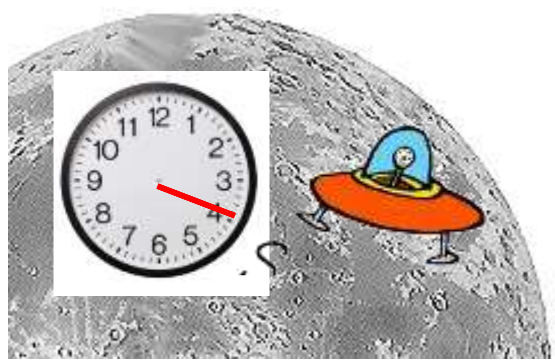
Review: Time Dilation

- In any given frame, observers will conclude that clocks run **slow** in all other frames
- The faster the relative motion, the bigger the effect!

Frame of alien on planet

Frame of alien on planet

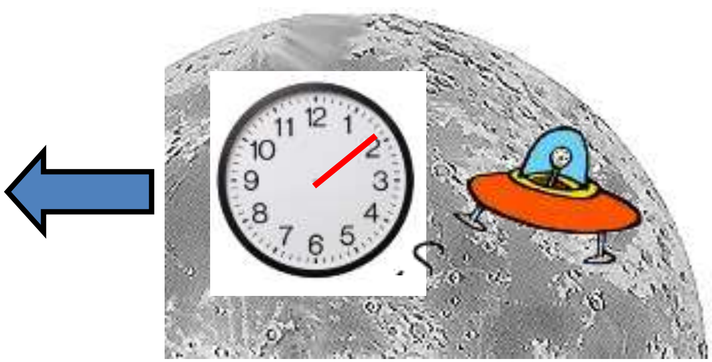


Frame of alien on planet

Frame of aliens on spaceship

Frame of aliens on spaceship

Frame of aliens on spaceship



Clicker

A spaceship passes me at 2/3 of the speed of light. What do I observe about what is occurring on board?

A) Clocks run slow

B) Chemical reactions occur more slowly than usual

C) Molecules vibrate more slowly than usual

D) Passengers think more slowly than usual

E) All of the above

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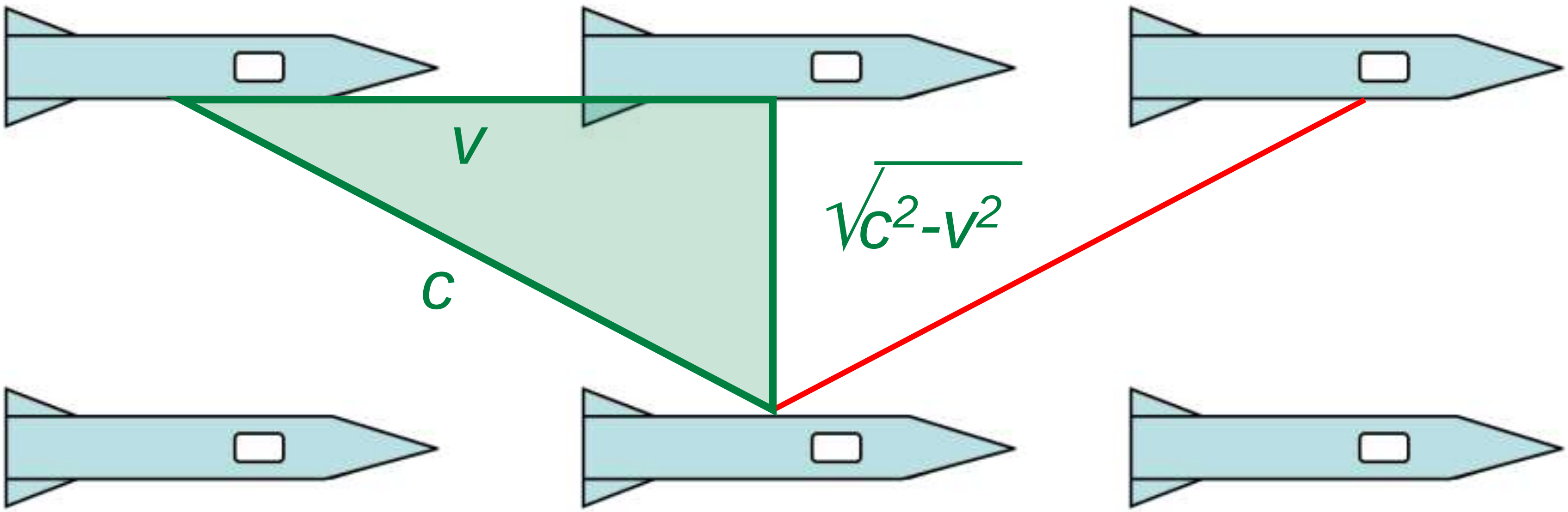

$$\frac{t'}{t} = \frac{c}{\sqrt{c^2 - v^2}} \qquad \Longrightarrow \qquad t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Time dilation

- *t* = the time measured in the frame where the clock (or observer) is at rest (also called proper time)
- *t'* = the time measured by stationary observer of the moving clock
- *v* = relative speed of two frames
- *c* = speed of light

$$t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

But wait…

- Who is really right?   Whose clock is really running slower?
  – Both are right! There is no absolute notion of time in Einstein’s theory!

But wait…

- I can look at my clock and see if it is running slow or not. Then I'll know if I'm at rest or not.
  - Wrong! Your brain is running slow too! It will look to you like the clock is ticking at a normal rate!

But wait…

- I can stop my rocket ship, dock on the asteroid, and compare the two clocks side by side. Then I'll know which is running slower!
  - Well, but then they'll be running at the same rate! Only when one is moving with respect to the other do they run at different rates.

But wait…

- Who is really right?   Whose clock is really running slower?
  - Both are right! There is no absolute notion of time in Einstein's theory!
  - Really!

Clicker

A person passes me at half the speed of light carrying a clock. What best describes time dilation?

A. If I see the moving clock run slow, the principle of relativity requires the moving person to see my clock run slow. This is a contradiction, thus dime dilation can't really be a thing.
B. My eyes are fooled into "seeing" the clock move slow, but it really doesn't.
C. From my perspective, all physical processes associated with the person and his clock slow down.
D. The passage of the person causes my brain to slow down, fooling me into thinking his clock slowed down.

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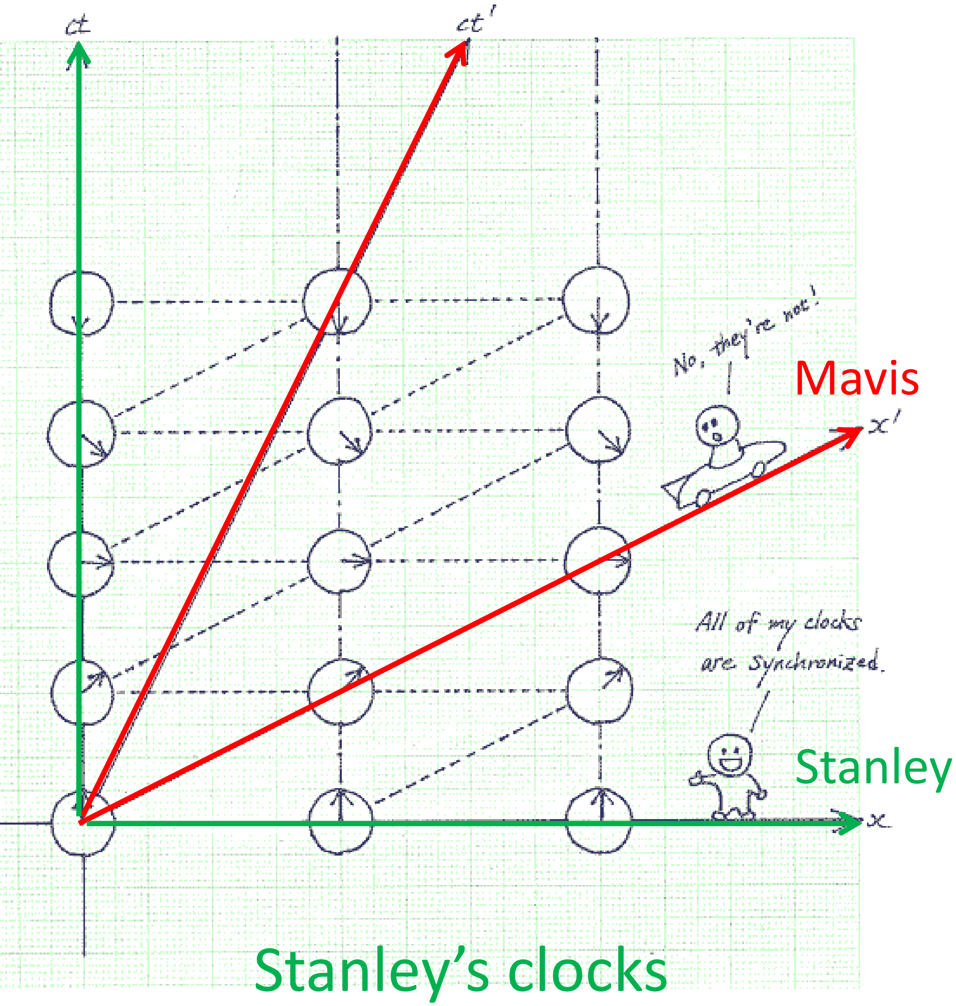
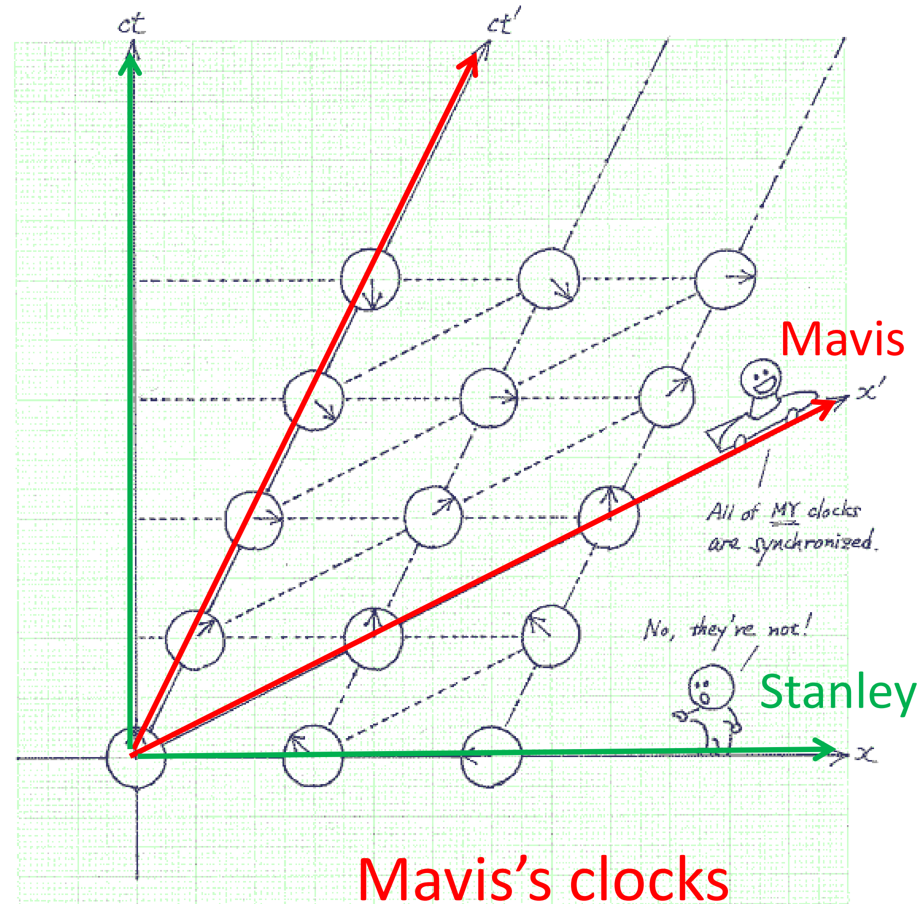
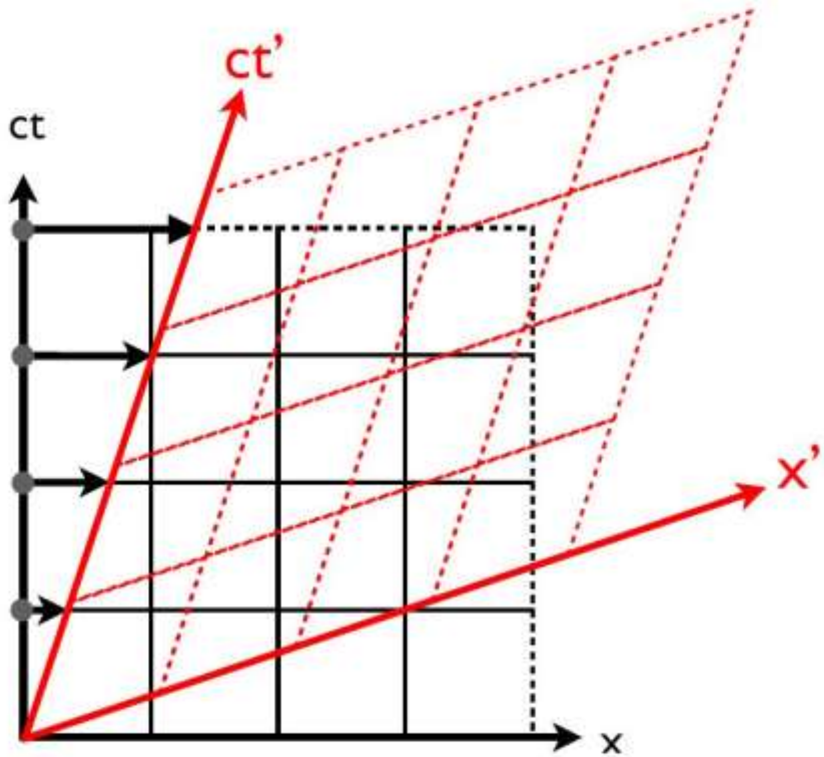
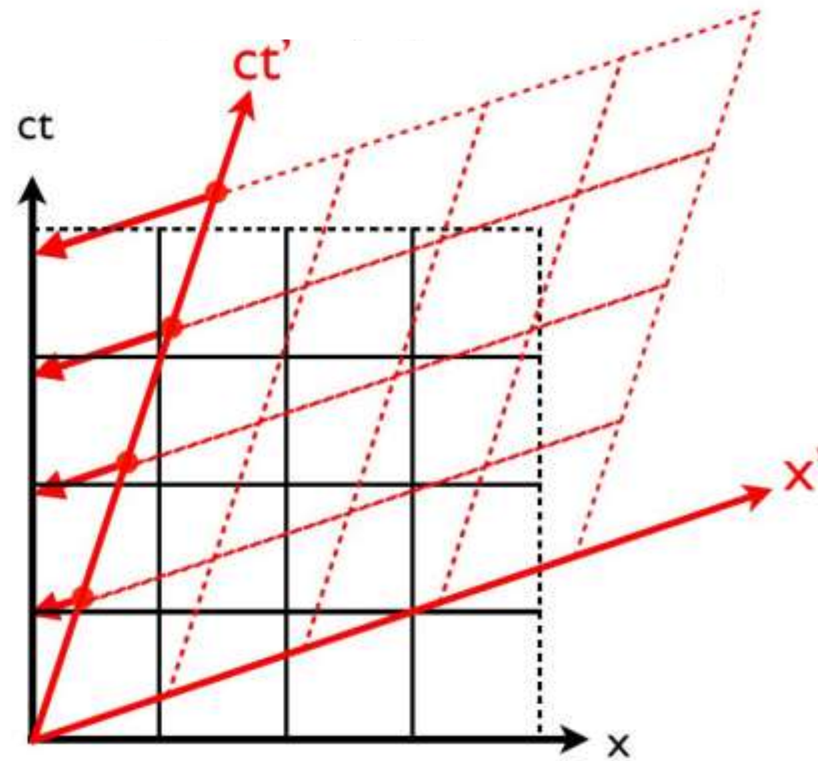
Space-Time Diagrams of Clocks in Space





