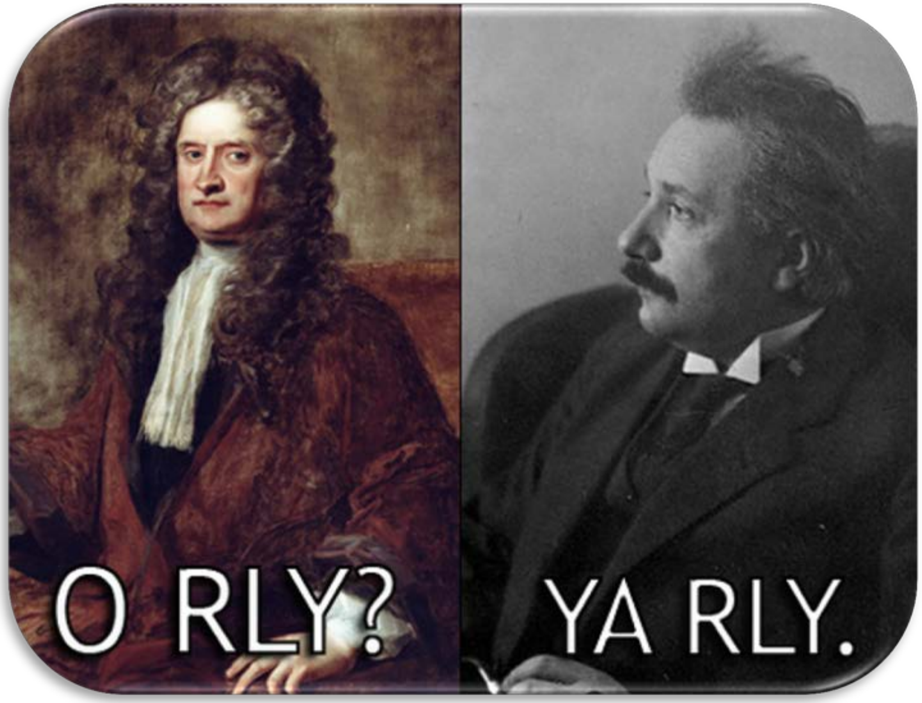

Newton and Einstein – probably would not have got along all that well!

The Bizarre World of Special Relativity

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SR = Special relativity

Feynman on Special Relativity

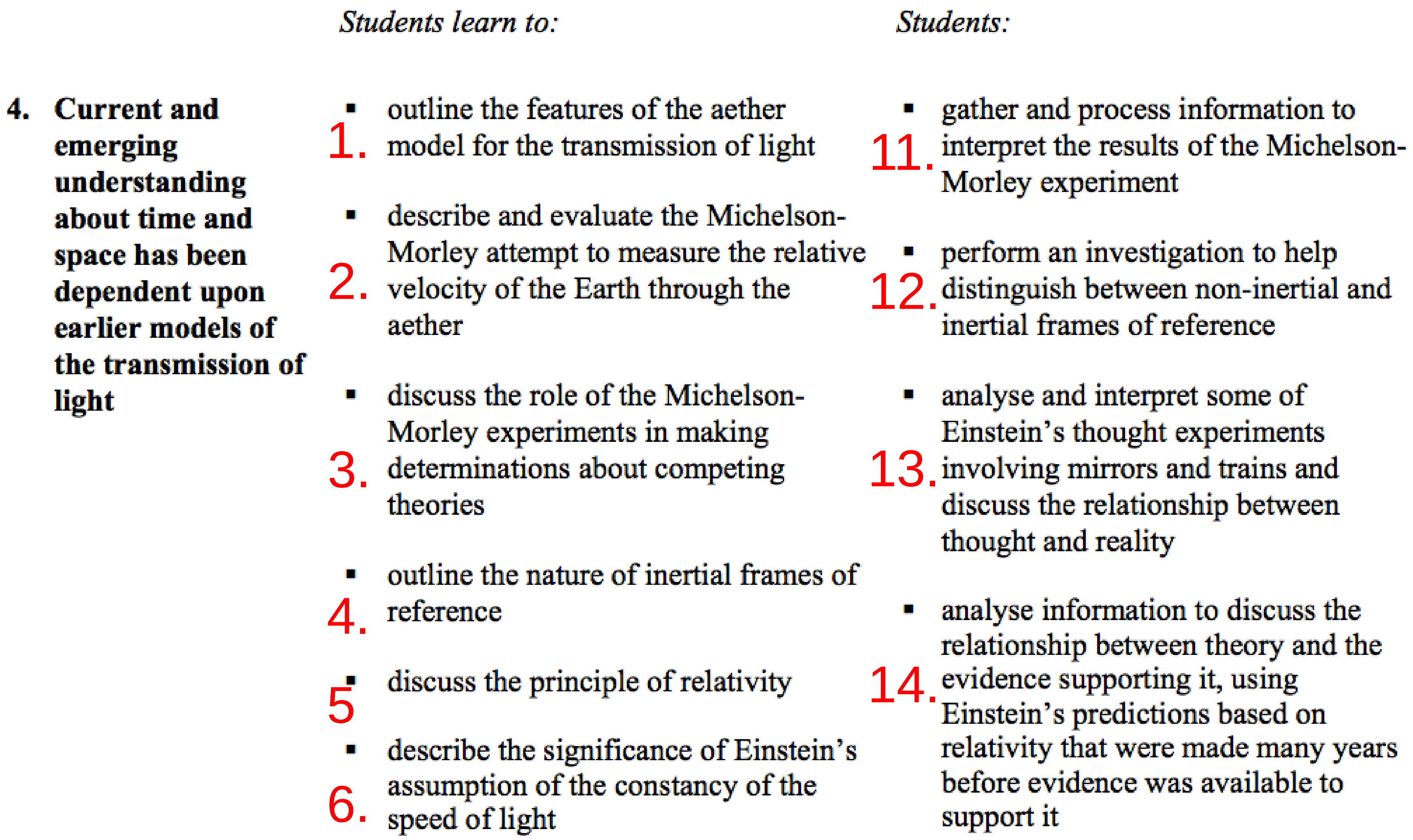
Richard P. Feynman

You will have to brace yourselves for this — not because it is difficult to understand, but because it is absolutely ridiculous.

