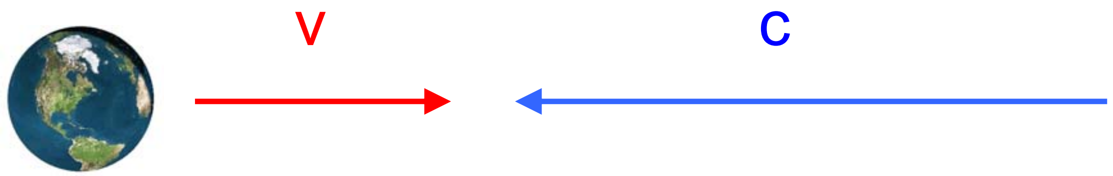


Clicker question 2

Set frequency to DA



Suppose the earth moves through space with speed *v*. A light wave traveling at speed *c* with respect to faraway stars is heading in the opposite direction. According to *Einstein's relativity*, what is the speed of the light wave as viewed from the earth?

A) c B) $c + v$ C) $c - v$

Time to talk about time

- Measuring time in different frames
- Synchronization of clocks
- What time is it? How do you know?

Clicker question 3 | Set frequency to DA

Q. The speed of light in a vacuum is 3.00×10^8 m/s. About how long does it take light to travel the length of your arm?

A. 1 ms (10^{-3} s)
B. 1 μs (10^{-6} s)
C. 1 ns (10^{-9} s)
D. 1 ps (10^{-12} s)
E. 1 fs (10^{-15} s)

Speed of light $c = 3.0 \times 10^8$ m/s
$= 0.3$ m/ns
$= 300$ m/μs

(Note also, c ~ 1 foot/ns, which is something I use all the time)

