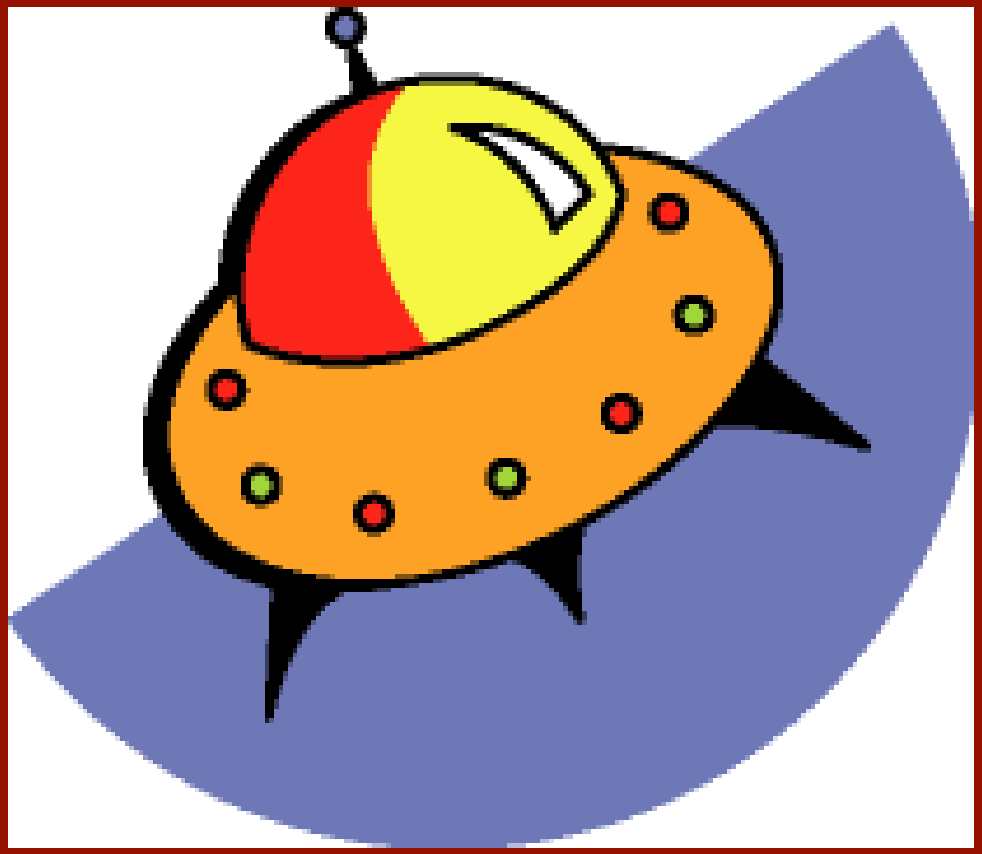
Special Relativity!



Time, as we know it, travels at 24 hours per day, or 60 minutes per hour, or 60 seconds per minute. However, motion through space is also related to motion in time.

Albert Einstein was the first person to understand the relationship between space and time. He stated in 1905 that when we move through space, we also change our *rate of proceeding into the future*. In other words, *time itself is altered*.

Einstein called this concept ***the special theory of relativity***.

The special theory describes how time is affected by motion in space at a constant velocity, and also how mass and energy are related.

Space-Time

Isaac Newton and other scientists before Einstein thought of space as an infinite "place" where everything exists.

It was not clear whether the universe exists in space or space "exists" within the universe. Is there space outside the universe, or is space only within the universe?

The same question can be asked about *time*. Does the universe exist in time, or does time exist only within the universe? No one really thought about this question until Einstein came along.

Einstein answered these questions and said that both space and time *only* exist in the universe and there is no space or time outside the universe.

Einstein then said that space and time are two parts of the same idea, which he called **space-time**.

In order to understand this, we must stop thinking about moving *through time* to moving through *space-time*. Everyone in the universe travels through a combination of space and time.

- When you stand still, all of your traveling is through time.

- When you move a bit, some of your travel is through space and time

- If you could go the speed of light, you would only travel through space, not time!
  - Light is the fastest speed **anything** can go. Nothing can travel faster in space than light.