Warning

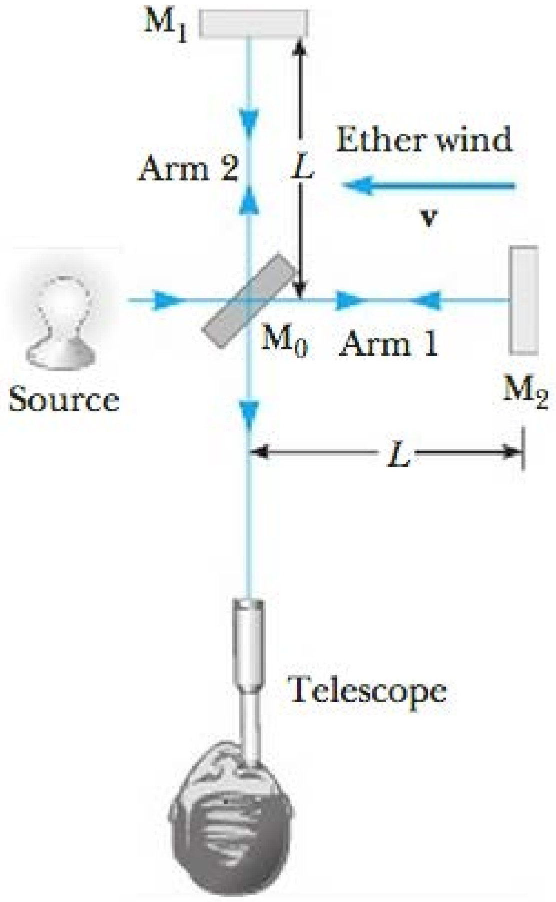
Special relativity is bizarre – if you are confused you are probably on the right track!

HSC Physics Syllabus



	Students learn to:	*Students:*
4. Current and emerging understanding about time and space has been dependent upon earlier models of the transmission of light	1. ▪ outline the features of the aether model for the transmission of light 2. ▪ describe and evaluate the Michelson-Morley attempt to measure the relative velocity of the Earth through the aether 3. ▪ discuss the role of the Michelson-Morley experiments in making determinations about competing theories 4. ▪ outline the nature of inertial frames of reference 5 ▪ discuss the principle of relativity 6. ▪ describe the significance of Einstein's assumption of the constancy of the speed of light	11. ▪ gather and process information to interpret the results of the Michelson-Morley experiment 12. ▪ perform an investigation to help distinguish between non-inertial and inertial frames of reference 13. ▪ analyse and interpret some of Einstein's thought experiments involving mirrors and trains and discuss the relationship between thought and reality 14. ▪ analyse information to discuss the relationship between theory and the evidence supporting it, using Einstein's predictions based on relativity that were made many years before evidence was available to support it

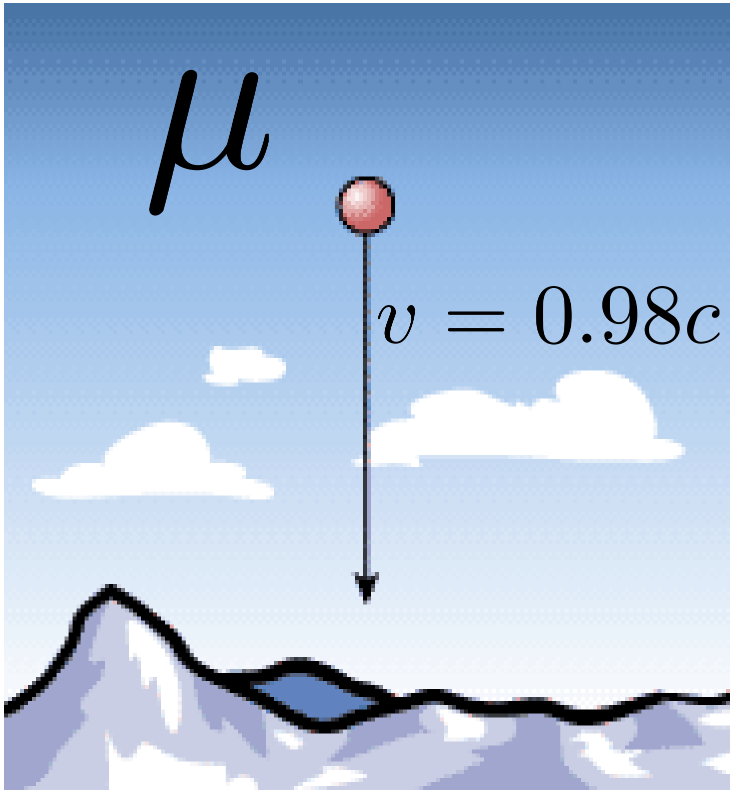
Why we need SR??



- **Michelson-Morley Experiment**
  - If the aether existed, light travelling in different directions relative to Earth should be travelling at different speeds.
  - Ruled out aether model.
  - SR explains this via its postulates.
  - Not a leading reason of why SR was invented but SR was able to explain the “null” result.

However, lets describe something easier to think about…

Imagine we are in 1900…



- **Muon decay – particles that travel at ~*c*.**
  - We find using a SR model we are able to accurately describe the decay time and distance travelled by the muon.
  - Just using Newtonian laws would lead to the wrong predictions.
  - This decay time is different depending on what “frame of reference” we are in.
  - This is really profound!

What are “Reference Frames”?

- We use reference frames all the time in everyday life. E.g.

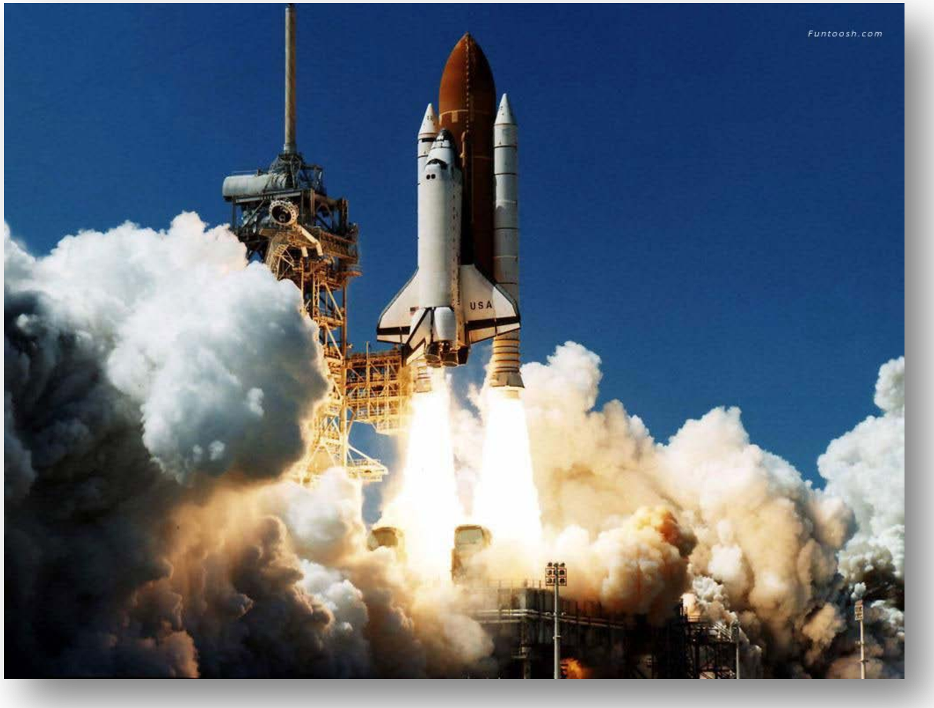
“I am travelling down the road at 100 km/h.”