Clicker question 4

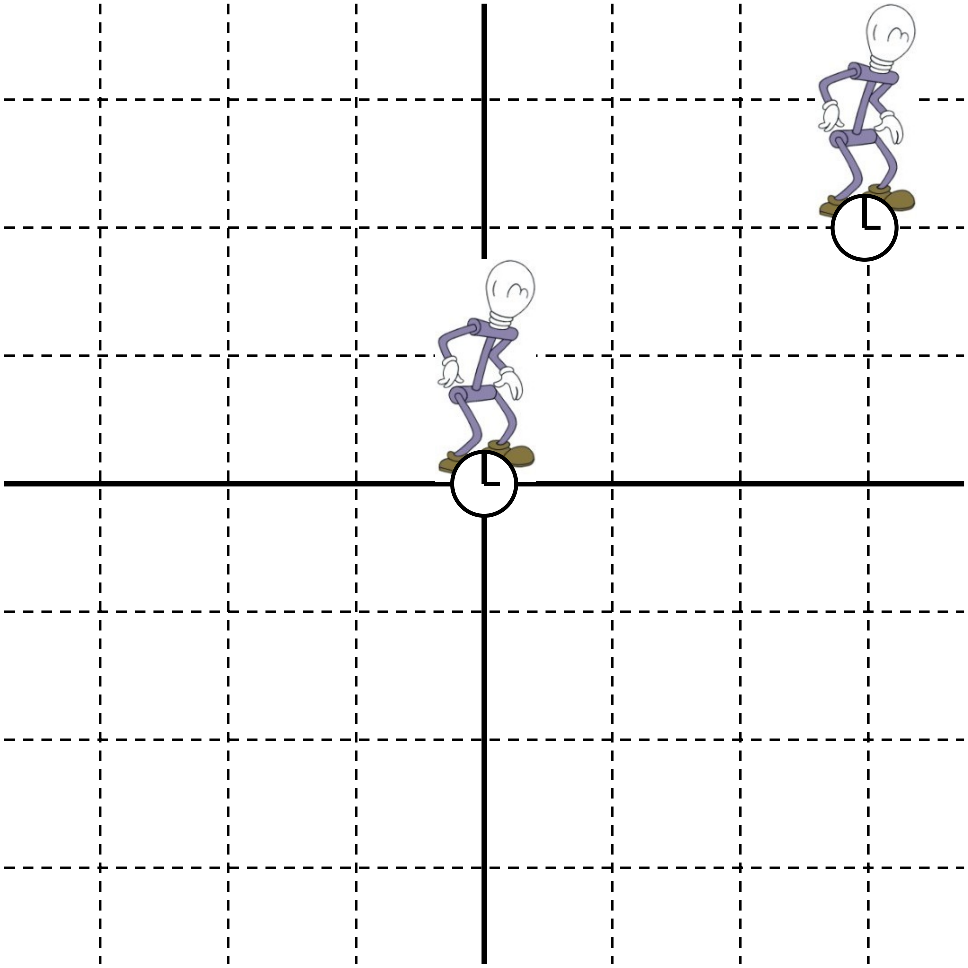
Set frequency to DA

Q. In a given reference frame, the time at which in event takes place is given by:

A. The time an observer at the origin of the reference frame observes the event.
B. The time anyone in the reference frame observes the event.
C. The time given by a local observer's clock located at the event.
D. The time given by a properly synchronized local observer's clock located at the event.

We have argued that to describe a physical event, we must specify both where it is (in some inertial coordinate system) and what time it occurs (according to some clock). But which clock?

More on reference frames

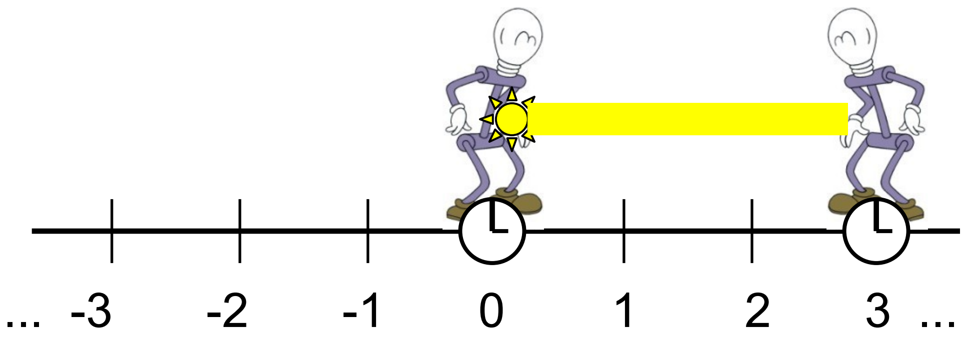


An observer at (0,0) has a clock; events there are covered.

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

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

Synchronizing clocks



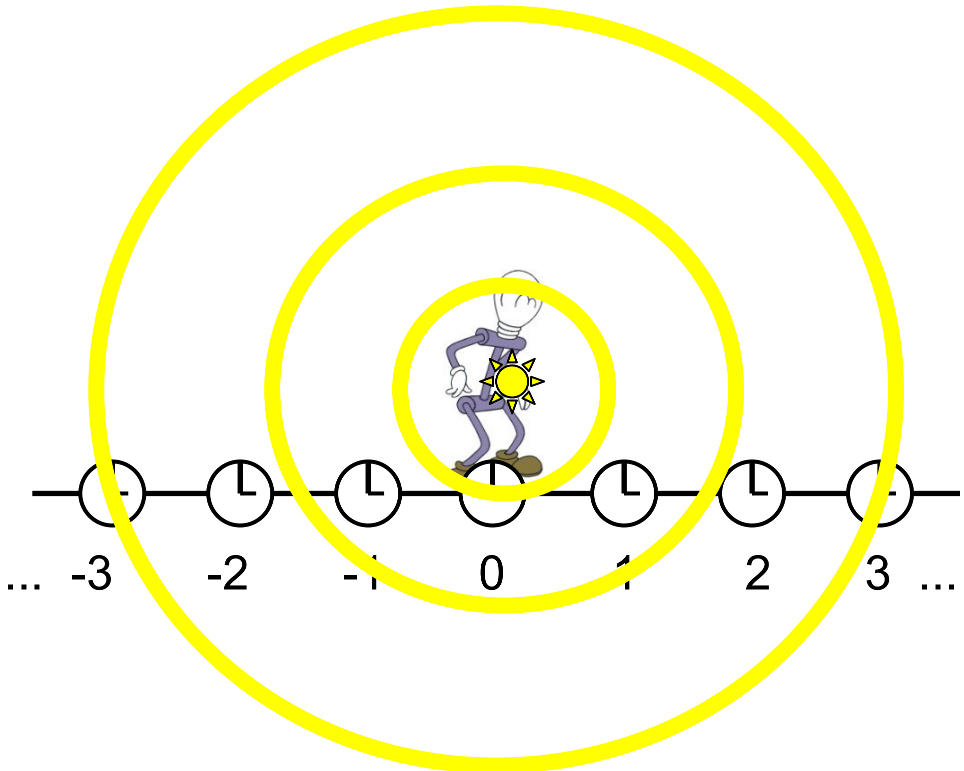
At the origin, at three o'clock, the clock sends out a light signal to tell everybody it's three o'clock.