As far as light is concerned, *there is no time.* Photons of light travel through space only!

Motion through space affects motion in time. Every time we move through space, we alter our movement into the future by a little, tiny bit.

We call this phenomenon time dilation. Time dilation is the stretching of time that occurs just a teeny-tiny bit for everyday speeds, but significantly at speeds approaching the speed of light.

Relative Motion

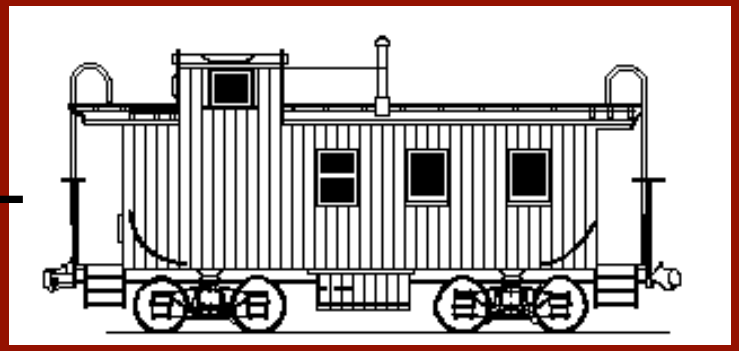
Whenever we talk about motion, we must consider the position from which the motion is being observed.

Example: You are inside a moving train that is traveling at 180km/hr. You walk down the isle of the train (in the same direction) at 5km/hr. How fast are you moving?

- Relative to the train, you are moving 5km/hr
- Relative to the ground, you are moving 185km/hr.

Speed is a relative quantity, and its value depends on where it is observed and measured

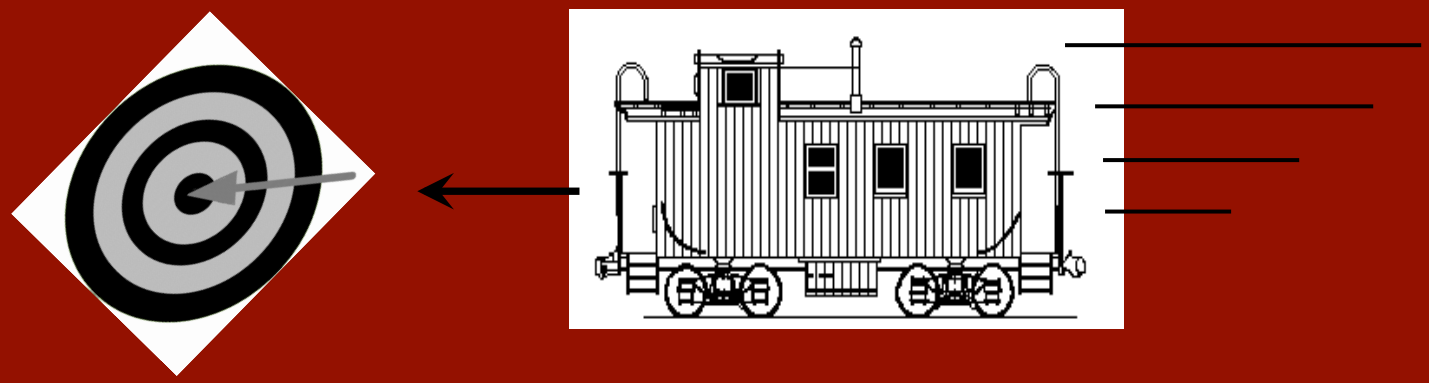
Example: Suppose you are standing on the caboose of a train that is not moving. You have a bow and arrow and you can shoot the arrow at 50km/hr. If you shoot a target, the target will be hit at 50km/hr (we have an arrow speed detector on the target):



Train at Rest

Train: 0km/hr, Arrow (relative to train): 50km/hr
Arrow hits target: 50km/hr

Now, if the train was backing towards the target at, say 20km/hr, the arrow hits the target at 20+50=70km/hr:

