From Last Time

- Light:
  - Made from changing electric and fields
  - A wave with all the typical wave properties

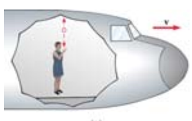
Modern Physics: Relativity

- Physics changed drastically in the early 1900's
- **Relativity one of the new discoveries**
  - Changed the way we think about space and time
  - Relativistic effects seen with very fast moving objects and very massive objects. Astronomical objects

Galilean relativity

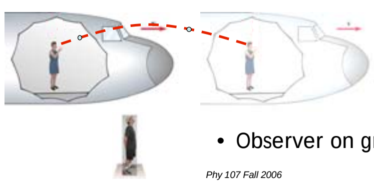
- Absolute velocity not clear, but we can seemingly agree on relative velocities.
  - In all cases the ball moves 40 mph faster than I do.
- Examples of two different reference frames
  - *On the bus*
  - *Off the bus*
- *In both cases we could talk about*
  - *the forces I put on the ball,*
  - *the acceleration of the ball, etc*

Example of Galilean relativity



- Observer in plane

- *Experiment may look different to different observers, but both agree that Newton's laws hold*
  - Can make observations agree by incorporating relative velocities of frames.

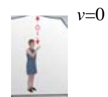


- Observer on ground

Galilean relativity: example

- *Experiment performed…*
  - in laboratory at rest with respect to earth's surface
  - in airplane moving at constant velocity

  …must give the same result.



- In both cases, ball is observed to rise up and return to thrower's hand
  - Process measured to take same time in both experiments
  - Newton's laws can be used to calculate motion in both.

Newton's laws in moving frames

- In both cases,
  the acceleration of the ball is the same.
- This is because the two reference frames move at a constant relative velocity.
- Newton's laws hold for each observer.
- Which is good, because we apparently can't determine our absolute velocity,
  or even if we are moving at all!

This is an example of *Galilean Relativity*

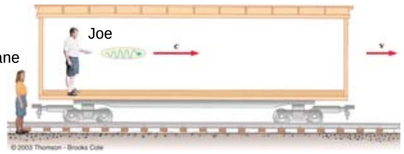
Turning this around…

- No experiment using the laws of mechanics can determine if a frame of reference is moving at zero velocity or at a constant velocity.
- Concept of *absolute motion* is not meaningful.
  - *There is no 'preferred' reference frame*

Inertial Frame:
reference frame moving in straight line with constant speed.

What about electromagnetism?

- Maxwell equations say that
  - Light moves at constant speed $c=3\times10^8$ m/sec in vacuum
- Seems at odds with Galilean relativity:



- Jane would expect to see light pulse propagate at $c+v$
- But Maxwell says it should propagate at c, if physics is same in all inertial reference frames.
- If it is different for *Joe* and *Jane*, then in which frame is it c?

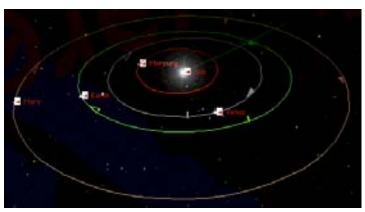
The Ether

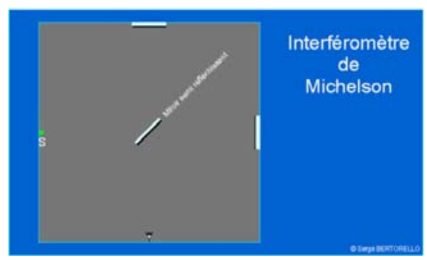
- To resolve this, 19th century researchers postulated existence of medium in which light propagates, rather than vacuum.
  - *i.e. similar to gas in which sound waves propagate or water in which water waves propagate.*
- Then Maxwell's equations hold in the ether

Pluses	*Minuses*
Allows speed of light to be different in different frames (Maxwell's eqns hold in frame at rest with respect to ether).	Ether must be rigid, massless medium, with no effect on planetary motion
Light then becomes like other classical waves,	No experimental measurement has ever detected presence of ether
Ether is absolute reference frame.	

