Intro to Special Relativity:

Reference Frames
Postulates of SR
Speed of Light
Simultaneity
Scattering of Light by Clouds

- Clouds consist of microscopic water droplets that scatter light.
- Thin clouds are white because they scatter all wavelengths equally.
- The bottom of thick clouds appears gray because much of the light is absorbed.
- The scattered light is unpolarized.
Scattering of Light by Air

- The sky is blue because the scattering of light by air molecules is proportional to $1/\lambda^4$.
- Blue (450 nm) scatters more than red (750 nm) by a factor of $(750/450)^4 \approx 8$.
- The blue light from the sky is polarized in a direction perpendicular to the line toward the sun.
Calcite is a crystal for which the index of refraction depends on the polarization of the light (birefringence).

The light is refracted into two images, each polarized differently.

Application: Make efficient polarizers!
Unpolarized light is incident on two ideal polarizers that are crossed at an angle of 60 degrees. Recall that $\cos(60\,\text{deg}) = 1/2$.

What fraction of incident light is transmitted through both polarizers?

a) $1/2$.
b) $1/4$.
c) $1/8$.
d) $1/16$.
e) It depends on whether the incident light is linearly or circularly unpolarized.
Theory of Relativity

- **Special Relativity**: A. Einstein, 1905
  - Concerns *relative motion* between observers (kinematics, as well as electromagnetism).

- **General Relativity**: A. Einstein, 1916
  - This is a geometric theory of gravitation.
  - A graduate-level physics course of its own (not covered in this course).
Frames of Reference - Coordinate Systems

We can have several observers using different coordinate systems observing the same physics happening.

The frames can move relative to one another. If the movement is at a low, constant speed, the transformation from one to another is pretty simple.

Velocities add. If an object moves at velocity $v$ in frame 1, and frame 2 moves at velocity $u$ in frame 1, then the object moves at velocity $v-u$ in frame 2.
Consider two coordinate systems ("reference frames") that coincide exactly at $t = 0$. The primed frame moves to right (+x) at speed $u$.

Frame $S'$ moves relative to frame $S$ with constant velocity $u$ along the common $x$-$x'$-axis.

Origins $O$ and $O'$ coincide at time $t = 0 = t'$.

This Galilean transformation was discussed last year in Physics 123.

We will now discover that it is only an approximation, applicable to speeds $\ll$ speed of light.
What is an Inertial Reference Frame?

• An inertial reference frame is a reference frame that is not accelerating.

• Think of an inertial reference frame as being on a spaceship, engines turned off, far from any star, etc., so that there are no external forces, not even gravity.

• While we usually think of ourselves here on the surface of the earth as being in a fixed non-accelerating reference frame. This is not strictly true, of course: The earth is slowly rotating, and there is gravity.

• But for many purposes we can approximate our on-the-surface-of-the-earth frame as an inertial reference frame. (The Earth’s gravity should be regarded as a Newtonian force rather than curved space-time, a force that is balanced by an equal and opposite normal force.)
The needle reads the same current whether you are in the frame in which the magnet is still, or the frame in which the coil is still.

All that matters is the relative motion of the two. We get the same EMF whether the coil or the magnet is moving at speed $v$. 
Special Relativity Postulates  
(postulate = assumption)

- First postulate: Physical laws are the same in every inertial reference frame.

- Second postulate: The speed of light (in vacuum) is the same in every inertial reference frame.

- The first might seem obvious - things should happen independently of how you look at them.

- But the second postulate seems odd. It is contrary to how we usually add velocities. If there are two cars moving in the opposite directions at speed $v$, they see each other as having a (relative) speed of $v + v = 2v$.

- However, if we actually measure the speed of light in vacuum, it turns out to be the same in all frames.
Adding Small Velocities

(a) A spaceship \((S')\) moves with speed \(v_{S'/S} = 1000 \text{ m/s}\) relative to an observer on earth \((S)\).