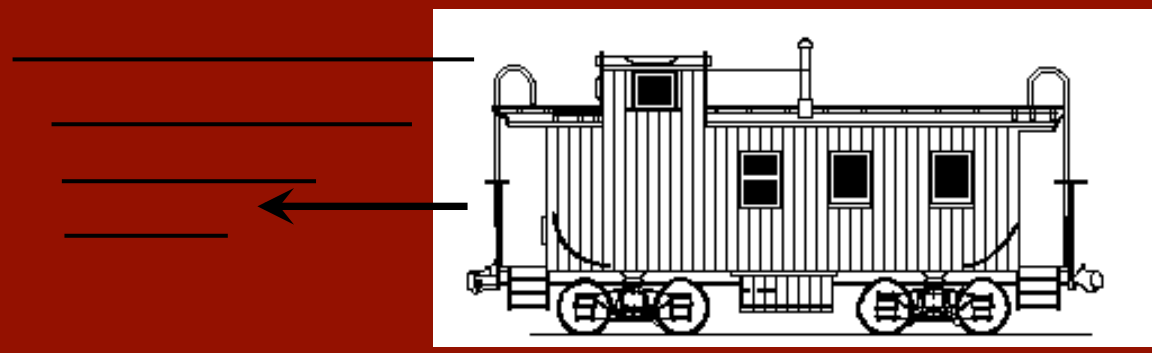


Train: 20km/hr

Arrow (relative to train): 50km/hr

Arrow hits target: 70km/hr

If the train was going forward away from the target at, say 30km/hr, the arrow hits the target at -30+50=20km/hr:



Train: -30km/hr

Arrow (relative to train): 50km/hr

Arrow hits target: 20km/hr

Speed of Light is Constant!

What if something weird started happening, and our arrow speed detector started measuring the arrow's speed at the **same speed** no matter what the speed of the train was? In other words, the arrow always hit the target at 50km/hr. You would probably think that something was wrong with your detector, because you would not expect it.

A. A. Michelson (from the speed of light experiment) and E.W. Morley did an experiment where they measured the speed of light relative to the earth's motion. They found it to be the **same** no matter which direction the earth was moving underneath. So, light behaves in this strange manner.

In 1887, Michelson and Morley found that light travels at approximately 3×10^8 m/s, regardless of the speed of the source or receiver.

The Physics community was very, very confused at this finding. They did the experiments over and over again, and continued to find the same result. Nothing could vary the speed of light. Physics looked like it was on very shaky ground.

In 1905, Albert Einstein came along and reevaluated what speed was. He realized that because

Speed = distance / time

speed is the amount of *space* traveled compared to the *time* of travel. Einstein had to rethink about the concepts of space and time, and he concluded that space and time were a part of a single entity he called **space-time**. Because light travels at a constant speed, Einstein unified space and time.

Einstein's Postulates

Postulate I: All the laws of nature are the same in all uniforaly moving frames of reference.

Einstein said that there is nothing "stationary" in the universe that we could measure motion against. *All motion is relative.*

A spaceship can only measure its speed relative to other objects, not to empty space.

If two objects drift past each other at constant speeds, neither spaceship will be able to tell which one is at rest, if one is at rest.

<u>Earthbound example 1:</u> if you are on a train at a stop and you look out the window, sometimes it looks like the train next to you is moving backwards, but you are actually moving forwards.

If you can't look out the windows of your car and you are going a constant speed on a perfectly smooth road, you can't tell that you are moving at all.

Earthbound example 2: If you flip a coin in a car moving at constant speed, it is just like you were standing still. When the flight attendant pours you a coke in the airplane, the coke pours just like it would if the plane were still on the runway.

These are both examples of postulate 1, and they say, basically, that there is no way to detect the state of uniform motion without having a reference.

Postulate 2: The speed of light in empty space will always have the same value regardless of the motion of the source or motion of the observer.

Go back to the train/arrow example again. What would the arrow look like if you flew along beside it? It would look like it was at rest.

Einstein asked the same question about light – If you could travel beside it, what would it look like? As it turns out (and this is weird), if you could somehow travel close to the speed of light, you would still measure the speed of light moving away from you at 300,000,000m/s.

In other words:

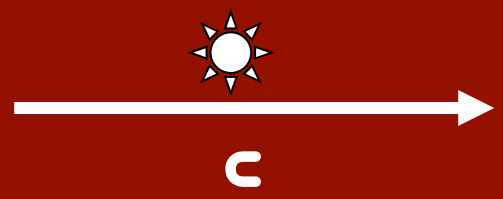
The speed of light in all reference frames is the same.

