## Lecture 20: Special \& General Relativity II

## Seeing the World

All information about the Universe is carried by light or things moving slower than light.

Speed of Light: $\mathrm{c}=299,792.458 \mathrm{~km} / \mathrm{sec}$
Compared to everyday scales:
$65 \mathrm{mph}=0.028 \mathrm{~km} / \mathrm{sec}=9.3 \times 10^{-8} \mathrm{c}$
light travels across this room in $\sim 30$ nanosec
Human Reflexes $\sim 0.1 \mathrm{sec}\left(\sim 10^{8}\right.$ nanosec $)$

## Relativity of Time

A Thought Experiment
Consider a simple photon clock:
Laser fires to a mirror 1.5 m away
Light bounces to a detector
Photon Path Length $=3$ meters
One "Tick" =Time of Flight
$=3$ meters $/ \mathrm{c}$
$=10^{-8}$ seconds

## Relativity with Dick \& Jane

Dick \& Jane fly past each other in rockets:
Constant Relative Speed $=0.8 \mathrm{c}$
They are carrying photon clocks
Each measures how long it takes between "ticks" of Jane's photon clock.
Why do they see?
When either Jane or Dick observes his or her own clock, the photon path is still 3 meters.

However, when Jane's clock is observed by Dick and compared with his own clock, it runs more slowly than his.

This is because the photon path for Jane's clock appears to be 5 meters long to Dick rather than 3 meters long.

## He Said, She Said...

Jane's Observations: Dick's Observations:
Jane's Speed $=0 \quad$ Jane's Speed $=0.8 \mathrm{c}$
Dick's Speed $=0.8 \mathrm{c} \quad$ Dick's Speed $=0$
Photon Speed $=\mathrm{c} \quad$ Photon $=\mathrm{c}$
Path Length $=3 \mathrm{~m} \quad$ Path Length $=5 \mathrm{~m}$
Tick $=3 / \mathrm{c}=10^{-8} \mathrm{~s} \quad$ Tick $=5 / \mathrm{c}=1.67 \times 10^{-8} \mathrm{~s}$
"My Clock Runs OK" "Your Clock Runs slow"

## Relative Time

This result is true for all kinds of clocks.
Conclusion: There is no absolute time
Time passes at different rates for observers moving relative to each other.
At speeds small compared to c , the difference is very small.
Verified experimentally using atomic clocks on airplanes and satellites.

## Muon Decay Times: Experimental Test of Special Relativity

Muons are created by energetic protons slamming into the top of the Earth's atmosphere and starting "particle showers."

Muon: a negatively charged particle, 207x the mass of an electron. Can cause mutation in cells. Half-life of 1.5 microseconds.

Newton's World
About 1 millisecond (=1000 microseconds) to travel through the Earth's atmosphere.

No muons would survive to reach Earth's surface.

## Einstein's World

Muons are traveling at speeds up to 0.99 c
They experience time more slowly than an observer on the ground According to them, it takes about 1 microsecond to reach the ground.
Lots survive.

## Consequences of Relativity

Observers moving relative to each other:
Do not measure the same times
Disagree on what events occur simultaneously
Do not measure the same lengths
Do not measure the same masses
Other Consequences
Mass and Energy are equivalent: $E=m c^{2}$
Massless particles must move at speed of light

## Spacetime

## Newton's View:

Space and time are separate and absolute.
Universe looks the same to all observers

## Einstein's View:

Space \& Time are relative
Spacetime is the same for all observers.
Only spacetime has an absolute reality independent of the observer.

## Extension: What the \&\%(@\#\%) is Spacetime?

Example:
You are on a spaceship moving close to the speed of light. You send out two pulses of light. From your perspective, the events are separated in time, but not in space.

However, to your friend at rest outside the spaceship, the events are separated in space (since you are moving) as well as time. Since "moving clocks run slow", your friend will think the interval between pulses is longer than you. When combined with the separation in space, you will both conclude that the separation was the same in spacetime.

## What about Gravity?

Special Relativity is restricted to uniformly moving (unaccelerated) observers.

But, objects are accelerated by gravity. (Newton: "They feel a gravitational force. ")

It took Einstein another 8 years to generalize relativity.
Led to a completely new theory of gravity.

