S2. Space and Time

Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.

Hermann Minkowski (1864 – 1909)
German physicist

Question 1

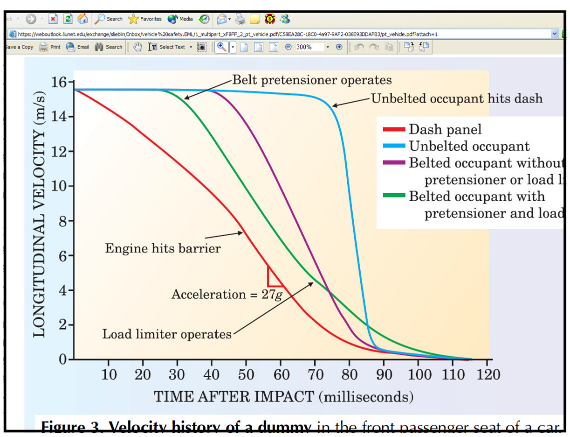
- What is relative in the special theory of relativity?
  1. Energy
  2. Motion
  3. Everything
  4. light

Question 2

- You sit in your lawn chair and watch Jackie fly by at a speed of 0.9c. Time dilation occurs in this case which means that
  1. Your watch stops as watch Jackie fly by.
  2. You observe your "second hand" move more slowly than Jackie's.
  3. You observe Jackie's "second hand" move more slowly than yours.
  4. You observe Jackie's aircraft looking longer than it really is.

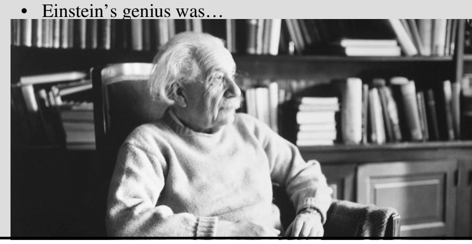
Agenda

- Expect 1 or 2 observations and possible field trip (as labs)
- Car crashes
- Discuss projects
- Special Relativity
- Lab 2



Relativity

- Relativity existed before Einstein—Galilean relativity
- Pre-Einstein, there were problems
  - No one could find any changes to the speed of light
  - No one could find evidence for a medium in which light would "wave"
- Einstein's genius was…



S2.1 Einstein's Revolution

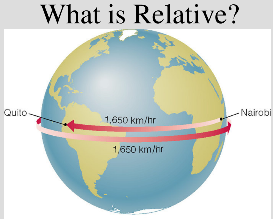
Our goals for learning:

- What is "relative" about the theory of relativity?
- What is absolute according to the theory of relativity?
- How are paradoxes useful to understanding relativity?

The Theory of Relativity

- Albert Einstein surprised the world in 1905 when…
  - he theorized that time and distance can not be measured absolutely
  - they only have meaning when they are measured relative to *something*
- Einstein published his theory in two steps:
  - **special theory of relativity** (1905)…how space & time are interwoven
  - **general theory of relativity** (1915)…effects of gravity on space & time
- What is "relative" in relativity?
  - motion…all motion is relative
  - measurements of motion (and space & time) make no sense unless we are told what they are being measured relative to
- What is absolute in relativity?
  - the laws of nature are the same for everyone
  - the speed of light (in a vacuum), c, is the same for everyone

What is Relative?



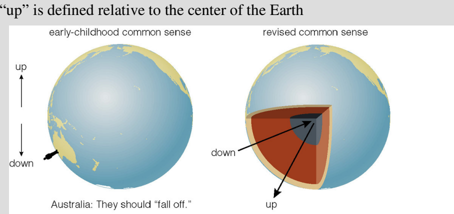
- A plane flies from Nairobi to Quito at 1,650 km/hr.
- The Earth rotates at the equator at 1,650 km/hr.
- An observer…
  - on the Earth's surface sees the plane fly westward overhead
  - at a far distance sees the plane stand still and the Earth rotate underneath it

