Einstein in a Nutshell

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Insight Cruises/Scientific American
January 15, 2011

Relativity in Recent News

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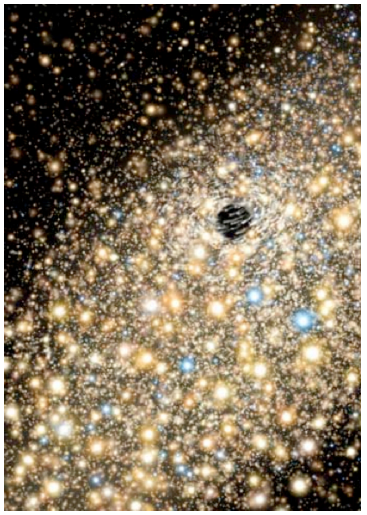
Record massive black holes discovered lurking in monster galaxies

By Robert Sanders, Media Relations | December 5, 2011

BERKELEY — University of California, Berkeley, astronomers have discovered the largest black holes to date -- two monsters with masses equivalent to 10 billion suns that are threatening to consume anything, even light, within a region five times the size of our solar system.



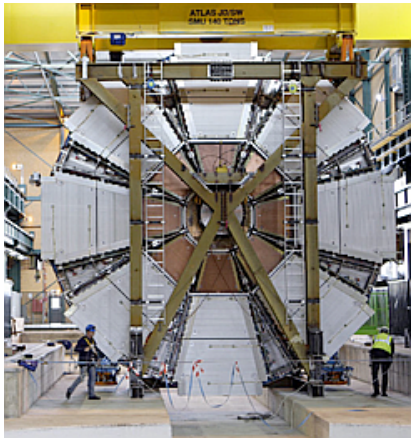
DiscoveryNews

FASTER-THAN-LIGHT NEUTRINOS RE-TESTED: SAME RESULT

CERN's OPERA experiment continues to clock the subatomic particles traveling faster than the speed of light.

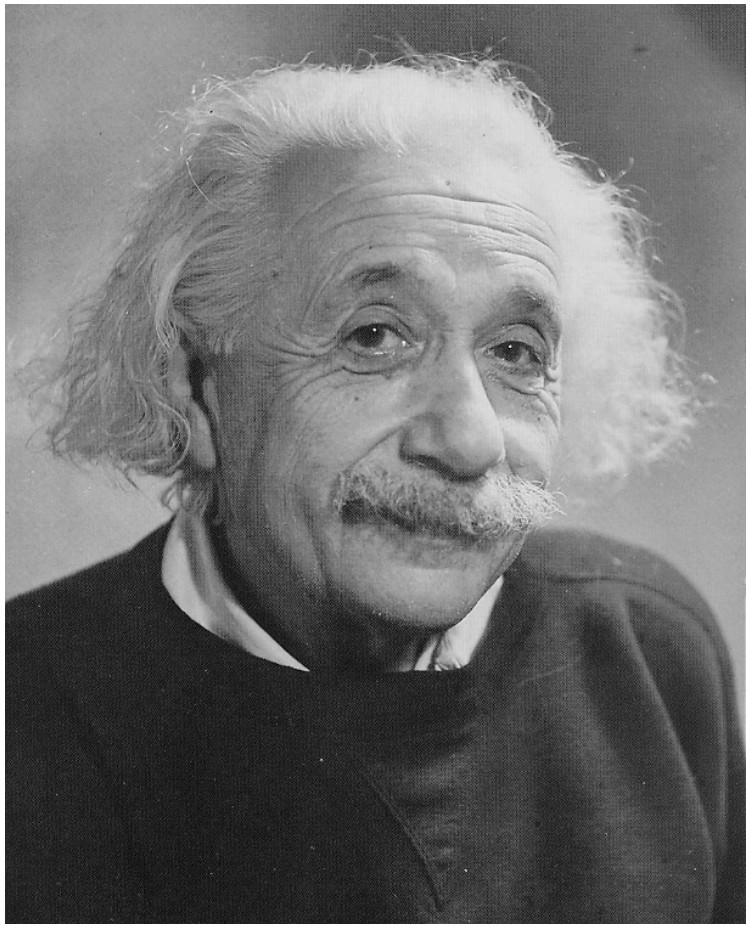
Fri Nov 18, 2011 01:17 PM ET
Content provided by AFP

- The fiercely contested CERN experiment has been re-run, but the result is the same.
- Traveling a distance of 454 miles, the neutrinos still appear to be traveling faster than the speed of light.
- Skeptics still point to an unforeseen systematic error, rather than a revolution in physics.



http://newscenter.berkeley.edu/2011/12/05/record-black-holes-bigger-than-our-solar-system/, http://news.discovery.com/space/faster-than-light-speed-neutrinos-re-run-111118.html

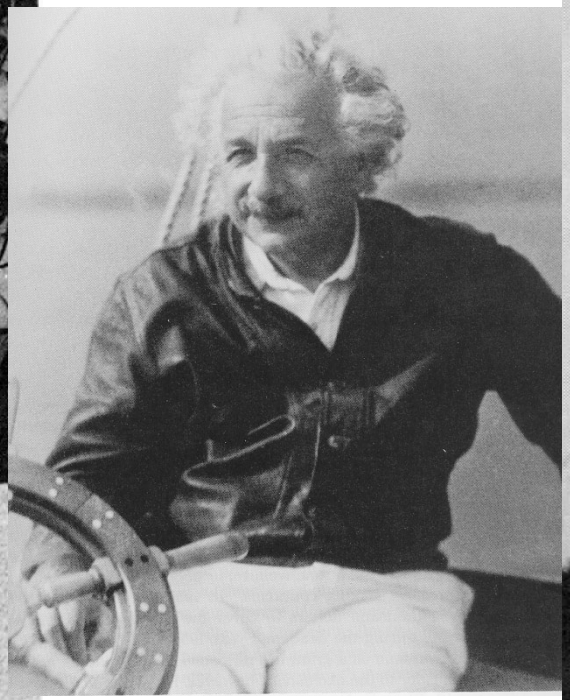
The Human Einstein



Source: *Einstein: A Portrait* (Pomegranate Artbooks, 1984)

Source: Einstein Archives, The Hebrew University of Jerusalem

The Playful Einstein



Source (all three photos): Clark, *Einstein: The Life and Times* (Abrams, 1984)

Einstein's Big (Science) Ideas

- 1905: Brownian Motion
  - Proof that molecules exist
- 1905: Photons
  - Quantization of light energy
- 1905: Special Relativity
  - Space and time
  - Matter and energy
  - A restricted theory: uniform motion
  - Simple and understandable (but bizarre consequences!)
- 1915: General Relativity
  - Gravity as curved spacetime
  - A general theory: valid for all states of motion
  - Mathematically complex
- ~~1920-1955: Unified Field Theory~~

A Brief History of Physics through 1900

- ~1600-1750: Galileo, Newton, and others develop a mechanical understanding of physical reality - laws of motion
  - Including a relativity principle

Relativity Principle?

- Physical reality works the same for everyone, regardless of their state of motion
  - As long as that motion is uniform (unchanging)
- Absolute motion is meaningless
  - "I am moving, period" is a meaningless statement
- So is "I am at rest"
- Only statements about *relative* motion are meaningful
  - "We're moving *relative* to the ocean at 25 miles per hour"

Tennis: A Physics Experiment

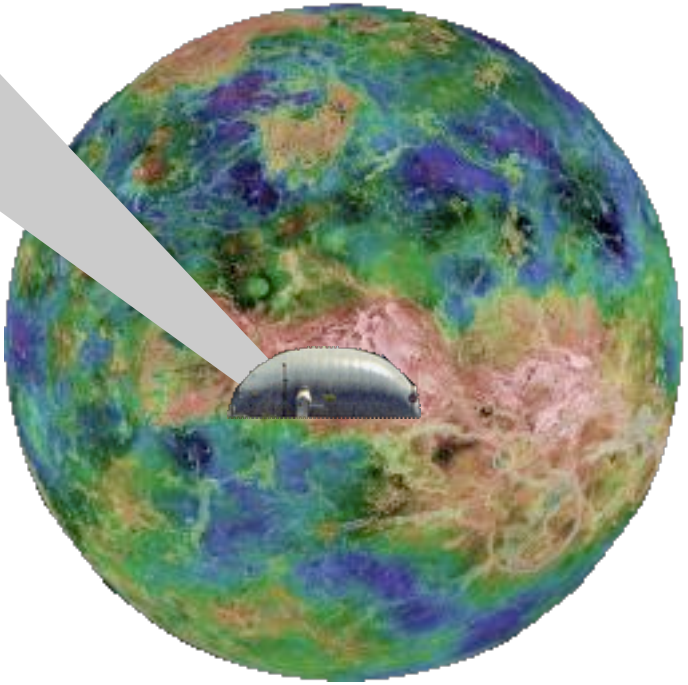
On Earth

Tennis: A Physics Experiment

On a Cruise Ship

Tennis: A Physics Experiment

On Venus



Tennis: A Physics Experiment

On an Earthlike planet in a distant galaxy, moving rapidly away from Earth

A Brief History of Physics through 1900

- ~1600-1750: Galileo, Newton, and others develop a mechanical understanding of physical reality - laws of motion
  - Including a relativity principle
- ~1750-1900: Maxwell and others develop an understanding of electromagnetic phenomena, including light
  - Does this, too, obey the relativity principle?
    - 19th century physicists: No; works only in a special reference frame
    - Einstein (1905): Yes; works in all reference frames
    - You (2012): ?

Microwaving: A Physics Experiment

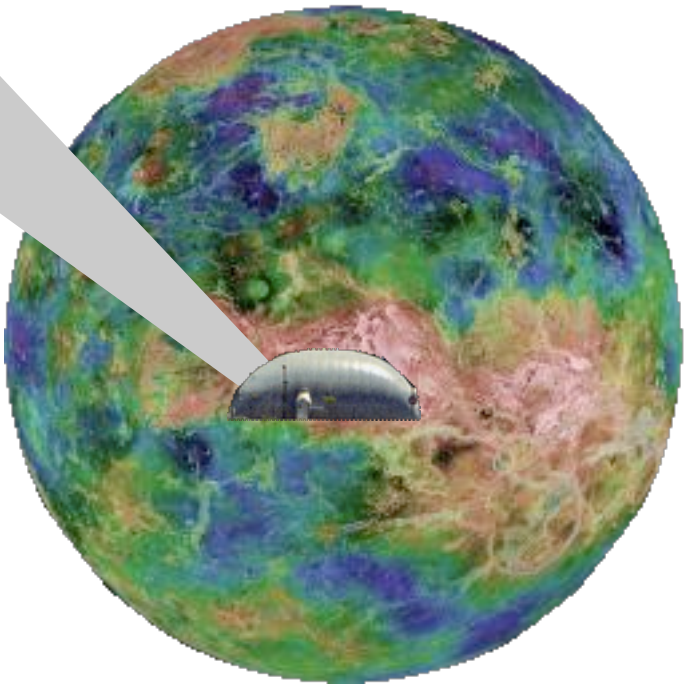
On Earth

Microwaving: A Physics Experiment

On a Cruise Ship

Microwaving: A Physics Experiment

On Venus



Microwaving: A Physics Experiment

On an Earthlike planet in a distant galaxy, moving rapidly away from Earth

In Einstein's Words

- Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relative to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest.