- Speed relative to *what/whom*??
  - Relative to a billboard: 100 km/h
  - Relative to a passenger: 0 km/h
  - Relative to oncoming traffic: 200 km/h

- In order to describe speed, you need to specify relative to a “*frame of reference*”.

Inertial Frames of Reference

- Inertial Frames of Reference are a **Special** kind frame of reference frame:
  - Moves at a constant speed relative to another frame of reference
  - **No** acceleration!

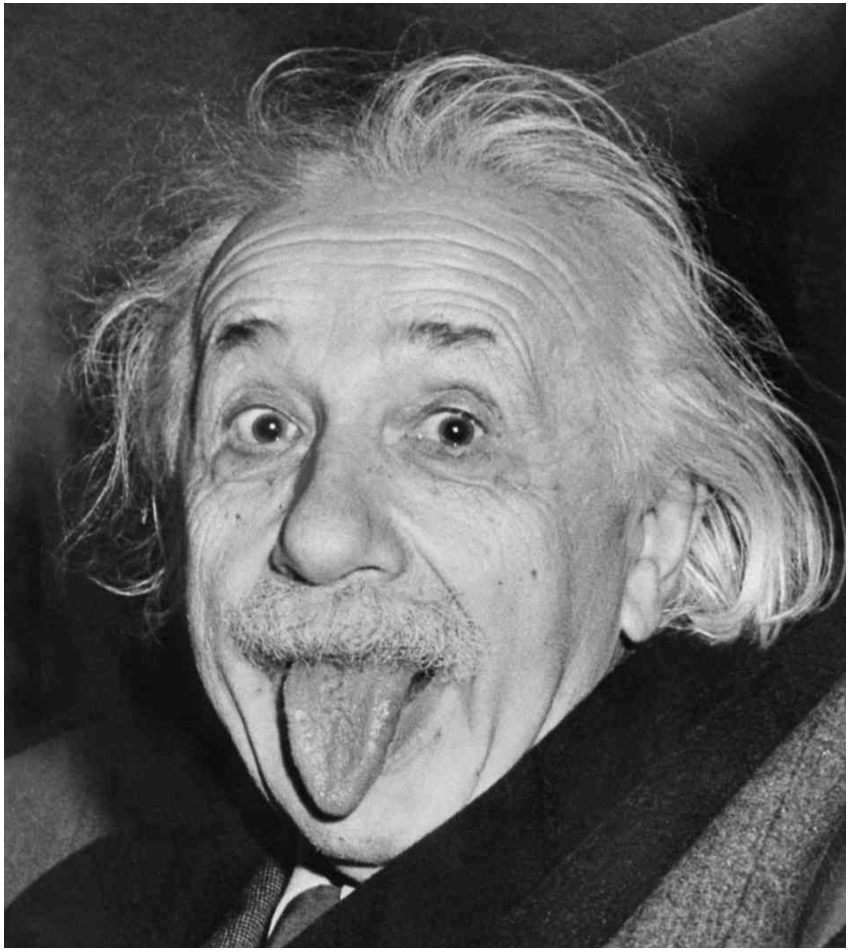


Einstein’s Postulates

1. Principle of relativity:

“The laws of physics are the same in every inertial reference frame.”

- What does this mean and why is it important?



You do an experiment in the classroom to measure the Earth’s gravitational force on a cricket ball.

Your friend does the same experiment on a train moving at a *constant speed*.

You will measure the same force!

Einstein’s Postulates

1. Principle of relativity:

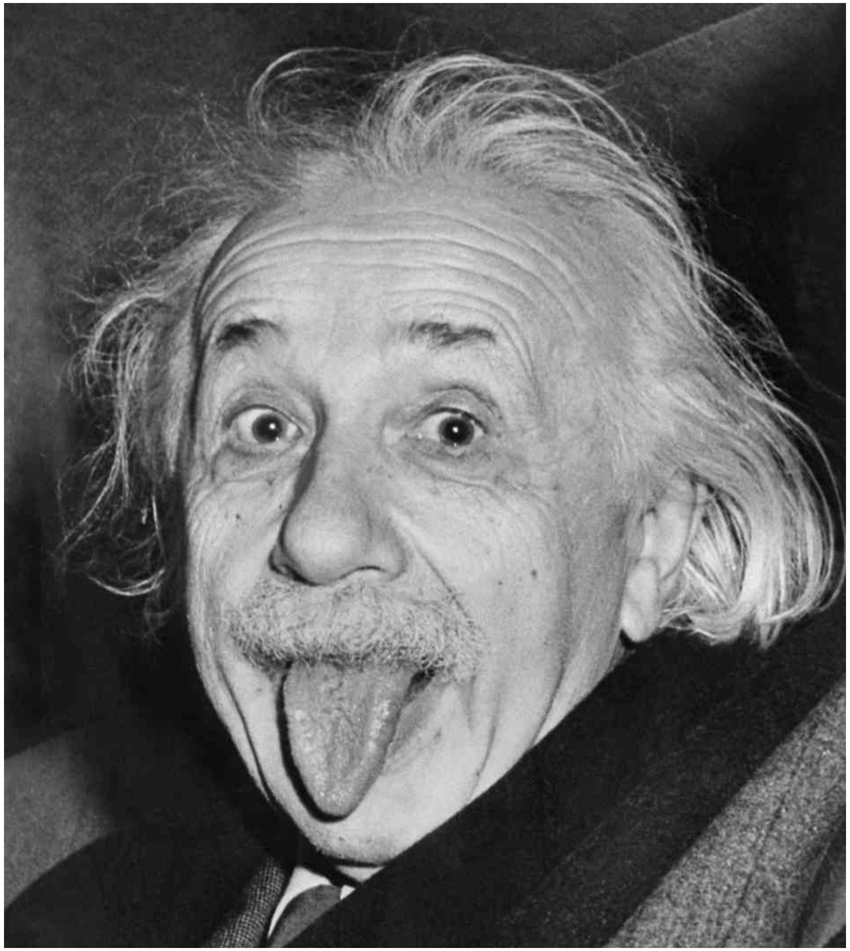
“The laws of physics are the same in every inertial reference frame.”