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***.

This is a properly synchronized clock

Simultaneity in *one* frame



Using this procedure, it is now possible to say that all the clocks in a given inertial reference frame read the same time.

Even if I don't go out there to check it myself.

So we can have observers anywhere in the universe (in the reference frame) with a properly synchronized clock

From the local observers we can know when and where events really happen, even if I don't find out until later (when the event reports get filed).

Simultaneity

- Now we've got clocks under control (in one inertial frame)
- Do events occur at the same time (i.e., simultaneously?)
- Says who?

Clicker question 5 | Set frequency to DA

Two firecrackers sitting on the ground explode. Lucy, sitting on the ground halfway between the firecrackers, sees each explosion at the same time. She knows the location of each explosion and reasons that they exploded at the same time. Ricky is sitting on the ground next to firecracker 2. According to Ricky, which firecracker explodes first?

A. Both explode at the same time
B. Firecracker 1 explodes first
C. Firecracker 2 explodes first

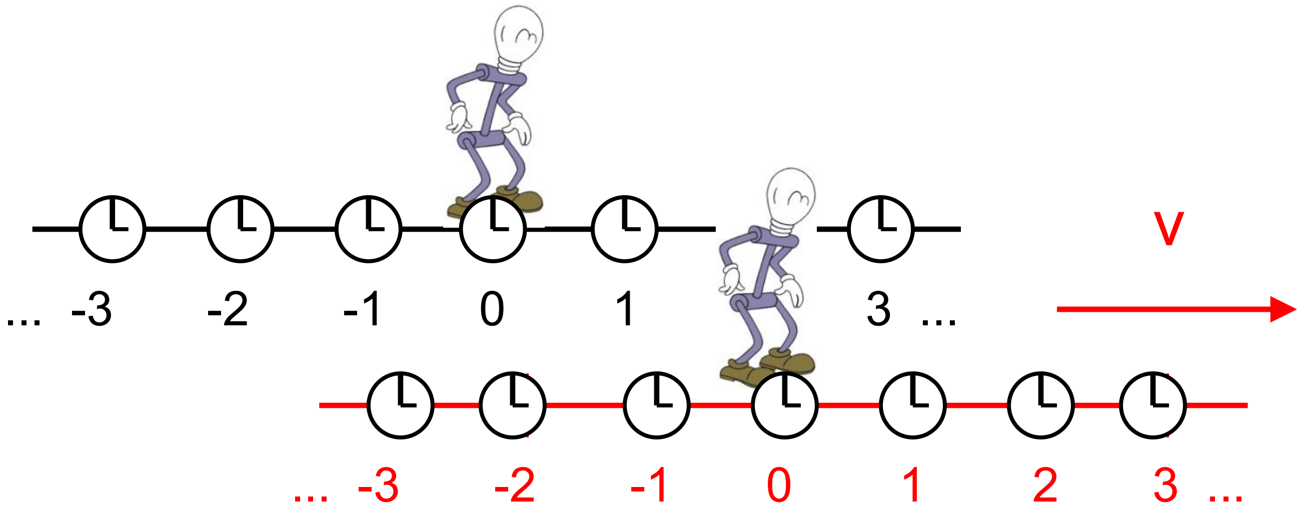
Note that Ricky knows how far away each firecracker is so the fact that he sees #2 first does not mean he thinks #2 explodes first.

Two firecrackers sitting on the ground explode. Lucy, sitting twice as close to #2 as #1, sees the two explosions at the same time. Which firecracker explodes first in her reference frame?