A Good Paradox

- Paradox…is a situation that seems to violate common sense or contradict itself.
  - the paradox is resolved when the rules of nature are better understood
- Ideas & consequences of relativity are not evident in everyday life.
  - we do not experience the <u>extreme</u> speeds & gravity required
  - so we have no *common* sense about relativity

The "Up" Paradox

- In childhood, we regard "up" as a single direction above our head.
- When we realize that people in Australia do not stand upside-down…
  - we revise our common sense
  - "up" is defined relative to the center of the Earth



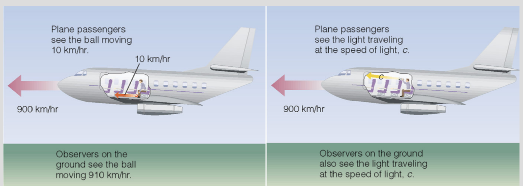
S2.2 Relative Motion

Our goals for learning:

- What do we mean by a reference frame in relativity?
- Why can't you reach the speed of light?

Reference Frames

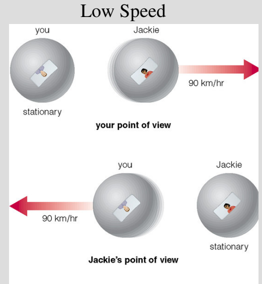
- Two or more objects which do not move relative to each other share the same reference frame.
  - they experience time and measure distance & mass in the same way
- Objects moving relative to the other are in different reference frames.
  - like the plane and ground below
  - they experience time and measure distance & mass in different ways



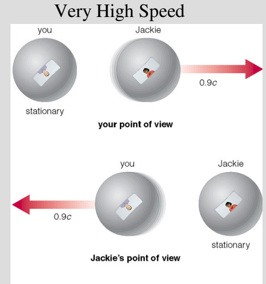
- Since ground observers see light move at c, the plane passenger is always slower.

Thought Experiments

Low Speed

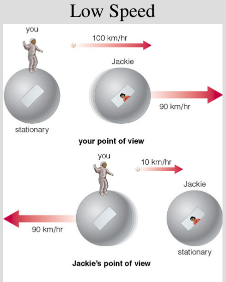


Very High Speed

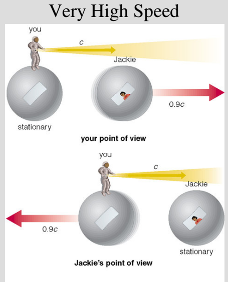


Thought Experiments

Low Speed



Very High Speed



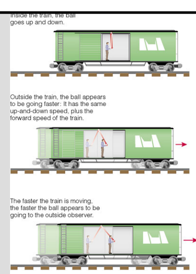
S2.3 The Reality of Space and Time

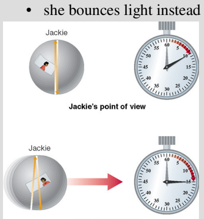
Our goals for learning:

- How are time, space, and mass different for a moving object than for an object at rest?
- Will observers in different reference frames agree when events happen at the same time?

Time Dilation

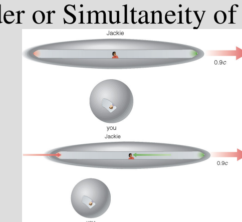
- To an observer outside the train, the ball appears to move faster.
  - makes *common sense*
- Now lets consider Jackie moving at close to the speed of light .
  - she bounces light instead of a ball





- The outside observer can **not** see the light moving faster than c.
  - yet the light <u>does</u> travel a longer distance as seen by the observer
  - so time <u>must</u> run more slowly for Jackie!