"On the Electrodynamics of Moving Bodies"

A. Einstein (Ann. Physik, 17, 891, 1905)

Einstein's Special Theory of Relativity

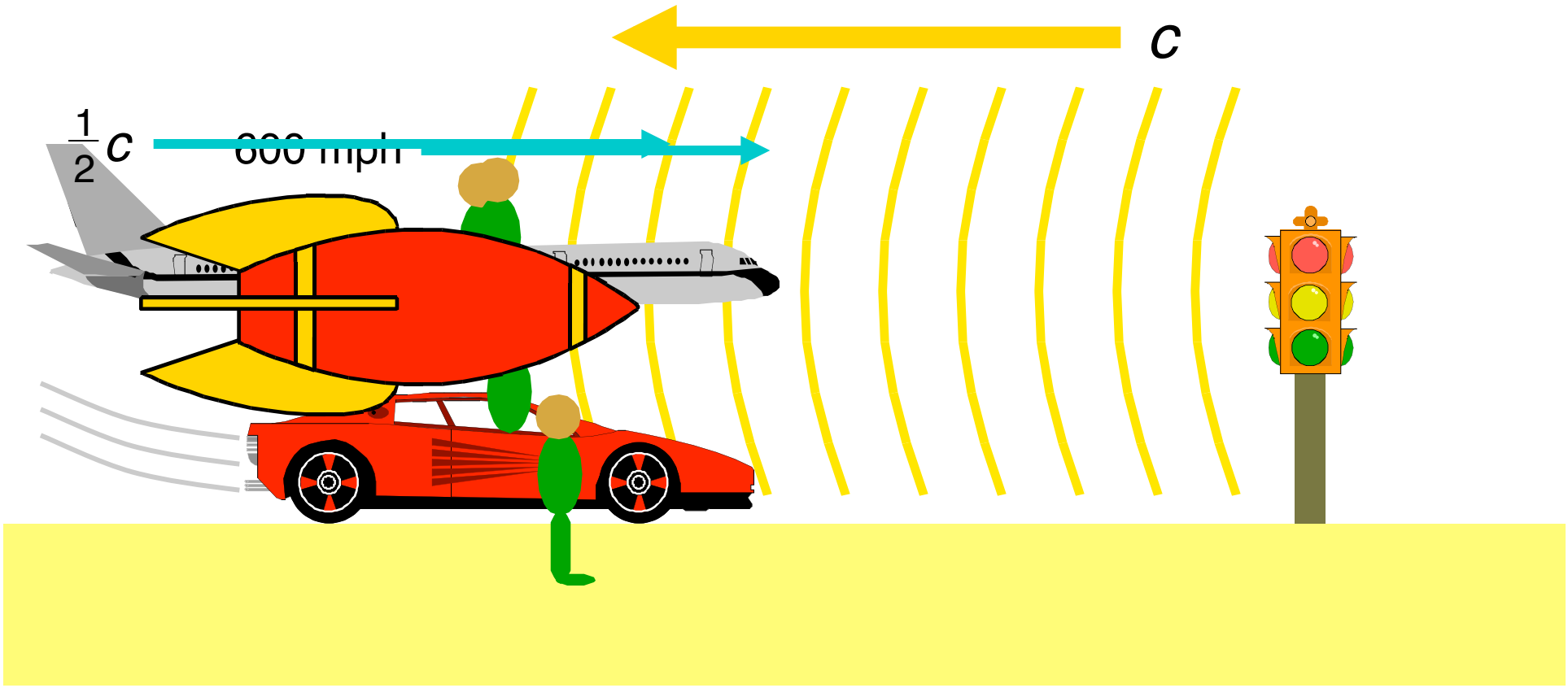
- The laws of physics are the same for everyone as long as they're in uniform motion
  - Nature works the same way for everyone
  - The laws of physics don't depend on your state of motion
  - The same experiment will give identical results for all uniformly-moving experimenters
    - Tennis works the same
    - Microwave ovens work the same
    - All the rest of physical reality works the same

- What's *special* about special relativity?
  - It's restricted to the *special* case of uniform motion

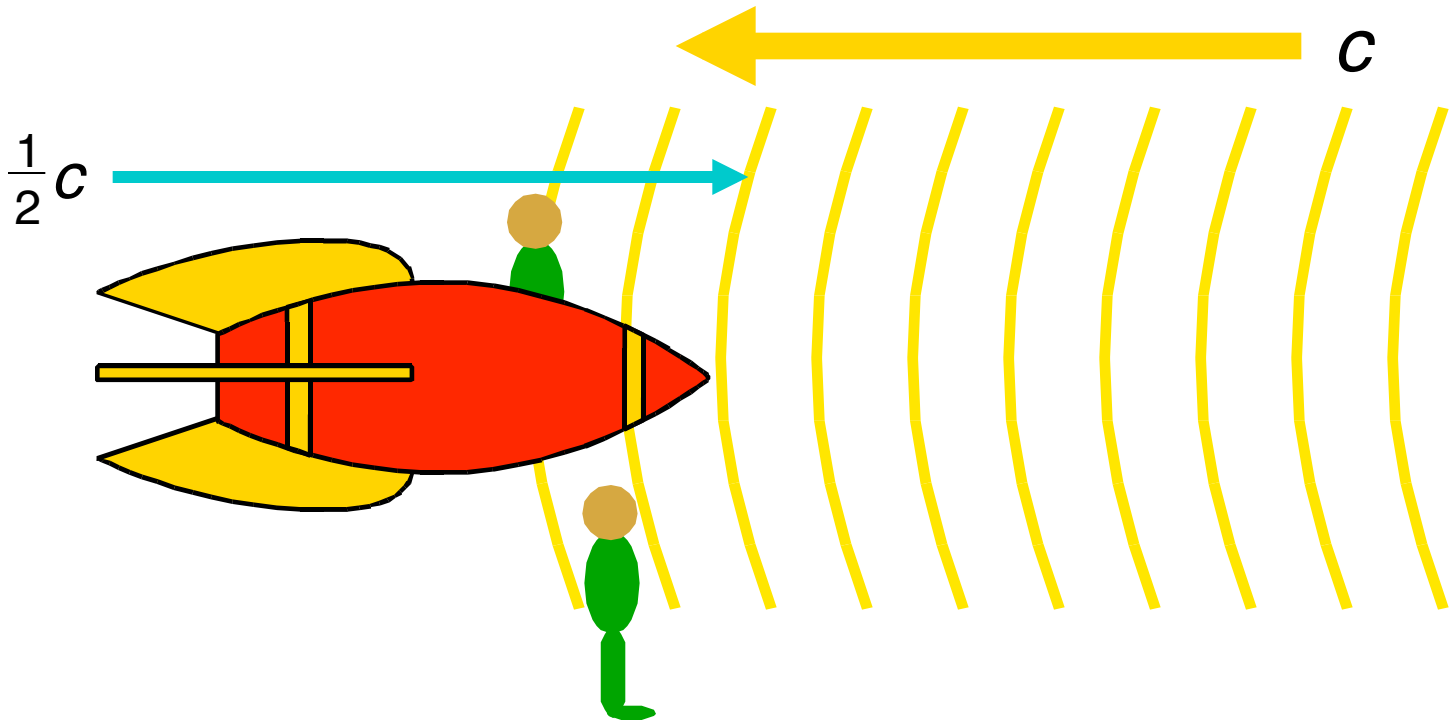
An Inference from Special Relativity

- The laws of physics are the same for all observers in uniform motion (Einstein, 1905)
  - This includes electromagnetism, with its prediction of electromagnetic waves (light) that travel at the speed of light, *c*
  - Therefore all observers in uniform motion will measure the same value for the speed of light

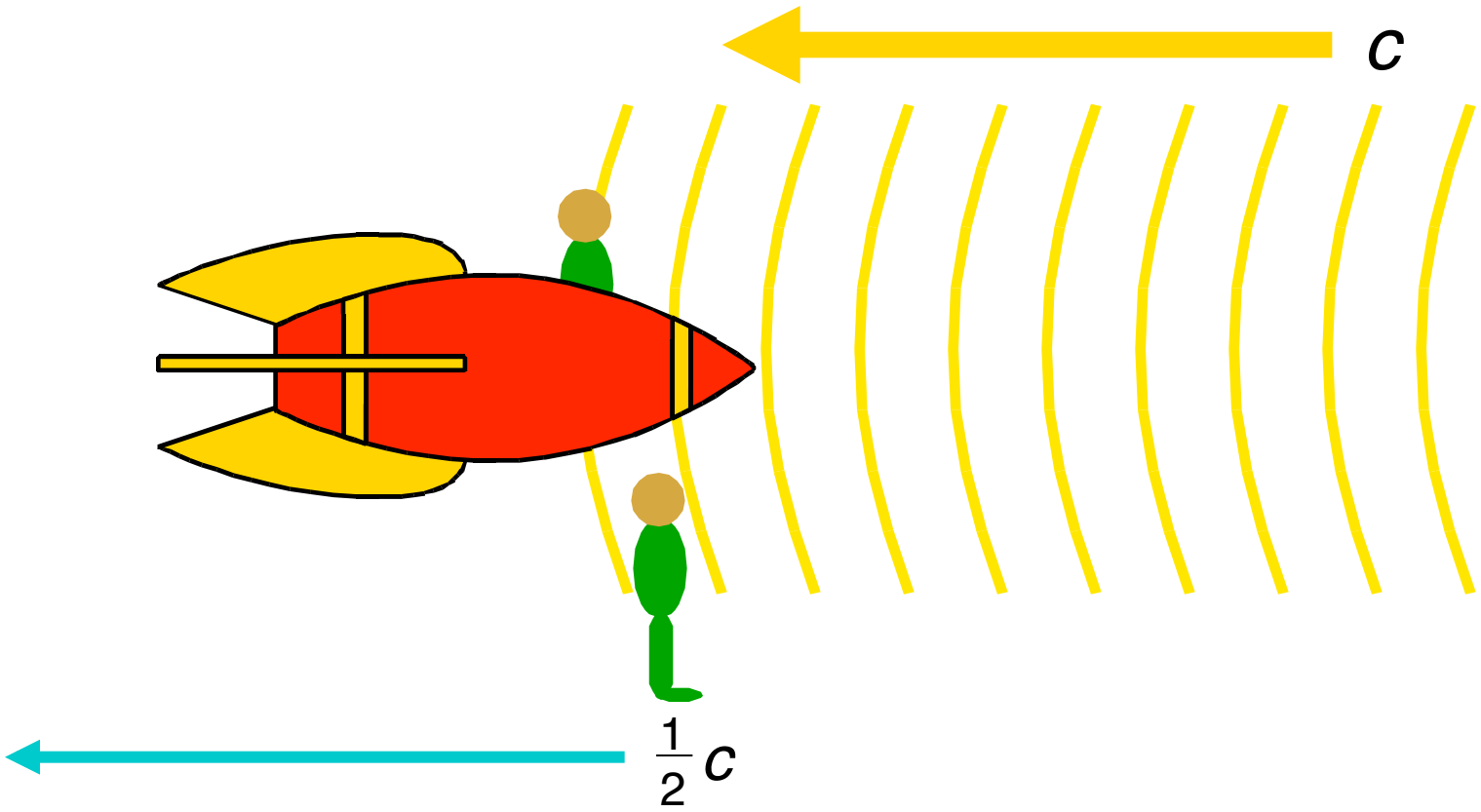
Measuring the Speed of Light



Measuring the Speed of Light



Measuring the Speed of Light



How Can This Be?

