

## *Astronomy 150: Killer Skies*



This Class (Lecture 24):  
Consequences of Fast

Next Class:  
Death by Black Hole:  
Spaghettification

**HW9 due Monday**

**Night Obs due Friday.**

**Exam 2 next Friday!**

**Computer lab due on Nov 15<sup>th</sup>**

*Music: Where Gravity is Dead– Laura Veirs*

## *Outline*



- Einstein's Special Theory of Relativity
  - Speed of light is a constant, hilarity ensues
- Einstein's General Theory of Relativity
  - What is gravity?

## *Exam 2*

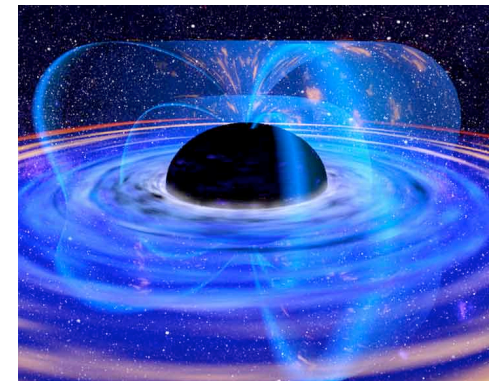


- Exam 2 in this classroom on Nov 5<sup>th</sup>
- 40 Multiple choice questions
- Will cover material from Lecture 12 to 25.
- May bring 1 sheet of paper with notes
  - Both sides
  - Printed/handwritten/whatever.. I don't really care
- Major resources are lecture notes, in-class questions, and homeworks
- Created and posted a study guide

## *Physics of Black Holes*



- Black holes are simple, yet strange objects
- Intense gravity due to compactness
- Newton's Laws cannot describe what happens in the nearby presence of such an intense gravitational field
- We need Einstein's *Theory of Relativity*



## We got a speed limit!



- No matter what we do, we can not go faster than the speed of light!
- That naturally occurs when one demands that the speed of light *must* be the same regardless of who measures it.
- This is completely counter-intuitive!
- Basis of Einstein's Theory of Special Relativity.



<http://www.rpi.edu/dept/phys/Dept2/APPhys1/optics/optics/node4.html>

## How Fast is Light?



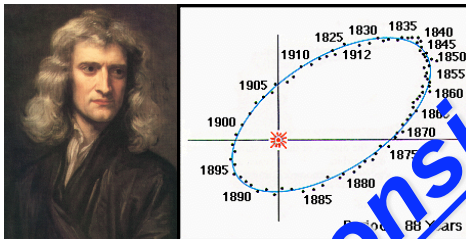
- The speed of light is  $c = 3 \times 10^8$  m/s (186,000 miles per second)!
- How fast is that?
  - Around the Earth over 7 times in a second
  - From Earth to the Moon in under 2 seconds (it took the astronauts 2 weeks)
  - From the Sun to the Earth in a little over 8 minutes
  - From the Sun to Pluto in about 5½ hours
  - From the nearest star to Earth, about 4 years



## Two Threads of Thought in Physics up to 1900



### Mechanics (Newton's Laws)



All motion is relative  
No speed is special

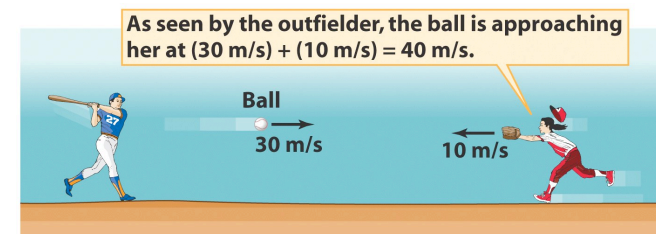
### Electromagnetism (Maxwell's Equations)



The speed of light is the **same** for all observers

**Inconsistent**

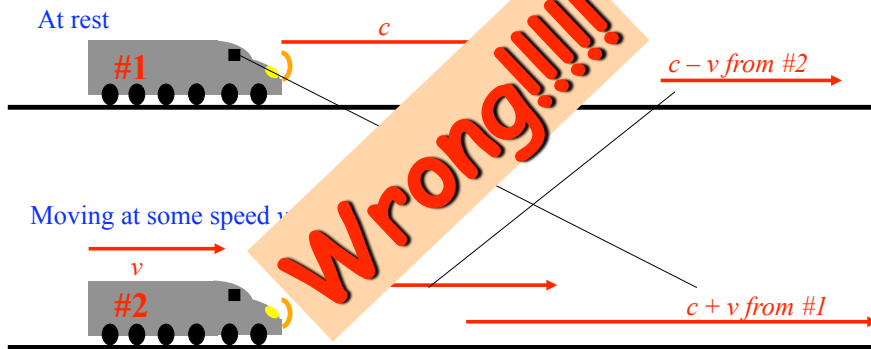
## Why Newton and Maxwell Can't Both Be Right



