Physics 294H

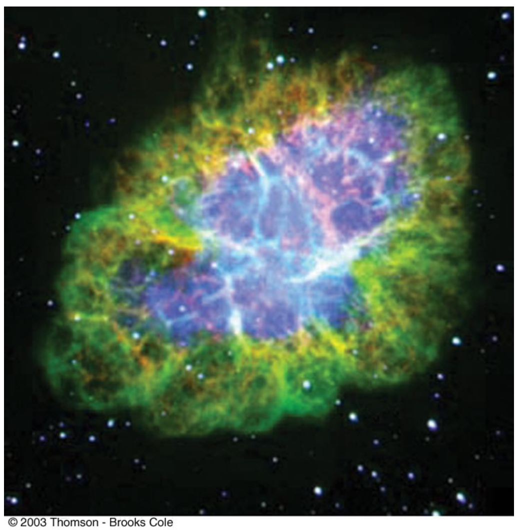
- Professor: Joey Huston
- email:huston@msu.edu
- office: BPS3230
- Homework will be with Mastering Physics (and an average of 1 hand-written problem per week)
  - **Help-room hours: 12:40-2:40 Monday (note change); 3:00-4:00 PM Friday**
  - **36.73 hand-in problem for next Wed**
- Quizzes by iclicker (sometimes hand-written)
- Average on 2nd exam (so far)=71/120
- **Final exam Thursday May 5 10:00 AM – 12:00 PM 1420 BPS**
- Course website: www.pa.msu.edu/~huston/phy294h/index.html
  - lectures will be posted frequently, mostly every day if I can remember to do so

Everything depends on γ

Velocity (m/s)	γ
100 m/s	1
1000 m/s	1
10,000 m/s	1.000000001
100,000 m/s	1.000000056
1,000,000 m/s	1.000005556
10,000,000 m/s	1.000556019
100,000,000 m/s	1.060660172
200,000,000 m/s	1.341640787
290,000,000 m/s	3.905667329

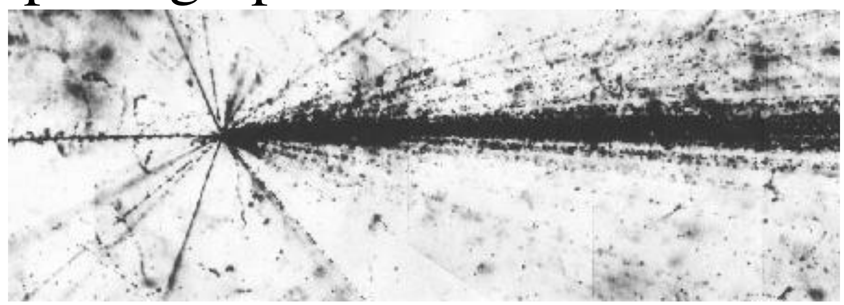
Cosmic rays

- Some come from the sun (relatively low energy) and some from catastrophic events elsewhere in the galaxy/ universe



Crab nebula

Collision of a high energy cosmic ray particle with a photographic emulsion

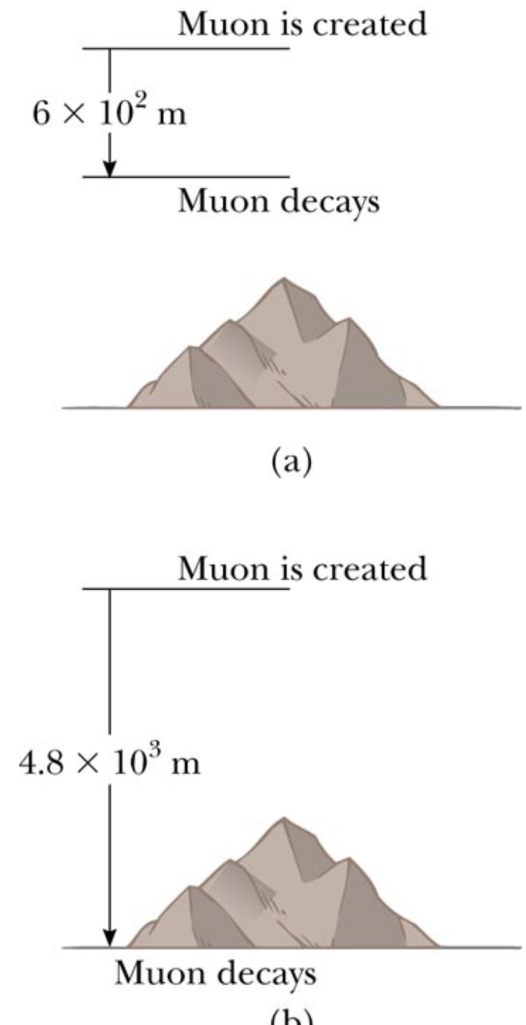


Cosmic rays interact with the Earth's upper atmosphere and produce a shower of particles; eventually only subatomic particles called muons are left.

We'll talk about muons later.