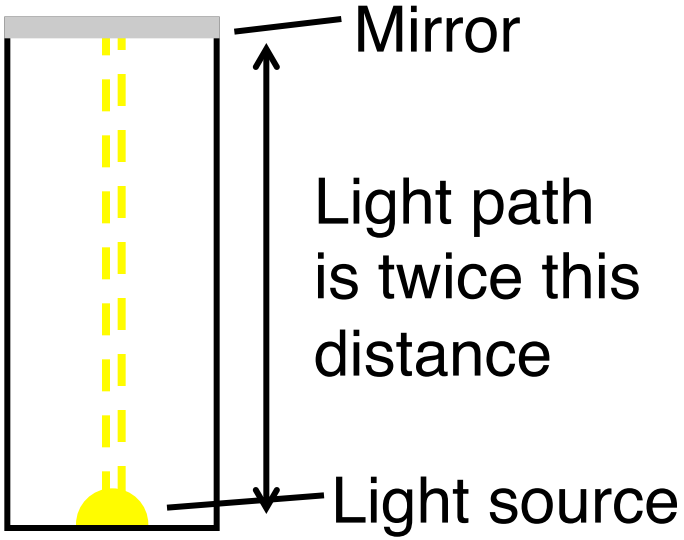
- Maybe motion does something strange to the clocks and measuring sticks in the car, airplane, and spaceship because they're moving

- Maybe time and space aren't absolutes, but depend on your frame of reference ✔

Time is Relative

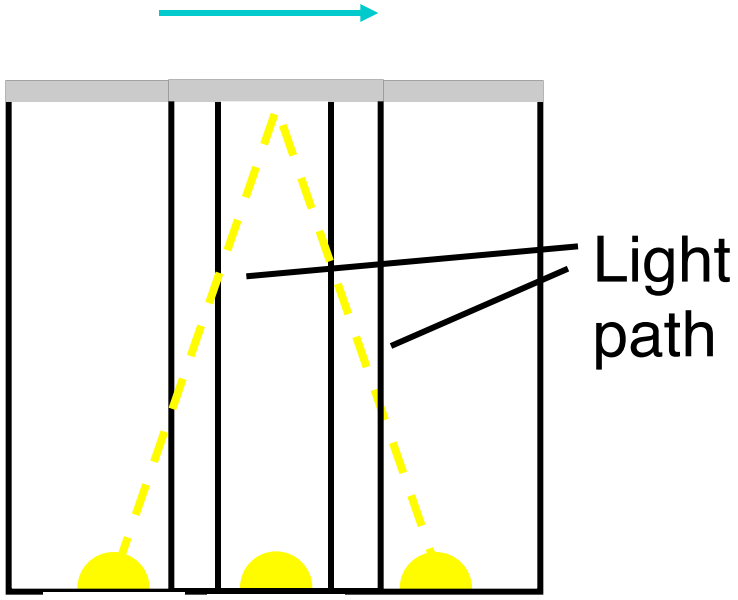
Time Dilation: A "Light Clock"

In a frame of reference at rest with respect to light clock:



Shorter path; **same speed**— LESS TIME

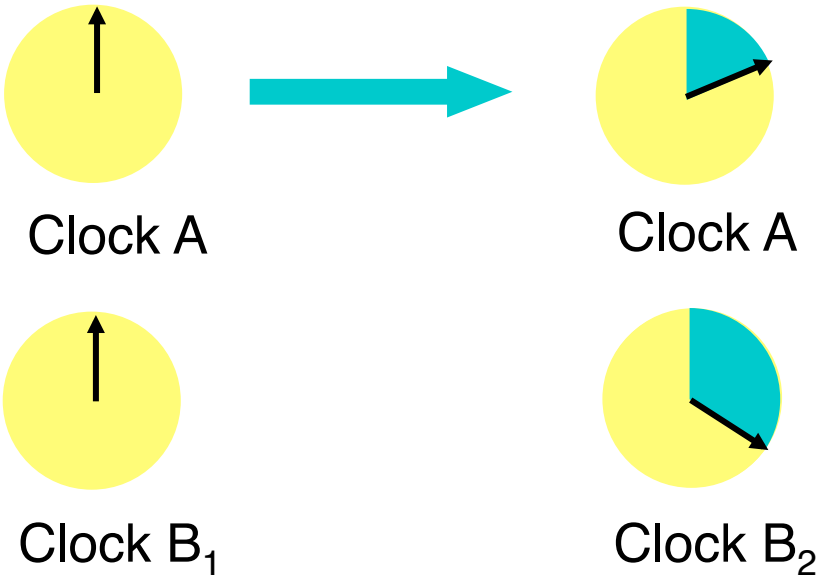
In a frame of reference in which the light clock is moving to the right:



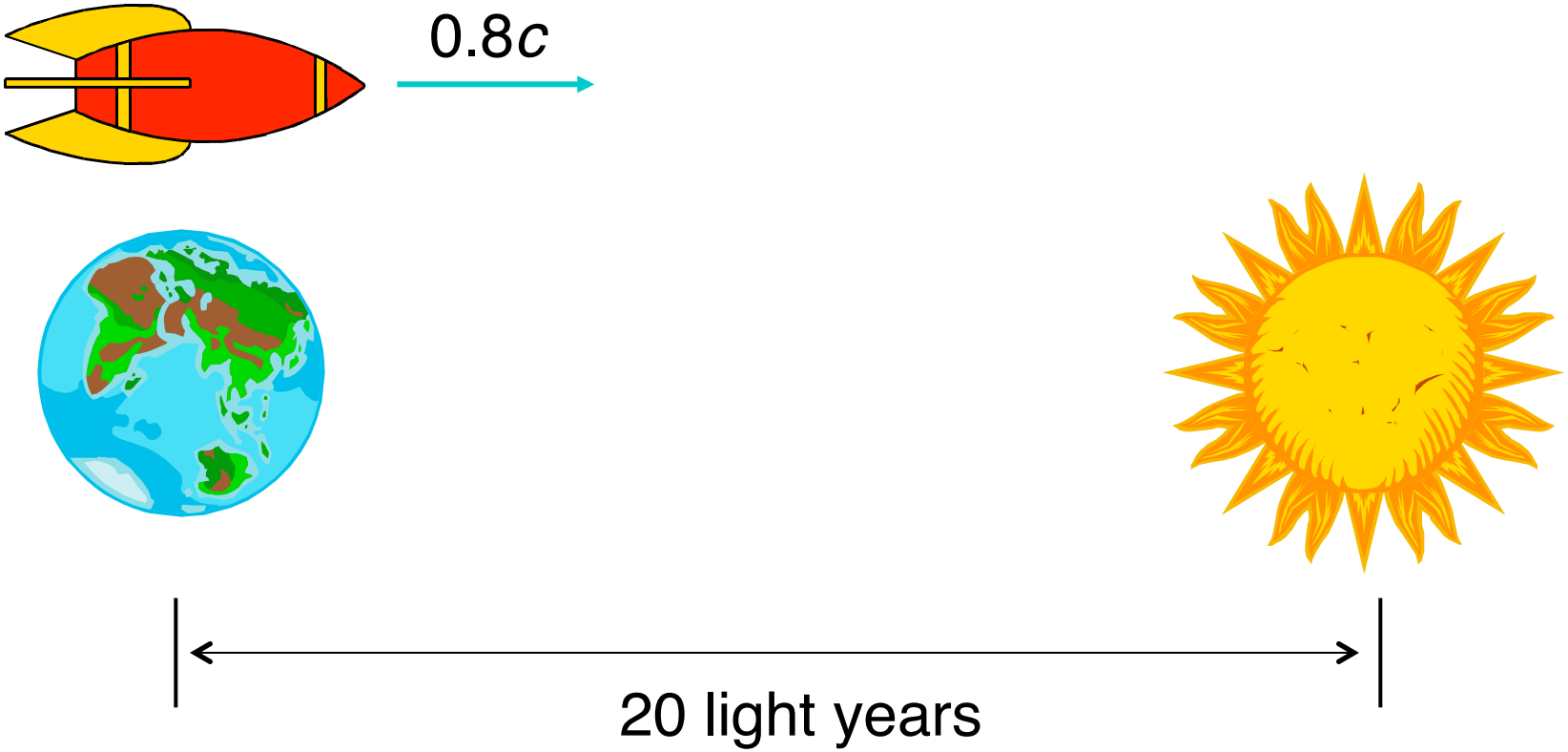
Longer path; **same speed**— MORE TIME

What Happens to Time

- ~~"Moving clocks run slow"~~ Bad wording: not RC!
  - When a clock moves relative to you, you will observe it to be keeping time at a slower rate than your clock
  - More precisely: The time between two events is shorter when measured by a single clock that's present at both events, than it is when measured by two separate clocks located at the two events



Star Trip!



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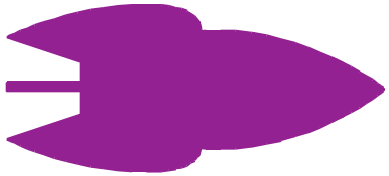
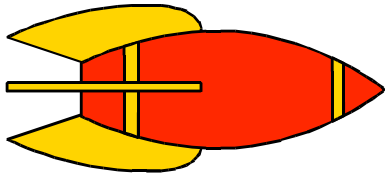
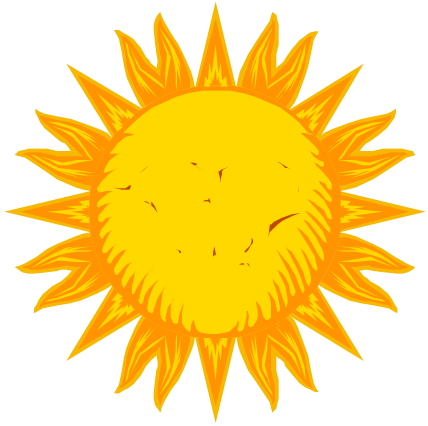


0.8*c*

Ship time: 15 years



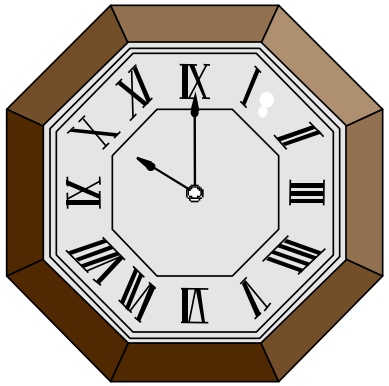


Earth/star time: 25 years

20 light years

Testing Your Faith

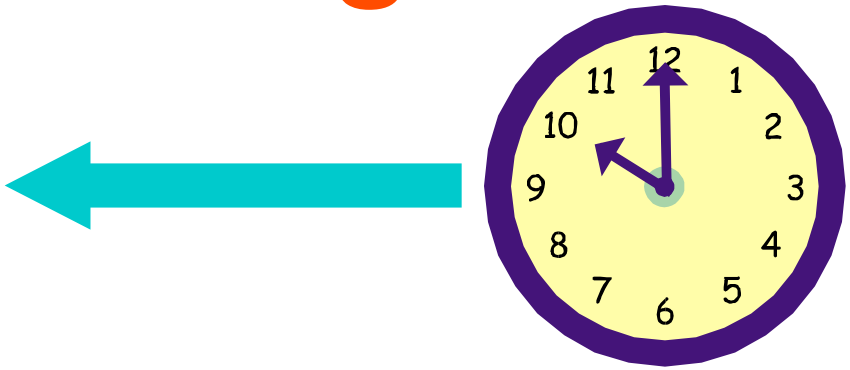
A: I'm at rest,
B is moving,
so B "runs slow"



Clock A

Who's right?

Both!



Clock B

B: I'm at rest,
A is moving,
so A "runs slow"

Where Did All This Nonsense Come From?

