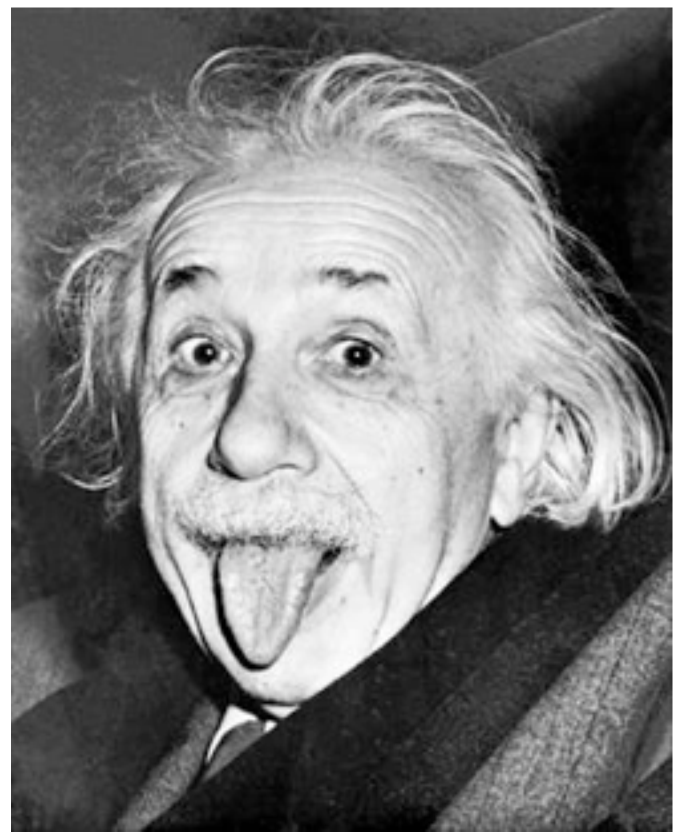
Einstein & Special Relativity



A. Einstein (1879-1955)

Dr. Greg Madsen

Univ. of Sydney

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THE UNIVERSITY OF SYDNEY

Physics Limerick

There was a young lady named Bright,
Whose speed was far faster than light;
She set out one day,
In a relative way,
And returned home the previous night.

- A.H.R. Buller (1923)

WARNING

Special relativity contradicts common sense!

If you are confused by this,
you are on the right track

WARNING

Reference Frames

- In order to describe **speed**, you have to specify a "reference frame" or point of view

- Example:
  "I am on the highway driving at 100 km/h"

  Speed relative to a billboard: 100 km/h
  Speed relative to your passenger: 0 km/h
  Speed relative to oncoming traffic: 200 km/h

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- **Special** kind of reference frame:
  "inertial reference frame" moves at a **constant speed** relative to another reference frame

Relativity

- Principle of Relativity:
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Example:

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*.

This principle says you will measure the same force!

Relativity

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  "The laws of physics are the same in every inertial reference frame"

- One law of physics:
  Light always travels at a constant speed
  ($c \approx 3.0 \text{x} 10^5$ km/s in a vacuum)

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- One law of physics:
  Light always travels at a constant speed
  ($c \approx 3.0 \times 10^5$ km/s in a vacuum)