Another example:cosmic ray muons

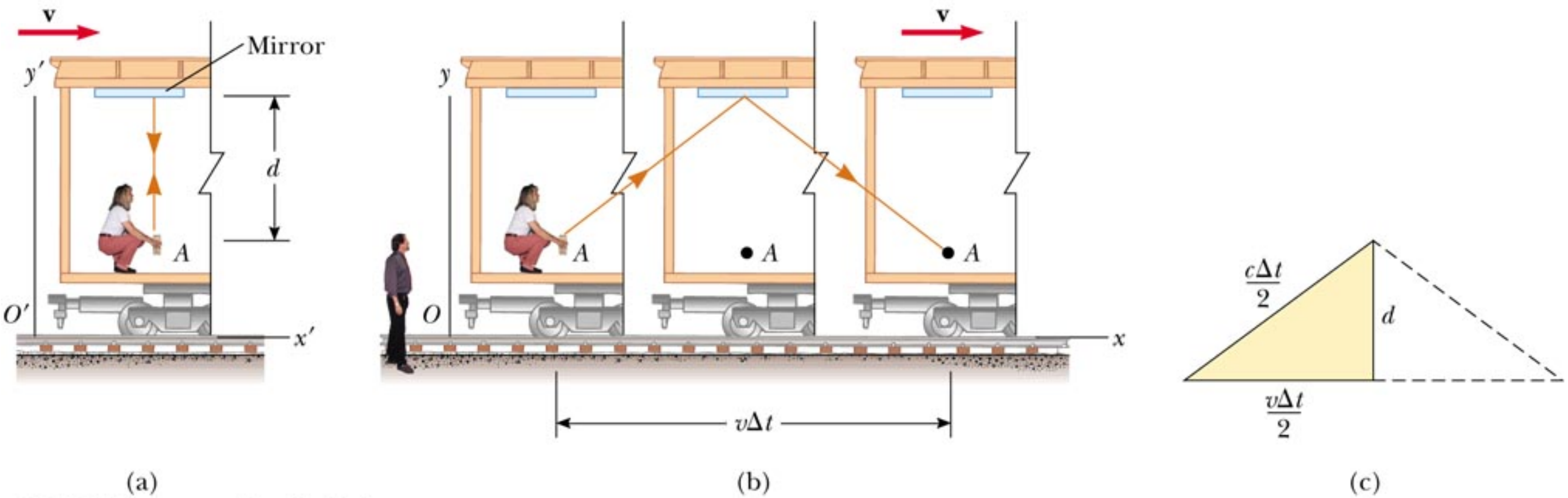
- Time dilation works for clocks, heartbeats, anything…
- Consider muons produced in the upper atmosphere
  - they have a lifetime of 2.2 μs
  - if they travel close to the speed of light, you might think they could only travel ($3X10^8$ m/s X 2.2 X 10^{-6} s = 600 m) before decaying
  - 2.2 μs is how long they live in their rest frame
  - but if they are travelling at 0.99c, then γ=7.1 and $\gamma c\Delta t_p$=4800 m (not 600 m)



Example

- A cosmic ray travels 60 km through the earth's atmosphere in 225 μs (according to an observer on the surface of the earth)
- How long does it take from the point of view of the muon?

