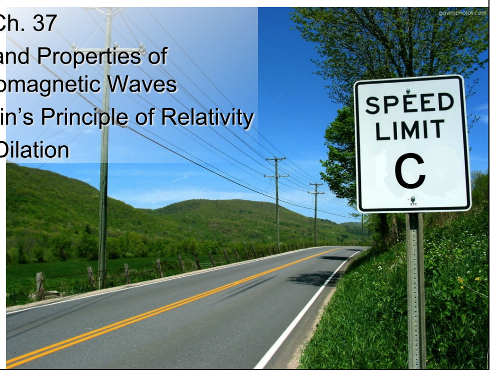
PHY132H1F Introduction to Physics II
Class 22 – **Outline:**

Today, Ch. 37
- Light and Properties of Electromagnetic Waves
- Einstein's Principle of Relativity
- Time Dilation



Properties of Electromagnetic Waves

The energy flow of an electromagnetic wave is described by the Poynting vector defined as

$$\vec{S} \equiv \frac{1}{\mu_0}\vec{E} \times \vec{B}$$

The units of S are [Watts / m^2]. The magnitude of the Poynting vector is

$$S = \frac{EB}{\mu_0} = \frac{E^2}{c\mu_0}$$

The intensity of an electromagnetic wave whose electric field amplitude is E_0 is

$$I = \frac{P}{A} = S_{avg} = \frac{1}{2c\mu_0}E_0^2 = \frac{c\epsilon_0}{2}E_0^2$$

Radiation Pressure

It's interesting to consider the force of an electromagnetic wave exerted on an object per unit area, which is called the radiation pressure p_{rad}. The radiation pressure on an object that absorbs all the light is

$$p_{rad} = \frac{F}{A} = \frac{P/A}{c} = \frac{I}{c}$$

where I is the intensity of the light wave. The subscript on p_{rad} is important in this context to distinguish the radiation pressure from the momentum p.

Quick Ch. 37 reading quiz..

A flashlight is moving forward at speed 0.1 *c* (10% of the speed of light, or 30,000 km/s).

How fast do the light waves emerge from the front of the flashlight, as observed by a person who is at rest on the ground?

A. *c*
B. 1.1 *c*
C. 0.9 *c*

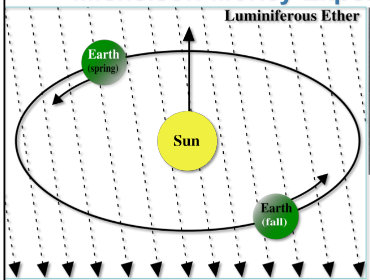
Quick Ch. 37 reading quiz..

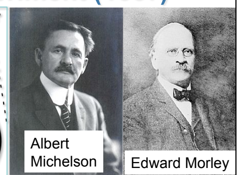
A flashlight is moving forward at speed 0.1 *c* (10% of the speed of light, or 30,000 km/s).

How fast do the light waves emerge from the front of the flashlight, as observed by the moving person who is holding on to the flashlight?

A. *c*
B. 1.1 *c*
C. 0.9 *c*

Michelson-Morley Experiment (1887)



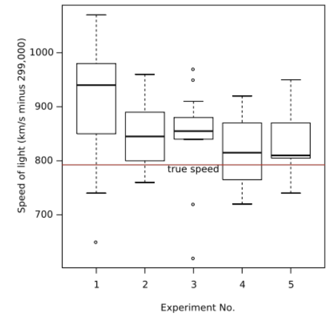


• In the 1800s physicists believed that light must wave in what was called the "Luminiferous Ether".
• Since the Earth is in motion, the speed of light should vary with direction and time of year.

Source: http://en.wikipedia.org/wiki/Michelson-Morley_experiment

Michelson-Morley Experiment (1887)

• **Result:** No variation. The speed of light was always exactly c in any direction at any time of year.



Apparently, there is no "Luminiferous Ether".

Light just always travels at *c* relative to the *observer*, even if the source is moving relative to the observer, or the observer is moving relative to the rest of the universe.

Source: http://en.wikipedia.org/wiki/Michelson-Morley_experiment

Einstein's Principle of Relativity (1905)

Principle of relativity All the laws of physics are the same in all inertial reference frames.

- Maxwell's equations are true in all inertial reference frames.
- Maxwell's equations predict that electromagnetic waves, including light, travel at speed $c = 3.00 \times 10^8$ m/s.
- Therefore, light travels at speed c in all inertial reference frames.

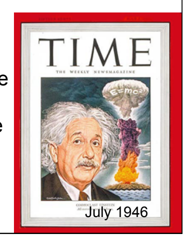
Every experiment to date (circa 2010) has found that light travels at 3.00×10^8 m/s in every inertial reference frame, regardless of how the reference frames are moving with respect to each other.

Einstein's Principle of Relativity (1905)

Principle of relativity All the laws of physics are the same in all inertial reference frames.