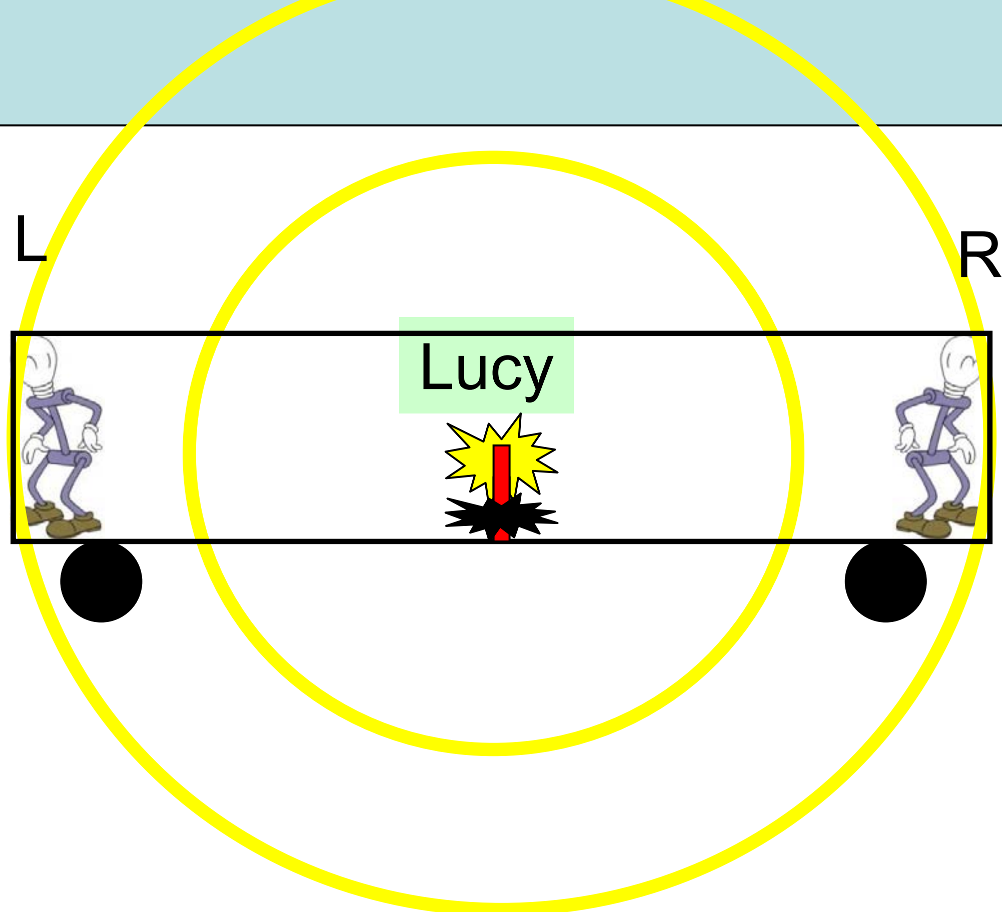
A. Both explode at the same time
B. Firecracker 1 explodes first
C. Firecracker 2 explodes first

If Lucy sees the light from both at the same time and knows that #1 is further away, it must have exploded first. Anyone else in her reference frame will come to the same conclusion!

Simultaneity in *two* frames



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



Now Lucy 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?

Reaches both ends at the same time.

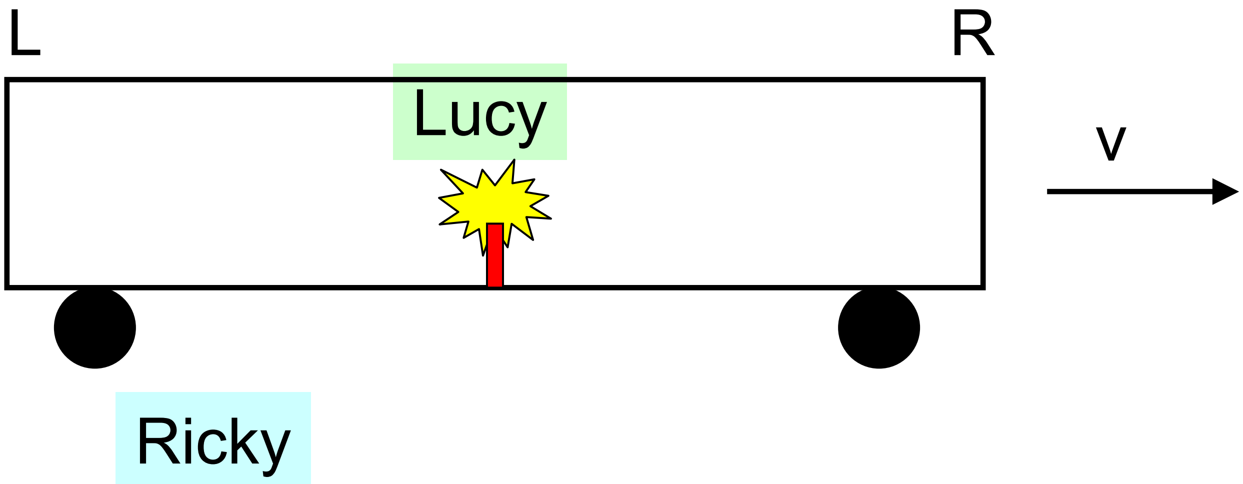
After the firecracker explodes, a spherical wave front of light is emitted.