- From the Principle of Relativity
  - Tennis works the same way on Earth, on a ship, on Venus, in a distant galaxy—all in motion relative to one another
  - So does a microwave oven
  - So do all the rules that govern the workings of physical reality—the laws of physics

Space is Relative

Star Trip, Revisited

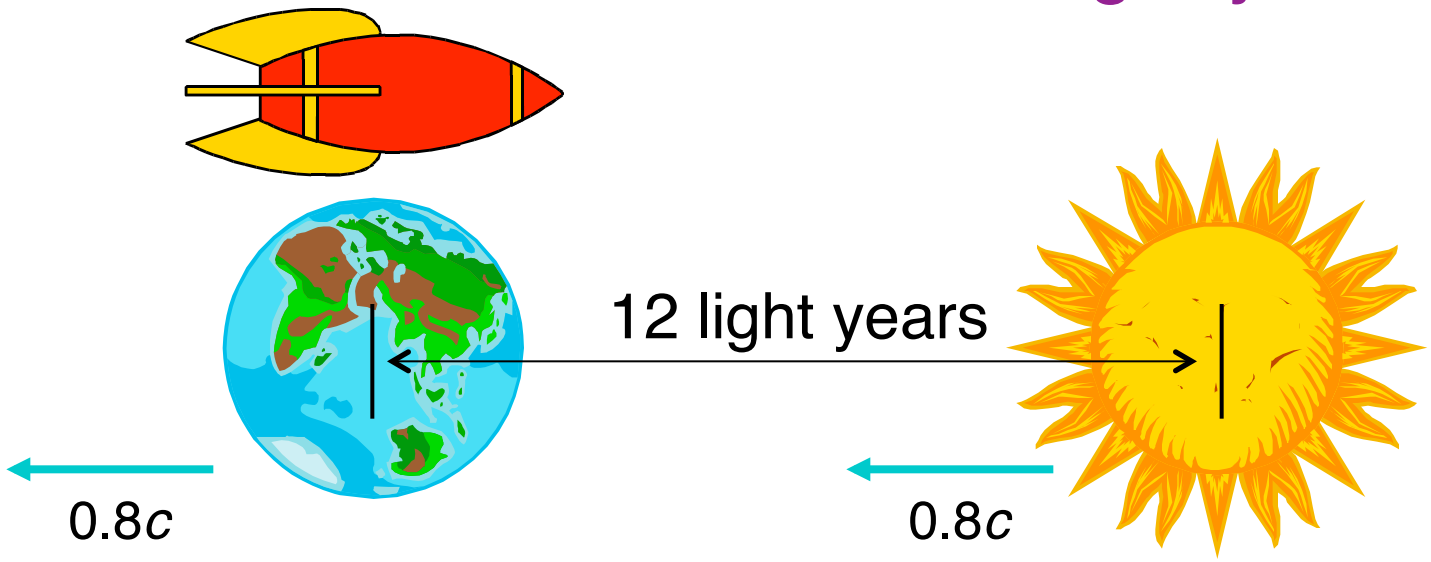
In spaceship's frame of reference:
Earth-star trip takes 15 years at 0.8*c*.

Therefore the distance is

distance = speed x time

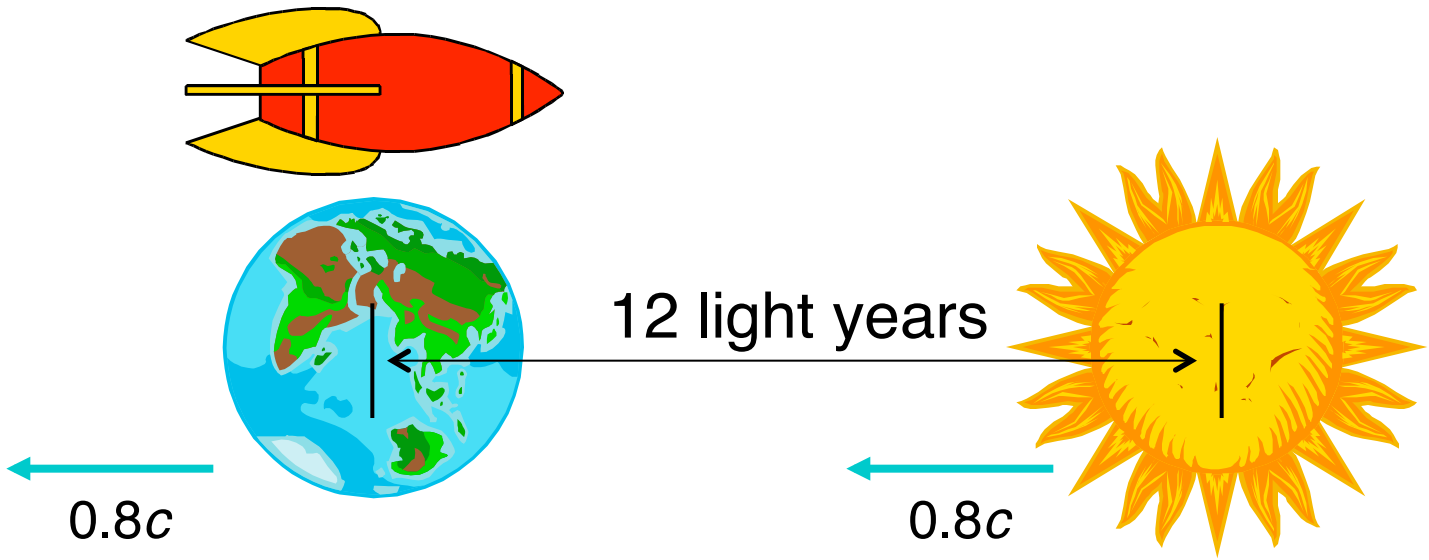
= (0.8 ly/y)x(15 years)

= 12 light-years



Star Trip, Revisited

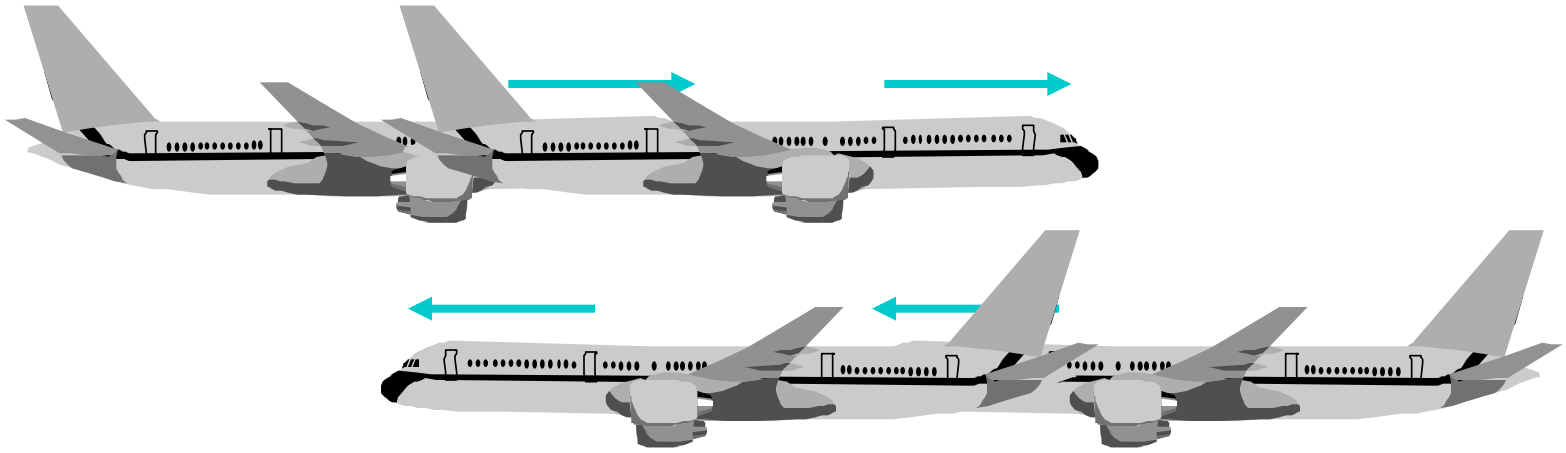
Length contraction:
The length of an object is greatest in a frame of reference in which it's at rest; in other frames it's shorter.



Simultaneity is Relative

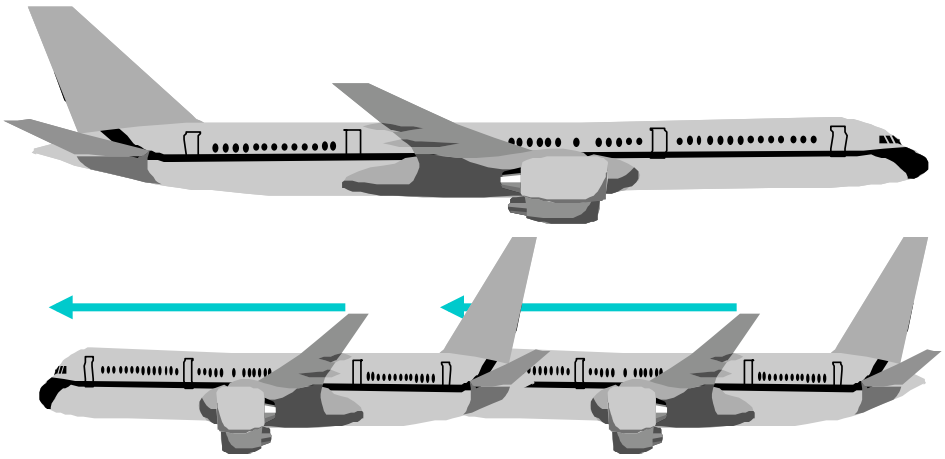
Two Identical Airplanes Pass

- In a frame where both are moving, their ends coincide at the same time:



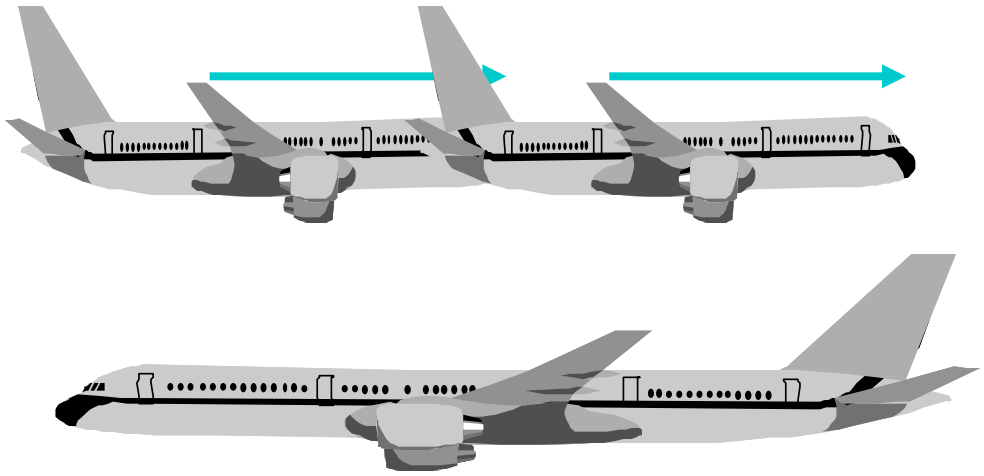
Two Identical Airplanes Pass

- In a frame where the upper plane is at rest, their right ends coincide first:



Two Identical Airplanes Pass

- In a frame where the lower plane is at rest, their left ends coincide first:



Testing Your Faith

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B is moving,
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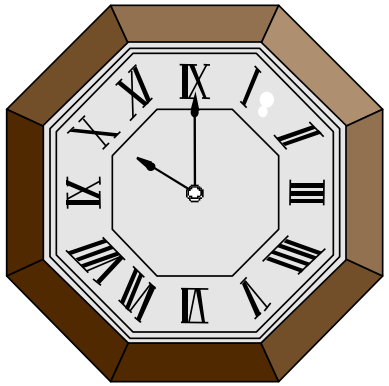
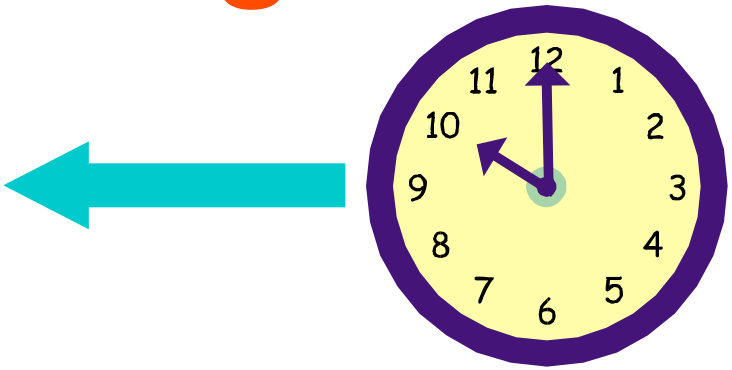


Clock A

Who's right?