This idea seemed to lead to many paradoxes in physics, and it concerned many physicists in the late 1800s. However, it was measured to be true, so Einstein set about trying to figure out what was going on.

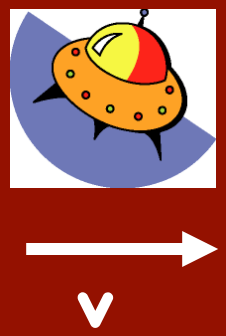
Example:

Mother ship

flash of light



baby ship



The baby ship *always* sees the speed of light as 300,000km/s, regardless of how fast either ship is going. Weird, but true.

Time Dilation

In order to best understand this tricky concept of "time dilation," we have to construct a little "thought experiment." Albert Einstein was famous for coming up with thought experiments and he did it to help people understand the concepts better.

Pretend you are in a spaceship sitting outside BHS. You look at the clock, and it says "12 noon." What does this mean?

- Light reflects off the clock and carries the information "12 noon" to your eyes.
- If you move your head, the light does not hit your eyes, and if someone out in space were to see the light, he or she would say, "It is 12 noon on Earth now."
- Both you and the other observer see 12 noon at *different times.*

Now pretend you are in the spaceship moving away from BHS at the speed of light. You would keep up with the information in the light that says it is "12 noon."

So, if you travel at the speed of light, then, always tells you it is 12 noon back home. Time is frozen!

These are the extremes of this thought experiment. What would happen in the middle? What would the time read if you were traveling slower than the speed of light?

- The clock will run somewhat slow, between 60 seconds in a minute and 60 seconds per infinity time.
- From your *moving frame of reference*, the clock and the events in the reference frame will be seen in slow motion.

This is called *time dilation*.

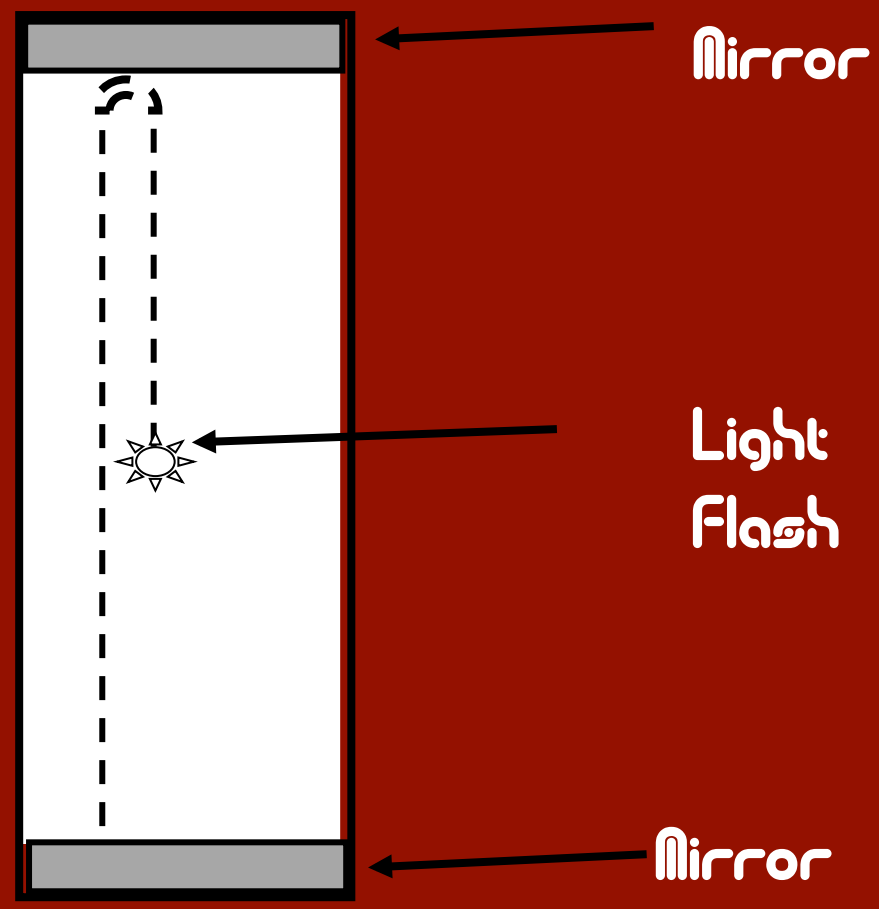
Special Relativity makes us think twice about our universe. We know that speed is relative, which means that it depends on the speed of the source *and* observers.