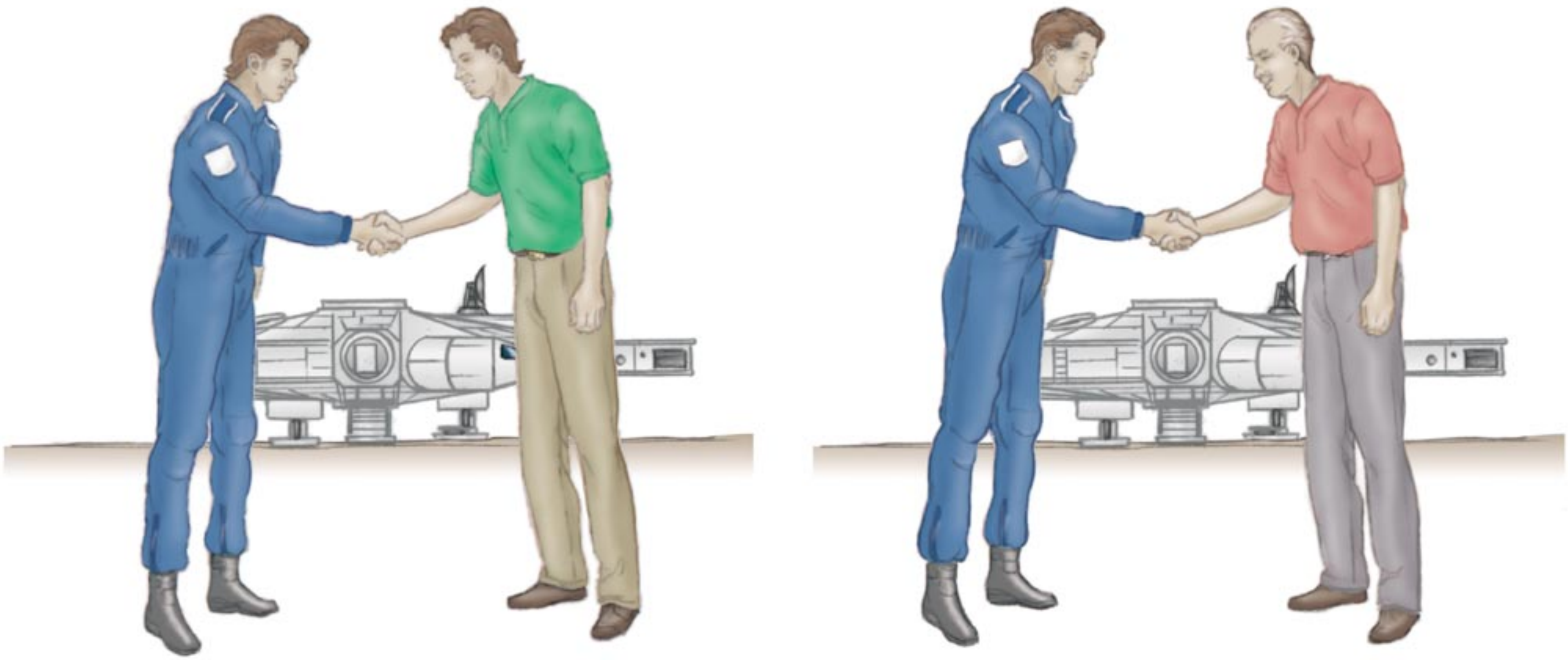
Let’s back up just a little



Observer O sees observer O’ moving off at velocity v; therefore he sees her clock runs slow.

But, from observer O’s point-of-view, she’s standing still and it’s observer O who is moving off to the left. And her perspective is perfectly valid. And she sees his clock run slow. Who is right?

Twin paradox

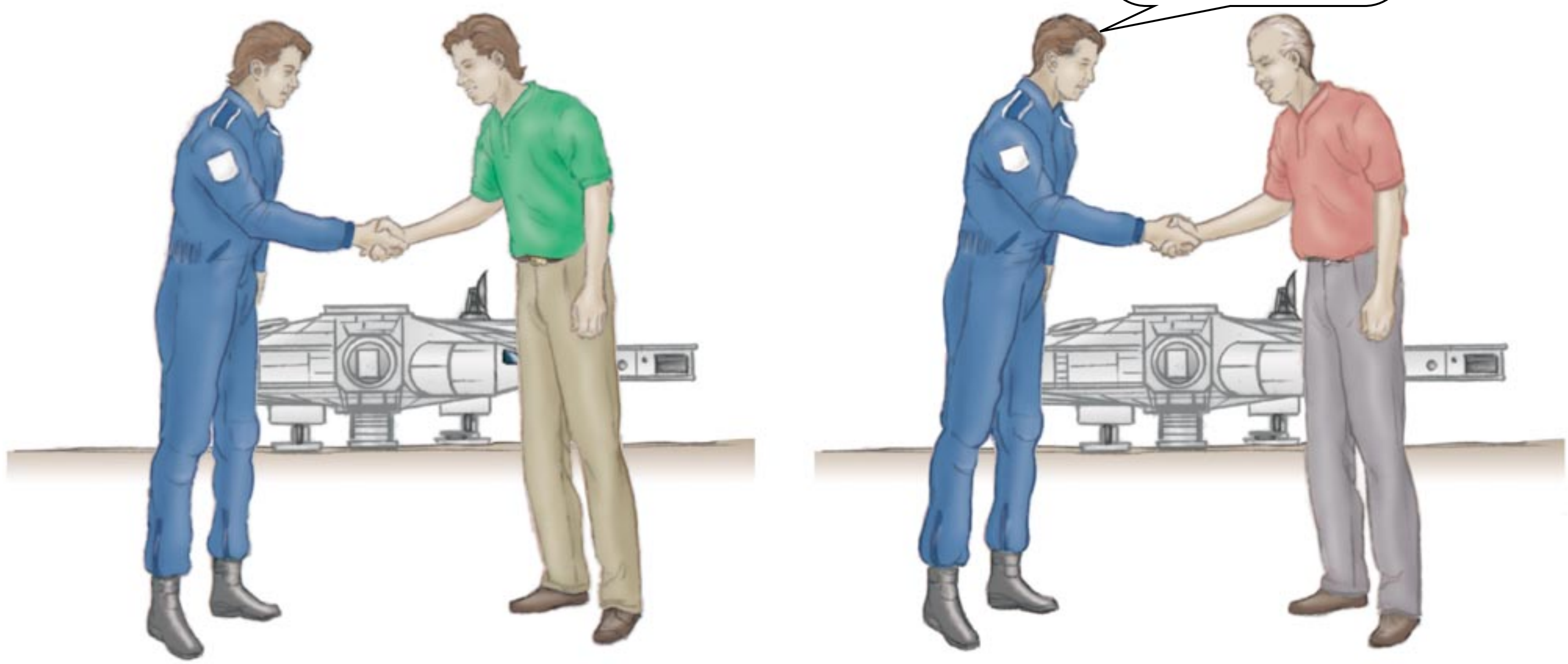


(a) (b)

Two twins aged 21. One stays home on earth. The other heads off in a spaceship travelling close to the speed of light (γ=25; 99.9% of the speed of light)

After 50 years have passed for the twin on earth, only 2 years have passed for the twin in the spaceship. Or is it the other way around?