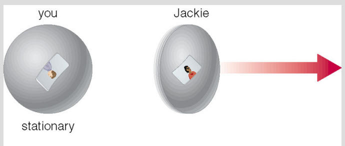
Order or Simultaneity of Events



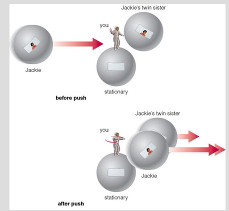
- The red & green flashes occur simultaneously for you.
  - Jackie's fast motion causes the green light to reach her first
  - you both agree on that
- But Jackie considers herself stationary in her reference frame.
  - she sees both lights travel the same distance at velocity c
  - yet she sees the green light first
  - so the green flash occurs before the red flash in her reference frame

Length Contraction

- As Jackie moves past you at high velocity…
  - she tries to measure the diameter of your ship
  - but time moves more slowly for her
  - so she measures a shorter length than you do (distance = velocity x time)
- Objects appear shorter to you in the direction which they are moving.



Mass Increase



- As Jackie moves by at high speed, you give both her & her identical sister a push.
  - time runs more slowly for Jackie, so she feels the push for a shorter time
  - Jackie accelerates less than her sister does
  - Newton's 2nd Law (F = ma) says if F is same, Jackie's mass must be greater
- Objects moving by you have a greater mass than when at rest.

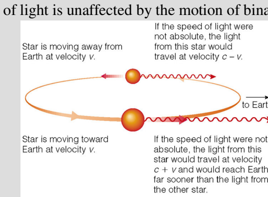
S2.4 Is it True?

Our goals for learning:

- How have experiments and observations verified that the speed of light is always the same?
- How have experiments verified other predictions of the special theory of relativity?

Is the Speed of Light Absolute?

- The speed of light was first measured by Olaus Roemer in 1675.
- Experimental evidence for the absoluteness of c came in 1887.
  - the **Michelson-Morley experiment**
  - A.A. Michelson & E.W. Morley used an interferometer to show that the speed of light is not affected by the Earth's motion around the Sun
  - the speed of light is unaffected by the motion of binary stars



Is the Speed of Light Absolute?

- Other tests of the special theory of relativity:
  - subatomic particles have been accelerated to speeds of 0.9999 c
  - no matter how much energy we put in, they never reach c
  - the π^+ meson particle decays in 18 nsec when at rest
  - at high velocities, it lasts longer…proving time dilation
  - the equation $E = mc^2$, exemplified by nuclear reactors and bombs, is a direct consequence of special relativity

S2.5 Toward a New Common Sense

Our goals for learning:

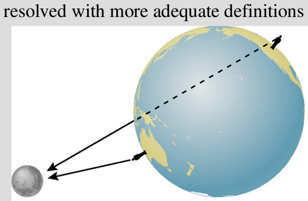
- If you observe time running slow in a spaceship moving by you at high speed, how do passengers in the spaceship view your time?

New Common Sense…It's All Relative!

- As Jackie moves by you at close to the speed of light…
  - you will see her time run slower, her length contract, and her mass increase
- But what does Jackie see?
  - she is stationary; she sees *you* moving by at high speed
  - since the laws of nature are the same for everyone
  - she sees *your* time run slower, *your* length contract, and *your* mass increase

New Common Sense…It's All Relative!

- How can both perceptions be correct?
  - just as an Australian can see the Moon "up" in the sky while simultaneously an American does not
  - a correct definition of "up" will resolve the dispute
  - the dispute between Jackie's and your perceptions of each other can be resolved with more adequate definitions of time & space



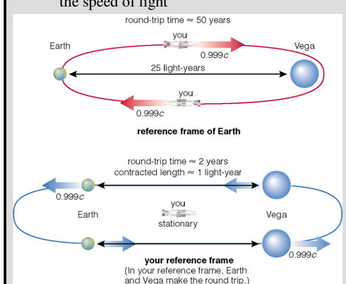
S2.6 Ticket to the Stars

Our goals for learning:

- How does special relativity offer us a ticket to the stars?

Ticket to the Stars

- Although we can not travel faster than the speed of light…
  - special relativity will make the journey seem shorter <u>if</u> we can travel close to the speed of light



- Time moves more slowly for the space traveler.
- The distance to be covered is contracted.
- Space travelers can reach distant stars in their lifetimes.
- Their friends and family will not be there to greet them when they return home to Earth.

What have we learned?