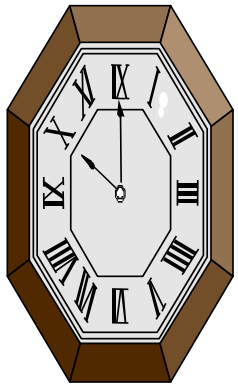
Both!



Clock B

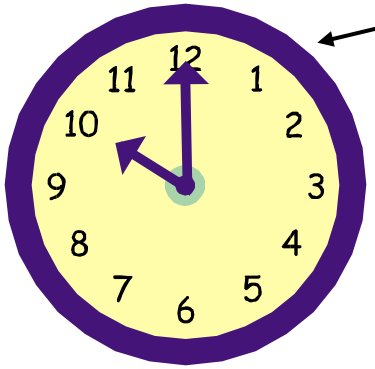
B: I'm at rest,
A is moving,
so A "runs slow"

The Situation in B's Frame of Reference

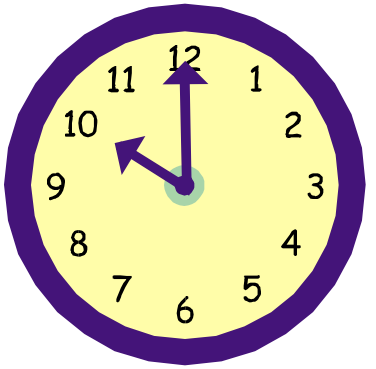


Clock A

B_1, B_2 are **synchronized**

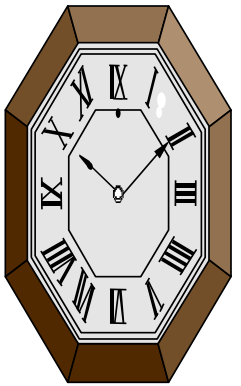


Clock B_1

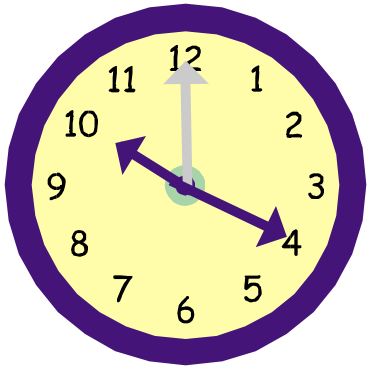


Clock B_2

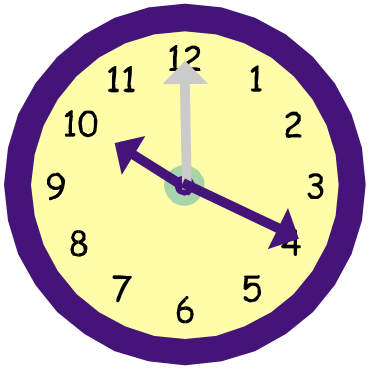
The Situation in B's Frame of Reference



Clock A

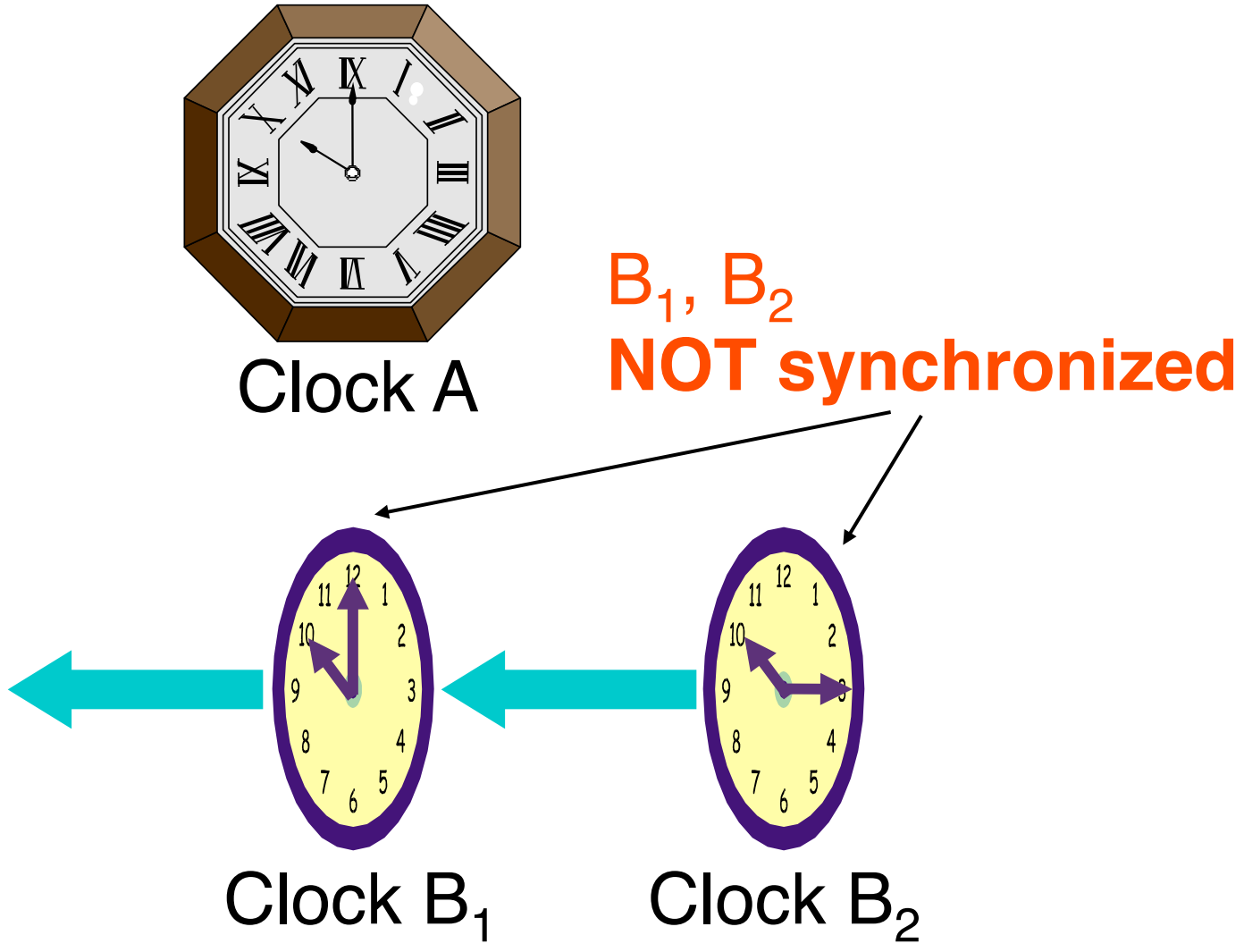


Clock B_1

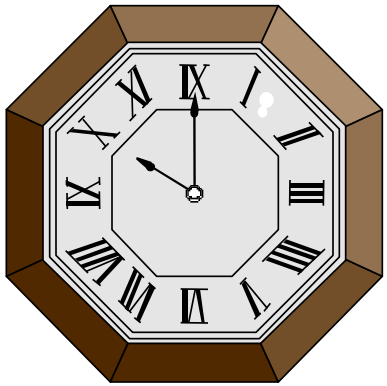


Clock B_2

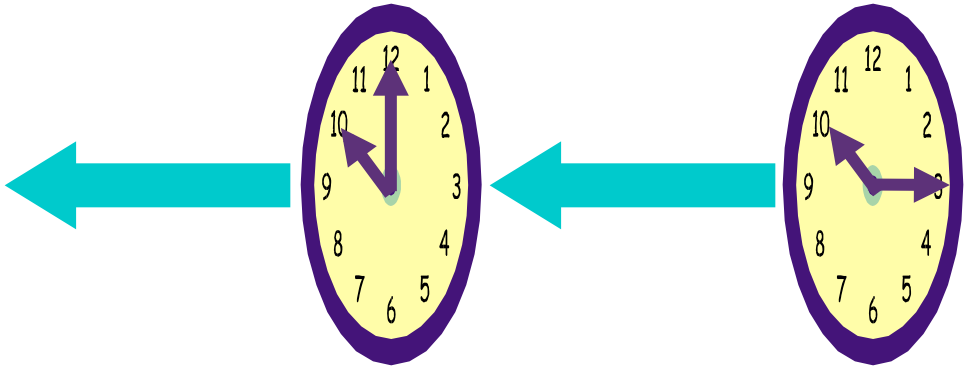
The Situation in A's Frame of Reference



The Situation in A's Frame of Reference

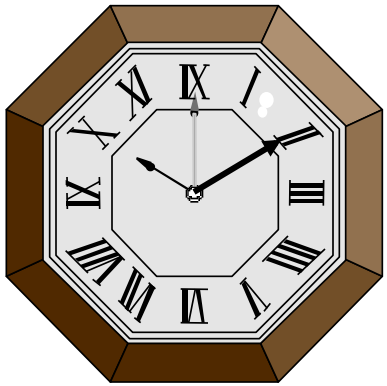


Clock A

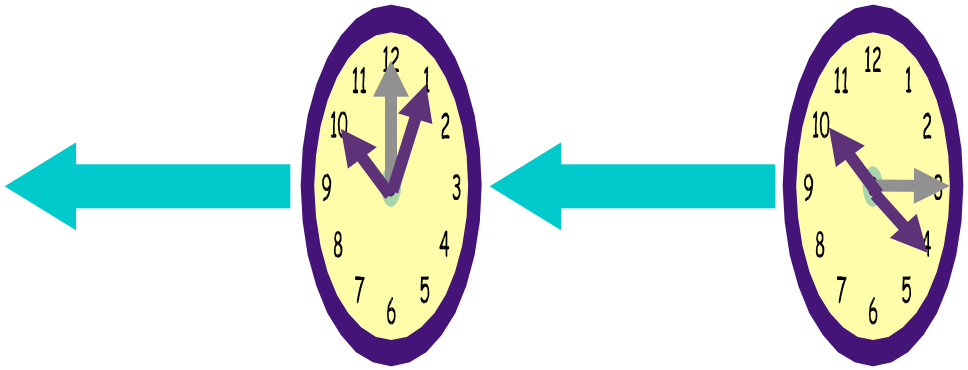


Clock B_1 Clock B_2

The Situation in A's Frame of Reference

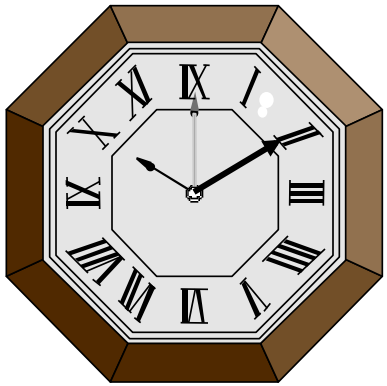


Clock A

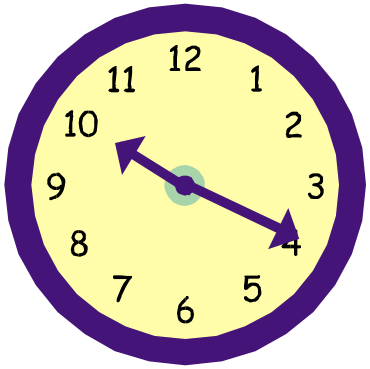


Clock B_1 Clock B_2

The End Result: Either Frame



Clock A



Clock B_2

When A and B_2 coincide:

Clock A reads 10:10
Clock B_2 reads 10:20

Different explanations:

B: Clock A is moving relative to me, so it "runs slow" and ends up reading less time than elapses on my two synchronized clocks

A: Because they're moving relative to me, both B clocks "run slow." But they aren't synchronized, and B_2 is ahead, so it ends up reading a later time than my A clock

No Contradiction!