Time Dilation and Principle of Relativity





As one of Mavis's clocks zooms past Stanley's synchronized clock array, we compare readings every time Mavis's clock passes one of Stanley's. We conclude Mavis's clock runs slow.

Thus, from Stanley's point of view, Mavis's clock runs slow.

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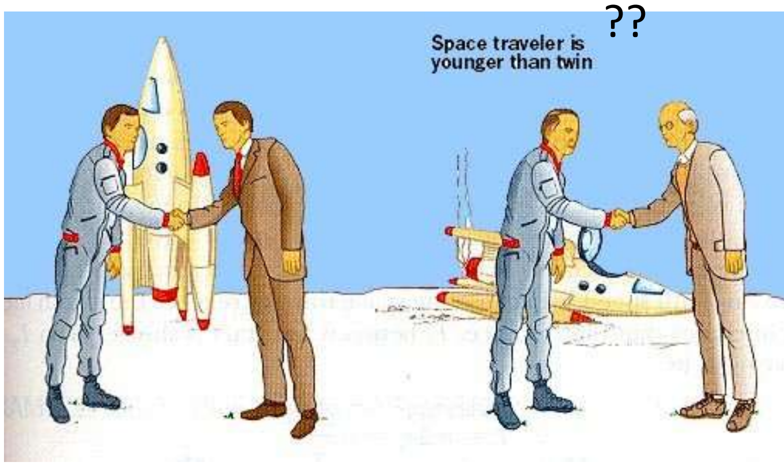
Thus, from Mavis's point of view, Stanley's clock runs slow.

Other time-sensitive phenomena

Any phenomenon that varies with time will exhibit the same behavior as the clocks – the melting of ice, the aging of animals, the decay of elementary particles, ...

"Twin Paradox"

- Al and Bert are identical twins, aged 20.
- Bert is sent on a very long space trip to a distant star, while Al stays behind on Earth.
- When Bert returns many years later,



a) Al is much older than Bert, because Bert was moving, so he aged in "slow motion".

b) Bert is older than Al, because from Bert's point of view, Al was moving, so Al was aging in "slow motion".

c) Because of the principle of relativity, these effects must somehow cancel, so Al and Bert are the same age when they reunite.

d) Age is relative: Al sees himself as old and sees Bert as his much younger brother. At the same time, Bert feels old and sees Al as his younger brother.

e) Answer d cannot be right because anyone can objectively decide which of the two is older, for example, by comparing hair color, wrinkles, etc.

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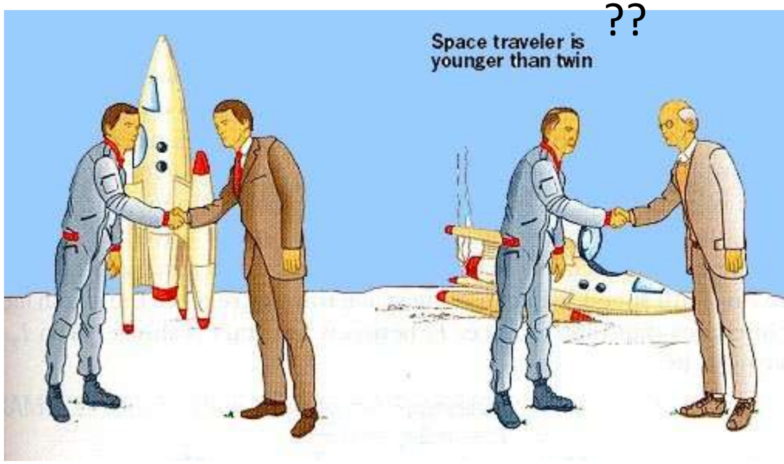

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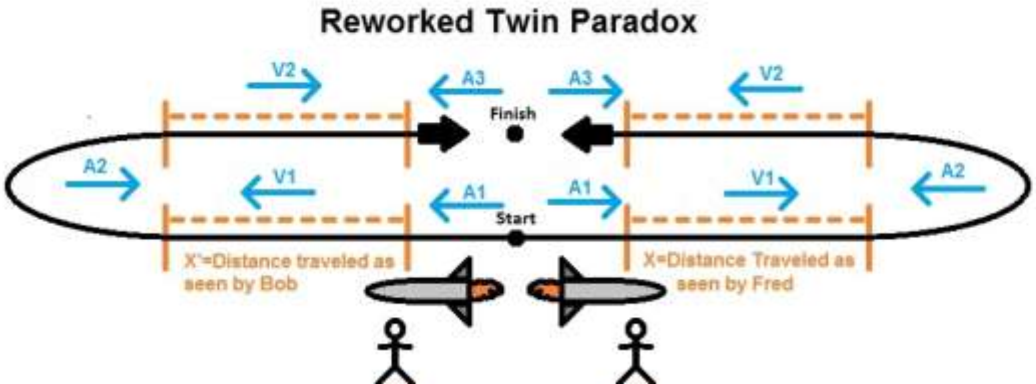
• Twin Paradox

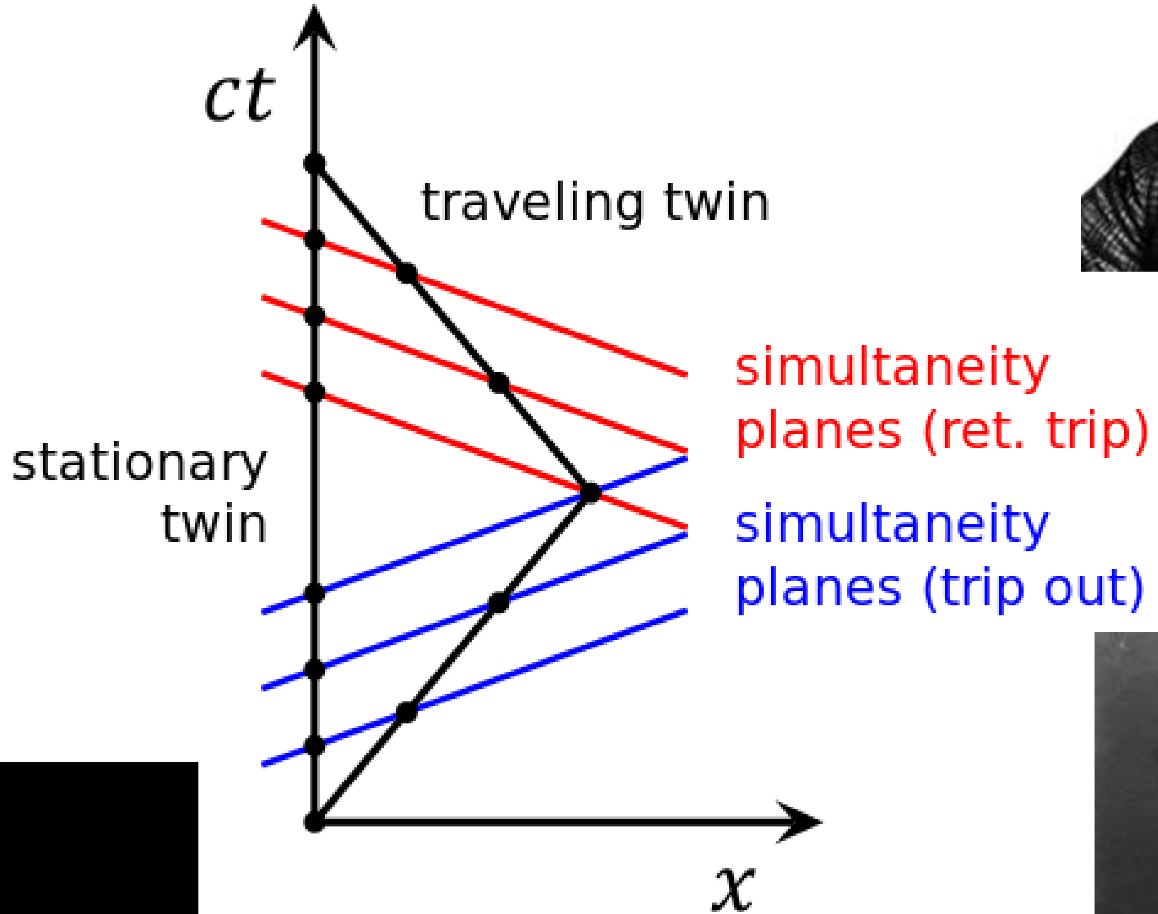
- According to the principle of relativity, there are no “special” frames of reference, so how can we decide who aged faster?
- The principle of relativity applies to inertial frames, i.e., non-accelerating frames.
- Bert’s spaceship, on his voyage, must have been accelerated so he could return to Earth.
- Thus Bert’s spaceship is not an inertial frame, and the principle of relativity does not apply.
- We can decide which twin aged more slowly by examining who was accelerated.
- If we symmetrize the problem by sending both twins to opposite ends of the galaxy, after hundreds of thousands of years they come back both equally young. All is well with the principle of relativity!