This wave front reaches the two ends at the same time.

Note that Lucy doesn't find out until later when the observers at each end with their synchronized clocks report in. But that is an unimportant detail.

Clicker question 7

Set frequency to DA

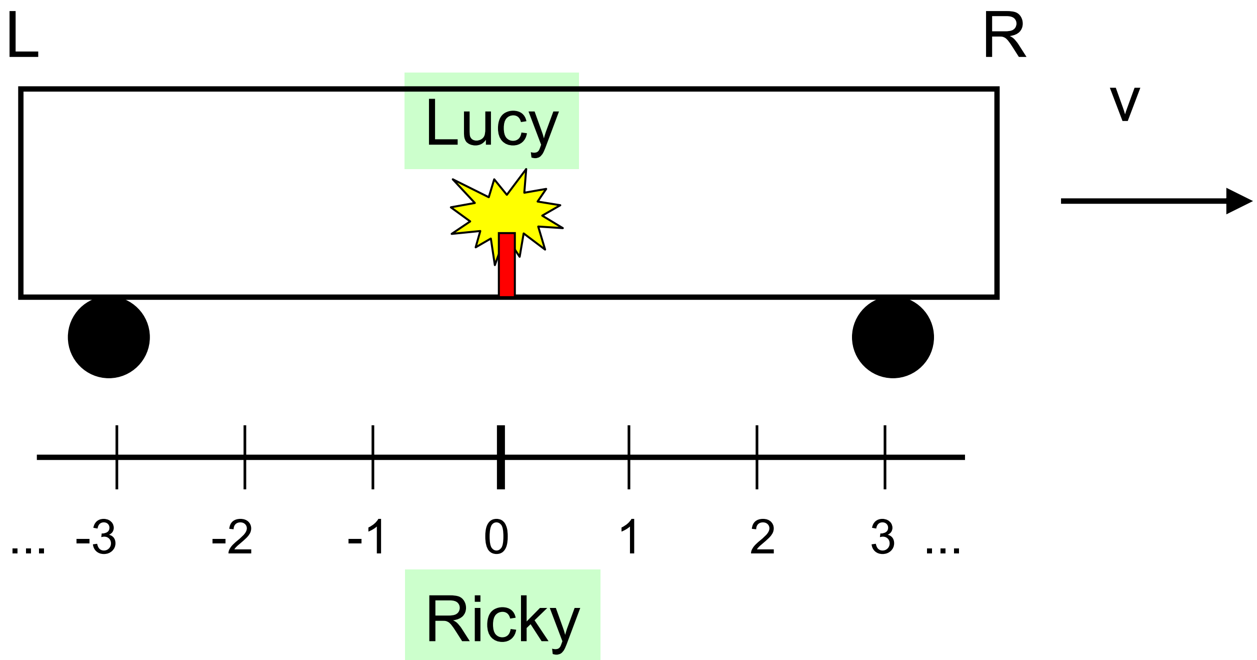


Ricky is standing still next to the tracks, watching the train move to the right. According to Ricky, which end of the train car does the light from the explosion reach first?