⇒ Light travels at speed *c* in every inertial reference frame

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

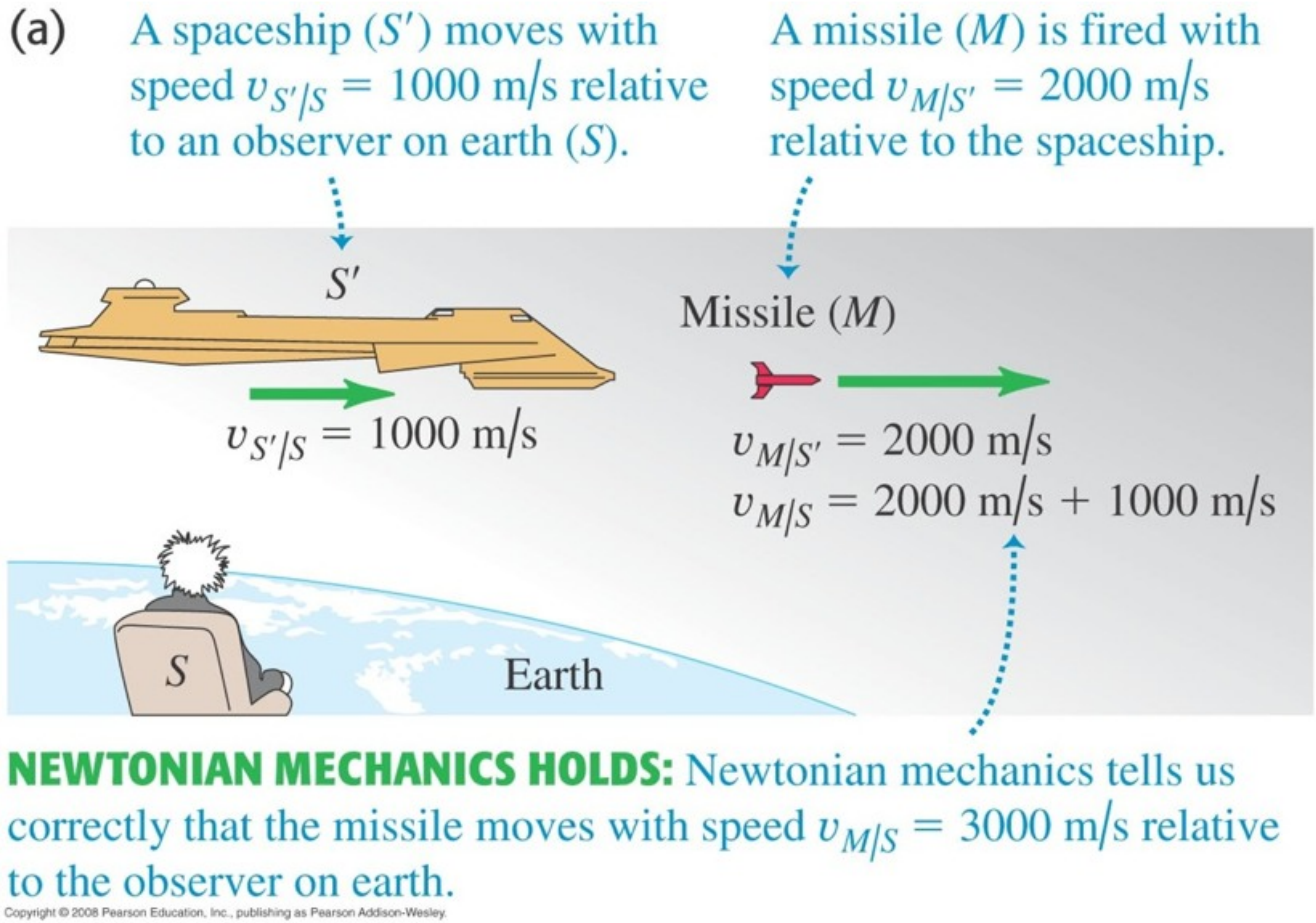
Relativity

- Consider two inertial reference frames:

S: Observer at rest on Earth

S′: A spaceship moving at constant speed

Relativity



(a)
A spaceship (S') moves with speed $v_{S'/S}$ = 1000 m/s relative to an observer on earth (S).
A missile (M) is fired with speed $v_{M/S'}$ = 2000 m/s relative to the spaceship.
S'
Missile (M)
$v_{S'/S}$ = 1000 m/s
$v_{M/S'}$ = 2000 m/s
$v_{M/S}$ = 2000 m/s + 1000 m/s
S
Earth
NEWTONIAN MECHANICS HOLDS: Newtonian mechanics tells us correctly that the missile moves with speed $v_{M/S}$ = 3000 m/s relative to the observer on earth.
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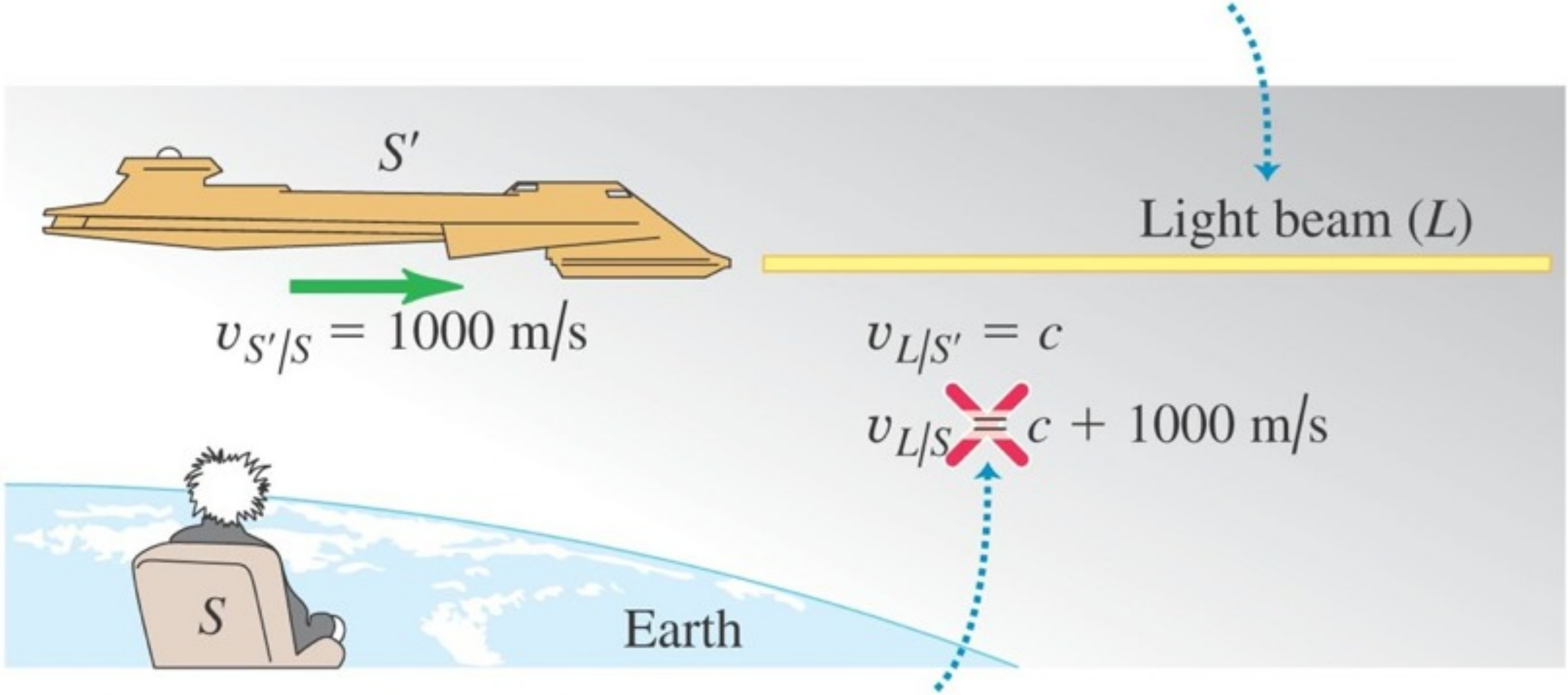
Relativity