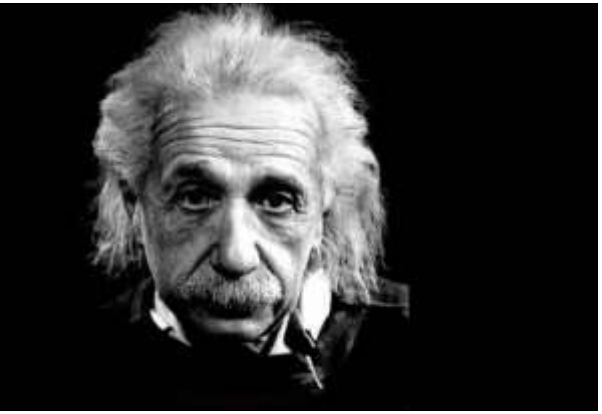


Twin Paradox Revisited

Al

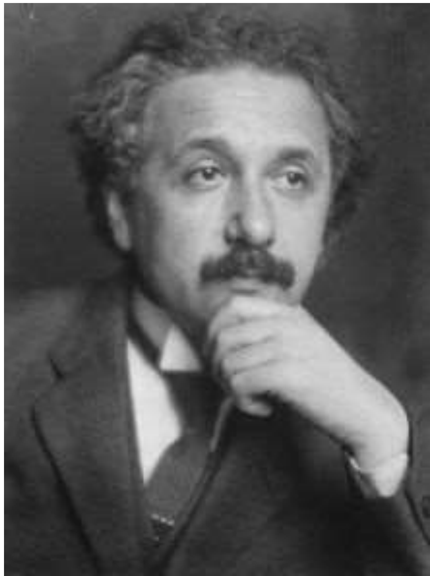
Bert





Al

Bert



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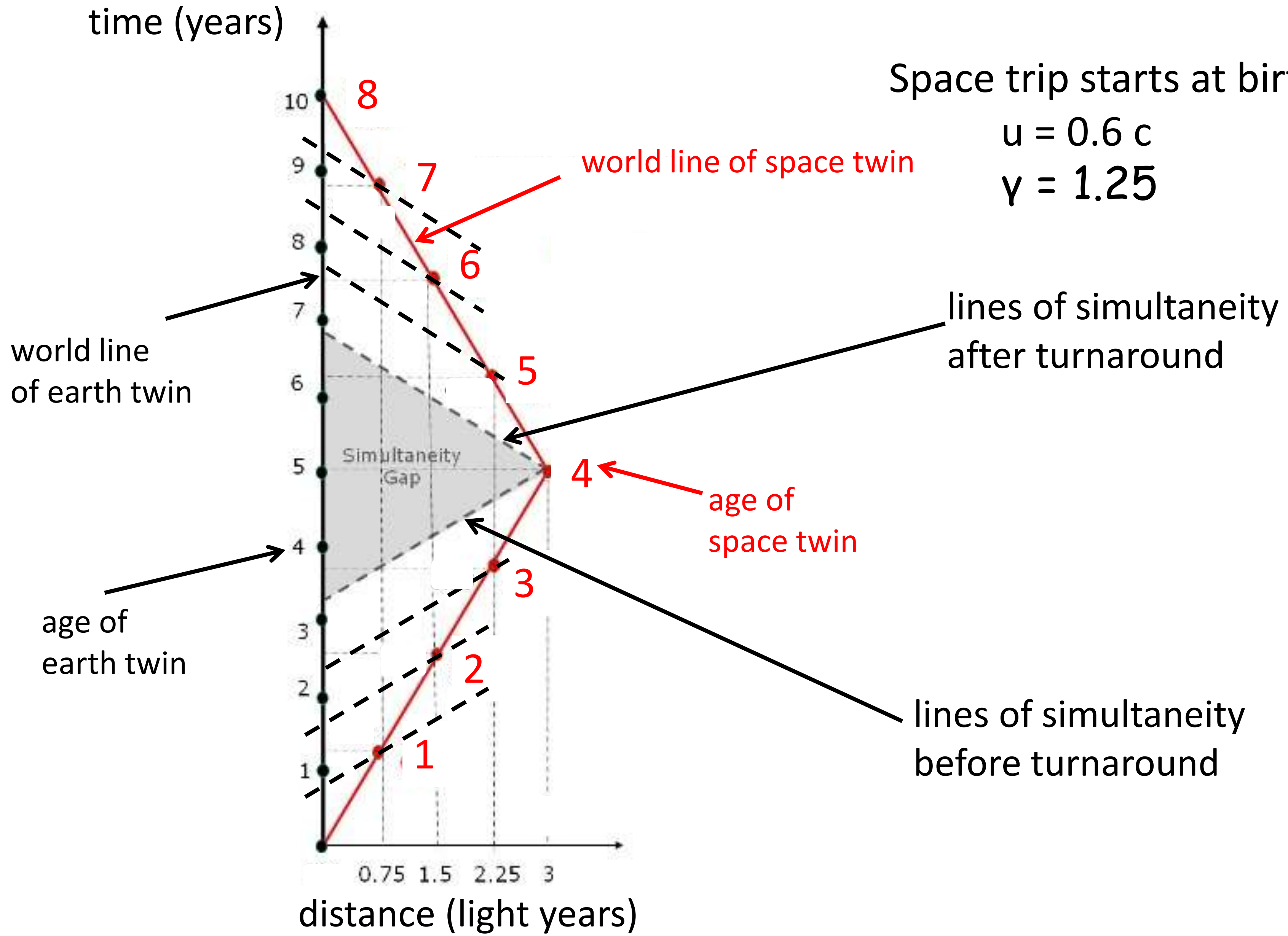

Space trip starts at birth

$u = 0.6\,c$

$\gamma = 1.25$

Clicker: Relativity Principle

We measure the following, first at rest on the ground, then in a train moving smoothly at 100 mph.

1. Drop ball and measure time to fall.
2. Period of oscillation of a pendulum.
3. Force between two magnets.
4. Rate of a particular chemical reaction.
5. Speed of an electromagnetic wave.

Which results come out to be the same in both measurements?

A. 1 through 4, but not 5.
B. 5 only.
C. 1 through 5.

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Einstein Relativity

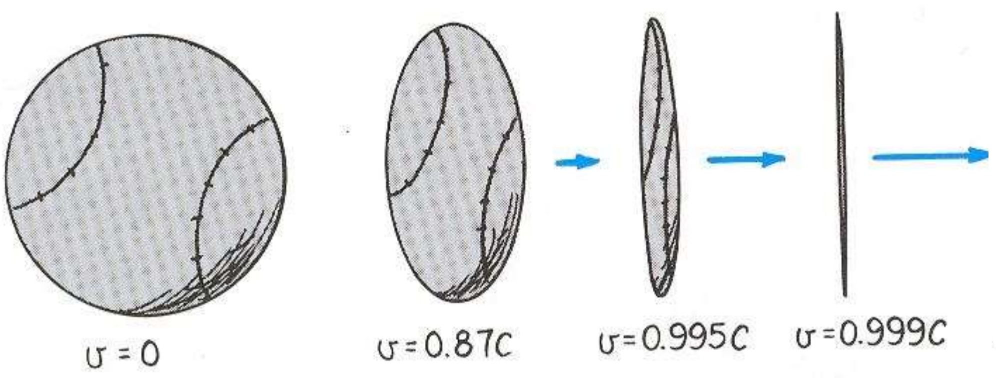
- So, time is modified for moving objects
- What about space?

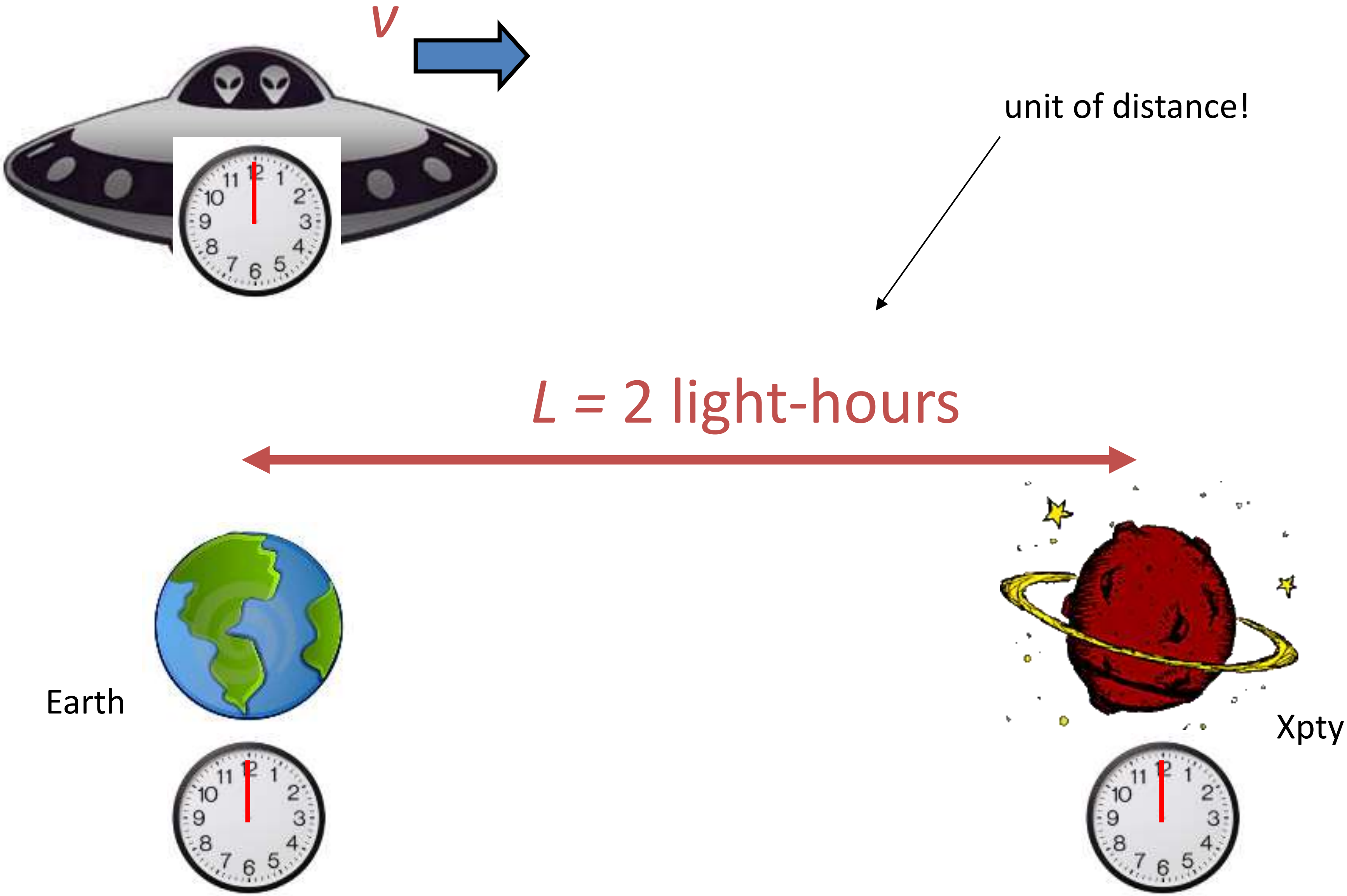
Space (or length) contraction

- In any given frame, observers will notice that objects in other frames have shrunk along the direction of motion.
- The faster the relative motion, the bigger the effect!