2. Speed of light:

“The speed of light (in vacuum) is the same in all inertial frames of reference, regardless the motion of the source.”

$c \sim 3\text{x}10^8$ m/s

The speed of light is independent of the speed of the source of light!



SR and Classical Mechanics

- Consider two inertial reference frames:

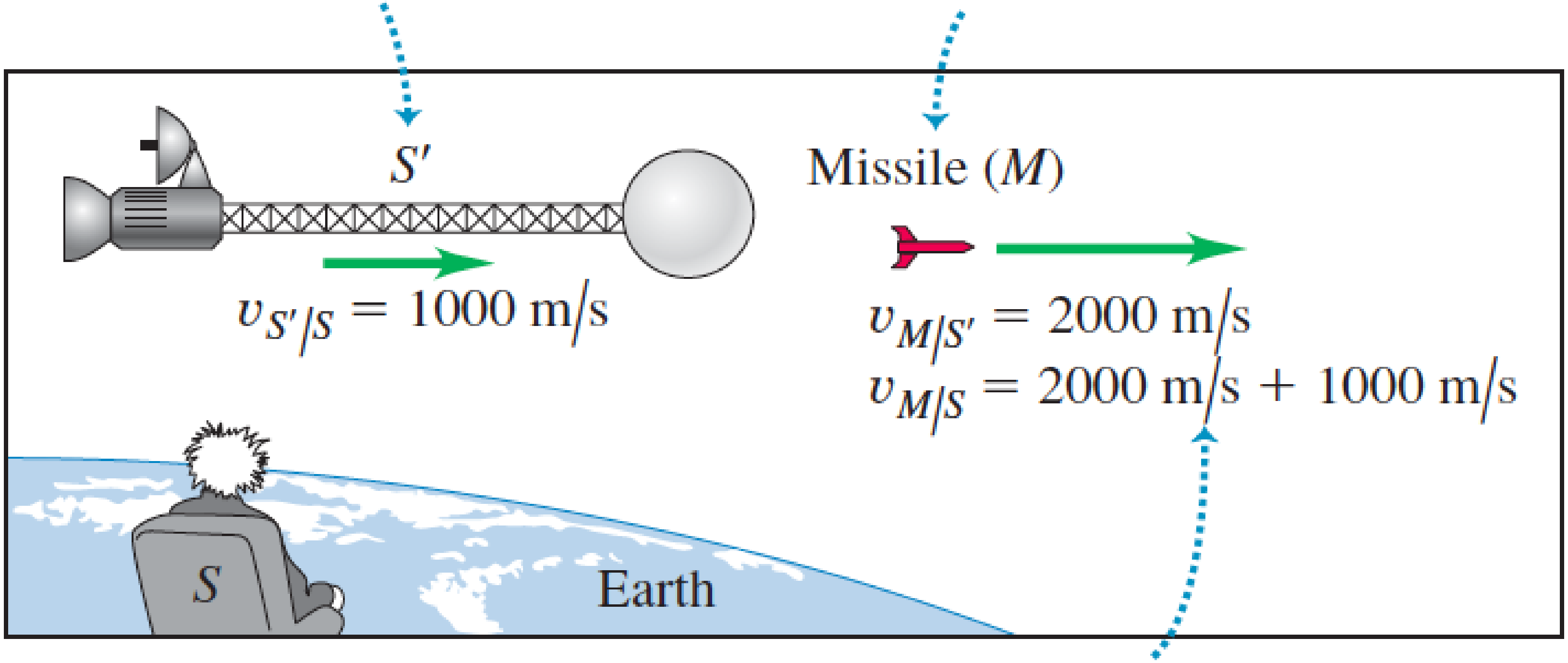
S - Observer at rest on Earth

S' - A spaceship moving at constant speed

Classical Mechanics

A spaceship (S') moves with speed $v_{S'/S} = 1000\ \text{m/s}$ relative to an observer on earth (S).

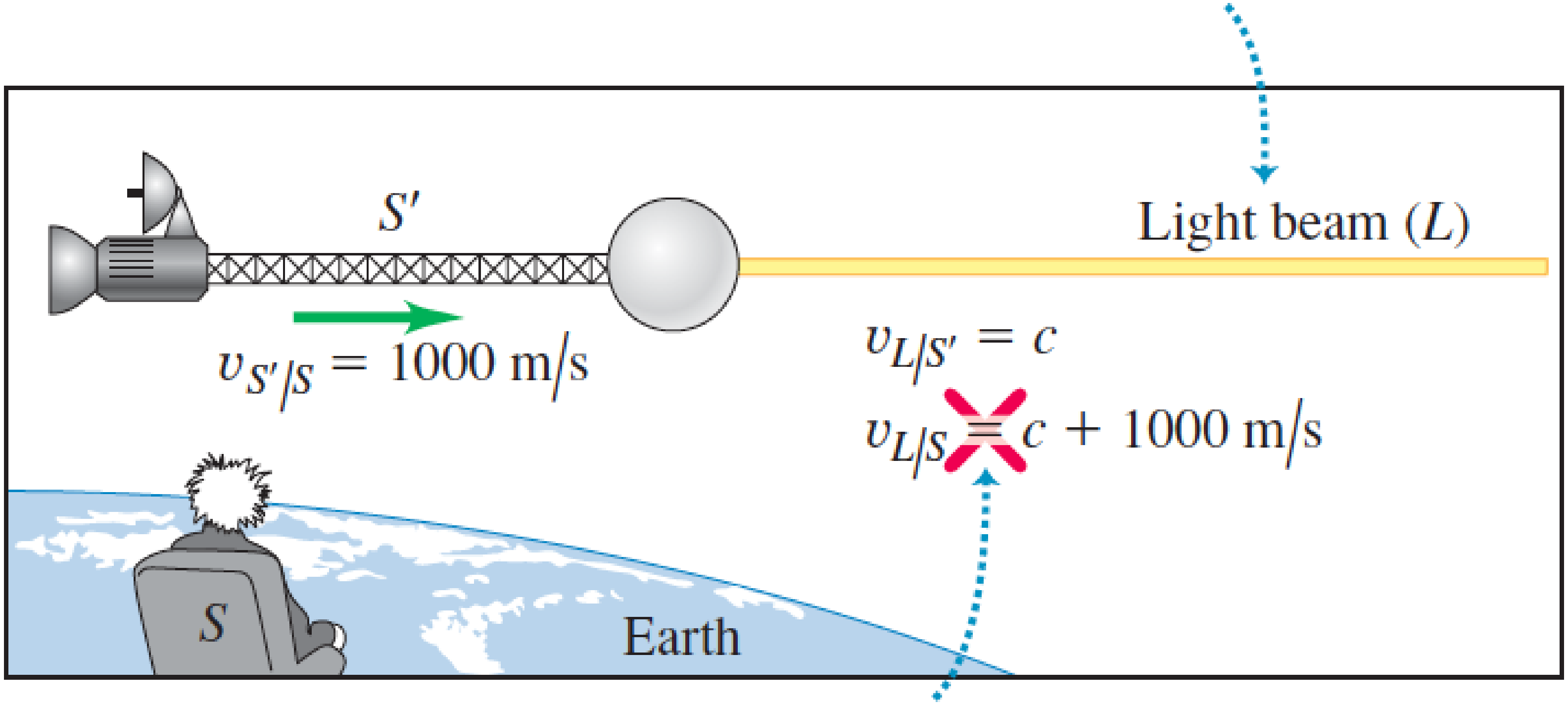
A missile (M) is fired with speed $v_{M/S'} = 2000\ \text{m/s}$ relative to the spaceship.



