Relativity and Modern Physics

- Physics changed drastically in the early 1900’s
- New discoveries – *Relativity* and *Quantum Mechanics*

- **Relativity**
  - Changed the way we think about space and time

- **Quantum mechanics**
  - Changed our conceptions of matter.

Special Relativity

- From 1905 to 1908, Einstein developed the special theory of relativity.
- Came up completely different idea of time and space.
- Everything is relative. No absolute lengths, times, energies.

  Showed that our usual conceptions of space and time are misguided.

Frames of reference

- Frame of reference:
  - The coordinate system in which you observe events.
  - e.g. The room around you.
  - You judge how fast a thrown ball goes by its velocity relative to some stationary object in the room.
  - You judge how high a thrown ball goes by distance from the floor, ceiling, etc.
  - You judge how fast you are moving by looking at objects around you

Which reference frame

Suppose you are on the bus to Chicago driving at 60 mph, and throw a ball forwards at 40 mph.

From your seat on the bus, the speed of ball is the same as in this classroom.

To the major league scout on the side of the road, your 40 mph throw has become a 100 mph fastball.

Who is correct?

You wouldn’t last long in the majors.

The important velocity in a baseball game is the relative velocity of ball with respect to pitcher or the batter.

But what exactly is the absolute velocity of the ball?

- Earth spins on its axis
  - One rotation in (24 hrs)(60 min/hr)(60 sec/min)=86400 sec
  - Point on surface moves $2\pi R_E$ in one rotation.
  - Surface velocity = $2\pi(6.4\times10^6 \text{ m})/86400 \text{ sec} = 465 \text{ m/s}$

- Earth revolves around sun
  - One revolution in (365 days)(86400 sec/day)=3.15x10^7 sec
  - Earth velocity = $2\pi(1.5\times10^{11} \text{ m}) / 3.15x10^7 \text{ sec}=3\times10^4 \text{ m/s}$

- Sun moves w/ respect to center of our galaxy
  - Sun velocity = $2.3\times10^4 \text{ m/s}$

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
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

Example of Galilean relativity

- Observer on ground
- 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.

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.

Some other examples

- On an airplane:
  - Pouring your tomato juice.
  - Throwing peanuts pretzel sticks into your mouth.
  - But when the ride gets bumpy...

- In a car:
  - Drinking coffee on a straight, smooth road
  - But accelerating from a light, or going around a curve

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.

Question

You riding in a car at 30 mph, and you throw a ball directly backwards at 20 mph just as you pass a stationary observer. The observer sees

A. Ball drops directly to the ground with no horizontal motion
B. Ball moves backwards at 20 mph and falls
C. Ball moves forwards at 10 mph and falls to ground.
Question

You riding in a car at 30 mph, and you throw a ball directly backwards at 30 mph just as you pass a stationary observer. The observer sees

A. Ball drops directly to the ground with no horizontal motion
B. Ball moves backwards at 30 mph and falls
C. Ball moves forwards at 60 mph and fall to ground.

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, 19\textsuperscript{th} 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

<table>
<thead>
<tr>
<th>Pluses</th>
<th>Minuses</th>
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<tbody>
<tr>
<td>Allows speed of light to be different in different frames (Maxwell’s eqns hold in frame at rest with respect to ether).</td>
<td>Ether must be rigid, massless medium, with no effect on planetary motion</td>
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<tr>
<td>Light then becomes like other classical waves, Ether is absolute reference frame.</td>
<td>No experimental measurement has ever detected presence of ether</td>
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The Michelson-Morley experiment

- The idea of the experiment
  - If the earth moves thru a medium thru which light moves at speed $c$, along the direction of the earth’s motion, light should appear from earth to move more slowly.

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)
The constancy of light speed

Jane is in spaceship traveling at 0.25c relative to Earth and turns on her headlights. Joe is on Earth, and observes the light from the headlights travel at

A. 0.75c
B. 1.25c
C. c

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.

Time and simultaneity

- What does it mean for two things to happen at the same time?

If you do not ask me what is time, I know it. When you ask me, I cannot tell it.
— St. Augustine

I do not define time, space, place, and motion, as being well known to all.
— Newton

Question

You hear two gunshots exactly 1/2 second apart. Did the gunshots occur at the same time?

A. No
B. Yes
C. Maybe

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) also 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
- Light flashes arrive at different times
  - Both flashes travel at $c$
- Therefore the lightning strikes at the boxcar ends are not simultaneous in the boxcar frame.

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.

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 sound 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 is forced to conclude that the flashes occurred at different times.

No universal simultaneity

- From a very basic assumption, that the speed of light is constant in all inertial reference frames, Einstein showed that not everyone will agree on simultaneity.
- Can also guess this means that the time interval between two events will not be agreed on.
- Suppose that the two events are two beats of an astronauts heart.