But, the speed of light is absolute – it is not dependent on the speed of the source *or* the observer.

We usually think of time as absolute, meaning that it passes at the same rate regardless of what is happening. Our spaceship example shows that this isn't true.

Stationary Light Clock

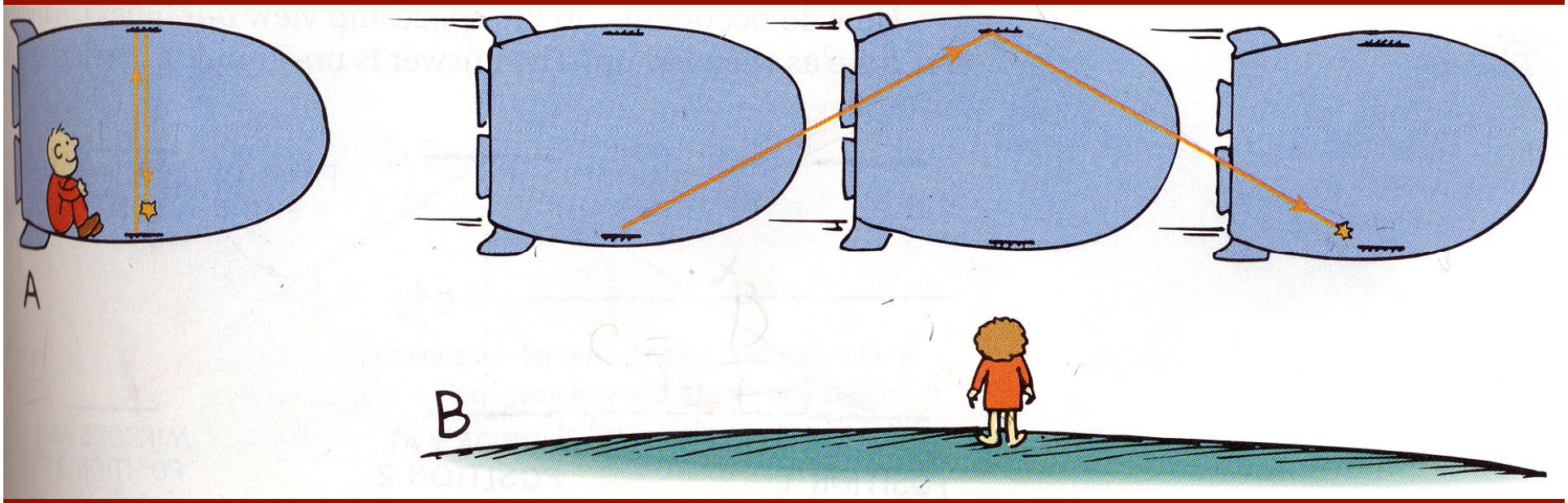
To continue with the thought experiment, imagine a "light clock." Our light clock consists of an empty tube with a mirror at each end:



A flash of light bounces back and forth between the parallel mirrors.

If the length of the tube is 3000 meters (a *big* tube), the light will take $3000m/3\times10^8 m/s = .00001s$ to go from one end to the other.

Let's say we put our tube in a spaceship, and we watch it go past us at high speed.



The person in the spaceship sees the light go up and down, and the person on the ground sees the light travel up and over and over and down.