NEWTONIAN MECHANICS HOLDS: Newtonian mechanics tells us correctly that the missile moves with speed $v_{M/S} = 3000\ \text{m/s}$ relative to the observer on earth.

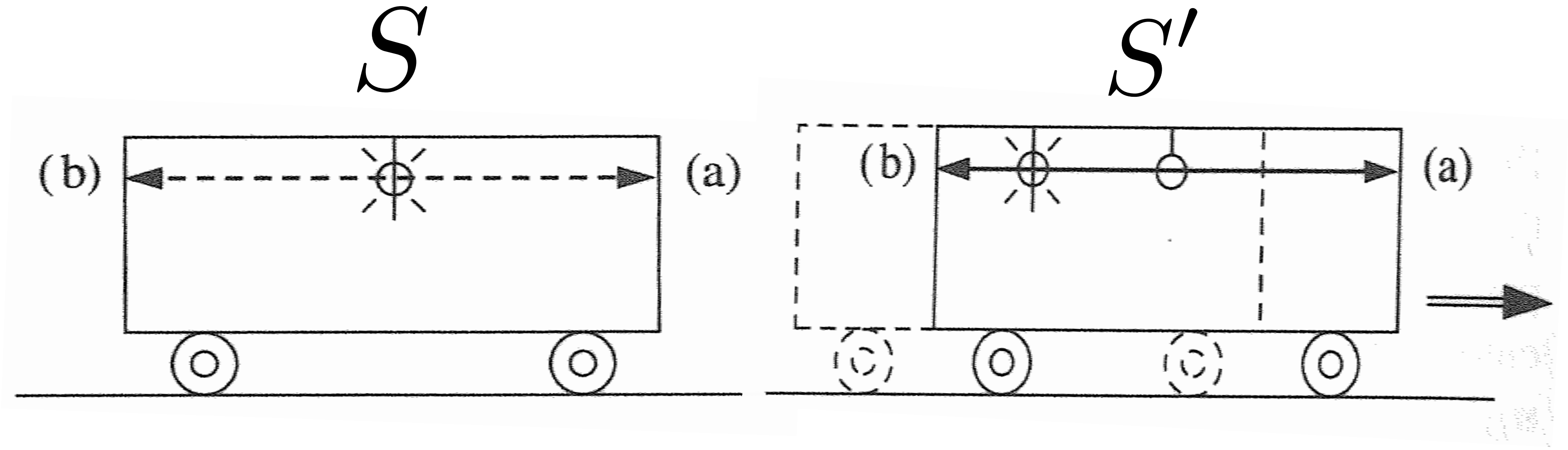
SR and Classical Mechanics

A light beam (L) is emitted from the spaceship at speed c.



NEWTONIAN MECHANICS FAILS: Newtonian mechanics tells us *incorrectly* that the light moves at a speed greater than c relative to the observer on earth ... which would contradict Einstein’s second postulate.

How do we fix this?



Space and time have become *relative*!

Events that are simultaneous in one reference frame are no longer simultaneous in another.

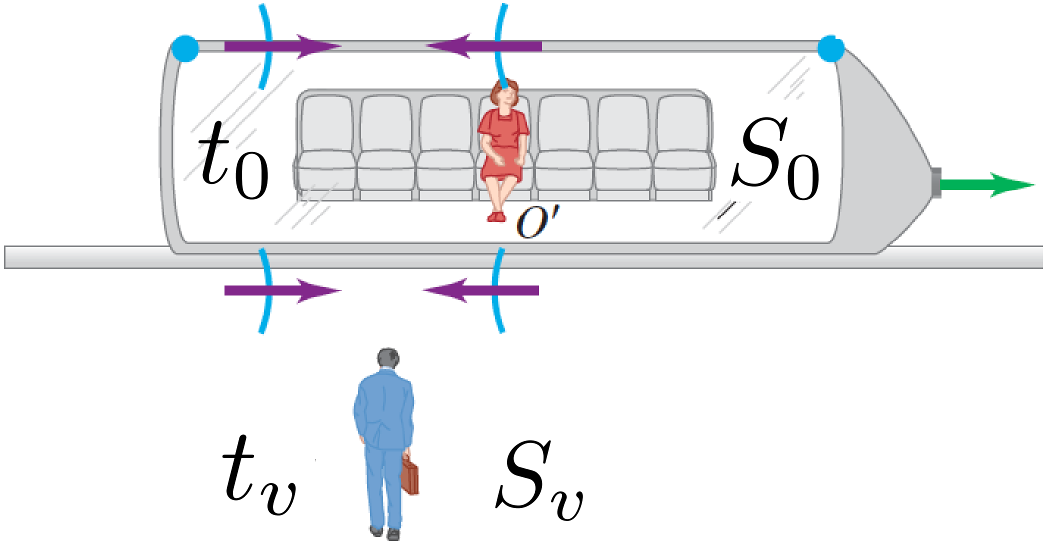
Time Dilation

$$t_v = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

What are t_0 and t_v?