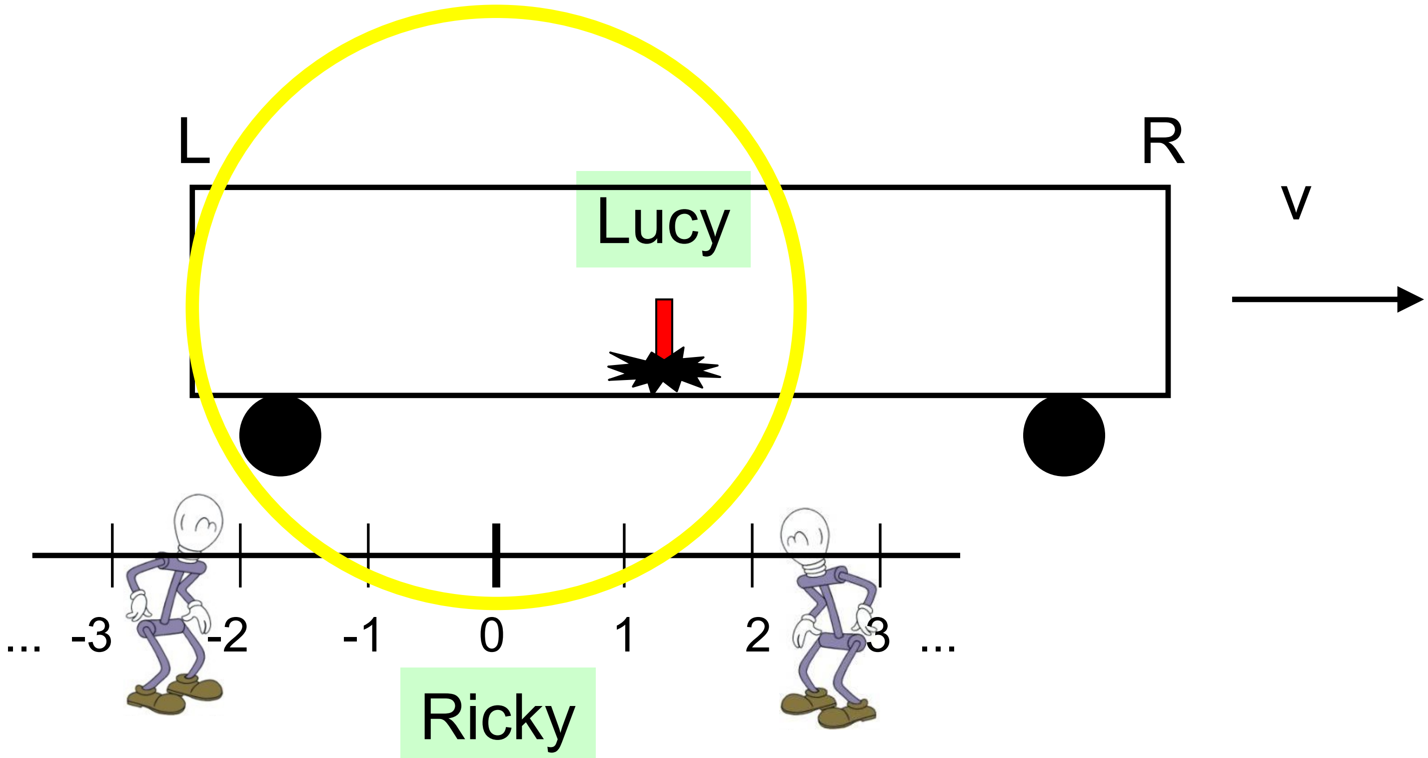
A. Both ends at the same time
B. Left end (L) first
C. Right end (R) first

In Ricky's frame, these events are *not* simultaneous.

Really, they are not simultaneous!