## Why Newton and Maxwell Can't Both Be Right



Consider two locomotives emitting light from their headlamps:



## Why Newton and Maxwell Can't Both Be Right



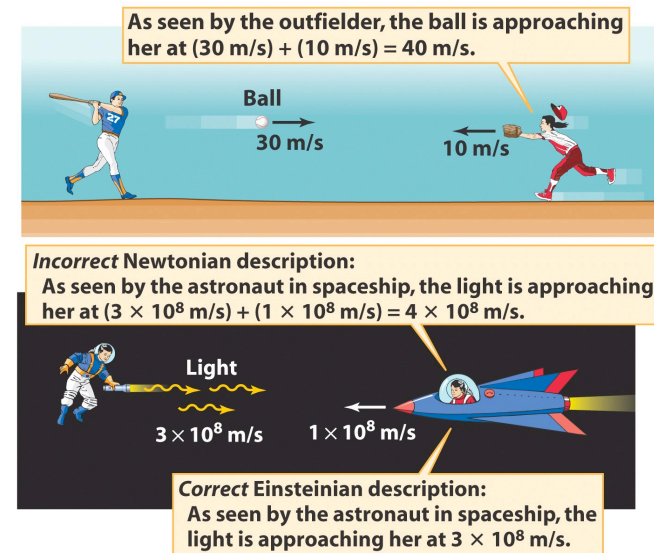
So the speed of light can't be the same for everyone if Newton – and our intuition – are right. But Maxwell says it is constant!

Something must happen. And what must happen for Newton and Maxwell to be both right, is that there is a modification of time and distance. Remember

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

Distance and time become relative to the observer.

## Why Newton and Maxwell Can't Both Be Right



## Question



You are at the back of a jet traveling at 400 mph. You shine a laser toward your friend in first class. What speed does your friend measure for the laser light?

- a)  $c + 400 \text{ mph}$
- b)  $c - 400 \text{ mph}$
- c)  $c$
- d)  $c/400 \text{ mph}$
- e)  $c/(c^2 - 400^2) \text{ mph}$

Where  $c$  is the speed of light.

## Approaching the “c”



- Time dilation – Moving clocks run slow.
- Length contraction – Moving objects contract along direction of motion.
- Mass increase – moving clocks get more massive



<http://www.richard-seaman.com/Travel/Japan/Hiroshima/AtomicBombMuseum/IndividualArtifacts/>

## Approaching the “c”: Impact



- The clocks on a ship accelerating to “c” would stop completely compared to someone at rest.
- The ship would appear to be infinitely thin in length along its direction of motion for someone at rest.
- The mass of an object as it approaches “c” becomes infinite for someone at rest.
  - So does its kinetic energy– requires more power.

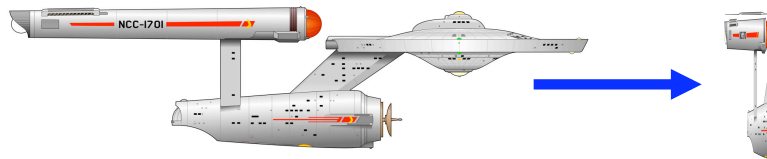


<http://www.richard-seaman.com/Travel/Japan/Hiroshima/AtomicBombMuseum/IndividualArtifacts/>

## Counterintuitive Result #1



**Moving objects appear shorter in the direction of relative motion**



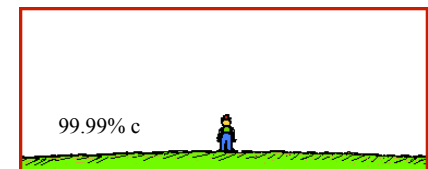
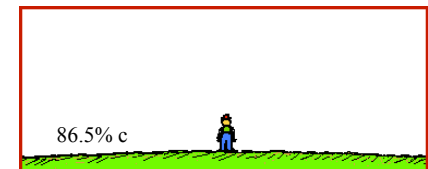
Fraction of the speed of light	% of original length
0.00	100%
0.001	99.99995%
0.01	99.995%
0.1	99.5%
0.5	86.6%
0.9	43.6%
0.99	14.1%