The Michelson-Morley experiment

- If the earth moves thru a medium in which light moves at speed c, along the direction of the earth's motion, light should appear from earth to move more slowly.





- Ether wind would change average speed of light on the different paths.
- Waves will interfere when they recombine.

Einstein's principle of relativity

- **Principle of relativity:**
  - *All* the laws of physics are identical in all inertial reference frames.
- **Constancy of speed of light**:
  - Speed of light is same in all inertial frames (*e.g.* independent of velocity of observer, velocity of source emitting light)

(These two postulates are the basis of the special theory of relativity)

Simultaneity with sound

- Suppose you hear two loud shots about 1/2 second apart.
- Did they occur at the same time?

- Let's think about it
- Suppose you find out one of the shots was fired closer to you than the other.
- Sound travels at 340 m/s.
- If one gun were fired 170m closer to you then they were fired at the same time.

Simultaneity

- If you know your distance from the shots, you can easily determine if they were simultaneous.
- And everyone will agree with you, after doing the same correction for distance.
- You might even come up with a definition
  - Event (x_1, t_1) is simultaneous with event (x_2, t_2) if sound pulses emitted at t_1 from x_1 and at t_2 from x_2 arrive simultaneously at the midpoint between x_1 and x_2.
- Einstein came up with a similar definition for relativistic simultaneity.
  - Due to the requirement of the consistency of speed of light not everyone agrees events are simultaneous

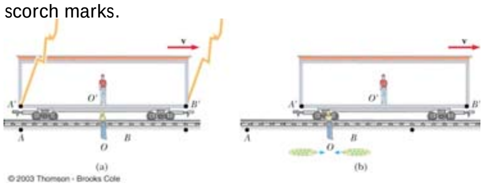
Consequences of Einstein's relativity

Many 'common sense' results break down:

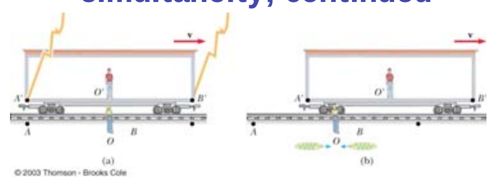
- Events simultaneous for observer in one reference frame not necessarily simultaneous in different reference frames.
- The distance between two objects is not absolute. Different for observers in different reference frames
- The time interval between events is not absolute. Different for observers in different inertial frames

Simultaneity thought experiment

- Boxcar moving with constant velocity *v* with respect to Jane standing on the ground.
- Joe rides in exact center of the boxcar.
- Two lightning bolts strike the ends of the boxcar, leaving marks on the boxcar and the ground underneath.
- On the ground, Jane finds that she is halfway between the scorch marks.

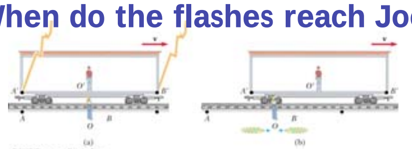


Simultaneity, continued



- Jane (on the ground) observes that light waves from each lightning strike at the boxcar ends reach her at exactly the same time.
- Since each light wave traveled at *c*, and each traveled the same distance (since *O* is in the middle), the lightning strikes **are simultaneous in the frame of ground observer.**

When do the flashes reach Joe?



- Jane can see when the two flashes reach Joe on the boxcar.
- When light from front flash reaches Joe, he has moved away from rear flash.
  - Front and rear flashes reach Joe at different times
- Since speed of light always constant
- Joe is equidistant from lightning strikes
  - Joe is equidistant from the lightning strikes
  - Light flashes arrive at *different* times
  - Both flashes travel at *c*
- Therefore for Joe, lightning strikes **are not simultaneous.**

Simultaneity and relativity, cont

- **Means there is no universal, or absolute time.**
  - The time interval between events in one reference frame is generally different than the interval measured in a different frame.
  - Events measured to be simultaneous in one frame are in general not simultaneous in a second frame moving relative to the first.
  - Has other consequences for time

Ether again

- If there were an ether, this wouldn't be a problem.
- The ether would be the medium that transmits EM waves.
- Speed of light is c relative to the ether.
  Suppose ether stationary with respect to Jane on ground.
- Joe sees the flash from the front of the train first because he is rushing towards it. The ether is rushing backwards, carrying the flash along with it. The train observer measures the wave from the front to travel faster than from the back.
- After accounting for this,
  he agrees with Jane that the strikes were simultaneous.