Time Dilation

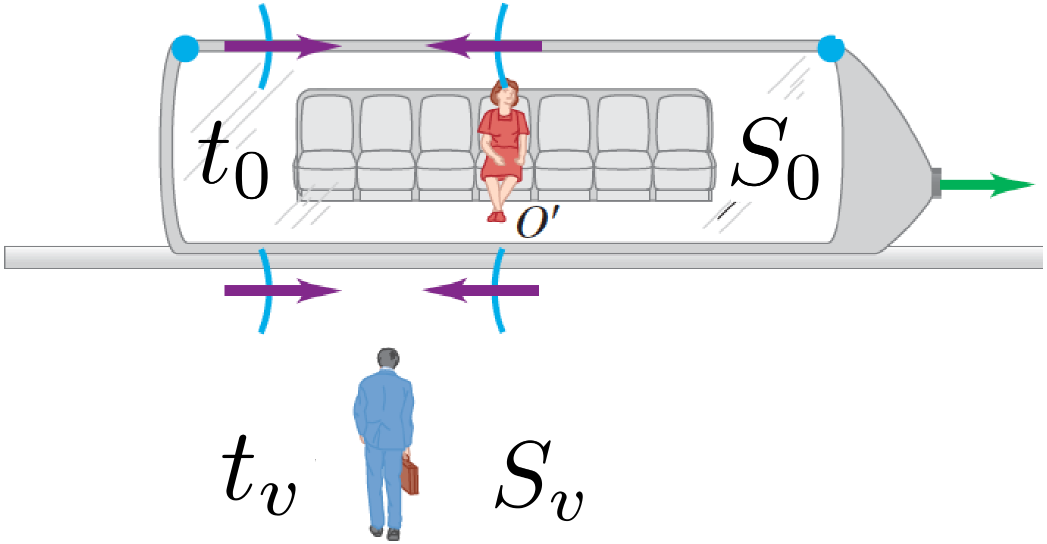
$$t_v = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$



- An observer at *rest* in frame S_0 observes a time t_0 elapse between two events that take place at the same point in space in. (e.g. spill coffee in lap on train)
- An observer *moving at v* in frame S_v observes a time t_v elapse between the two events that take in S_0

Time Dilation

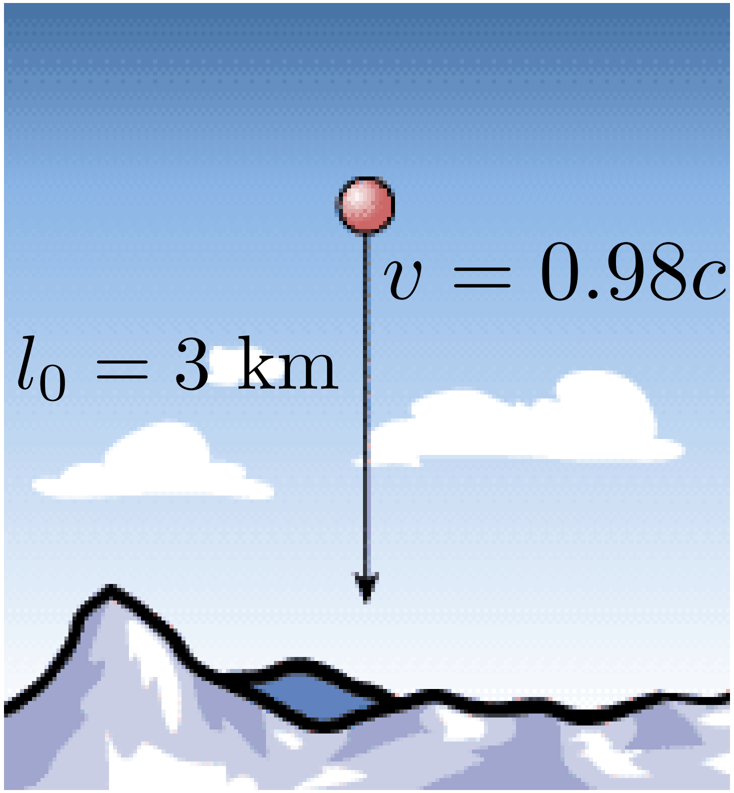
$$t_v = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$



"Moving clocks run slow"

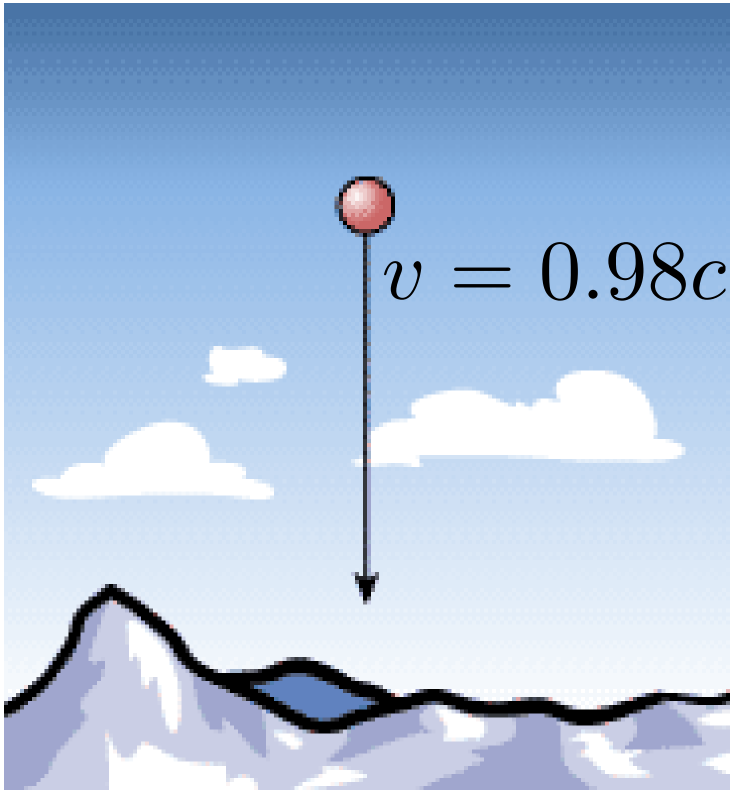
$$v = 0.01c \implies t_v = 1.00005 \times t_0$$
$$v = 0.5c \implies t_v = 1.155 \times t_0$$