## Counterintuitive Result #1



**Moving objects are shorter in the direction of relative motion**

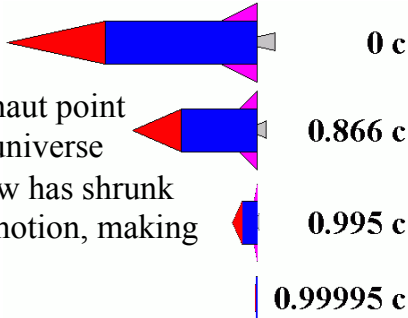


<http://www.physicsclassroom.com/mmedia/specrel/lc.html>

## Length Contraction



- This effect has some benefits:
  - Outside observers will measure that the length of the spaceship has shrunk.
    - This doesn't really help or harm us
  - But, from the astronaut point of view, the entire universe outside their window has shrunk in the direction of motion, making the trip shorter!
- It's all relative.



## Question



Your best friend is going on a near light speed trip. When at rest you measure her spaceship to be 100 feet long. Now, she's in flight and you're on the Earth, and she measures her spacecraft to be

- a) Exactly 100 feet long.
- b) Less than a 100 feet long.
- c) More than a 100 feet long.

## Question



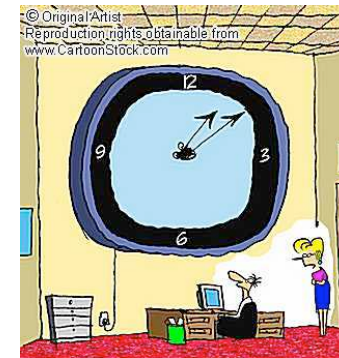
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## Counterintuitive Result #2



**Clocks on Moving objects slow down**



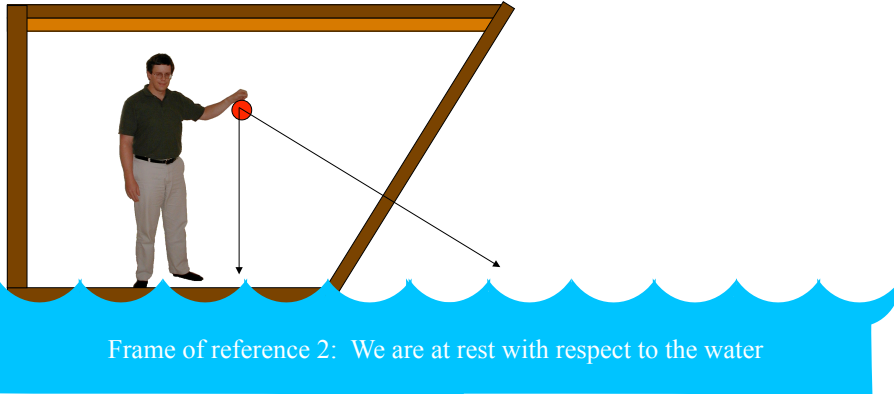
"Try not to watch the clock. It only makes the day go slower."

## Galileo's ship thought experiment



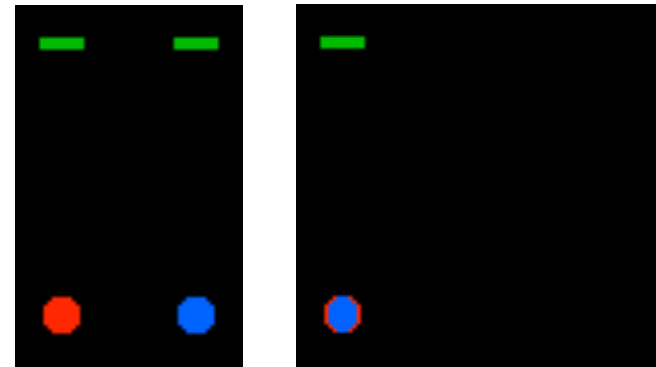
No experiment within the ship's cabin can detect the ship's motion if the ship moves in the same direction at a constant velocity. This is still true, even when considering the speed of light.