- B: Clock A is moving, so A "runs slow"
- A: Clock B is moving, so B "runs slow"
- Why no contradiction?
  - Because simultaneity is relative!
- Relativity of simultaneity gets you out of most situations where relativity seems contradictory

That Famous Equation: $E=mc^2$

- Einstein, November 1905: "Does the Inertia of a Body Depend on Its Energy Content?"
  - Demonstrates interchangeability of mass and energy
  - Energy, like mass, exhibits inertia (hard to accelerate)
  - Therefore a body moving rapidly with respect to you has more inertia than when it's at rest—so it's harder to accelerate—and you can't get it to speed *c*
  - Is about every form of energy—not just nuclear energy!

General Relativity: A Quick Look

- *Special* relativity is restricted to *special* case of uniform motion

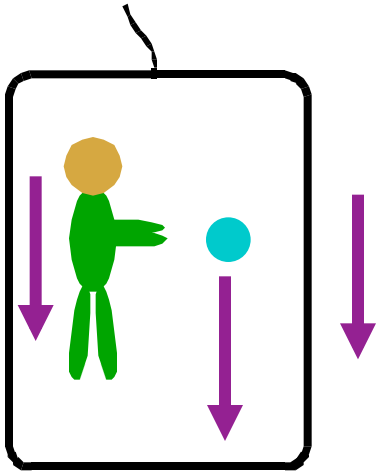
- Why should one's state of motion matter at all?
  - Why not "Laws of physics are the same for all frames of reference, period"?
- Problem with special relativity
  - How to be sure we're in uniform motion?
- Problems with Newtonian gravity
  - Newtonian gravitation is inconsistent with relativity because gravity force acts instantaneously over distance
  - Gravitational force depends on distance between objects. But when? And in whose reference frame?
- Problem with accelerated reference frames
  - Can't tell effect of acceleration from gravity

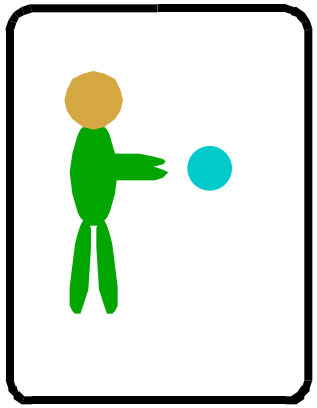
Einstein's "Happiest Thought" (1907)

Earth

Intergalactic Space

Free fall,
in gravity



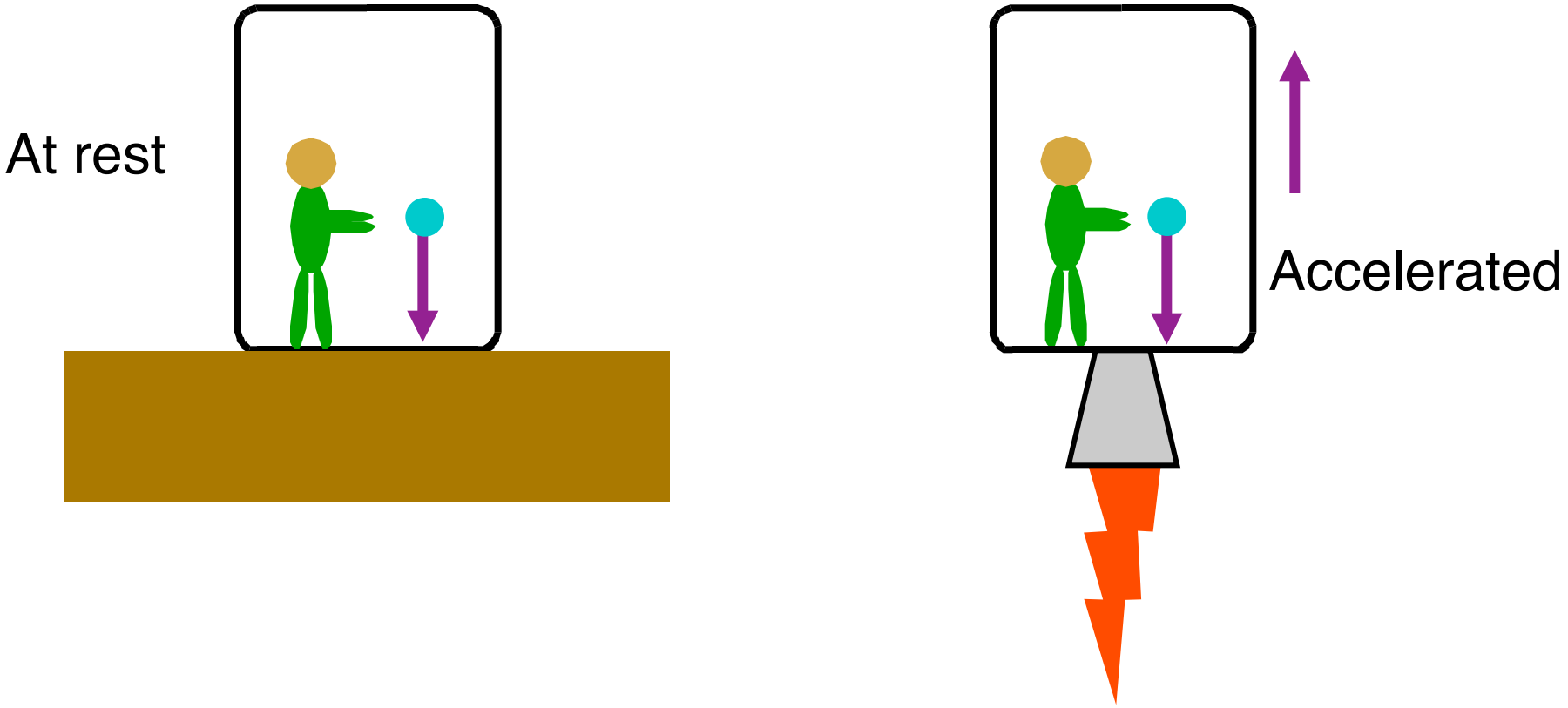


Uniform
motion,
no gravity

Einstein's "Happiest Thought" (1907)

Earth

Intergalactic Space



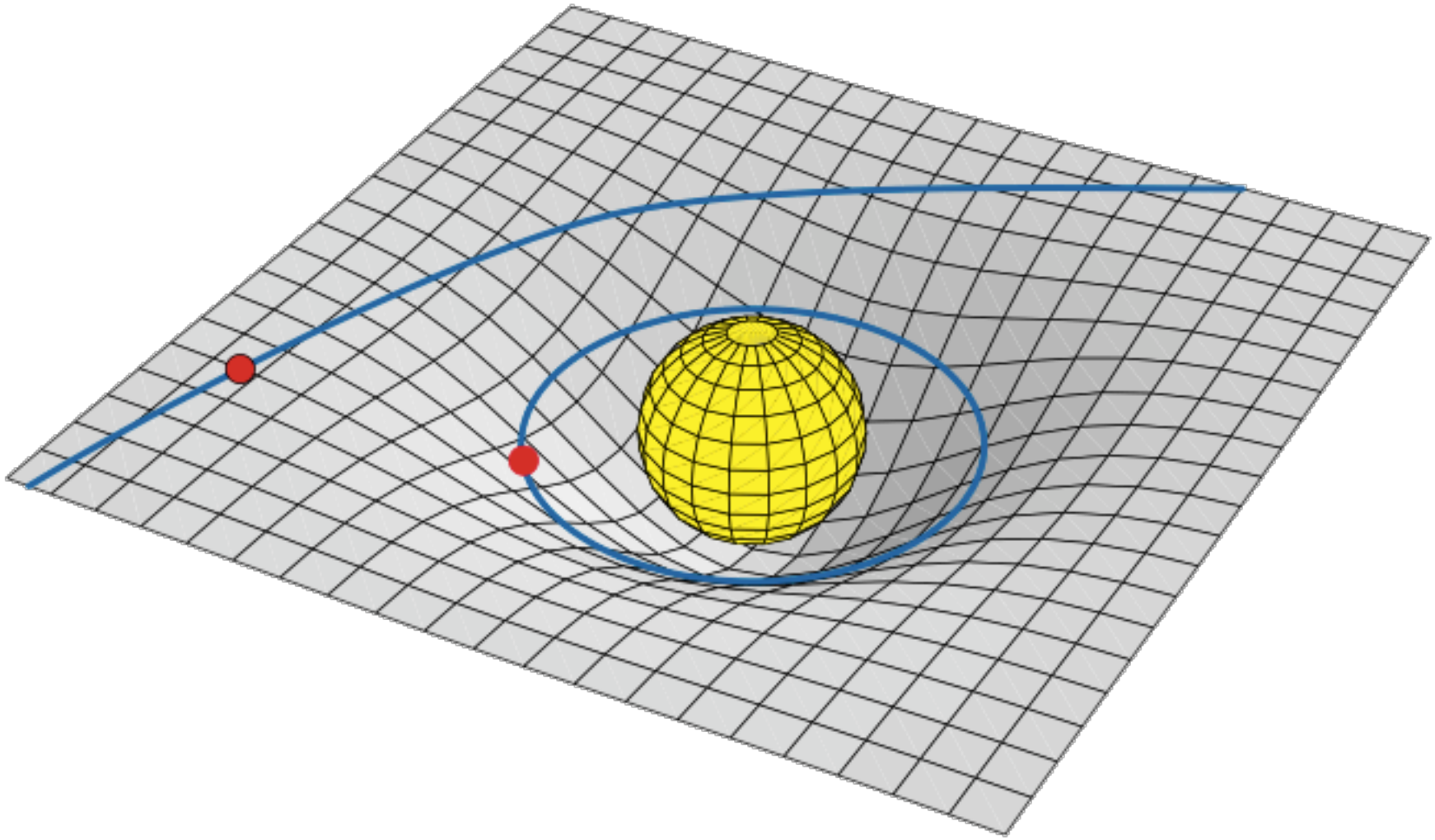
The Principle of Equivalence

- The effects of gravity and acceleration are indistinguishable
  - At least in a small enough region of spacetime

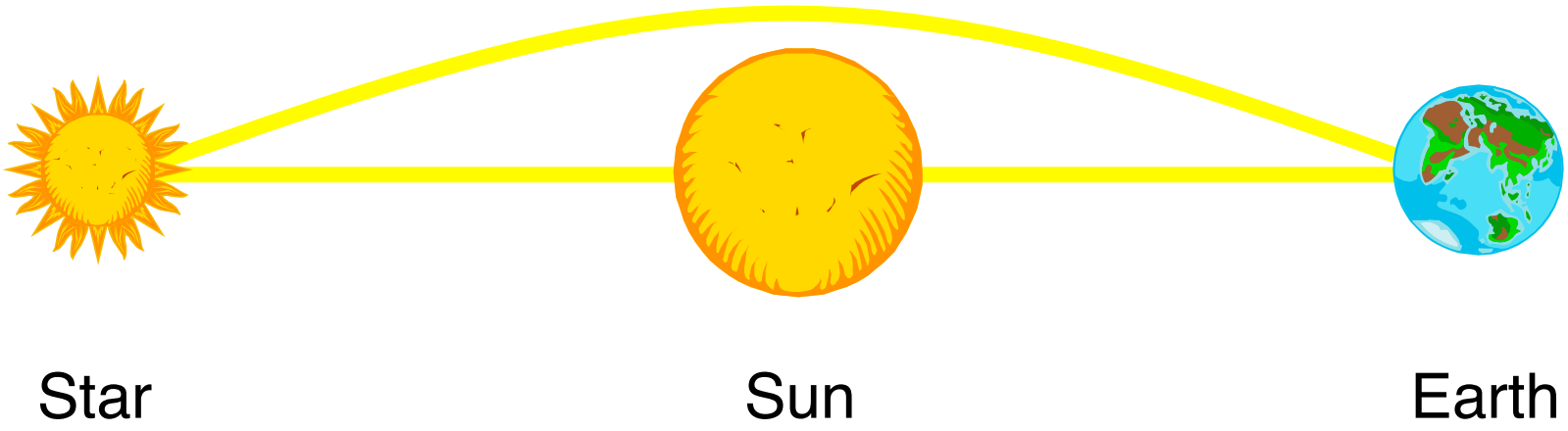
So What's Gravity?

