From Last Time...

- Range of visible light from 400 nm to 700 nm
- Eye interprets different wavelengths as different colors but has only three 'sensors', cones S, M, L with overlapping sensitivities.
- Lets colors be described as combination of three 'primaries'
- This makes a 'color space', colors can be described as amount of primaries needed.
- Most methods of generating colors have a 'gamut', a limited range of possible colors that in general do not contain pure spectral colors.

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
- Has led to multitude of technological achievements

Relativity and 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.

- Different frames
  - Suppose you are on the bus to Chicago driving at 60 mph, and throw the ball.
  - 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 fastball has become 100 mph.

Preferred reference frame

- Who is correct?
  - If the scout is right, your pitching for the Sox this weekend.
  - However, you wouldn't last long in the playoffs.
  - That's because the important velocity in a baseball game is the relative velocity of ball with respect to pitcher or the batter.
  - Then what is the absolute velocity of the ball?

Relative velocities

- Earth spins on its axis
  - One rotation in (24 hrs)(60 min/hr)/(60 sec/min)=86,400 sec
  - Point on surface moves 2πR_e in one rotation.
  - Surface velocity = 2π(6.4x10^6 m)/86400 sec = 465 m/s

- Earth revolves around sun
  - One revolution in (365 days)(86400 sec/day)=3.15x10^7 sec
  - Earth velocity = 2π(1.5x10^11 m)/3.15x10^7 sec = 3x10^4 m/s

- Sun moves w/ respect to center of milky way galaxy
  - Sun velocity = 2.3x10^3 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.

- This is an example of Galilean relativity:
  - The laws of mechanics are the same in all inertial frames of reference

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

Example of Galilean relativity

- Observer on ground
  - **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 in plane

Galilean relativity

- 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

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.

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 $c$?

  - Jane
  - Joe
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

<table>
<thead>
<tr>
<th>Pluses</th>
<th>Minuses</th>
</tr>
</thead>
<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>
</tr>
<tr>
<td>Light then becomes like other classical waves,</td>
<td>No experimental measurement has ever detected presence of ether</td>
</tr>
<tr>
<td>Ether is absolute reference frame.</td>
<td></td>
</tr>
</tbody>
</table>

Proposed influence of ether on light propagation

- Ether was presumed to be the medium in which light waves traveled.
- If ether is in motion with respect to observer, then speed of light with respect to observer will be different.

The idea of the experiment

- If the earth moves through 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.

Michelson-Morley experiments

- Tried to measure motion of earth with respect to the ether
- Earth changes its direction of motion on a regular basis as it revolves around sun.
- So ether wind changes direction relative to the interferometer
- Ether wind would change average speed of light on the two paths
- Waves will interfere when they recombine at the telescope.
- Null result showed that ether does not exist.

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 that seem to be simultaneous are not simultaneous in different inertial frames
- The distance between two objects is not absolute. It is different in different inertial frames
- The time interval between events is not absolute. It will be different in different inertial frames
- Velocities don’t always add directly

Many of these consequences can be demonstrated in simple ‘thought experiments’

Simultaneity and relativity

- When are two events are simultaneous?
  - Easy if they are at the same spatial location.
  - Different spatial locations require some synchronization, which requires signal transmission between locations.

- Simultaneity of separated events:
  - Event \((x_1, t_1)\) is simultaneous with event \((x_2, t_2)\) if light signals emitted at \(t_1\) from \(x_1\) and at \(t_2\) from \(x_2\) arrive simultaneously at the midpoint between \(x_1\) and \(x_2\)

- In this theory, simultaneity in time does not have an absolute meaning.
  - Mixes the time and space coordinates
  - Means there is no universal, or absolute time.

Simultaneity thought experiment

- Boxcar moving with constant velocity \(v\) with respect to observer \(O\) on the ground.
- Observer \(O’\) 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.
- Observer \(O\) on the ground finds that she is halfway between the scorch marks.

Simultaneity, continued

- Observer \(O\) (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.

The events in boxcar (\(O’\)) frame

- When light from front flash reaches boxcar observer \(O’\), he has moved away from rear flash.
  - Light from rear flash has not yet reached him.
- Both light waves travel at \(c\) in the boxcar frame,
  - Observer \(O’\) is equidistant from the 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.
Analogy with sound

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

- Obviously not.
- But suppose you find out one of the shots was fired closer to you than the other.
- Sound travels at 340 m/s.
- The sound pulse closer to you would arrive first, even if they were fired at the same time.

But can everyone agree?

- 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.

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.

Sound waves

- If we were using sound pulses (the crack from the lightning hitting the train), there would be no problem.
- The air (medium that transports sound waves) provides an absolute reference frame.
- Speed of sound is 340 m/s relative to the stationary air.
- For the observer on the train, the sound from the front of the train is heard first because he is rushing towards it. The air is rushing backwards, carrying the sound pulse 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 the ground observer that the strikes were simultaneous.

The situation with relativity

- But in relativity, there is no such absolute reference frame.

  - There is no such thing as stationary ether.
  - The observer on the train sees that the train is stationary, and the ground observer is rushing backwards.
  - The observer on the train sees the light pulses from the front and rear travel at exactly the same speed.
  - Since they arrive at different times, and he is equidistant between them, he is forced to conclude that they occurred at different times.

Time dilation

- 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.
- This time interval is different for the two observers.
Phy 107, Lecture 17

Time dilation, continued

- 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?

- \( \Delta t \) = time interval between events in frame \( O \) (observer on ground).
- \( \Delta t \) satisfies \( (c/\Delta t)^2 = (\Delta t/2)^2 + d^2 \).
- \( \Delta t = 2d/\sqrt{1-(v/c)^2} \).

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 \( 0.5c \) with respect to laser/mirror.
- 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, \( \Delta t_p \).

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 \( \gamma(5 \text{ min}) \).
To this observer, clock is moving, and is measured to run slow by factor \( \gamma^{-1} \).

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!