Back to the Muon - Lab



- **LAB FRAME**

Back to the Muon - Lab



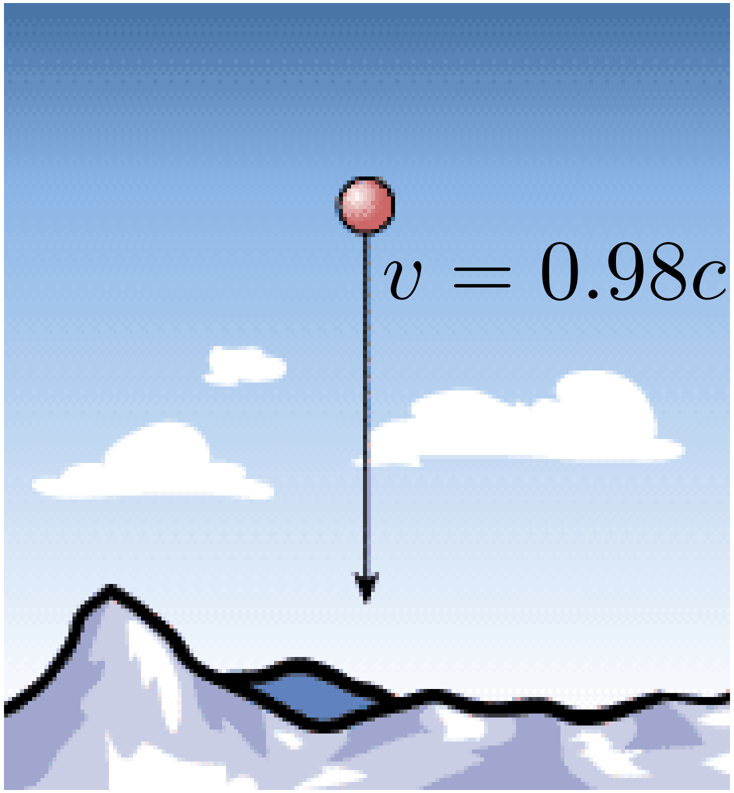
- **LAB FRAME**
  - We want to know the decay time when measured from our lab.
  - Our work on muons *at rest* has told us that they decay with on a time scale of 2 x 10^{-6} s.

$$t_v = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$t_0 = 2.6 \times 10^{-6}\mathrm{s}$$

$$v = 0.98c$$

Back to the Muon - Lab



$$t_0 = 2.6 \times 10^{-6}\mathrm{s}$$

- **LAB FRAME**

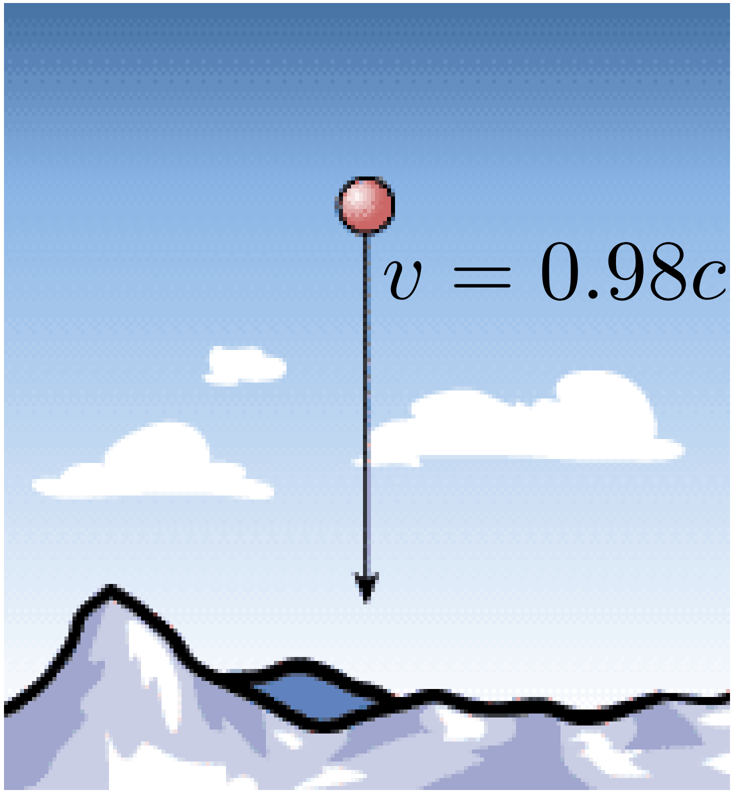
$$t_v = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$t_v = \frac{2.6 \times 10^{-6}}{\sqrt{1 - \frac{(0.98c)^2}{c^2}}}$$

$$t_v = \frac{2.6 \times 10^{-6}}{\sqrt{1 - (0.98)^2}}$$

$$t_v = 13 \times 10^{-6}\mathrm{s}$$

Back to the Muon - Lab



$$t_0 = 2.6 \times 10^{-6}\text{s}$$

- **LAB FRAME**
  - If we observed a decay time of 1.3 x 10^{-5} s, how far would it travel before decaying?