- Not the "heaviness" you feel standing on Earth
  - That can't be real because it's not there in another reference frame (in free fall)
- Einstein: Gravity is the curvature of spacetime

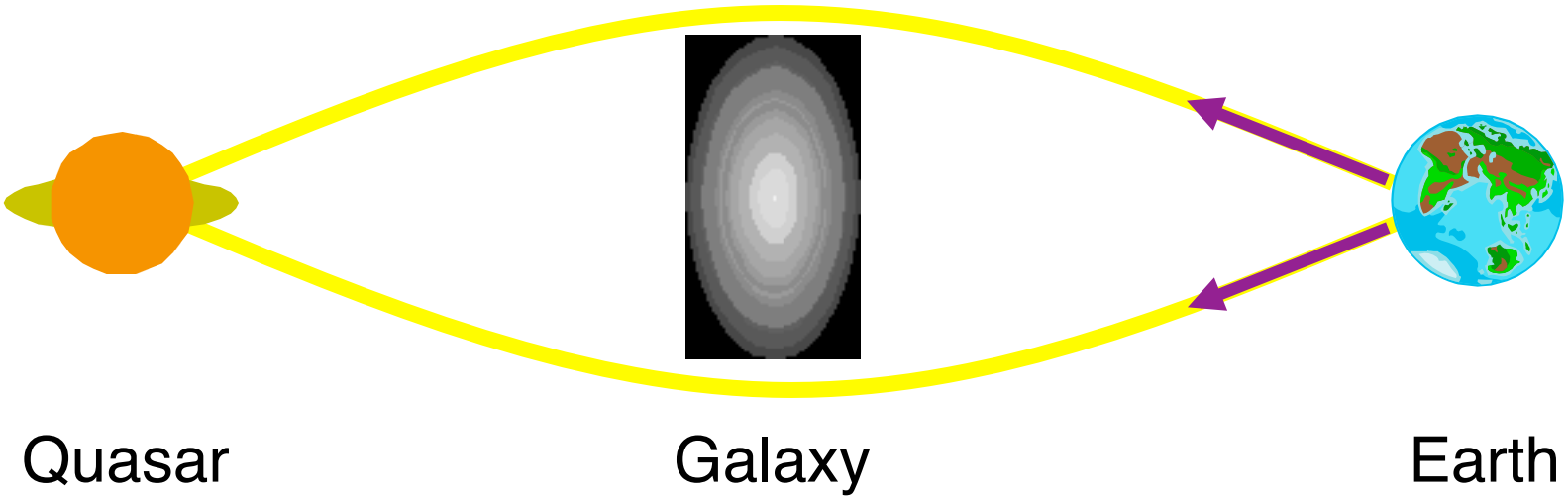
Gravity: Curved Spacetime



Bending of Light

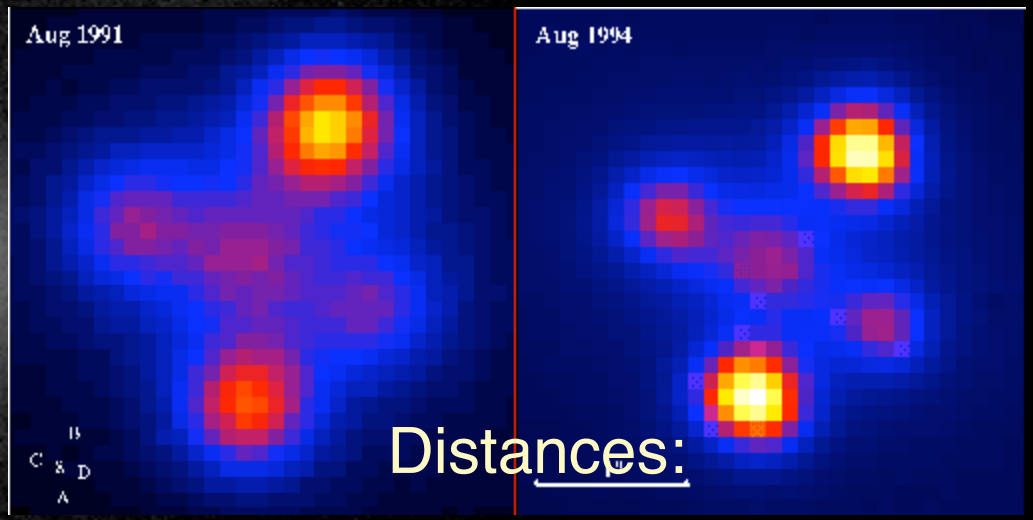


Gravitational Lenses



The Einstein Cross: A Gravitational Lens

Microlensing the Einstein Cross



Distances:

Hubble Space Telescope image from www.antwrp.gsfc.gov/apod/image/9612/eincross_wht.gif

galaxy: 500 million ly
quasar: 9 billion ly

Hubble Space Telescope image from www.astr.ua.edu/keel/agn/qso2237.htm

A Cosmic Lens

Einstein: Still With Us!

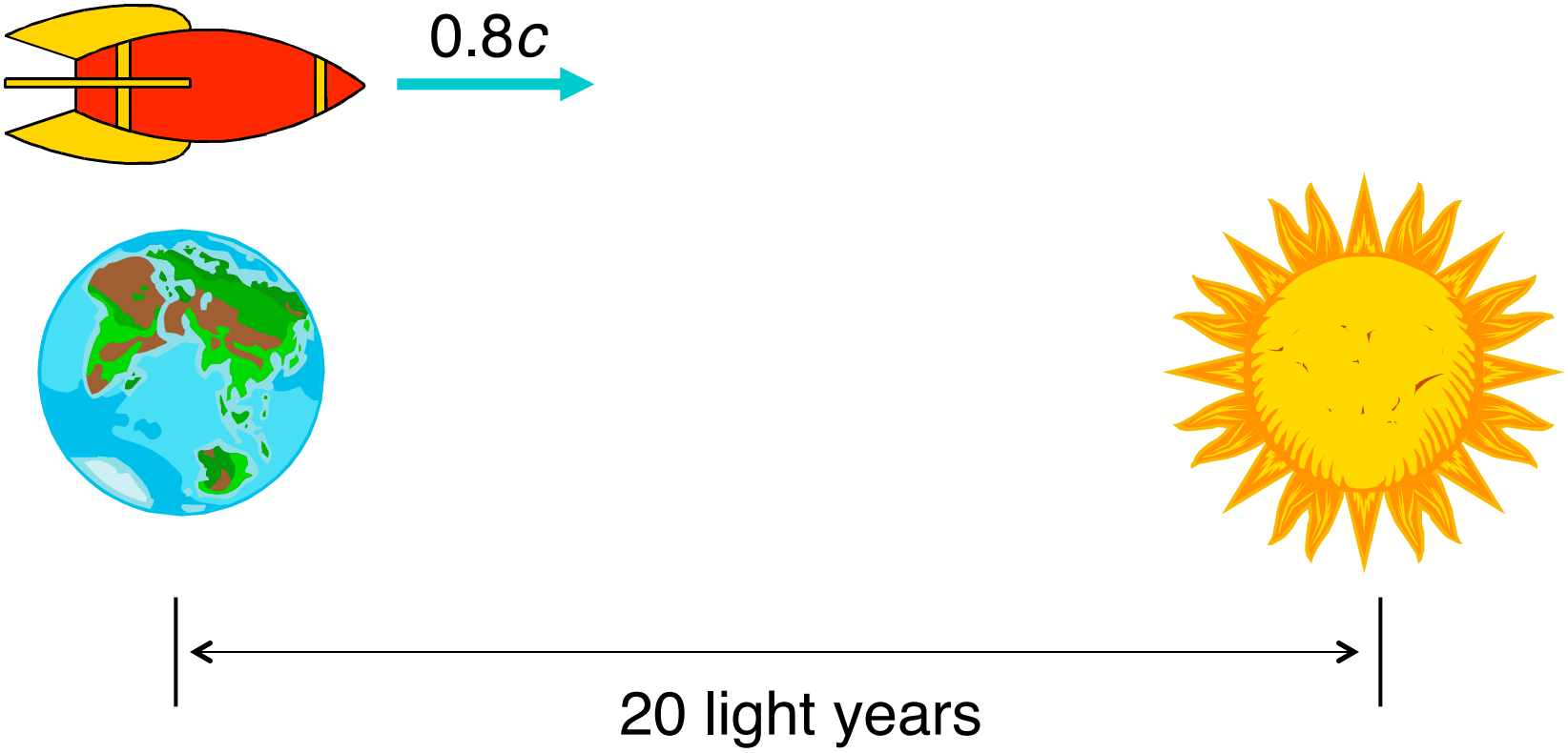
- Einstein, 1916
  - General relativity predicts the Universe must be expanding
  - Einstein (and everyone else): But it isn't
  - Einstein: Fudge the equations so it won't expand
- Hubble, 1920s
  - Observations prove: Universe is expanding!
  - Einstein: Cancel that fudge factor. "My greatest blunder"
- Astrophysicists, 1998
  - Expansion should be slowing
  - But observations show it's accelerating!
  - Bring back Einstein's fudge—"dark energy"

Final Exam

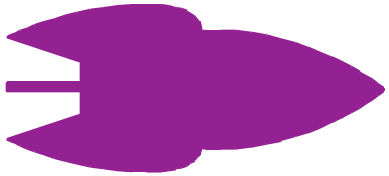
- What's the essence of relativity?
  a) Moving clocks run slow
  b) Space and time are relative
  c) Gravity warps spacetime
  d) $E = mc^2$
  e) The laws of physics are the same in all frames of reference

Bonus Material: The Twins Paradox

Star Trip!

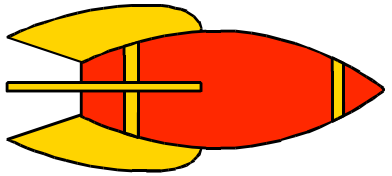


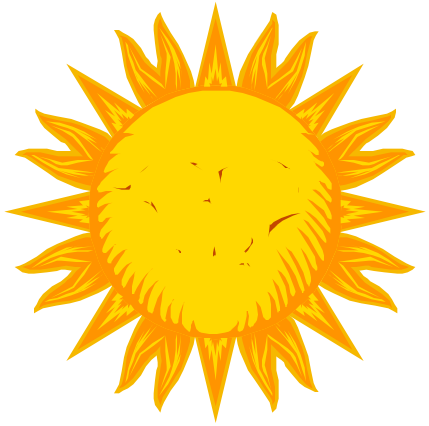
Star Trip!



0.8*c*

Ship time: 15 years

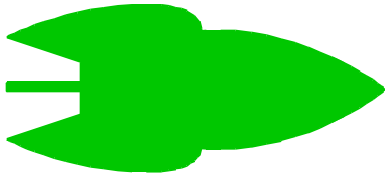




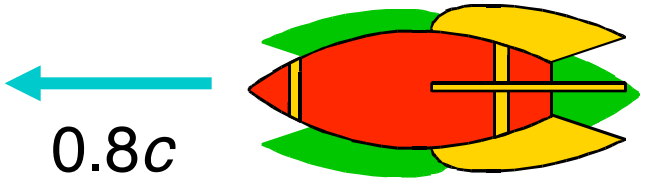
Earth/star time: 25 years

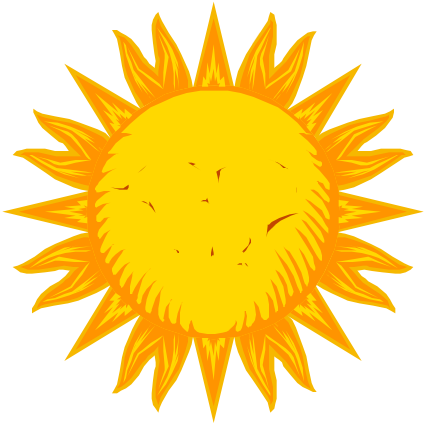
20 light years

Star Trip!