Twin paradox



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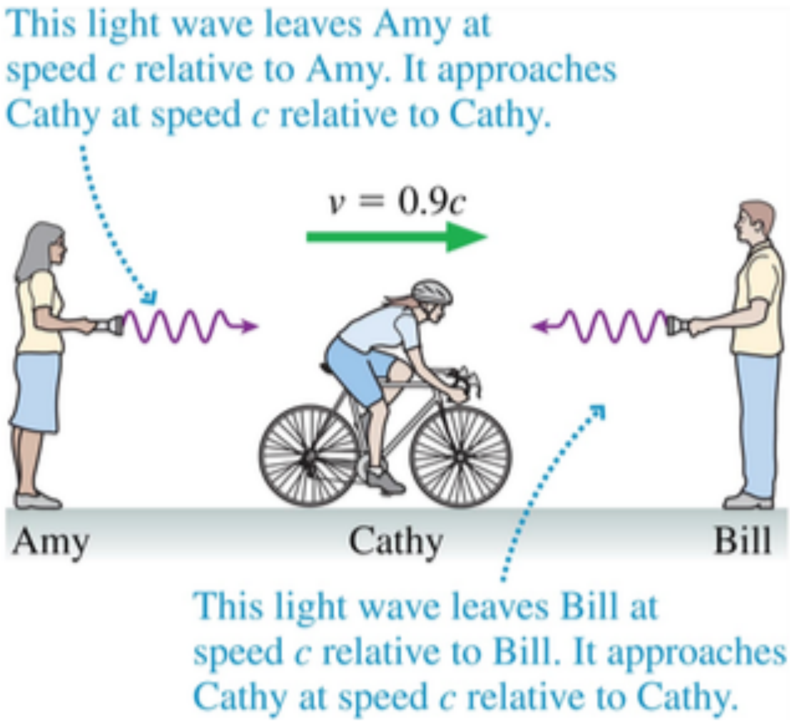
from wikipedia

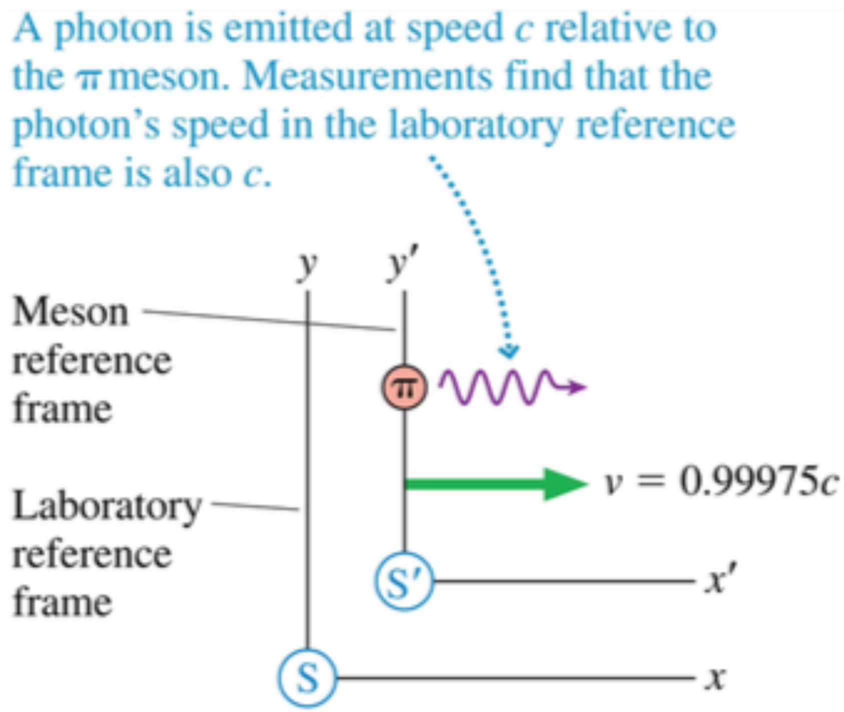
- This outcome is predicted by Einstein's special theory of relativity. It is due to an experimentally verified phenomenon called time dilation, in which a moving clock is found to experience a reduced amount of proper time as determined by clocks synchronized with a stationary clock. Another experiment confirmed time dilation by comparing the effects of speed on two atomic clocks, one based on earth, the other aboard a supersonic plane. They were out of sync afterwards: the atomic clock on the plane was slightly behind.The paradox arises if one takes the position of the traveling twin: from his perspective, his brother on Earth is moving away quickly, and eventually comes close again. So the traveler can regard his brother on Earth to be a "moving clock" which should experience time dilation. Special relativity says that all observers are equivalent, and no particular frame of reference is privileged. Hence, the traveling twin, upon return to Earth, would expect to find his brother to be younger than himself, contrary to that brother's expectations. Which twin is correct?It turns out that the traveling twin's expectation is mistaken: special relativity does not say that all observers are equivalent, only that all observers in inertial reference frames are equivalent. But the traveling twin jumps frames (accelerates) when he does a U-turn. The twin on Earth rests in the same inertial frame for the whole duration of the flight (no accelerating or decelerating forces apply to him) and he is therefore able to distinguish himself from the traveling twin.

