Conceptual Physics
Electromagnetic Induction
Light

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Last time

- electric potential
- circuits, current, resistance
- magnetism

Overview

- interactions between electricity and magnetism
- light and the speed of light
- reflection and refraction
- polarization

Force on a Moving Charge

There is a force on a moving electric charge in a magnetic field:

$$F_B = q\, v\, B \sin\theta$$

where B **is the magnetic field**, v is the velocity of the charge, θ is the angle between the directions of v and B, and q is the electric charge.

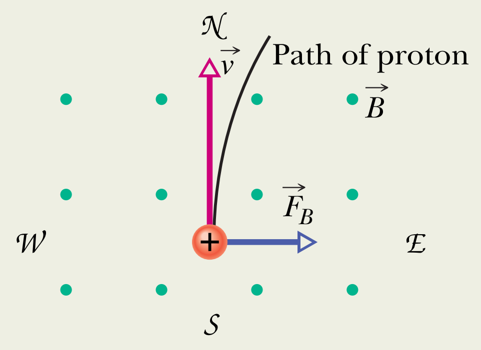
The direction of the force is **perpendicular** to the directions of B and v.

Notice this is similar to the relation between electrostatic force and electric field.

$$\mathbf{F}_E = q\mathbf{E} \quad \longrightarrow \quad \mathbf{F}_B = q\,(\mathbf{v} \times \mathbf{B})$$

Force on a Moving Charge

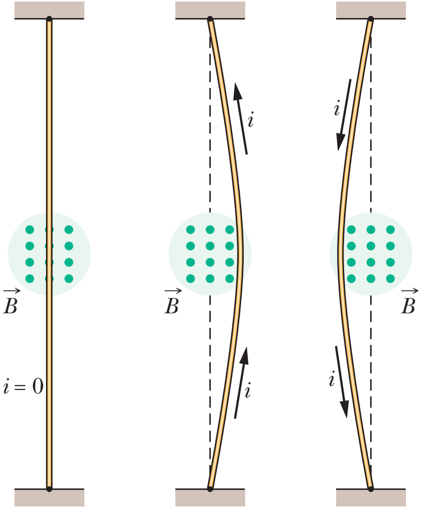
For example: here the dots indicate the field is directed upward out of the slide.



The force on the particle is $\perp$ to its velocity and the field.

[1]Figure from Halliday, Resnick, Walker, 9th ed.

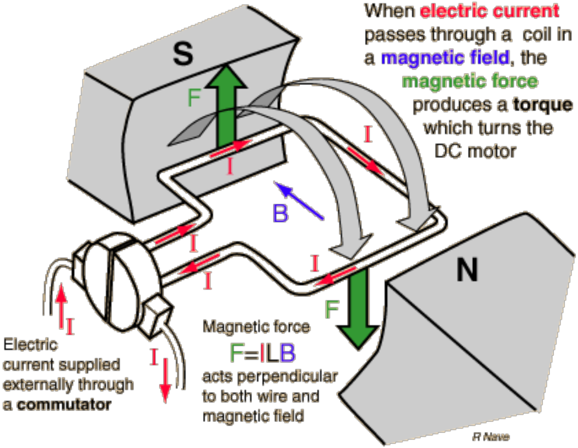
Force on a wire with a current in a magnetic field



The direction of the force depends on the direction of the current, and is perpendicular to the current and field.

Electric Motors

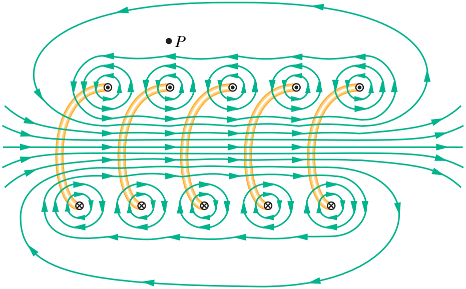
This effect can be used to turn electricity into mechanical work.