Ship time: 15 years



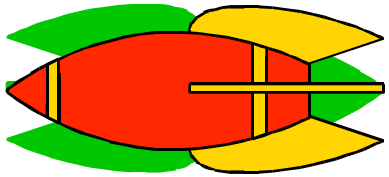


Earth/star time: 25 years

20 light years

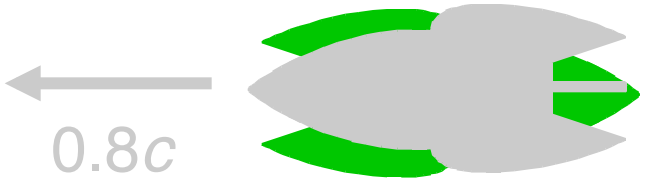
Star Trip!

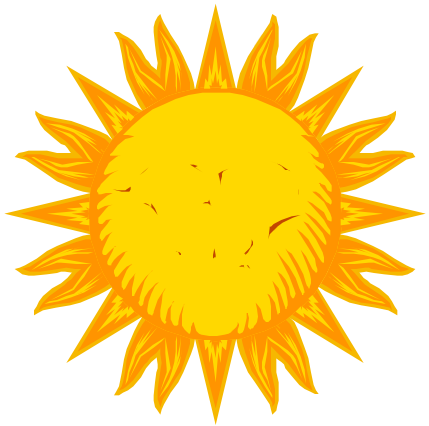
Ship time: 30 years



Earth/star time: 50 years

Ship time: 15 years



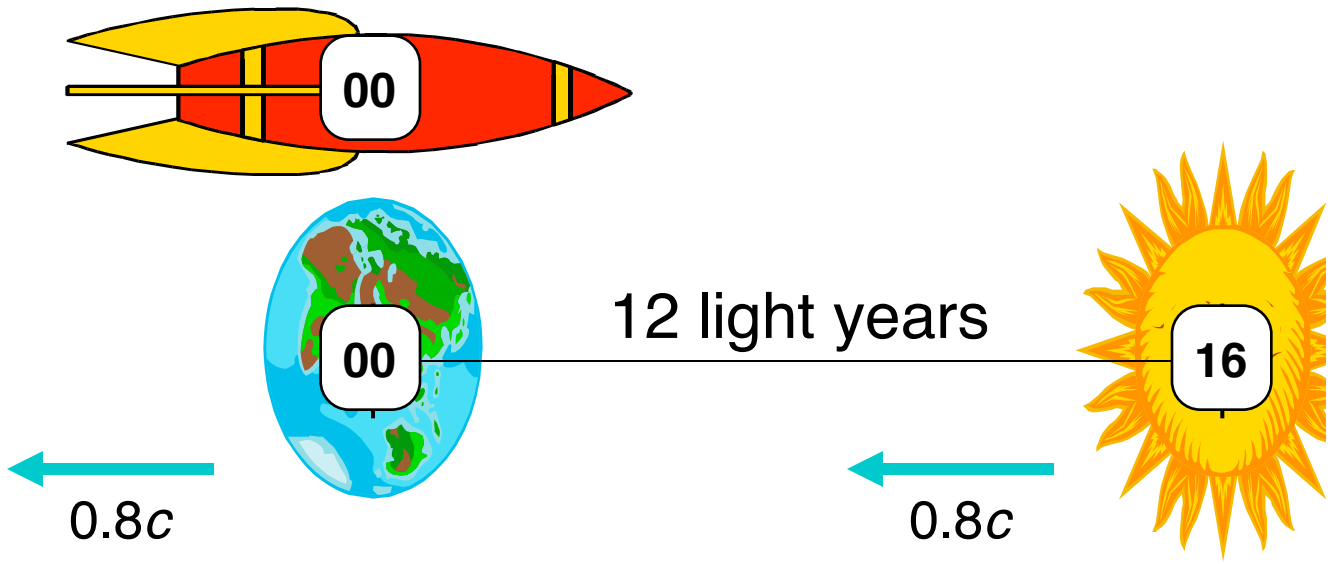


Earth/star time: 25 years

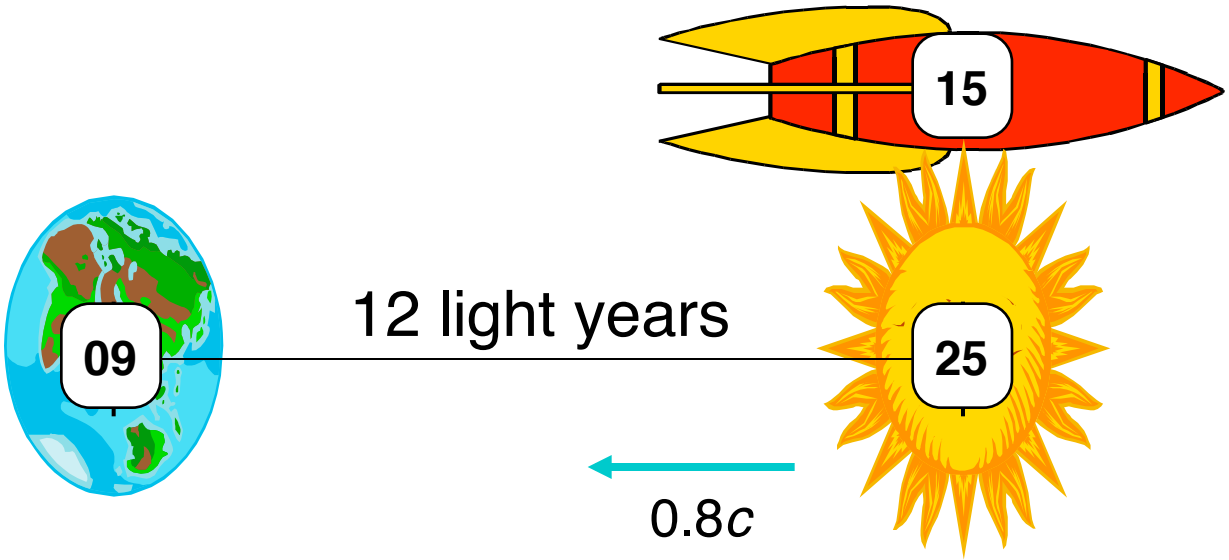
Simultaneity is Relative!

Events that are Simultaneous in One Frame of Reference are Not Simultaneous in Another Frame!

Star Trip, Outgoing, Ship Frame #1

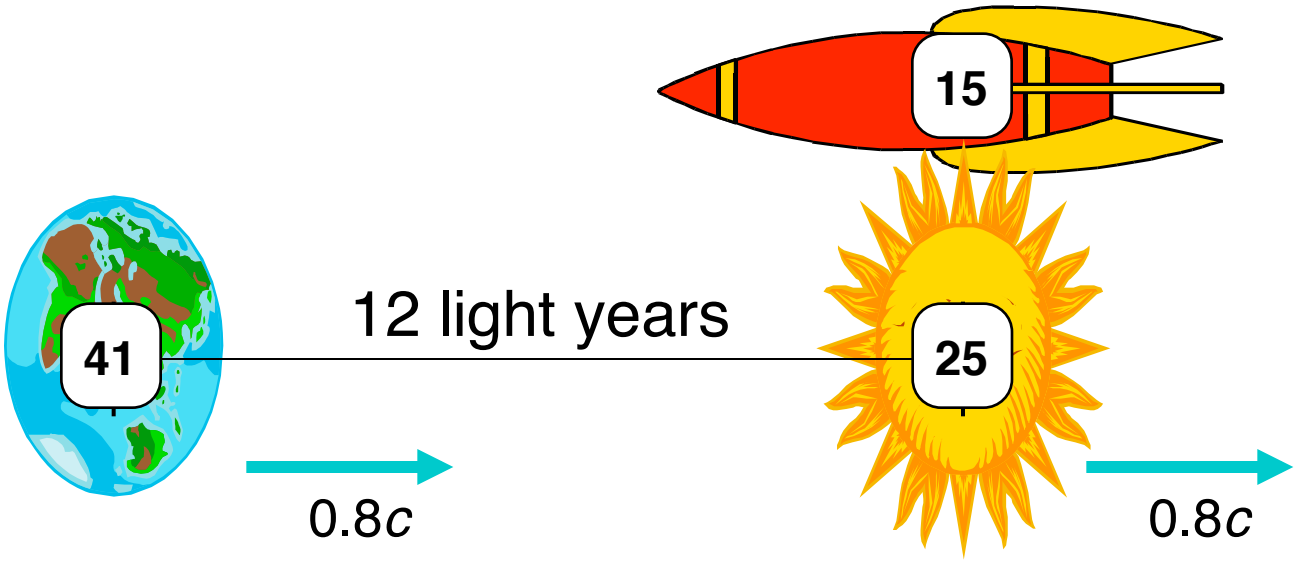


Star Trip, Arrival, Ship Frame #1

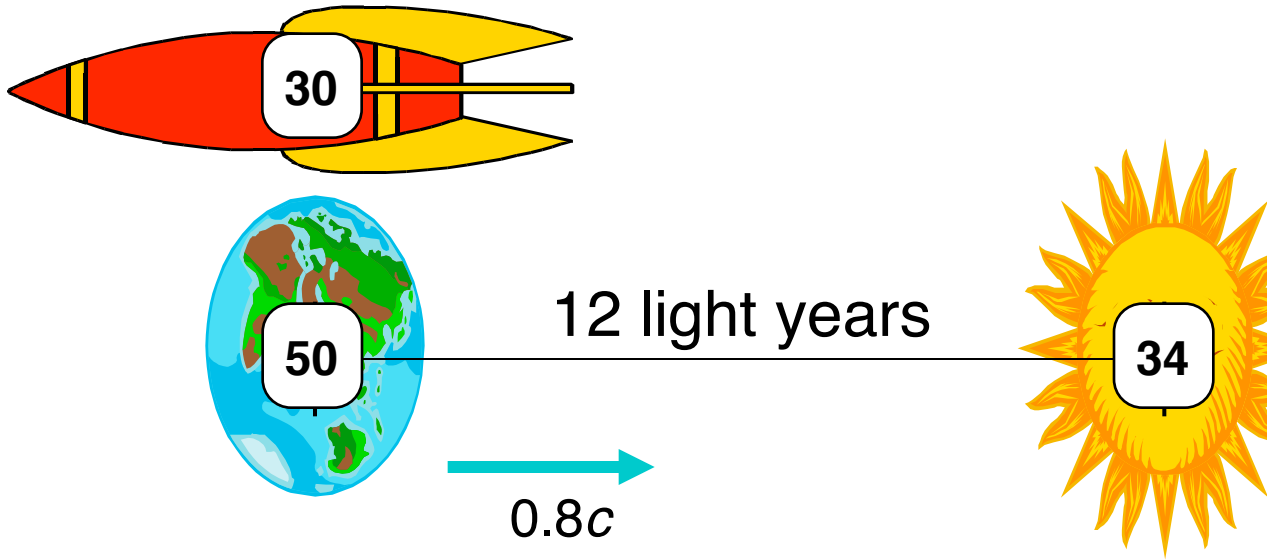


Star Trip, Return, Ship Frame #2

A different ship frame!



Star Trip, Home, Ship Frame #2



More on Relativity…