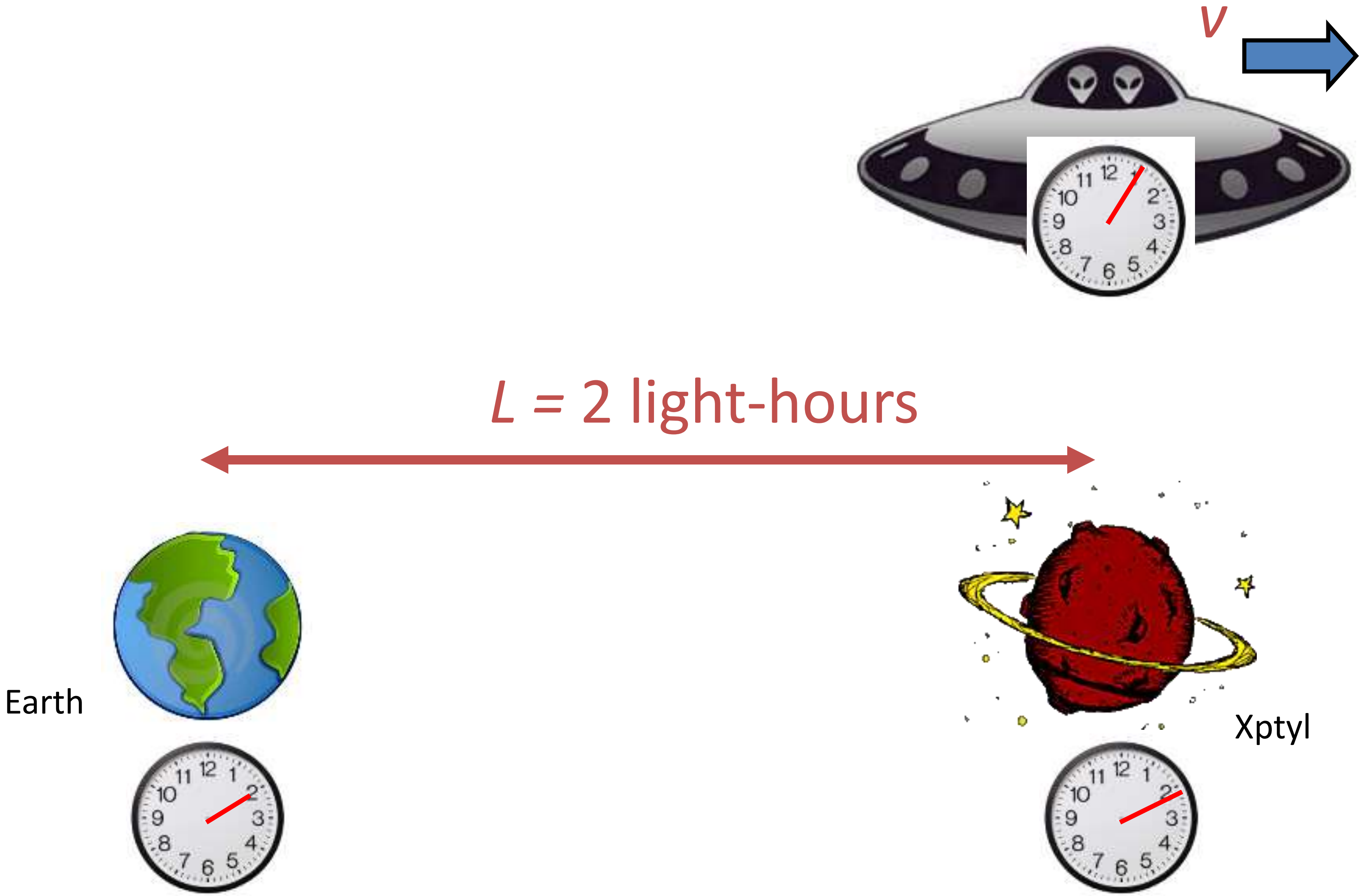
Length Contraction

- To measure the length of an object, we use a ruler or meter stick.
- To measure the length of a moving object, we need to compare the position of the front of the object to the position of the rear of the object, taking great care that the two position measurements are done simultaneously.
- Since simultaneity is relative to the observer, it is not surprising that different observers will assign different lengths to the same object!
- What happens is that the length of a moving object is contracted. Here is the shape of a speeding baseball:



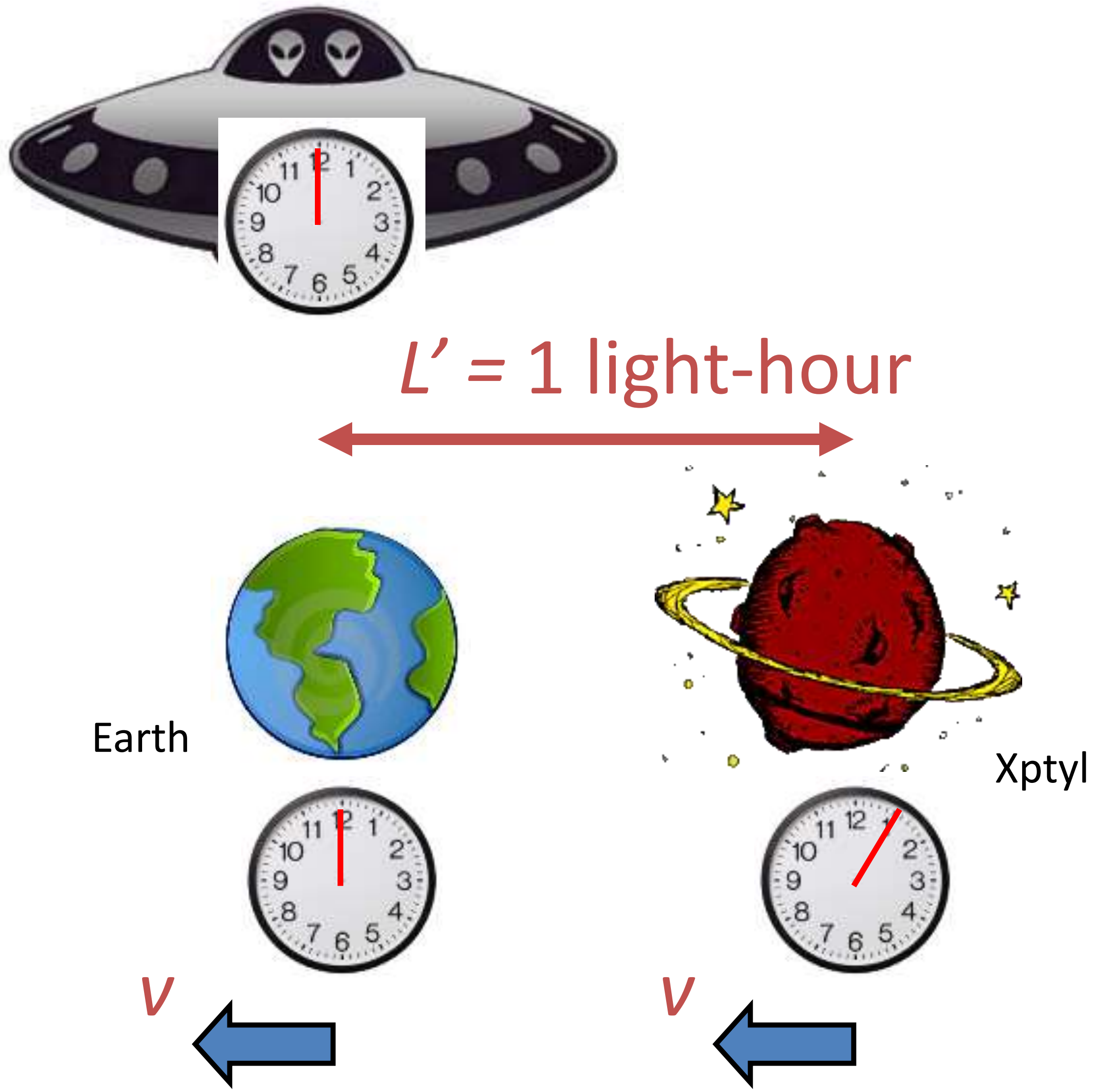


Frame of planets

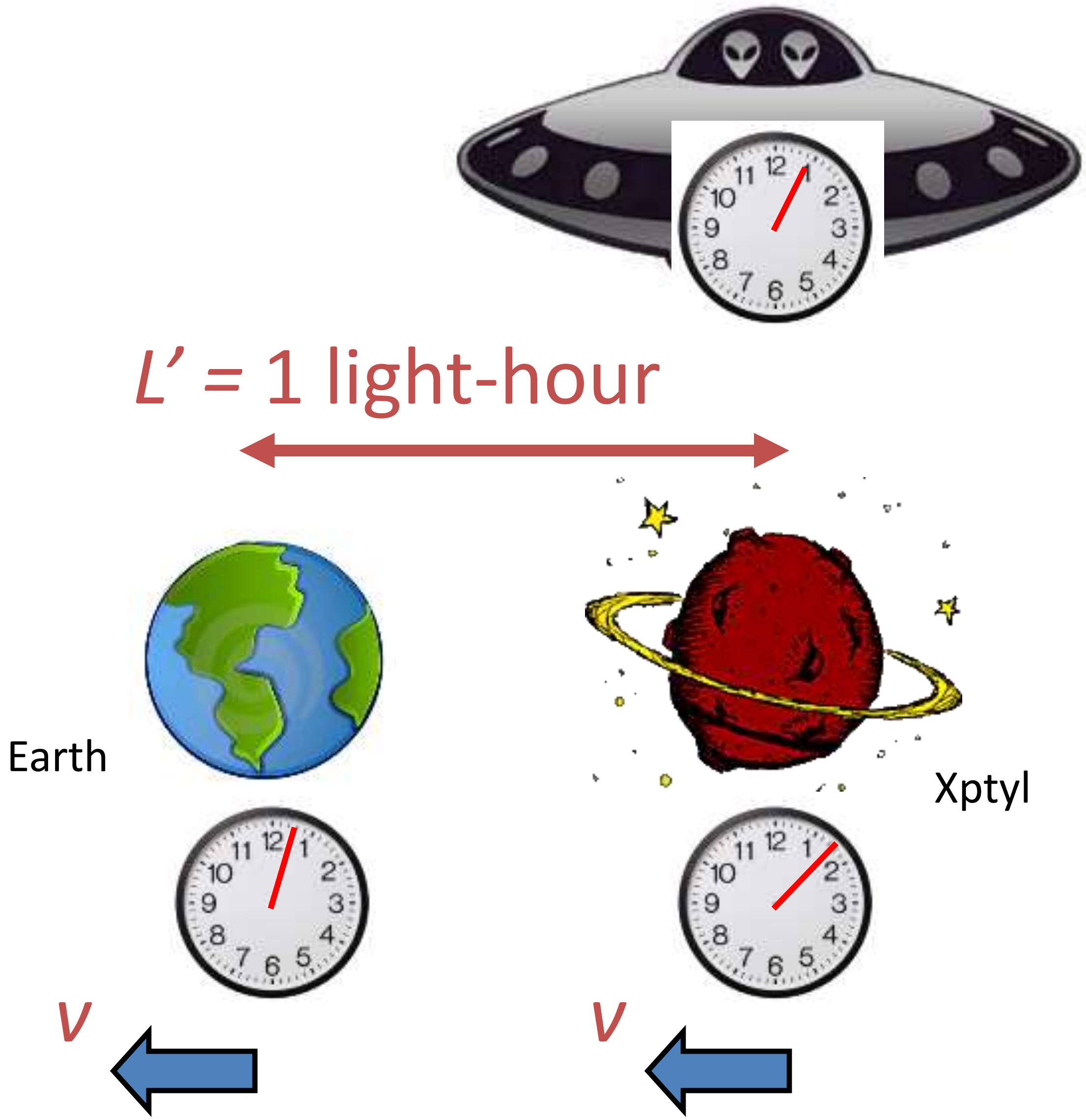


Frame of planets

Frame of aliens



Frame of aliens



Space contraction!