[1]Figure from hyperphysics.phys-arstr.gsu.edu

Coil as a magnet

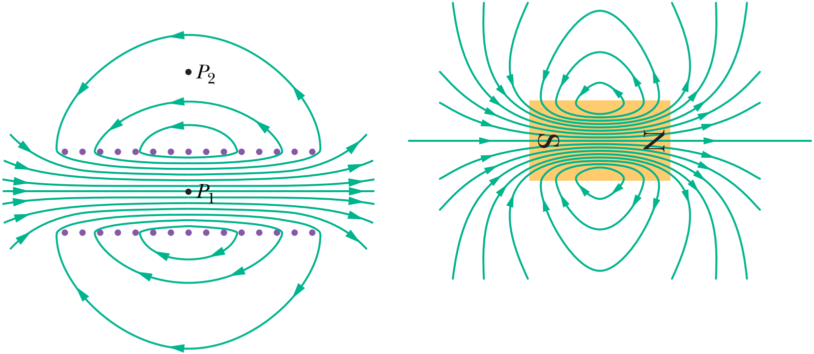
Wires carrying current also create a magnetic field.



Each turn of wire locally has a circular magnetic field around it. The fields from all the wires add together to create very dense field lines inside the solenoid.

[1]Figure from Halliday, Resnick, Walker, 9th ed.

Magnetic Field of a solenoid

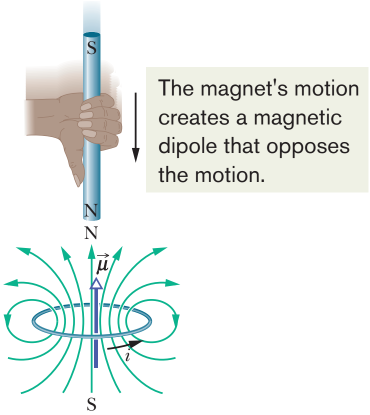


The coil has a magnetic field similar to a bar magnet!

[1] Figures from Halliday, Resnick, Walker, 9th ed.

Faraday's and Lenz's Laws

It is possible to use a magnet to create a current!



Faraday's Law of Induction

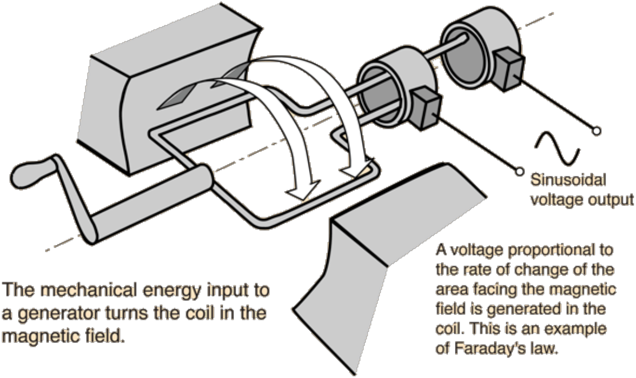
A changing magnetic field gives rise to an electric field.

Lenz's Law

An induced current has a direction such that the magnetic field due to the current opposes the change in the magnetic field through the loop that caused the current.

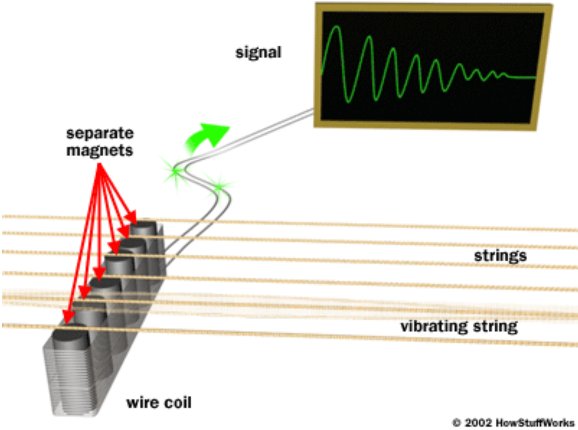
[1] Figure from Halliday, Resnick, Walker, 9th ed.

Electric Generators



[1]Figure from hyperphysics.phys-arstr.gsu.edu

Electric Guitar Pickups



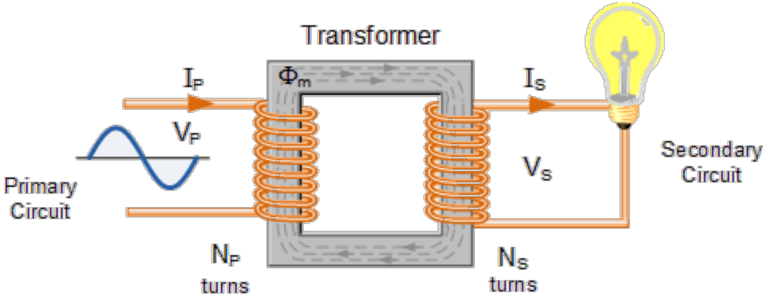
Strings are made of ferrous metal: steel (iron) or nickel, which become magnetized by the permanent magnets.