A missile \((M)\) is fired with speed \(v_{M/S'} = 2000 \text{ m/s}\) relative to the spaceship.

\[
v_{S'/S} = 1000 \text{ m/s}
\]

\[
v_{M/S'} = 2000 \text{ m/s}
\]

\[
v_{M/S} = 2000 \text{ m/s} + 1000 \text{ m/s}
\]

**NEWTONIAN MECHANICS Holds:** Newtonian mechanics tells us correctly that the missile moves with speed \(v_{M/S} = 3000 \text{ m/s}\) relative to the observer on earth.

Adding parallel velocities gives the simple algebraic sum.
Adding Large Velocities

If the 2nd postulate is right, adding velocities is more complicated than the simple algebraic sum!
**The Speed of Light is Constant: Experiment**

- The light in a Michelson Morley interferometer travels through 2 orthogonal arms before interfering.
- The earth moves at great speed around the sun.
- Thus, if the speed of light depended on whether it travels along the earth's motion, or perpendicular to it, the interference fringes should move as we rotate the interferometer by 90 degrees.

- But the interference pattern stays perfectly fixed! It is an **experimental fact** (not just a postulate) that the speed of light is the same in all directions, and is independent of the motion of the source.
Is Special Relativity Crazy?

Because the second postulate is counter-intuitive (but experimentally confirmed!), it leads to all kinds of counter-intuitive consequences:

- ambiguity of simultaneity
- time dilation
- length contraction
- various so-called "paradoxes"

Normal intuition fails us here, and such behaviors appear “crazy” or even “wrong”. However, they are not mere speculation, but have been accurately confirmed by experiments.

For example, a GPS receiver can provide your exact location on the planet because relativistic effects are correctly taken into account during processing of the signals received from the GPS satellites orbiting the earth.
As a high-speed spaceship flies past you at half the speed of light, a strobe light fires at the center of a room aboard the spaceship. As measured by you, the light from the strobe

A. reaches point A before it reaches point B.
B. reaches point B before it reaches point A.
C. reaches points A and B simultaneously.
D. The light will never reach A nor B.
E. The ship would have to go at warp speed for this to work.
Simultaneity of Events

• An “event” has a definite time and position in space.
• Two events are considered simultaneous if they occur at the same time for a given observer.
• Two events happening at the same place and at the same time are clearly simultaneous.
• Also, we can consider two events simultaneous if the light emitted from the events reaches an observer midway between the two points at the same time.
Simultaneity of Events

(a) Stanley is standing half-way between the points A and B.
Mavis is sitting half-way between the points $A'$ and $B'$.

(b) Inside the train, Mavis moves toward the light coming from the front of the train and away from the light coming from the back of the train.

Lightning hits the front and back of a train (points $A'$ and $B'$) and hits the ground at points A and B.
Simultaneity of Events

- Stanley concludes that the lightning strikes occurred simultaneously.
- Mavis concludes that the front lightning strike occurred before the rear strike.

Mavis sees the light from the front of the train first, so she believes that the lightning hit the front of the train first.

Stanley sees the lightning hit the two points at the same time; so he believes that the lightning hit the two ends of the train simultaneously.

(The light from the rear of the train has not reached Mavis yet.)
Did the lightning strike A and B simultaneously or not? Who is right - Stanley or Mavis? Why?

a) Stanley, because he is in a rest frame and sees the lightning strikes both ends at once.
b) Stanley, because we know Mavis is moving, but Stanley is not.
c) Mavis, because she is in an inertial frame.
d) Mavis, because Stanley can calculate what she sees.
e) They are both right, from their respective points of view: Simultaneity is relative to the observer.
Let’s revisit the previous iClicker problem:

As a high-speed spaceship flies past you at half the speed of light, a strobe light fires at the center of a room aboard the spaceship. As measured by you, the light from the strobe

(Answer:) reaches point B before it reaches point A.

But what about an observer on the ship? She will conclude that the light must have reached points A and B at the same time, since strobe was fired from the mid-point between A and B.

Thus here again we see that whether or not two events occur simultaneously depends on the observer.