- What is "relative" about the theory of relativity?
  - The theory is based on the idea that all *motion* is relative. That is, there is no correct answer to the question of who or what is really moving in the universe, so motion can be described only for one object relative to another.
- What is absolute according to the theory of relativity?
  - (1) The laws of nature are the same for everyone, and (2) the speed of light is the same for everyone.
- How are paradoxes useful to understanding relativity?
  - Because paradoxes *seem* to violate common sense or to be self-contradictory, many of the ideas of relativity can best be understood by confronting the paradoxes and finding their underlying resolutions.

What have we learned?

- What do we mean by a reference frame in relativity?
  - Two (or more) objects share the same reference frame if they are *not* moving relative to each other. In that case, the objects will experience the passage of time and measurements of distance and mass in the same way. Time, distance, and mass will be different for objects in different reference frames.
- Why can't you reach the speed of light?
  - Light always travels at the same speed, so your own light (light that you emit or reflect) is always moving ahead of you at the speed of light. All other observers will also see your light moving at the speed of light— and because it is moving ahead of you, the observers will always conclude that you are moving slower than the speed of light.

What have we learned?

- How are time, space, and mass different for a moving object than for an object at rest?
  - If you observe an object moving by you at high speed, you'll find that its time is running slower than yours, its length is shorter than its length when at rest, and its mass is greater than its mass when at rest.
- Will observers in different reference frames agree when events happen at the same time?
  - They will not agree unless both events also occur in the same place. In general, when an observer in one reference frame sees two events happen simultaneously, observers in other reference frames will claim that one event preceded the other.

What have we learned?

- How have experiments and observations verified that the speed of light is always the same?
  - The Michelson-Morley experiment showed that the speed of light is not affected by the motion of Earth around the Sun. Observations of binary star systems also confirm that the speed of light is unaffected by motion, because otherwise we would not see the two stars in binary systems as distinct points of light.

What have we learned?

- How have experiments verified other predictions of the special theory of relativity?
  - Experiments in particle accelerators can measure how time and mass are affected for subatomic particles moving at speeds very close to the speed of light. The results are in perfect agreement with the predictions of the theory. The predictions have also been verified at relatively low speeds in aircraft and spacecraft. Nuclear power plants and nuclear bombs release energy in accord with the formula $E=mc^2$, which is also a prediction of special relativity.

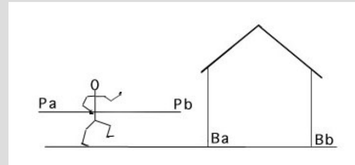
What have we learned?

- If you observe time running slow in a spaceship moving by you at high speed, how do passengers in the spaceship view your time?
  - They view your time as running slow. Because you both are experiencing the same laws of nature and your motion is relative, you must each see the same effects on the other.

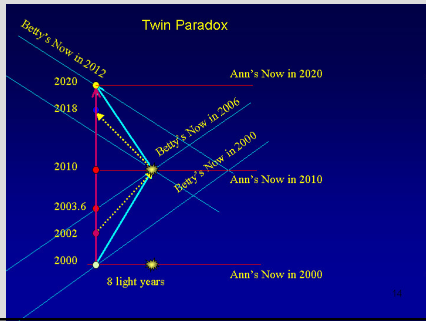
What have we learned?

- How does special relativity offer us a ticket to the stars?
  - Although the theory tells us that journeys to the stars will always take many years from the point of view of Earth, it also tells us that time for passengers will be much shorter if they travel at speeds close enough to the speed of light. Thus, the passengers may be able to make very distant journeys within their lifetimes, even though their friends back on Earth will not be there to greet them when they return.

The Barn Paradox



The Twin Paradox



Einstein's Genius

- Too easy to look back and say "Hey, this is complicated stuff, but it makes sense since that's what the experiments were telling us"
- He disposed of the idea of an absolute time!
- He disposed of the idea that light needs something in which to wave.
- He's the ideal theorist…accept experiment, and go from there!

Lab 2

- How can we measure the changes in location of the Sun through the seasons?