Plucked strings create a changing magnetic field that produces a current in the pickup coil.

[1]Figure from HowStuffWorks.

Transformers

Transformers change voltage, V, and current simultaneously, while keeping average power constant (conservation of energy).



This works via mutual inductance. **If the current in the first coil did not constantly change (AC) this would not work.**

$$V_s = V_p \frac{N_s}{N_p}$$

[1]Figure from electronics-tutorials.ws

Relation between Electric and Magnetic Fields

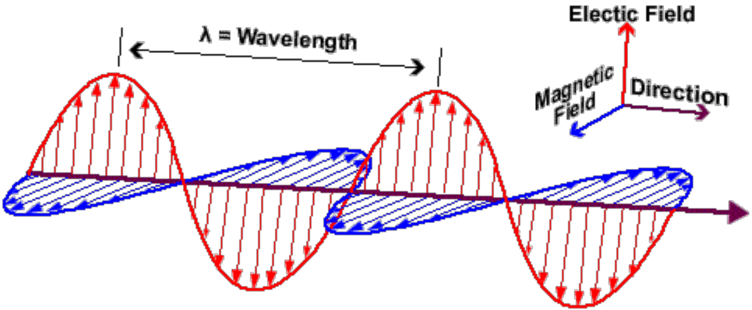
Faraday's Law of Induction

A changing magnetic field gives rise to an electric field.

Ampere-Maxwell Law of Induction

A changing electric field gives rise to an magnetic field.

Electromagnetic Waves



Light (Electromagnetic Radiation)

From the earliest philosophers people were curious about what light is.

By the late 1600s there were two main camps:

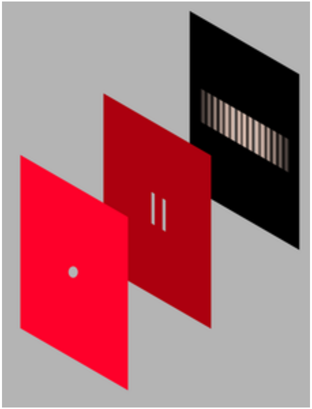
- light is composed of particles - Newton, influenced by Pierre Gassendi
- light is a wave - Christiaan Huygens (1678), following the suggestion of Hooke, also Leonhard Euler

Both the particle and the wave models of light could explain reflection and refraction of light, but initially the wave theory was less popular.

Young's Double-Slit Experiment

Thomas Young in 1801 did the first experiment that conclusively showed the interference of light from 2 sources.

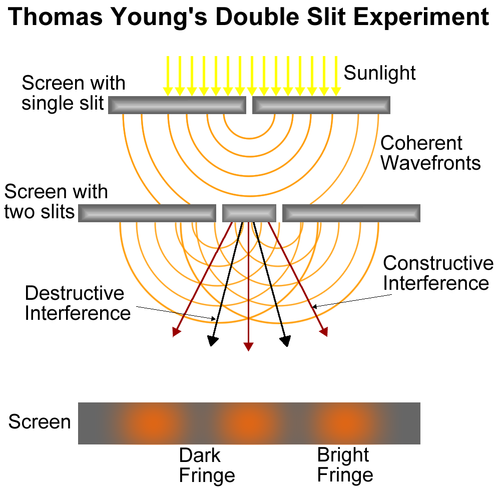
He filtered sunlight to make as source of red light, then shone the light through a series of narrow apertures (slits).



[1]http://www.lightandmatter.com/

Young's Double-Slit Experiment

The filtered coherent light then goes through two slits cut from the same mask. The light from these two sources interferes.

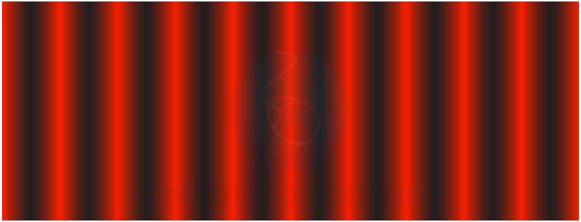


The light strikes a screen where bright and dark areas can be seen.