Space Contraction

- *L* = the length of an object measured in the frame where observer is at rest (also called proper length)
- *L'* = the length measured by stationary observer of the moving object
- *v* = relative speed of two frames
- *c* = speed of light

$$L' = L\sqrt{1 - \frac{v^2}{c^2}}$$

L'<L

So moving objects are contracted, or shrunk, as measured by an observer past whom the object is moving, in the direction of motion

But wait…

- Who is really right?   Who shrank and who didn't?
  - Both are right! There is no absolute notion of space in Einstein's theory!

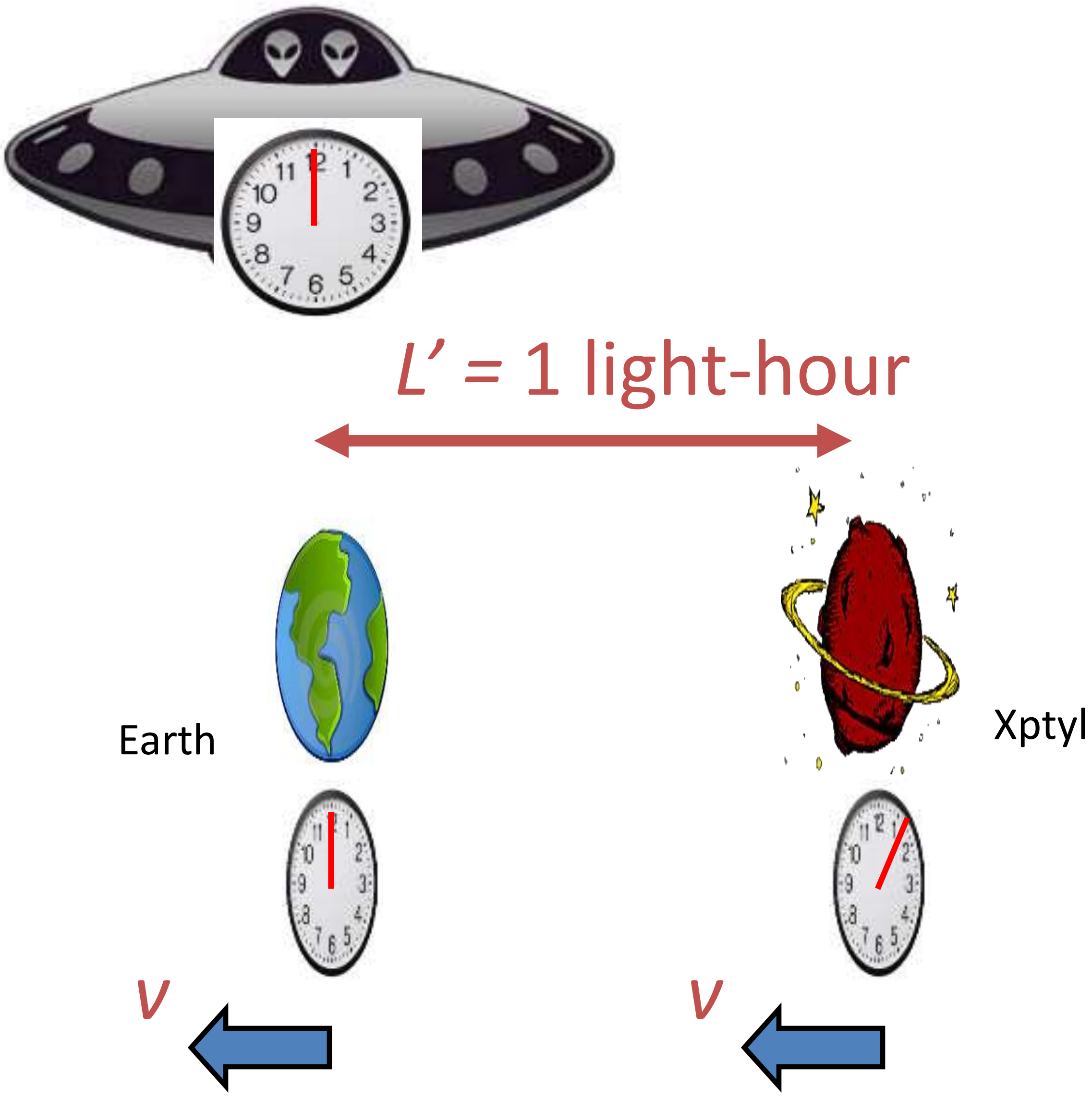
But wait…

- I can look at myself and see if I really shrank. Then I'll know if I'm at rest or not.
  - Wrong! Your brain also shrank!

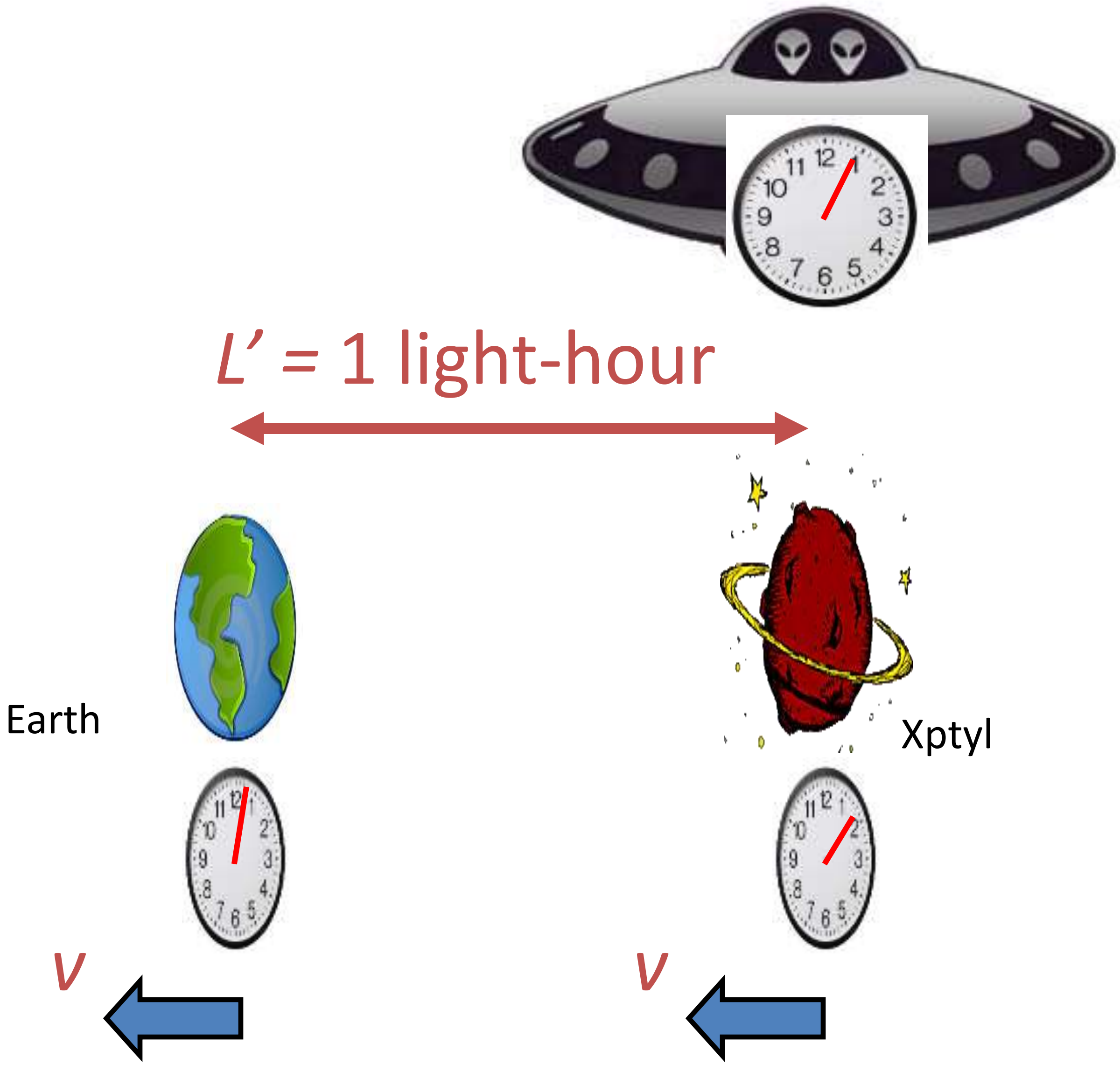
But wait…

- I can stop my rocket ship, dock on the asteroid, and compare sizes. Then I'll know who shrank!
  - Well, but then we'll be the same size! Only when one is moving with respect to the other does the other appear to shrink.