Relativity and the Red Queen

- Why sometimes I've believed as many as **six impossible things before breakfast"**. (Lewis Carroll)

Relativity says that the speed of light **c** is constant in **<u>any</u>** reference frame





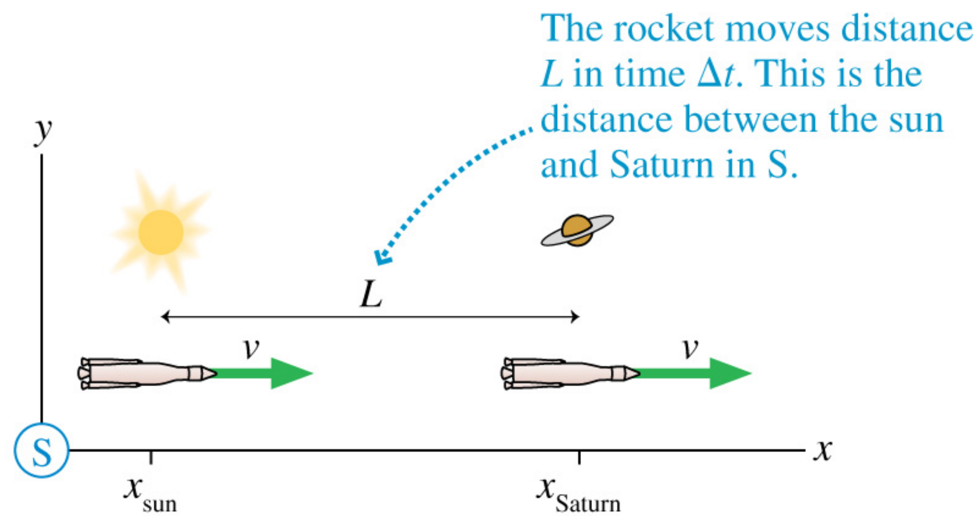
$$c = \frac{dist}{time}$$

If c is constant in any reference frame than the ***time AND distance*** *must be different in different reference frames!*

Length contraction

- Relativity requires us to rethink our idea of time
- Also of space
- Consider a rocket travelling from the sun to Saturn
- Define $L=\Delta x=x_{Saturn}-x_{sun}$ in frame S
- The rocket's speed is $v=L/\Delta t$ where Δt is the time measured in frame S for the journey

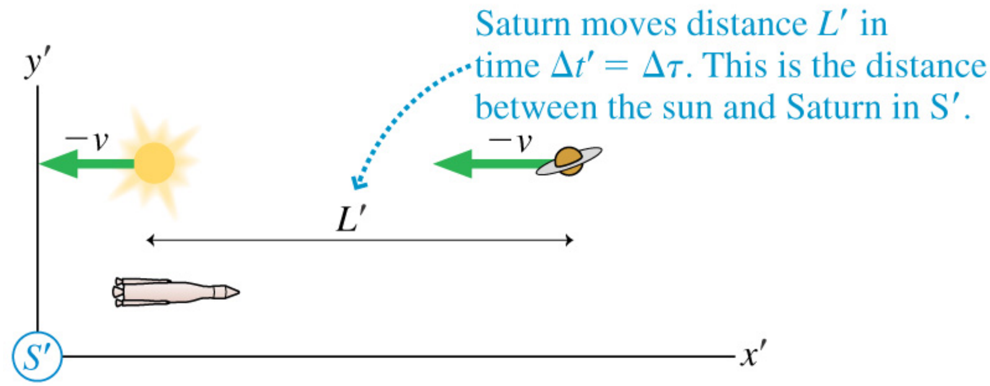
(a) Reference frame S: The solar system is stationary.



Length contraction

- Let's go to frame S', where the rocket is at rest and Saturn and the sun are moving
- The sun and Saturn move to the left at a speed v=L'/Δt', where Δt' is the time measured in frame S' for Saturn to travel a distance L'

(b) Reference frame S′: The rocket is stationary.