Young's Double-Slit Experiment

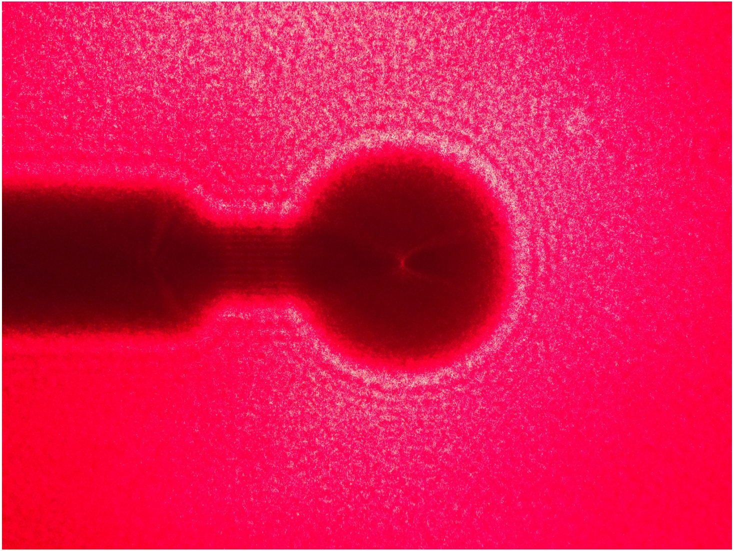
A pattern of light and dark “fringes” (stripes of light and darkness) appear on the screen.

Zoomed in view:



Light (Electromagnetic Radiation) as a Wave

Light will also form diffraction patterns:



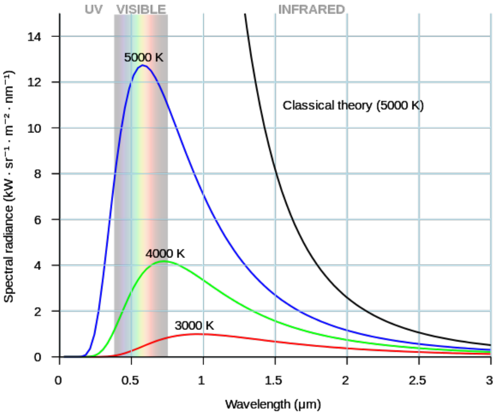
What is Light?

Thomas Young experimentally demonstrated the interference of light, which confirmed that it needed to be considered as being wave-like.

This fit with the understanding of Maxwell's equations, which govern electromagnetism.

Demonstrations of the diffraction of light were a victory for the wave camp, however, a pure wave model of light could not predict the shape of the distribution of radiation with temperature ("blackbody radiation")

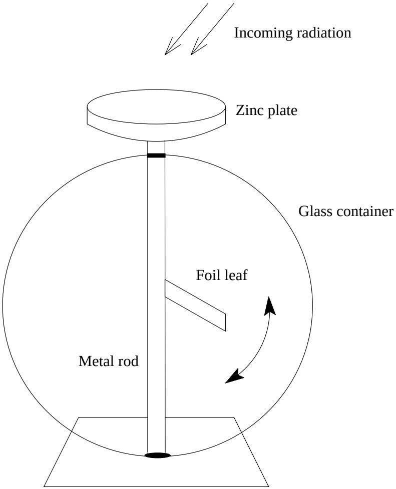
Light and the Blackbody radiation curve



Planck was able to fit a model to this by assuming that light was composed of "chuncks" of energy, called **quanta**.

Hertz then discovered the **Photoelectric effect** and was unable to explain it with a wave model of light.

Photoelectric Effect



Even very intense light at a low frequency will not allow the plate to discharge. As soon as just a little light at a high frequency falls on the plate it begins discharging.

What is Light?

Einstein resolved the issue by taking literally Max Planck's quantization model and showing that light behaves like a wave, but also like a particle.

The "particles" of light are called **photons**.