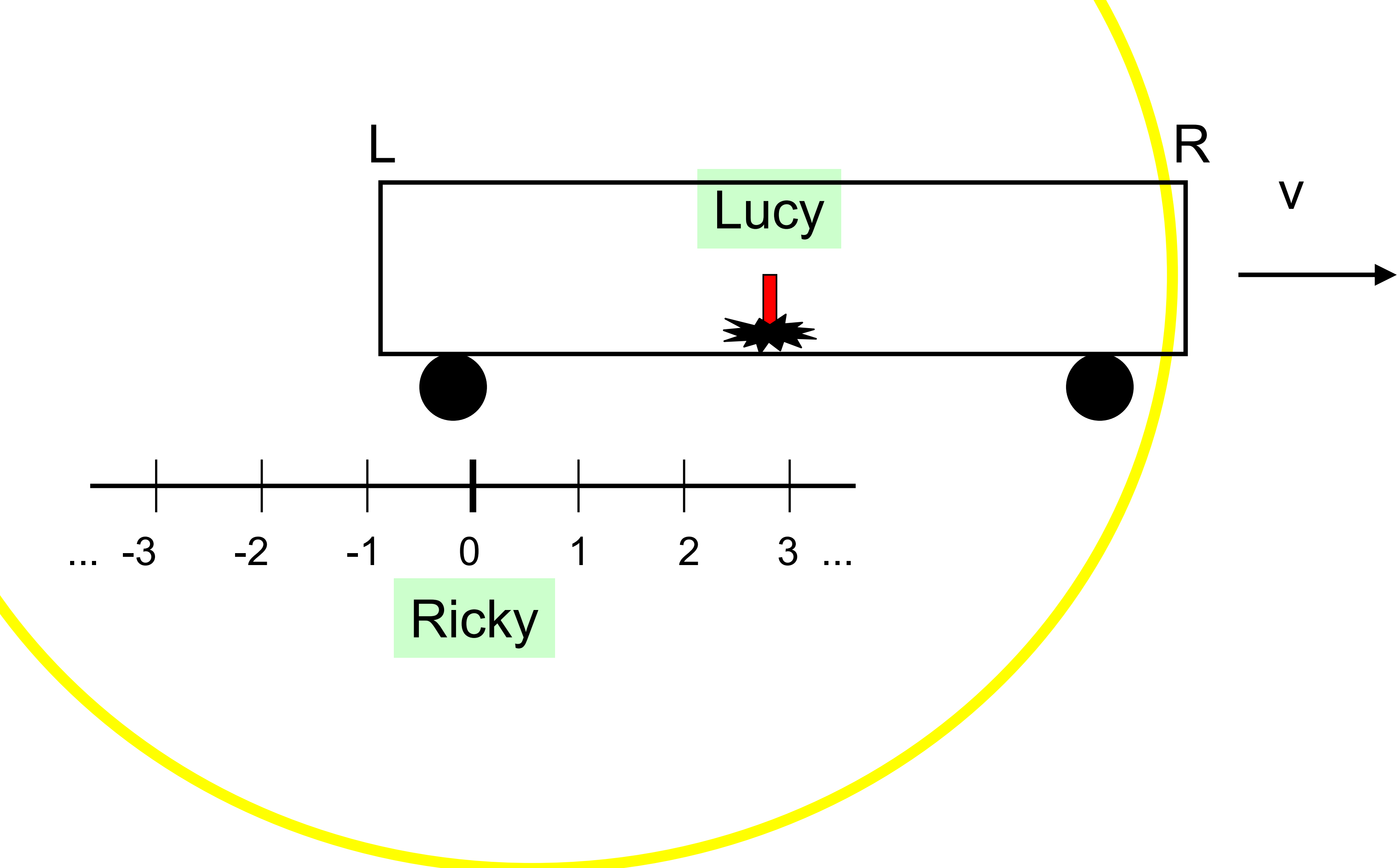


Suppose Lucy's firecracker explodes at the origin of Ricky's reference frame.



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

Local observers at ±2.5 in Ricky's frame say the light arrived there at the same time but at this point only the left end of the car is at −2.5, the front end is way off at 6 or so.



Sometime later, in Ricky's frame, the light catches up to the right end of the train (the light is going faster than the train).

Simultaneity is relative!

Given two events located at **different** positions:

1) light hits the right end of the train car
2) light hits the left end of the train car