Frame of aliens - More accurate

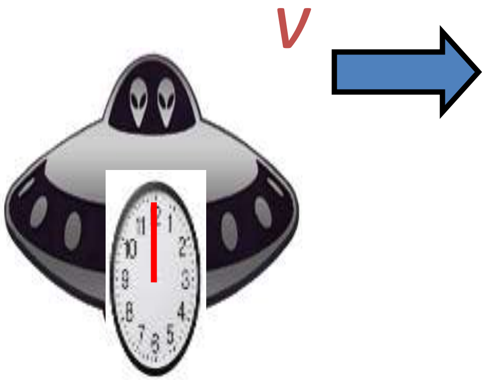


Frame of aliens - More accurate

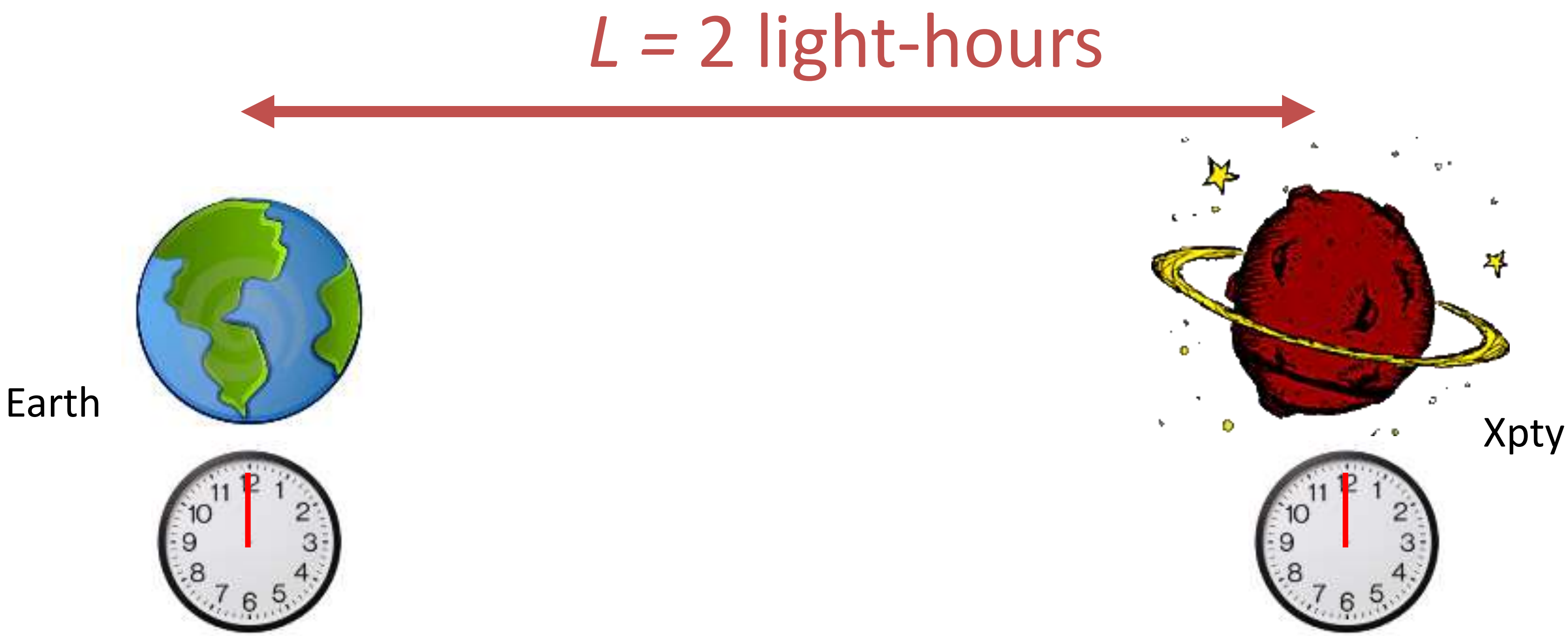


Space contraction!

("Length" contraction)

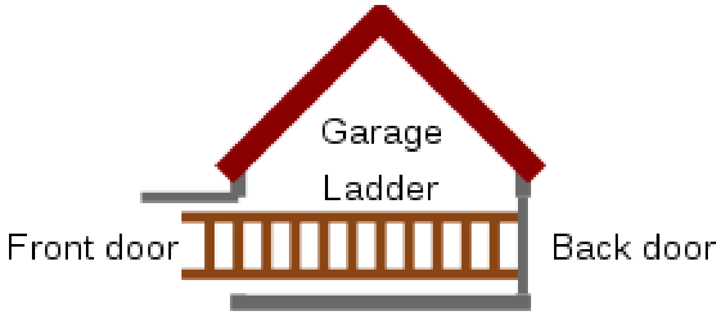


Length contraction

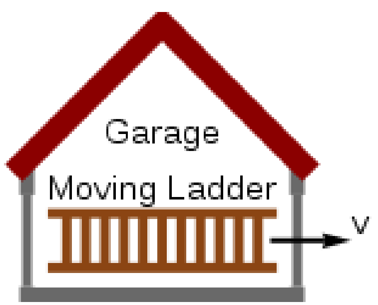


Frame of planets - More accurate

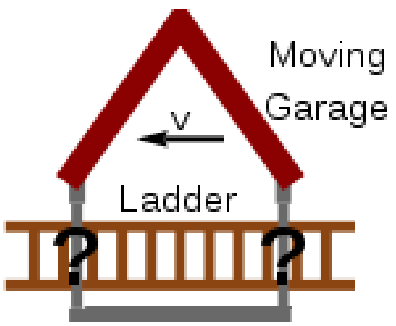
Ladder in Garage Paradox



Ladder won't fit into garage! What to do?



If the ladder is shoved in fast enough, it will (momentarily) fit due to length contraction!



Yet, from the point of view of the ladder, the garage is moving and is contracted. So the ladder doesn't fit after all! What gives?

iClicker

a) The ladder fits in the garage due to ladder's length contraction.

b) The ladder does not fit in the garage because of contraction of garage.

c) Ladders will never move fast enough for this to work.

d) The ladder fits into the garage as seen in the garage's frame of reference, but not in ladder's frame.

e) This is a logical contradiction that disproves special relativity.

iClicker

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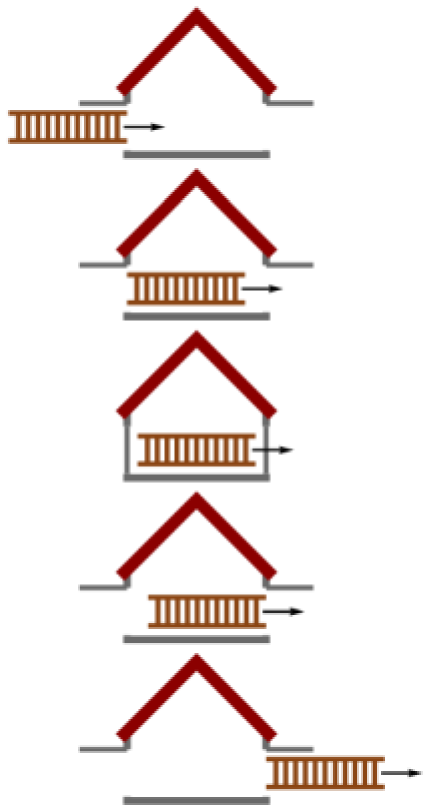
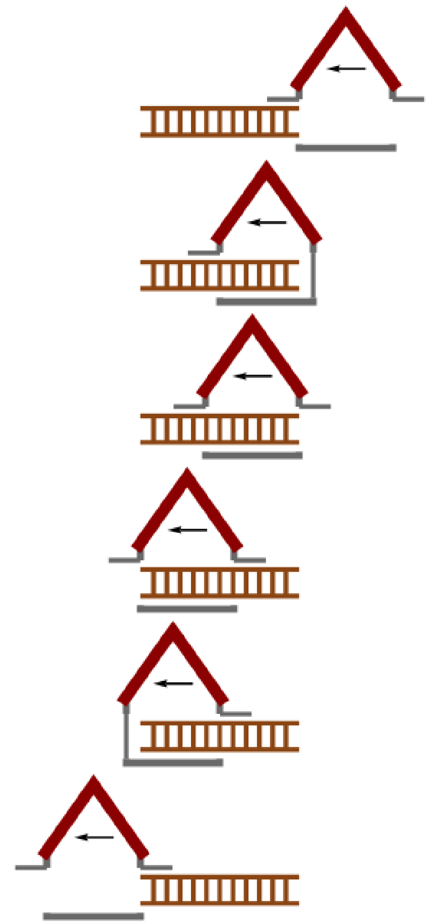
Ladder in Garage Paradox



Stationary garage, moving ladder:
Doors close simultaneously!



Stationary ladder, moving garage:
Doors close one after the other!

Clicker

What best describes what a stationary observer concludes about a moving system?

A) Events occurring at the same place at different times in the moving system occur at different places in the stationary system

B) Events occurring at the same time at different places in the moving system occur at different times in the stationary system

C) Events occurring at the same time and place in the moving system occur at the same time and place in the stationary system

D) All of the above

Clicker

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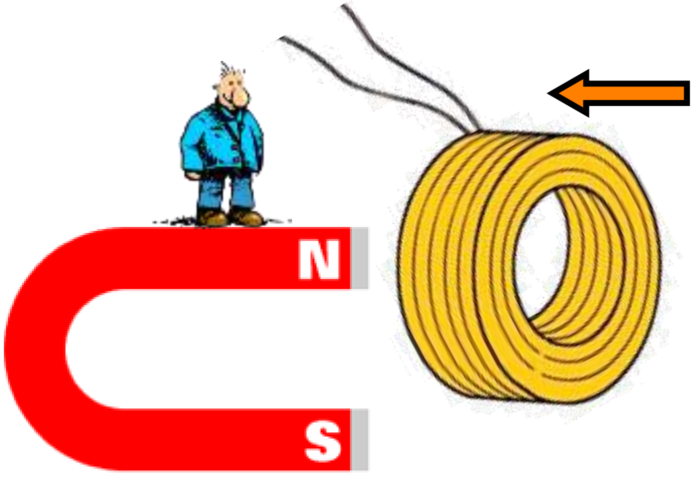
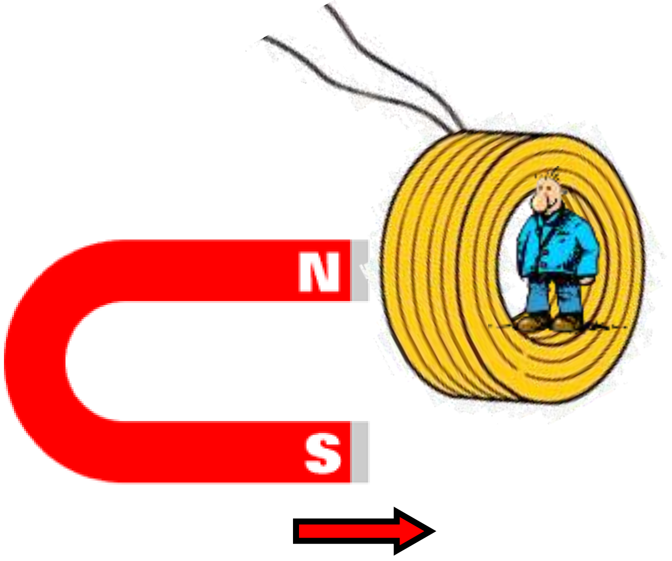
Maxwell: Faraday Induction



Frame of reference of observer on magnet



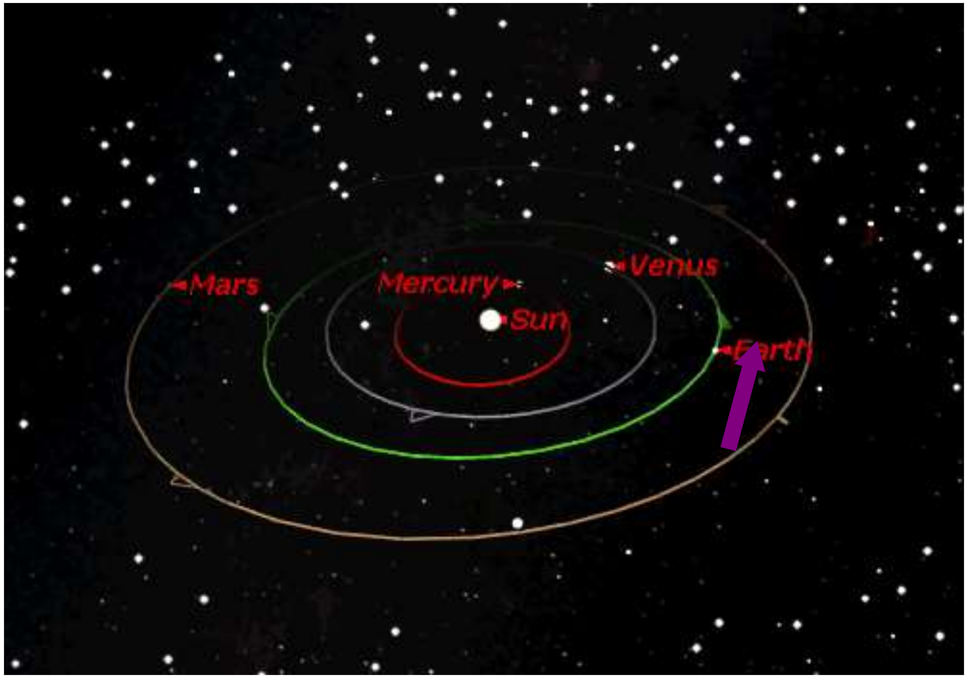
Frame of reference of observer on coil

- Only relative motion matters.
- There is no such thing as “absolute motion”.