Frame of reference 1: We are moving with the ship



Frame of reference 2: We are at rest with respect to the water

## If the Ball is light?

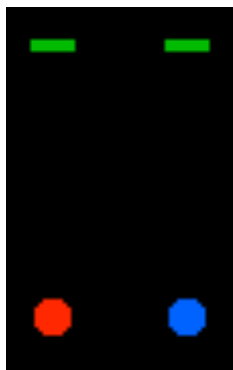


A. Hamilton (Colorado)

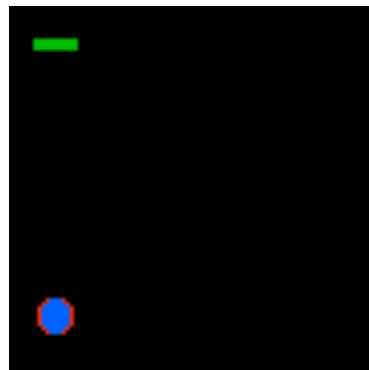
## Counterintuitive Result #2



**Time appears to advance more slowly for moving objects (time dilation)**



Red & blue at rest

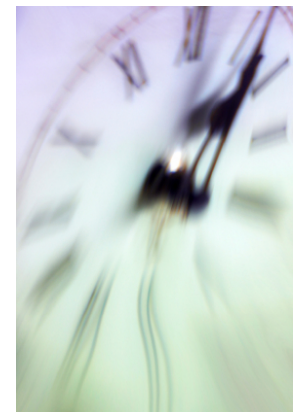


Blue moving to right

## Time Dilation



- The effects of time dilation are curious but not prohibitive for space travel
  - Astronauts will age less than the Earth-bound folks waiting for the return. Can spoil the homecoming celebrations.
  - The faster you go, the bigger difference between astronaut time and Earth time
- Example: Trip to the center of the Galaxy and back. Accelerate at 1g for the first half and decelerate for second half and you can go 30,000 ly in 20 years! But more than 30,000 years has elapsed on Earth!



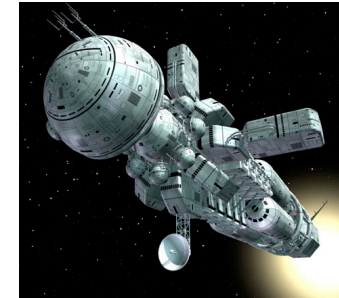
## Counterintuitive Result #3

### Mass increases for moving objects



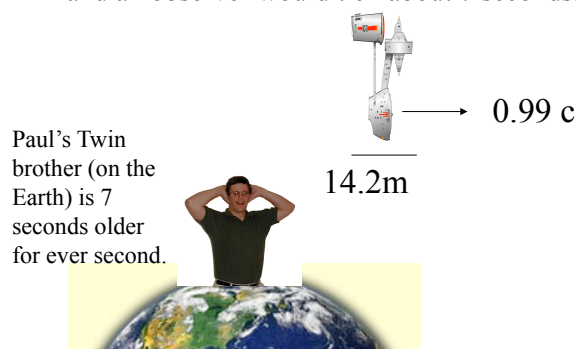
## Mass Increase

- The increase of effective mass (and kinetic energy) with velocity makes acceleration and deceleration more difficult if you intend to travel close to “c”
  - This translates to very costly starflight in terms of required energy.
  - And now the interstellar dust that you strike at relativistic speeds appear as larger mass.
  - For 99% speed of light travel, 5.5 meters of shield would erode every year.



## So, what does that mean?

- If you're on a 100m spaceship going near the speed of light ( $.99c$ ), the spaceship measures 100m long, but someone on the Earth would measure the spaceship to only be 14m long.
- As you speed by the Earth your clock would tick 1 second, and an observer would tick about 7 seconds.

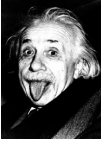


And Paul's measured mass increased by a factor of 7.

## Question

You are traveling near light speed. You see the Earth slide past your window. You notice that you left a clock (readable from space), and for every second that passes on the spacecraft

- Exactly 1 second passes on Earth.
- Less than a second passes on Earth.
- More than a second passes on Earth.



## Special Relativity Summary



**All motion is relative, except for that of light.  
Light travels at the same speed in all frames of  
reference.**

**Objects moving close to the speed of light appear to  
shrink in the direction of travel.**

**Time appears to advance more slowly for objects  
moving close to the speed of light.**

**Mass of the moving object appears to rapidly increase  
as an objects moves close to the speed of light.**

## Relativity



- We have talked about special relativity, where time and distance are actually relative to the observer.
- Of and by itself this is not so relevant to class except in the way it interfaces with general relativity.
- Now, we will talk about how some aspects depend on where you are relative to massive objects.

## Question



Okay, so length and time can change, then what exactly is a constant?

- a) The speed of light.
- b) The length of an iron pipe.
- c) The time it takes for a photon to cross the Universe.
- d) The speed of sound.
- e) The speed of a class.. it is always too slow.