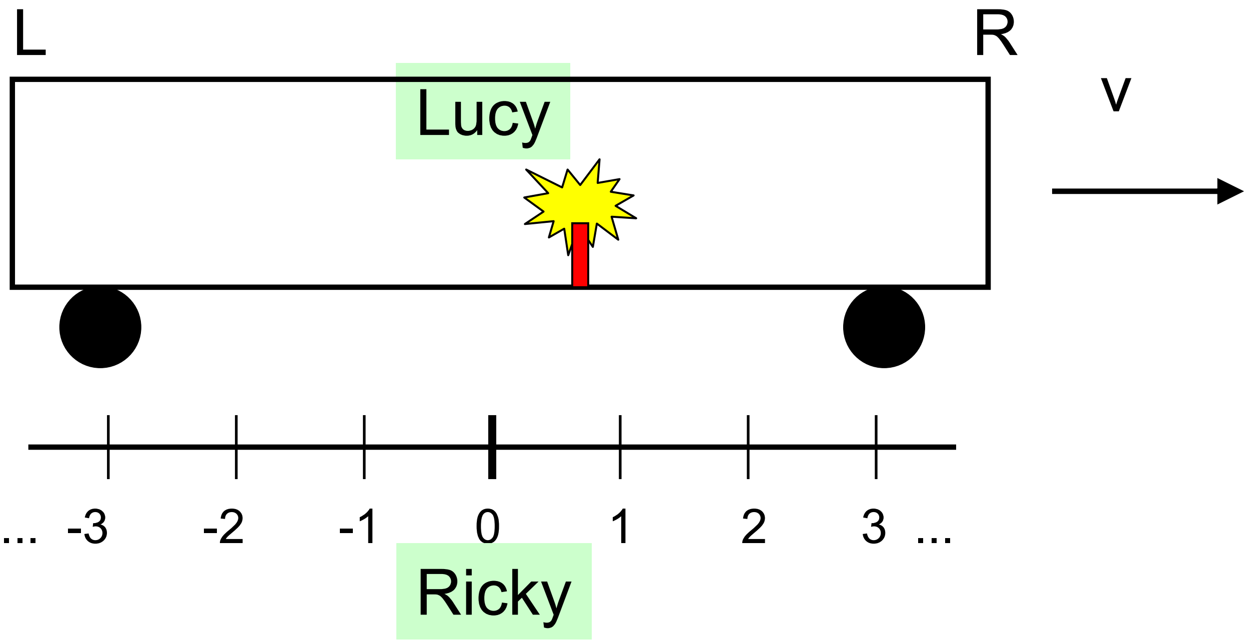
Lucy finds that the events are simultaneous.

Ricky (in a different reference frame) finds that they are *not* simultaneous.

And they're both right!

Clicker question 8

Set frequency to DA



Suppose Lucy's firecracker is *just slightly* toward the right end of the train, so slightly that Ricky still measures the light hitting the **left** end first. According to Lucy, which end gets hit first?

A. Both ends at the same time
B. Left end (L) first
C. Right end (R) first

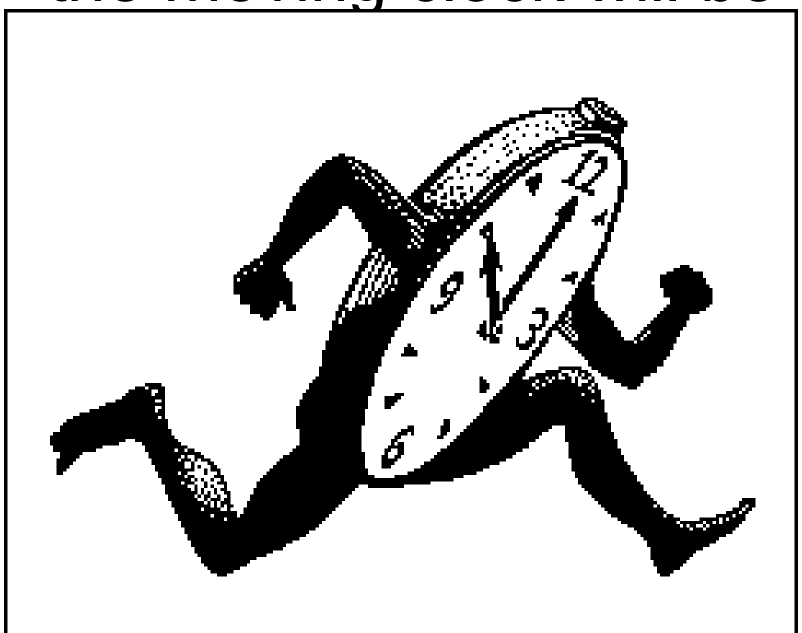
The order of events isn't even absolute

Not only can observers in the two frames not agree whether the events at different locations are simultaneous, they may not even agree which event came first.

And that's the relativity of simultaneity.

Executive Summary of Time Dilation

- The proper time $\Delta t'$ is the time between two events in the reference frame where both events take place at the same location.
- So, the proper time of a clock keeping time is the time in the reference frame where the clock is not moving.
- In an inertial reference frame in which the clock is moving, the moving clock will be slower by a factor of γ : $\Delta t = \gamma \cdot \Delta t'$



where $\gamma = \dfrac{1}{\sqrt{1-\beta^2}}$ and $\beta = \dfrac{v}{c}$

We will cover time dilation for real next Wednesday.