Michelson-Morley Experiment

Before Einstein, an alternative point of view was held by many physicists:

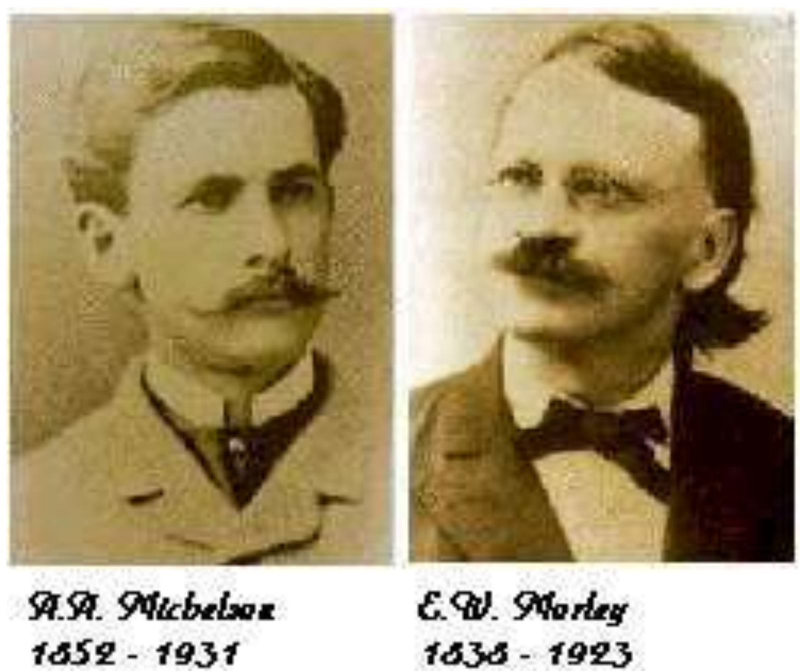
All things, including light, move with respect to a hypothetical “stationary” background medium, called the “ether”.



If the imagined ether were stationary with respect to the Sun, the Earth in its orbit would experience “ether wind”.
Such an “ether wind” should not go unnoticed...

Michelson-Morley Experiment

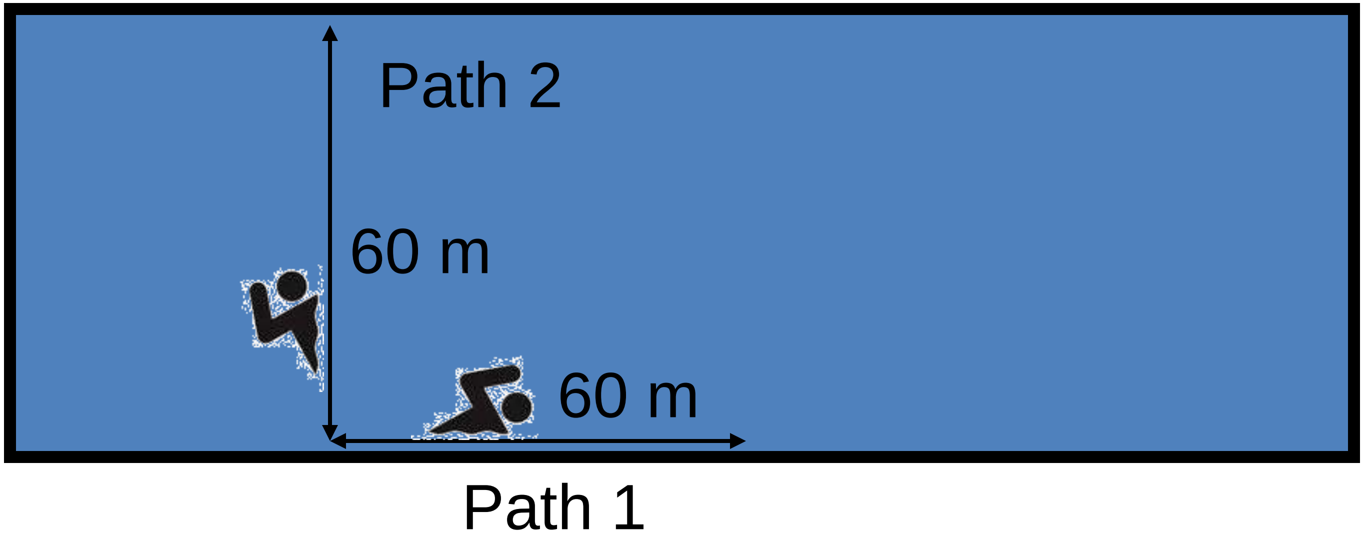
An ingenious attempt was made to **measure the velocity of the earth relative to the ether** by these guys...



Cleveland, Ohio, USA, 1887

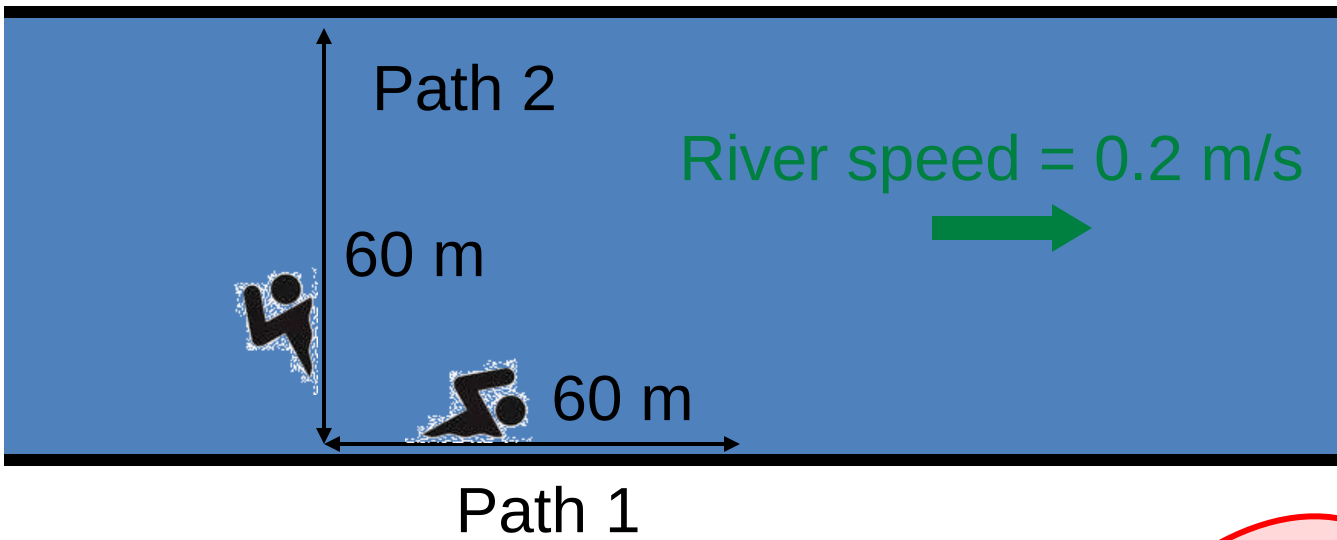
Imagine light traveled with respect to a background medium (ether), like swimmers with respect to the water:

Swimmer in a pool can swim at 1 m/s



$$t_1 = t_2 = \frac{120\,\mathrm{m}}{1.0\,\mathrm{m/s}} = 120\,\mathrm{s}$$

Now replace the stationary pool with a flowing river:

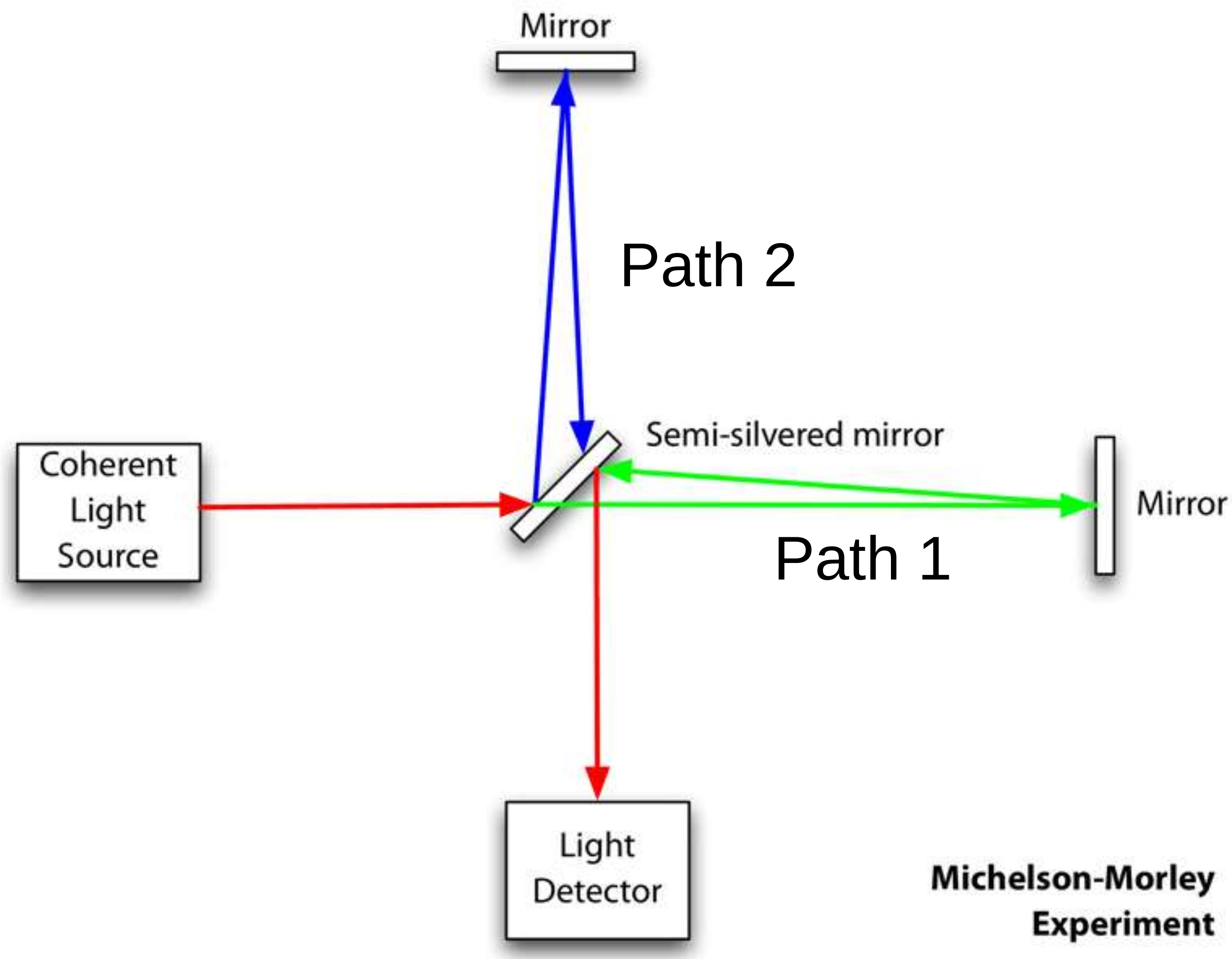


$$t_1 = \frac{60\,\mathrm{m}}{1.2\,\mathrm{m/s}} + \frac{60\,\mathrm{m}}{0.8\,\mathrm{m/s}} = 50\,\mathrm{s} + 75\,\mathrm{s} = 125\,\mathrm{s}$$

$$t_2 = (\text{requires trig}) = \frac{120\,\mathrm{m}}{0.9798\,\mathrm{m/s}} = 122.5\,\mathrm{s}$$

Different!