(b)

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.

Relativity

- How can we make sense of this?

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$\Rightarrow$ For c to be constant in all inertial reference frames, then distance and time must be stretched/compressed in different reference frames!


S. Dali

$\therefore$ concepts of distance and time depend on our reference frame!

Time Dilation

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occur over a *longer time interval* $t_v = \dfrac{t_0}{\sqrt{1 - \dfrac{v^2}{c^2}}}$

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- The larger v is, the bigger the effect
- This is only a big effect if v is close to c
- Example

$$v = 0.01c \Rightarrow t_v = 1.00005 \times t_0$$
$$v = 0.1c \Rightarrow t_v = 1.005 \times t_0$$
$$v = 0.5c \Rightarrow t_v = 1.155 \times t_0$$

Time Dilation

Queen Elizabeth XX flies from London to Sydney (18,000 km) on a spaceship at a constant speed of 30,000 km/s (0.1c).

How much time does the trip take:
a) measured by observer on the ground?
b) measured by observer on the spaceship?

Time Dilation

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Identify events and reference frames.

Event 1: Leave London
Event 2: Arrive Sydney

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From observer on ground, events take place at *different points in space*.

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⇒ Observer on ground is in frame S_v

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Queen Elizabeth XX flies from London to Sydney (18,000 km) on a spaceship at a constant speed of 30,000 km/s (0.1*c*).

a) Observer on ground (S_v) measures time between events

$$t_v = \frac{18{,}000\text{km}}{30{,}000\text{km/s}} = 0.600\text{s}$$

Time Dilation

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b) Observer on spaceship (S_0) measures time between events

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

$$= 0.600\text{s}\sqrt{1 - {1}/{10^2}}$$

$$\approx 0.597\text{s}$$

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a) Observer on ground (S_v) measures

$$t_v = 0.600\text{s}$$

b) Observer on spaceship (S_0) measures

$$t_0 \approx 0.597\text{s}$$

⇒ Time passes by more slowly on spaceship

⇒ Observed by actual clocks on actual planes

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Tips & Tricks

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

- For time dilation:
  - identify events
  - identify reference frame in which the events happen at same point in space (S_0, t_0)
  - identify reference frame in which the events happen at different point in space (S_v, t_v)
  - apply formula

Other Implications

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

  1. distance between points changes with speed
  2. mass increases with increasing speed
  3. a mass m at rest has non-zero energy $E = mc^2$
  4. if $m \neq 0$, it cannot be accelerated to speed of light
  5. concept of simultaneous events is limited

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- Practical applications
  - Global Positioning System (GPS)
  - Particle accelerators (e.g. Large Hadron Collider)
  - Observations of jets from black holes

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