Now comes the algebra

- Both frames of reference agree on the value of v

$$v = \frac{L}{\Delta t} = \frac{L'}{\Delta t'}$$

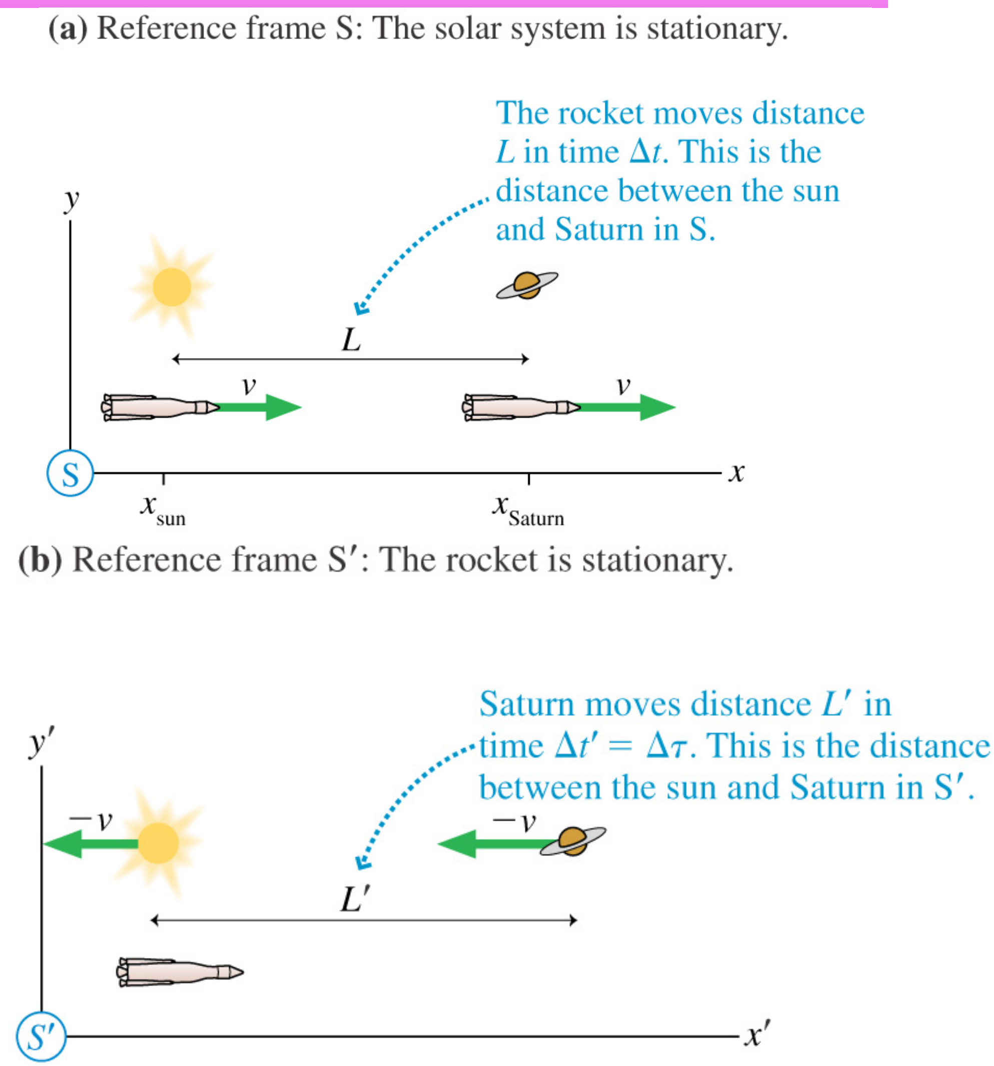
- The time interval Δt' in frame S' is the proper time Δτ

$$\frac{L}{\Delta t} = \frac{L'}{\Delta \tau} = \frac{L'}{\sqrt{1-\beta^2}\,\Delta t}$$

- So we can write

$$L' = \sqrt{1-\beta^2}\,L$$

- Length contraction
  - applies to distances
  - applies to length of an object
  - the length of an object is greatest in its rest frame
  - it will appear shorter in any frame moving with respect to the rest frame

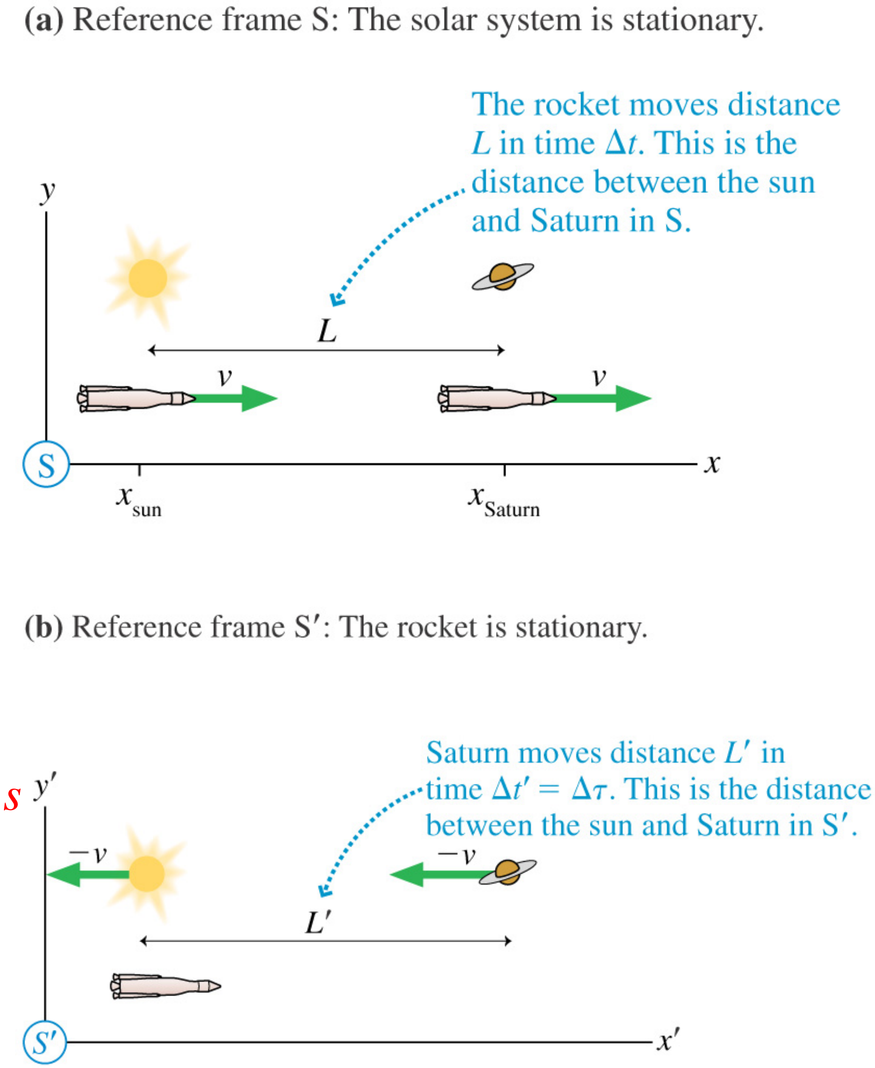


Example from the book

- Saturn is $1.4X10^{12}$ m from the sun; a rocket is travelling at a speed of 0.9c relative to the solar system
- How long does it take from the point of view of an observer on the earth? By an astronaut on the rocket

$$\Delta t = \frac{\Delta x}{v} = \frac{1.43X10^{12}m}{0.9X(3X10^{8}m/s)} = 5300s$$

$$\Delta t' = \Delta\tau = \frac{\Delta t}{\gamma} = \sqrt{1-\beta^2}\,\Delta t = \sqrt{1-0.9^2}\,(5300s) = 2310s$$



Example

- How far did the rocket travel from the sun to Saturn from its perspective?