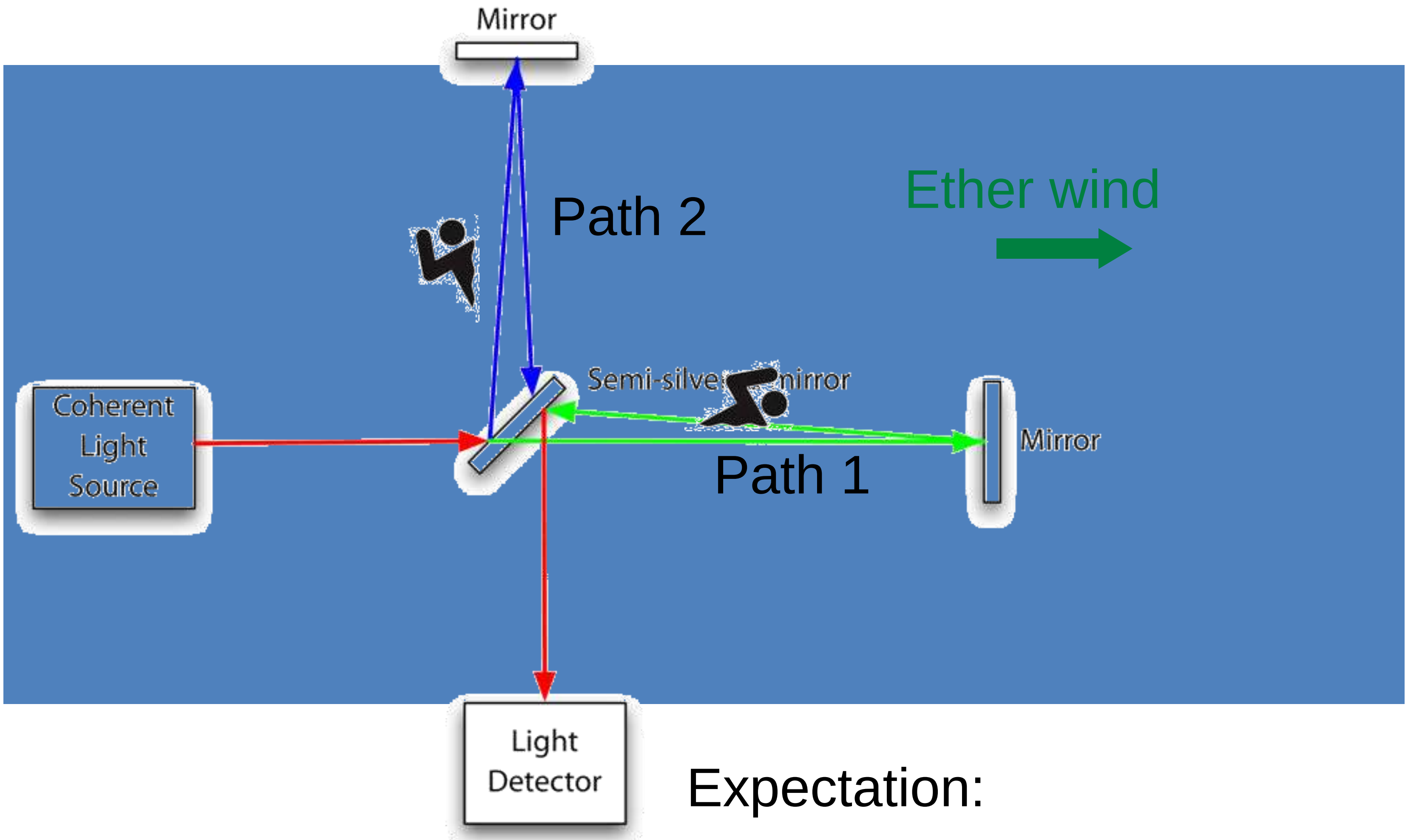
Michelson-Morley Experiment



Light was thought to behave like the swimmer.

Ether wind (due to orbital motion around the sun) is like the speed of the river.

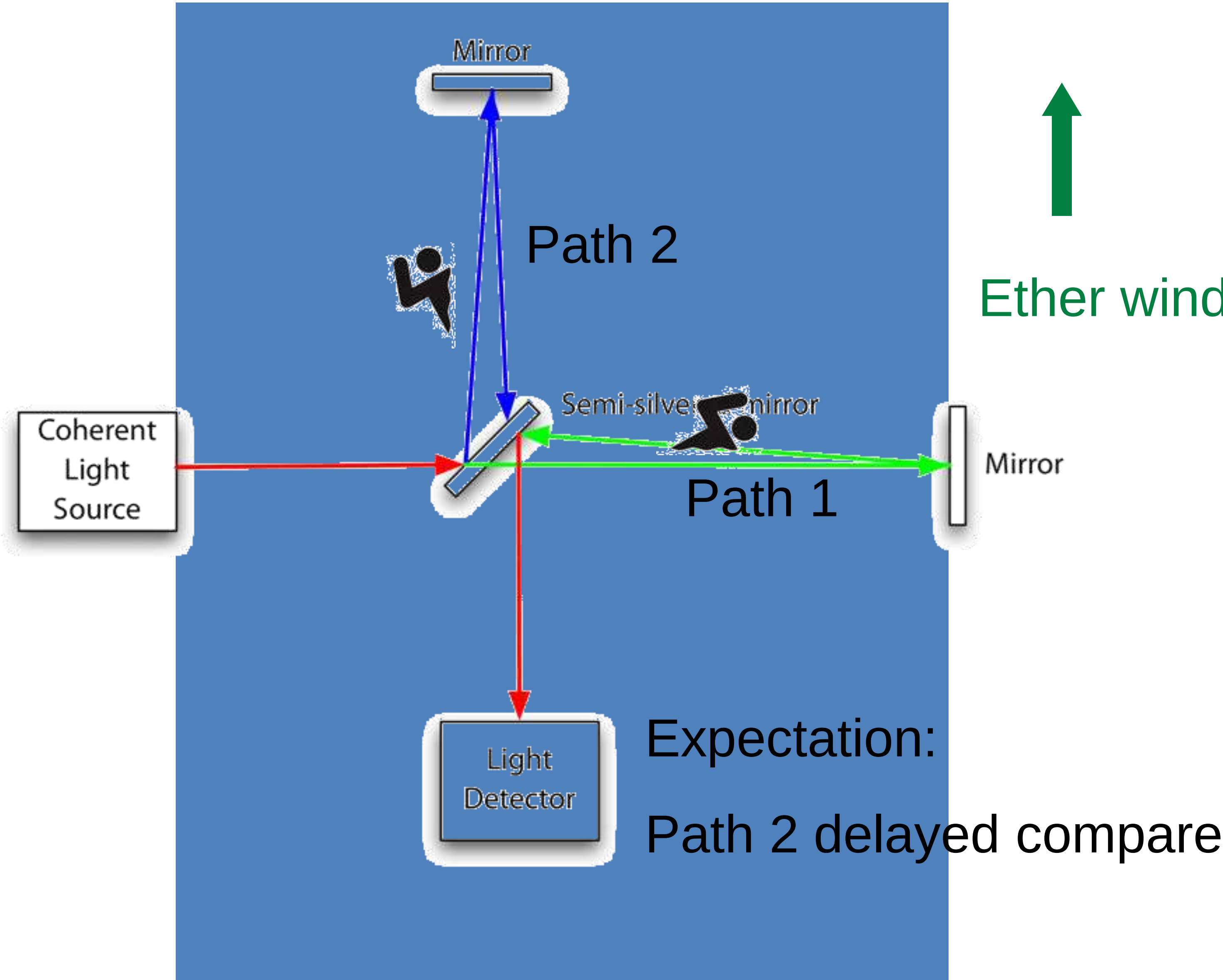
Michelson-Morley Experiment



Expectation:

Path 1 delayed compared to path 2!

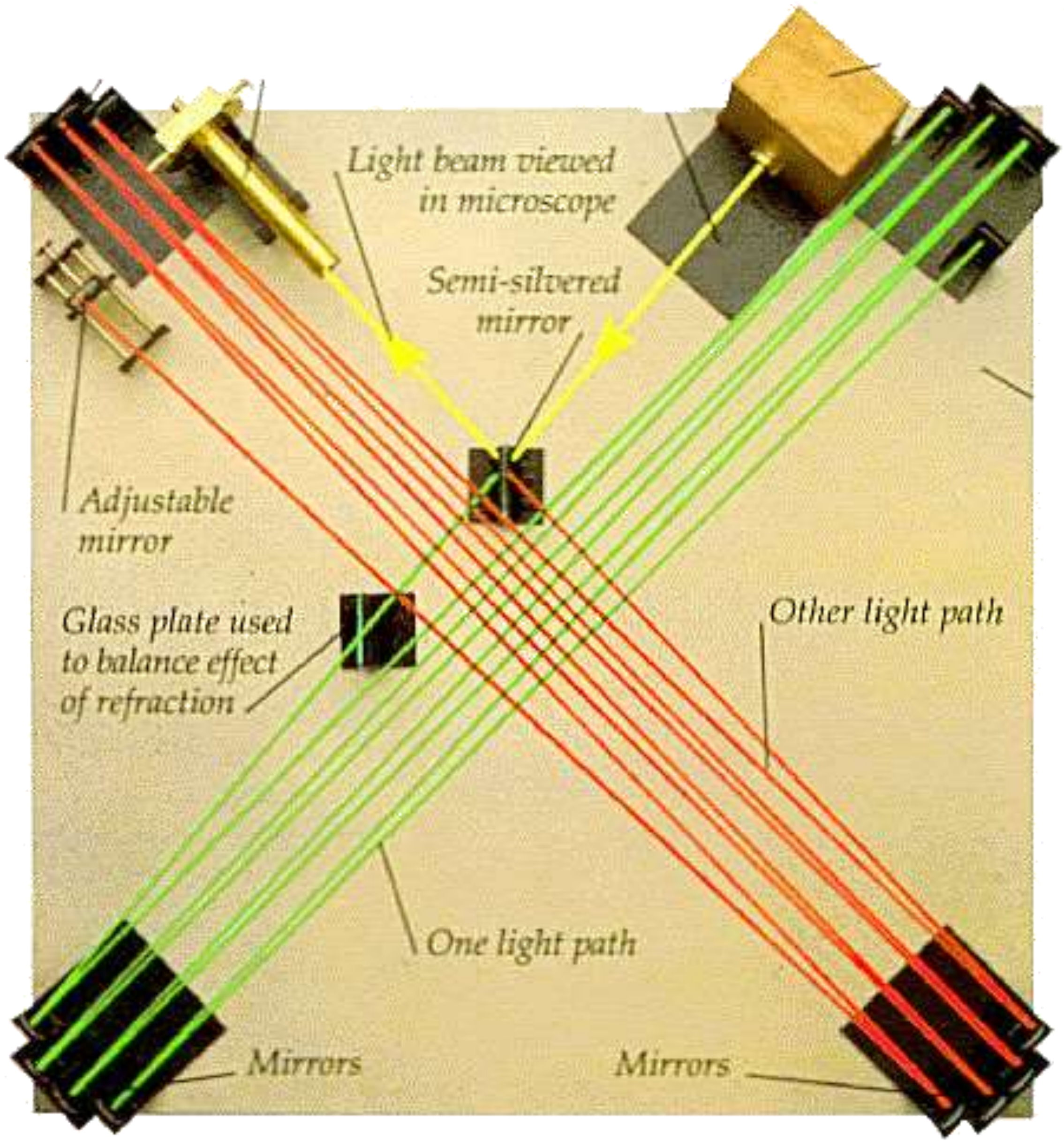
Michelson-Morley Experiment



Expectation:

Path 2 delayed compared to path 1!

Michelson-Morley Experiment



Michelson-Morley Experiment

- Result: No delay observed!
- Michelson and Morley were disappointed...
- But: In hindsight the result served as a great confirmation of Einstein's theory:
  - There is no ether!
  - Light always travels at the same speed in all reference frames, unaffected by any "ether wind".
  - There is no absolute motion!