All the results of relativity follow from this simple principle, which implies that light travels at 3.00×10^8 m/s in every inertial reference frame. Examples:

- The relativity of time – moving clocks run slow.
- The relativity of space – moving objects are shorter along the direction of motion.
- The relativity of mass – moving objects are more massive.
- *c* as the speed limit – impossible to accelerate an object to or beyond *c*.
- $E = m c^2$



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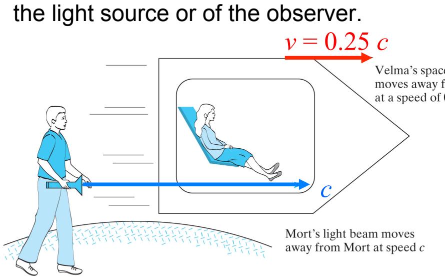
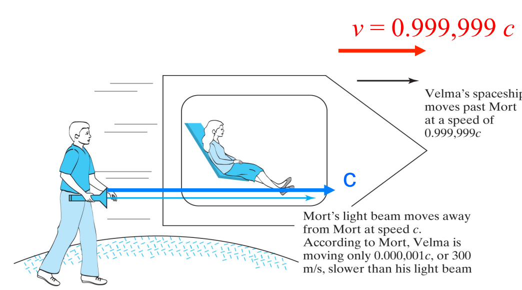
Principle of Constancy of Lightspeed

The speed of light (and of other electromagnetic radiation) in empty space is the same <u>for all nonaccelerated</u> observers, regardless of the motion of the light source or of the observer.



The light moves at speed *c* relative to Mort <u>and</u> relative to Velma.

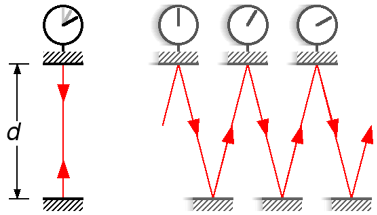
Another Version



Even here, both Mort and Velma observe the speed of light to be *c*.

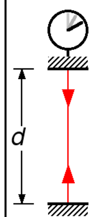
Light Clocks

A "light clock" is made up of two parallel mirrors, separated by a vacuum and held at a fixed distance of d.



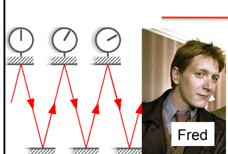
A short pulse of light bounces between the mirrors, "ticking" for each bounce.

Twin Paradox



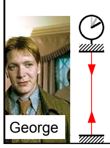
Fred and George are identical, and so have identical life-spans. They each have a light clock. This light clock "ticks" once every millisecond, so they both expect to observe 2.5×10^{12} ticks in their 80 year life-span.

Twin Paradox



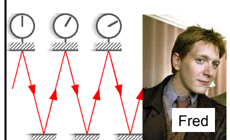
Fred flies on his broomstick to the right at 20% of the speed of light. George stays on the ground.

Over his life, George sees 2.5×10^{12} ticks of his stationary clock.
How many "ticks" of Fred's clock does George observe?



A. More than 2.5×10^{12}
B. Less than 2.5×10^{12}
C. 2.5×10^{12}

Twin Paradox



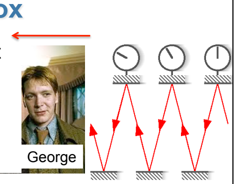
Fred flies on his broomstick to the right at 20% of the speed of light. George stays on the ground.

After George sees 2.5×10^{12} ticks of his stationary clock, he dies of old age. How do you expect his twin brother is doing?

A. Fred will also probably die at this time.
B. Fred has more life to live.
C. Fred has already been dead for some time.

Twin Paradox

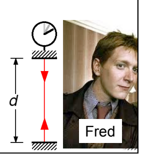
Fred flies on his broomstick to the right at 20% of the speed of light. George stays on the ground.



According to Fred, in his reference frame, he is stationary, and his brother is moving to the left at 20% of the speed of light.

Over his life, Fred sees 2.5×10^{12} ticks of his clock, which is stationary relative to him.
How many "ticks" of George's clock does Fred observe?

A. More than 2.5×10^{12}
B. Less than 2.5×10^{12}
C. 2.5×10^{12}



Time Dilation

The time interval between two events that occur at the *same position* is called the proper time $\Delta\tau$. In an inertial reference frame moving with velocity $v = \beta c$ relative to the proper time frame, the time interval between the two events is

$$\Delta t = \frac{\Delta\tau}{\sqrt{1-\beta^2}} \geq \Delta\tau \qquad \text{(time dilation)}$$

The "stretching out" of the time interval is called time dilation.

Length Contraction

The distance L between two objects, or two points on one object, measured in the reference frame S in which the objects are at rest is called the proper length ℓ. The distance L' in a reference frame S′ is

$$L' = \sqrt{1 - \beta^2}\,\ell \leq \ell$$

NOTE: Length contraction does not tell us how an object would *look.* The visual appearance of an object is determined by light waves that arrive simultaneously at the eye. Length and length contraction are concerned only with the *actual* length of the object at one instant of time.

Recall the Galilean Transformations

Consider two reference frames S and S′. The coordinate axes in S are x, y, z and those in S′ are x', y', z'. Reference frame S′ moves with velocity v relative to S along the x-axis. Equivalently, S moves with velocity −v relative to S′.

The *Galilean transformations of position* are:

$$x = x' + vt \qquad y = y' \qquad z = z' \qquad \text{or} \qquad x' = x - vt \qquad y' = y \qquad z' = z$$

The *Galilean transformations of velocity* are:

$$u_x = u'_x + v \qquad u_y = u'_y \qquad u_z = u'_z \qquad \text{or} \qquad u'_x = u_x - v \qquad u'_y = u_y \qquad u'_z = u_z$$