Now, the light we see has to travel farther (from our point of view). Remember Einstein's 2nd postulate, though: The speed of light will be measured by *any* observer as c (3×10^8 m/s). In order for that to happen, a clock "tick" must take longer for us as observers:

$$c = \frac{\text{Distance}}{\text{Time}} = \frac{\text{Distance}}{\text{Time}} = c$$

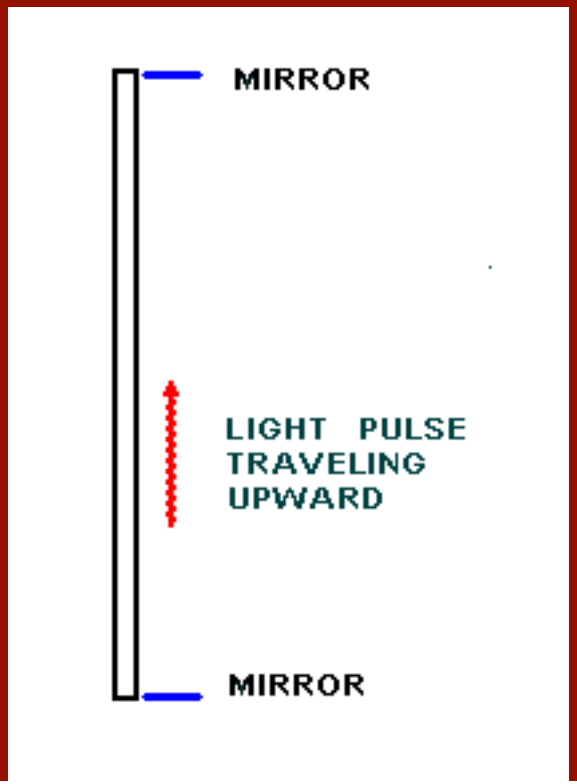
Same!

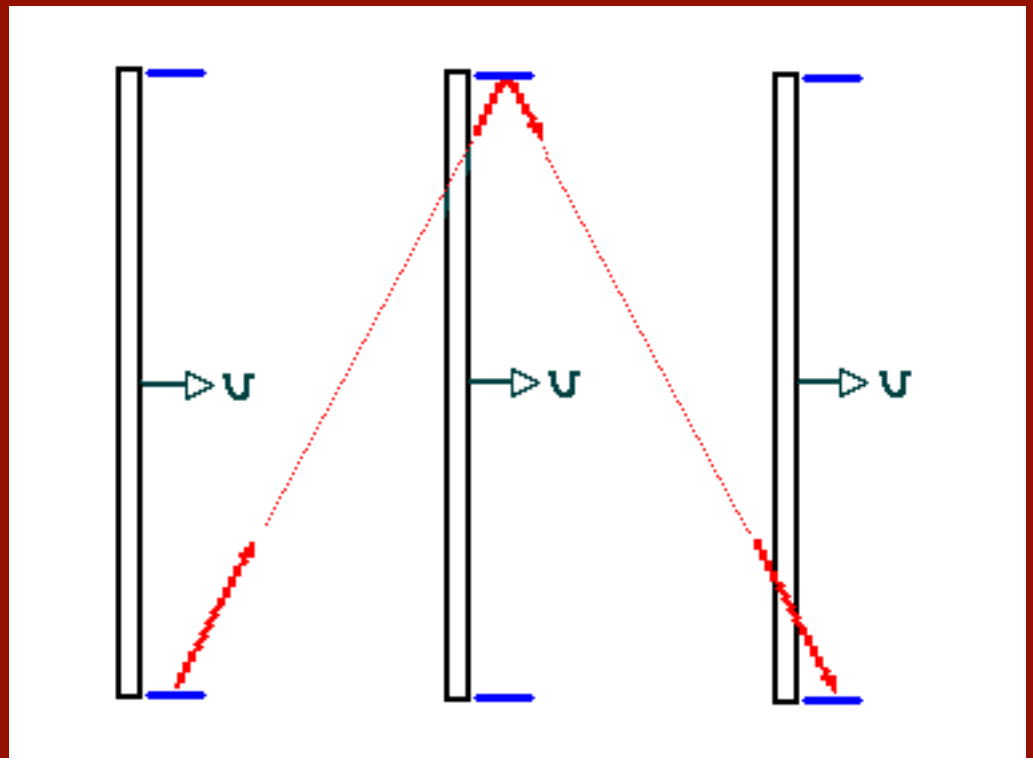
The slowing of time is not only for the light clock – it is time itself in the moving frame of reference *as viewed our frame of reference*

The occupants of the spaceship do not notice *anything* different about the time in their spaceship (Einstein's second postulate: all laws of nature are the same in uniformly moving frames of reference).