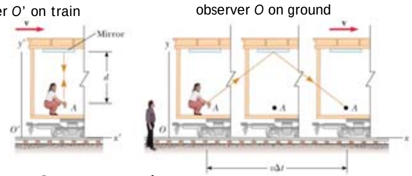
But there is no ether

- No stationary ether, no absolute reference frame.
- Joe sees that the train is stationary,
  and that Jane is rushing backwards.
- Joe sees the light pulses from the front and rear travel at exactly the same speed.
- Since the flashes arrive at different times,
  and Joe is equidistant between them, Joe concludes that the flashes occurred at different times.

Time dilation

Reference frame of observer *O*' on train

Reference frame of observer *O* on ground

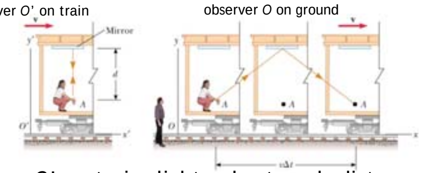


- Observer *O* on ground
- Observer *O*' on train moving at *v* relative to *O*
- Pulse of light emitted from laser, reflected from mirror, arrives back at laser after some time interval.
- *Lets figure out what this time interval is for the two observers*

Time dilation, continued

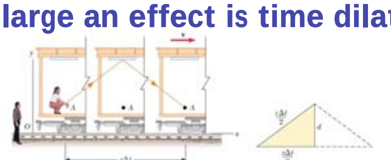
Reference frame of observer *O*' on train

Reference frame of observer *O* on ground



- Observer *O*' on train: light pulse travels distance $2d$.
- Observer *O* on ground: light pulse travels farther
- Relativity: light travels at velocity c in both frames
  - Therefore time interval between the two events (pulse emission from laser & pulse return) is *longer* for stationary observer
- This is *time dilation*

How large an effect is time dilation?



- Δt = time interval between events in frame *O* (observer on ground)
- Δt satisfies $(c\Delta t/2)^2 = (v\Delta t/2)^2 + d^2$,

$$(\Delta t)^2(c^2 - v^2)^2 = (2d)^2$$

$$\Delta t = 2d/\sqrt{c^2 - v^2} = \frac{2d}{c}\frac{1}{\sqrt{1-(v/c)^2}}$$

Time dilation

- Time interval in boxcar frame *O*'

$$\Delta t_p = \frac{round\ \ trip\ \ distance}{velocity} = \frac{2d}{c}$$

- Time interval in ground frame *O*

$$\Delta t = \frac{2d}{c}\frac{1}{\sqrt{1-(v/c)^2}} = \frac{\Delta t_p}{\sqrt{1-(v/c)^2}} = \gamma \Delta t_p$$

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

Example

- Suppose observer on train (at rest with respect to laser and mirror) measures round trip time to be one second.
- Observer *O* on ground is moving at 0.5*c* with respect to laser/mirror.

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}} = \frac{1}{\sqrt{1-(0.5c/c)^2}} = \frac{1}{\sqrt{1-0.25}} = 1.15$$

- Observer *O* measures 1.15 seconds

Which way does time dilation go?

- The shortest time measured between events is in the frame in which the events occur at the same spatial location.
- This is called the 'proper time' between events, Δt_p

- Example: The two events could be
  1) Minute hand on clock points at '3'
  2) Minute hand on clock points at '4'

  In the rest frame of the clock, these occur at the same spatial location, and the time interval is 5 minutes.

  In frame moving with respect to clock, time interval is γ(5 min)
  To this observer, clock is moving, and is measured to run *slow* by factor γ^{-1}

Special Relativity: GPS

- GPS satellites have atomic clocks accurate to 1 nanosecond (one billionth of a second)
- Positions computed by comparing time signals from several satellites.
- Satellites moving at 14,000km/hr
- Special Relativity:
  Clocks run slow by 7000ns per day!