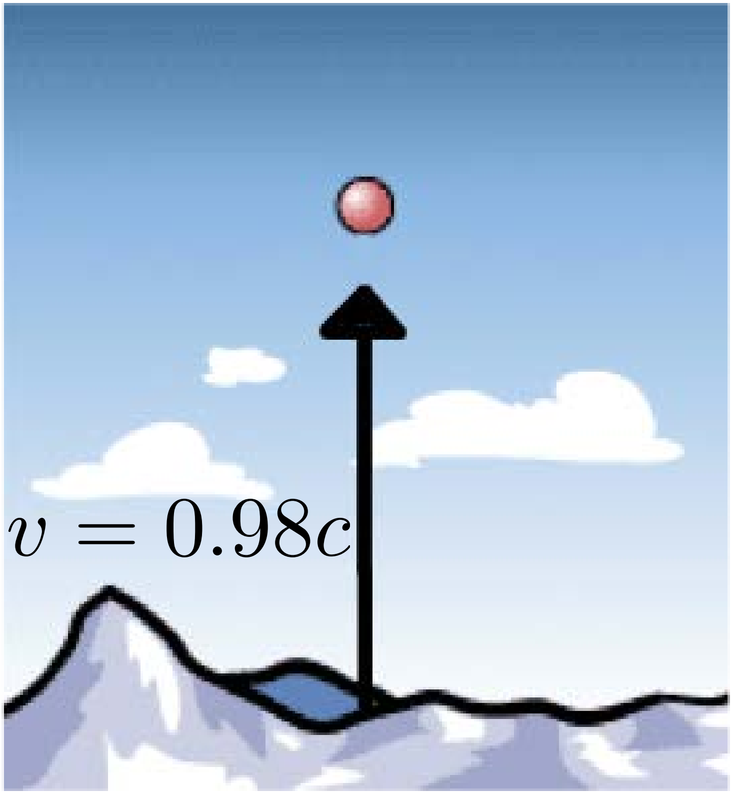
$$l_0 = vt$$

$$l_0 = 0.98c \times 1.3 \times 10^{-5}$$

$$l_0 = 3.8 \text{ km}$$

Muon Frame

- **MUON FRAME**



Muon Frame

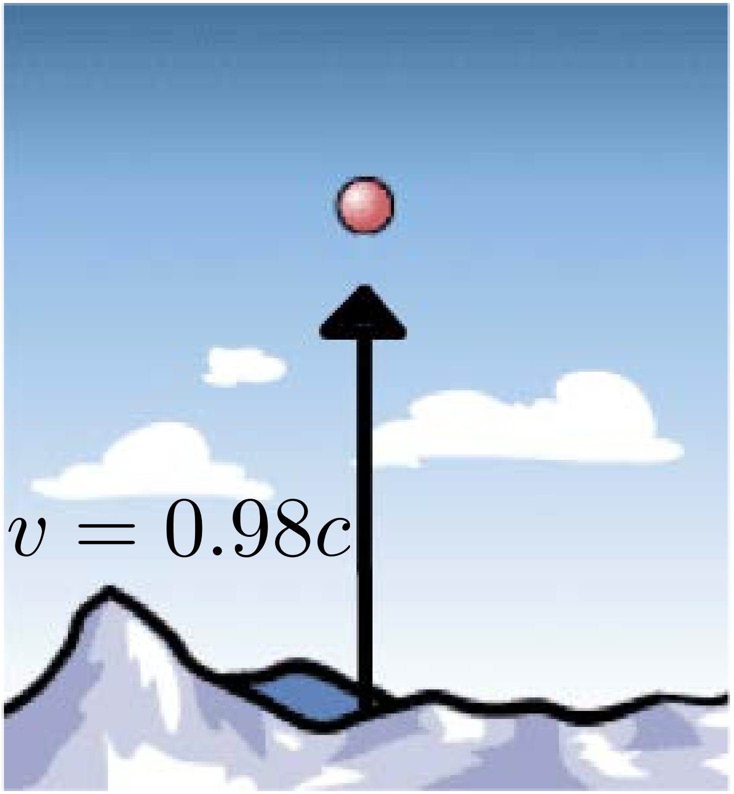
- **MUON FRAME**
  - Since we know the lifetime of a muon at rest, we can easily calculate the distance it seems to travel in its frame:

$$l_v = 0.98c \times 2.2 \times 10^{-6}$$

$$l_v = 0.64 \text{ km}$$

But $l_0 = 3.8 \text{ km}$

  - How do we interpret these two distances?



Length Contraction!

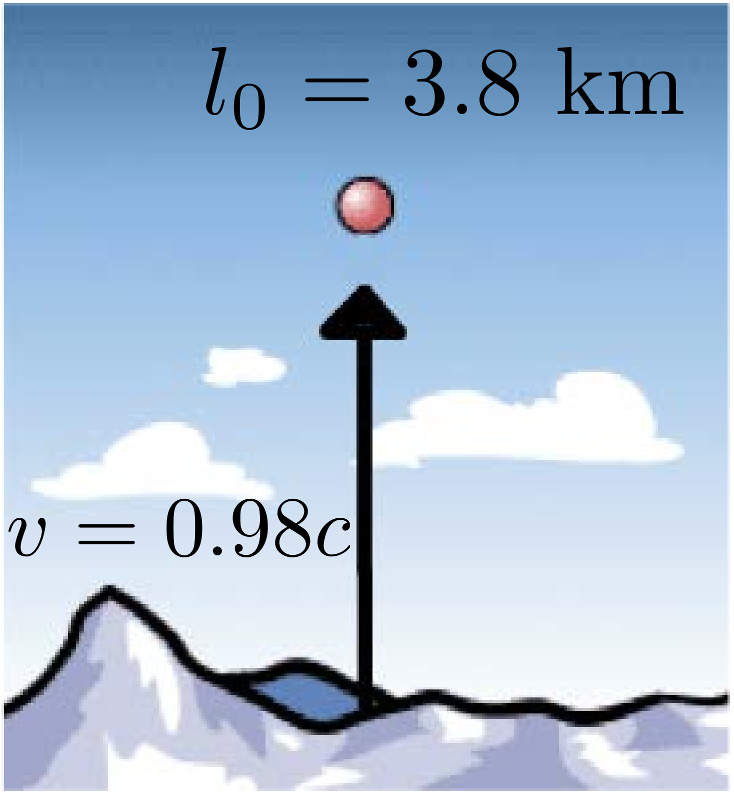
- **MUON FRAME**
  - Imagine muon appears at the top of a mountain of height 3.8 km. Relative to an observer travelling with the muon, the mountain will have its length contracted to:

$$l_v = l_0\sqrt{1-\frac{v^2}{c^2}}$$

$$l_v = 3.8\sqrt{1-\frac{(0.98c)^2}{c^2}}$$

$$l_v = 0.64\ \mathrm{km}$$

“Moving objects are shortened”



So length contraction is consistent with time dilation.

Some General Tips

- It is easy to confuse reference frames - each frame sees the other one moving!
- Common error: using wrong numbers in equations

- Remember the rules of thumb:

“Moving clocks run slow”

“Moving objects are shortened”

“Moving objects are more massive”

Other Implications

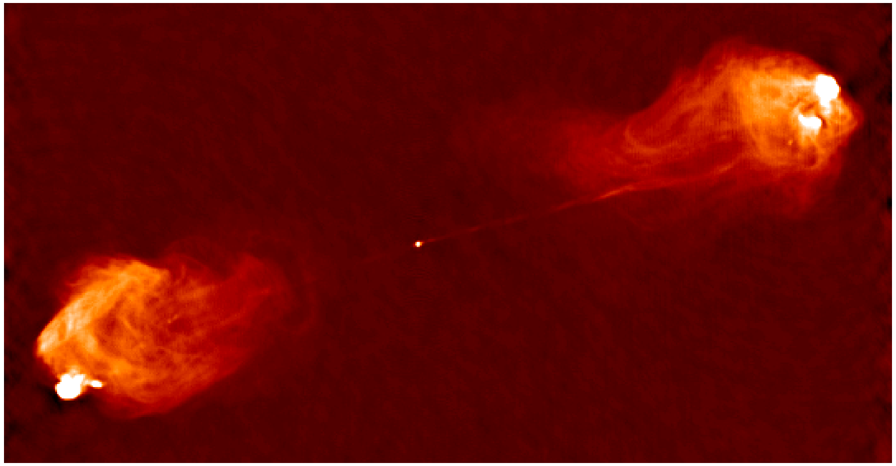
› The principle of relativity can also be applied to show:

1. Mass increases with increasing speed
2. A mass m at rest has non-zero energy E = mc^2
3. if m ≠ 0, it cannot be accelerated to speed of light

$$m_v = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

› Practical applications:

- Global Positioning System (GPS)
- Particle accelerators
- Observations of jets from black holes



Cygnus A

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FOR ALL-SKY ASTROPHYSICS

Feynman on Special Relativity

Richard P. Feynman

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Warning

Special relativity is bizarre – if you are confused you are probably on the right track!

Thank you!

Further Reading

- *Six Not-So-Easy Pieces*, Richard Feynman
- *$E = mc^2$ – A Biography of the World's Most Famous Equation*, David Bodanis
- *Relativity – The Special and the General Theory*, Albert Einstein