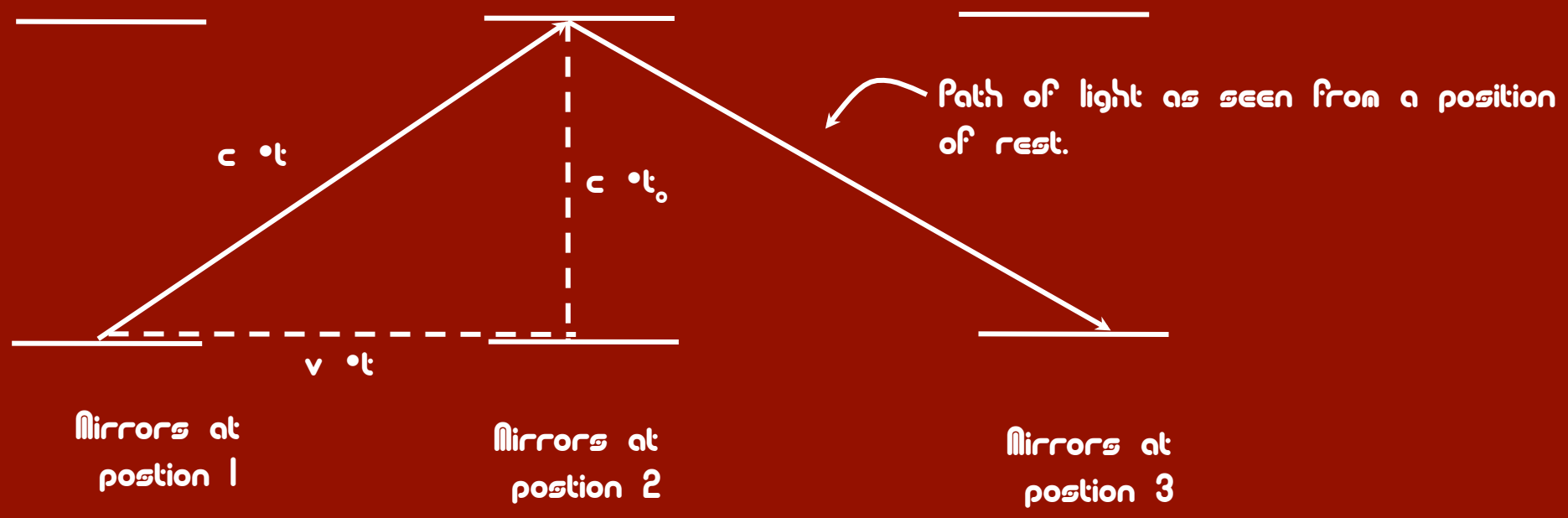
How do the spaceship occupants view *our* time? They see US as slowed down! From their frame of reference, they see our time running slow, just as we see theirs running slow.

Not a paradox because the measurements do not need to agree; they are in different frames of reference. They will agree on the speed of light!





The Time Dilation Equation



The Light Clock is moving to the right at speed v

The diagonal lines show the path of the light flash as it starts from the lower mirror at position 1, goes to the upper mirror at position 2, and then back to the lower mirror at position 3.

From the clock's frame of reference, the time it takes light to go between the two mirrors is t_o.

- This is straight up and down time

- Because c is constant, the vertical distance is $d = vt = ct_o$

- The vertical distance is the same for both frames.

The symbol t represents the time it takes for the light to move from one mirror to the other as seen from the outside.

- The speed of the flash is still c, and the time to go from position 1 to 2 is t, so the diagonal distance is vt.

These three distances make up a right triangle, and we can do some math to solve for *t*:

$$(ct)^2 = (ct_o)^2 + (vt)^2$$

$$(ct)^2 - (vt)^2 = (ct_o)^2$$

$$t^2[1 - (v^2 / c^2)] = t_o{}^2$$

$$t^2 = \frac{t_o{}^2}{1 - (v^2 / c^2)}$$

$$t = \frac{t_o}{\sqrt{1 - (v^2 / c^2)}}$$