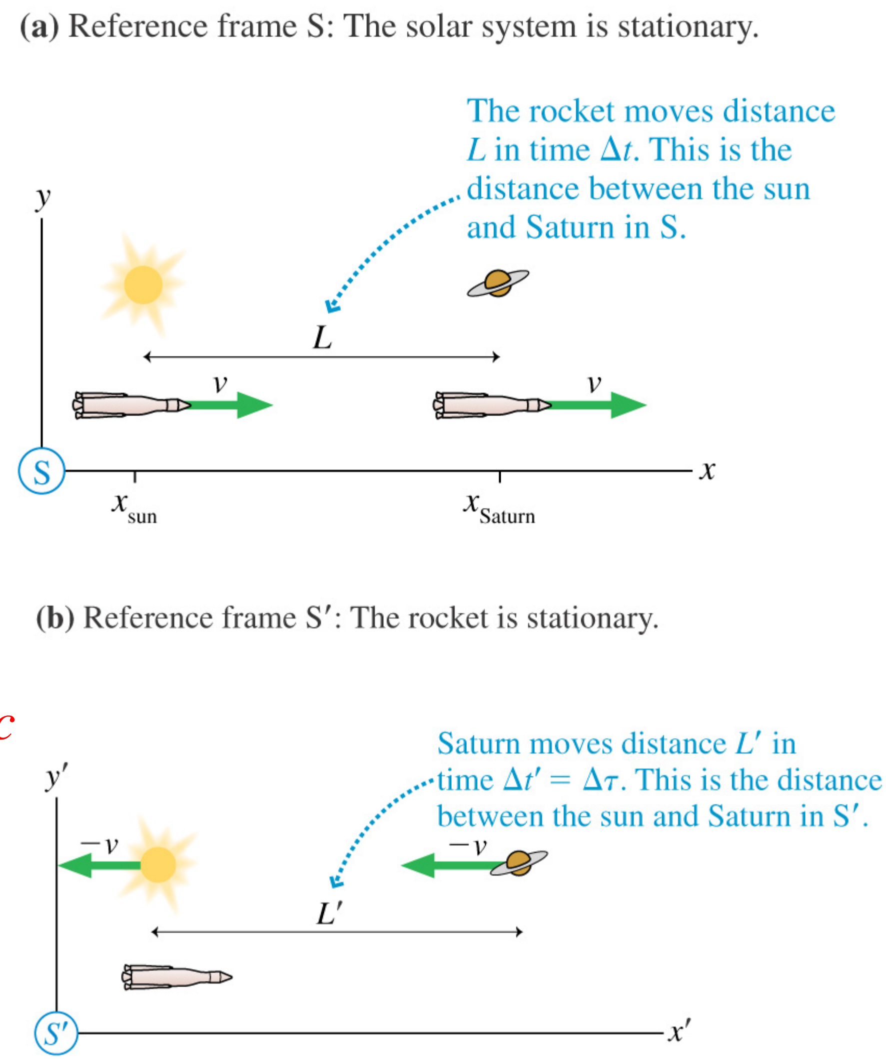
$$L' = \sqrt{1-\beta^2}\,L = \sqrt{1-0.9^2}\,(1.43X10^{12}m)$$
$$= 0.62X10^{12}m$$

- How fast is the ship travelling in the earth's frame of reference?

$$v = \frac{\Delta x}{\Delta t} = \frac{1.43X10^{12}m}{5300s} = 2.7X10^{6}m/s = 0.9c$$

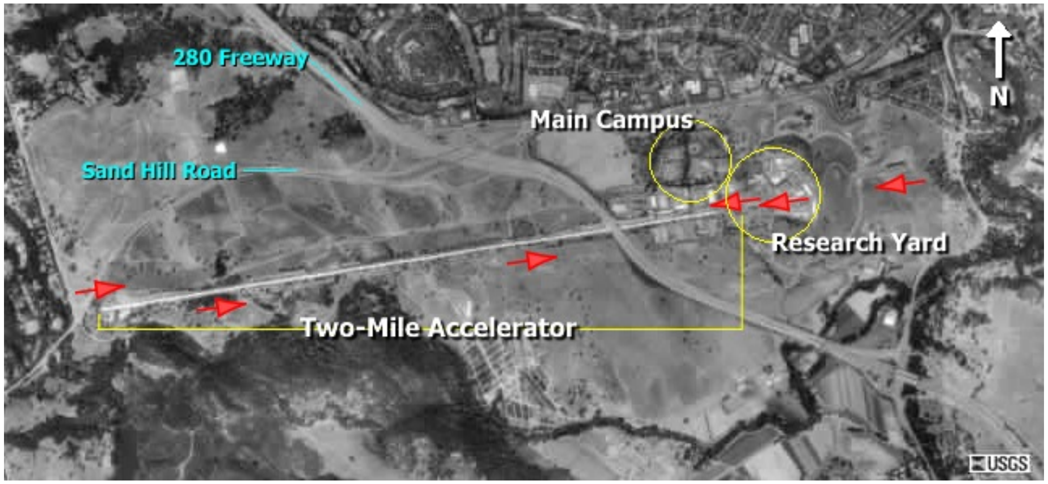
- What about in the rocket's frame? How fast is Saturn travelling towards them?

$$v' = \frac{\Delta x'}{\Delta t'} = \frac{0.62X10^{12}m}{2310s} = 2.7X10^{6}m/s = 0.9c$$

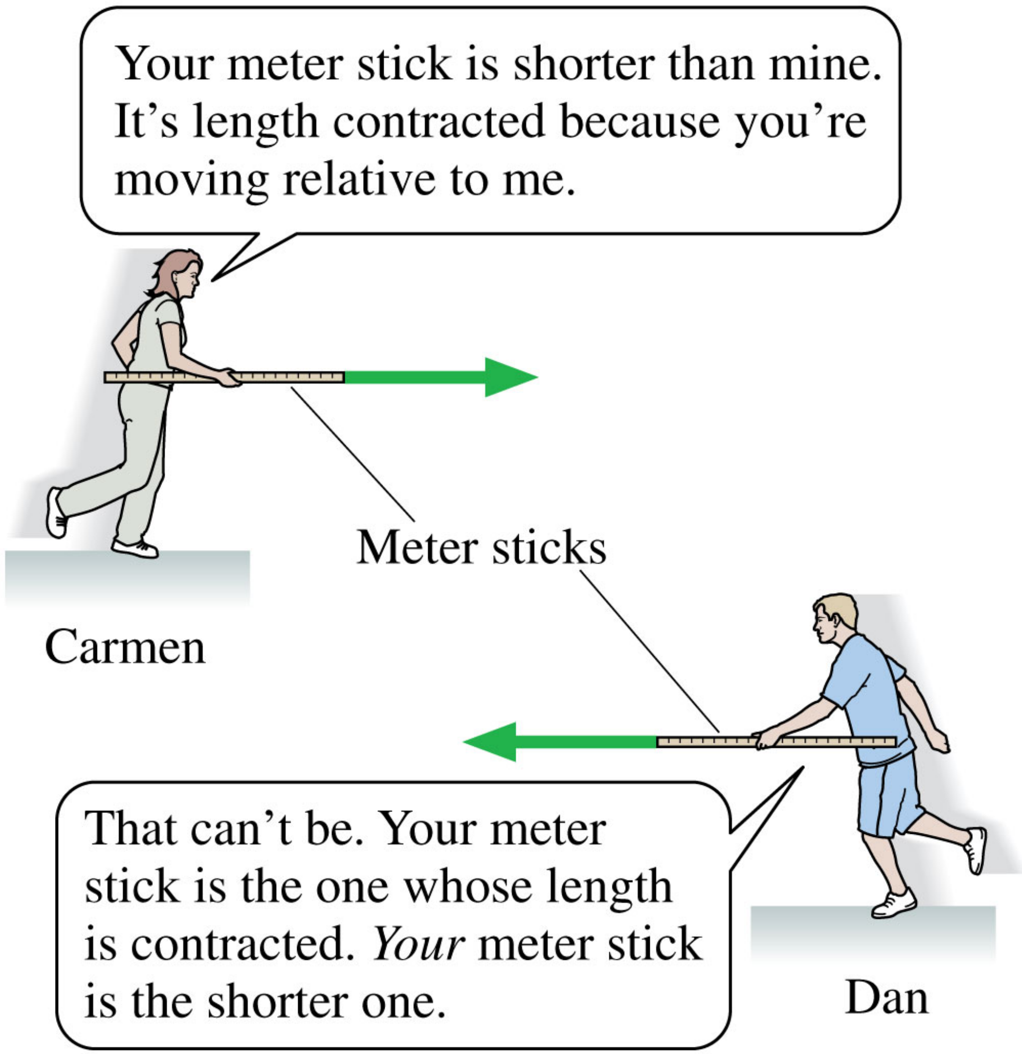


Example

- At SLAC, electrons are accelerated to v=0.99999997c in a 3.2 km long accelerator
- How long is the accelerator from the electron's point of view?



Another paradox?



- Carmen and Dan each carry meter sticks, and run past each other, in opposite directions, at a relative speed $v = 0.9c$.
- Dan's meter stick can't be both longer and shorter than Carmen's meter stick.
- Is this another paradox?

- Relativity allows us to compare the *same* events as they're measured in two different reference frames.
- But the events by which Dan measures the length of Carmen's meter stick are *not the same events* as those by which Carmen measures the length of Dan's meter stick.
- In Dan's reference frame, Carmen's meter stick has been length contracted, and is less than $1\ \mathrm{m}$ in length.
- In Carmen's reference frame, Dan's meter stick has been length contracted, and is less than $1\ \mathrm{m}$ in length.
- There's no conflict between their measurements!