The energy of a photon depends on its frequency:

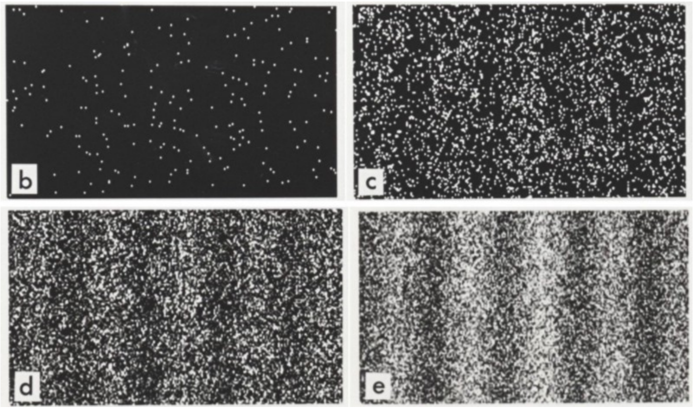
$$E = hf$$

where $h = 6.63 \times 10^{-34}$ J s is **Planck's constant**.

Light (Electromagnetic Radiation)

Photons are "particles", but they obey quantum mechanics, therefore they behave like waves in many ways.

(Amazingly, one photon can interfere, like a wave, with itself!)



[1]Wikimedia Commons users Dr. Tonomura and Belsazar. Electron interference. No. of samples: 200 (b), 6000 (c), 40000 (d), 140000 (e).

Light (Electromagnetic Radiation)

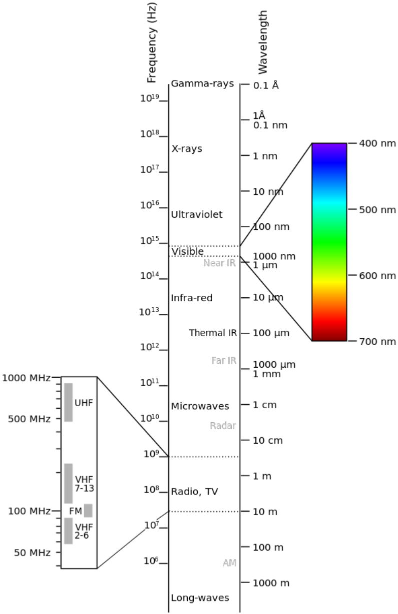
All light waves in a vacuum travel at the same speed, the speed of light, $c = 3.00 \times 10^8$ m s^{-1}.

All observers, no matter how they move relative to one another all agree that any light wave travels at that same speed. (Relativity.)

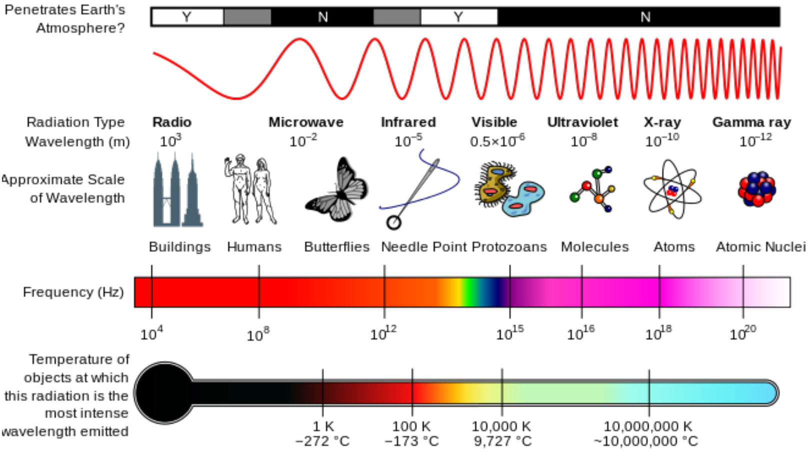
Since light travels at this fixed speed and $c = v = f\lambda$, if the frequency of the light is given, you also know the wavelength, and vice versa.

$$\lambda = \frac{c}{f} \quad ; \quad f = \frac{c}{\lambda}$$

Electromagnetic spectrum



Electromagnetic spectrum



Measurements of the Speed of Light

Since light propagates so quickly it is difficult to measure its speed in practice.

Many scientists worked to find ways to measure it:

- Galileo Galilei, 1638
- Ole Rømer, 1675 - observed the orbit of Io, a moon of Jupiter, and noticed its period varied depending on whether the Earth approaches Jupiter or recede from it
- Armand Fizeau, 1850 - used a toothed wheel
- Léon Foucault, 1850 - used a rotating mirror
- Albert Michelson, 1920s - improved the rotating mirror, obtained a value only 0.001% from accepted value

Speed of Light in a Vacuum

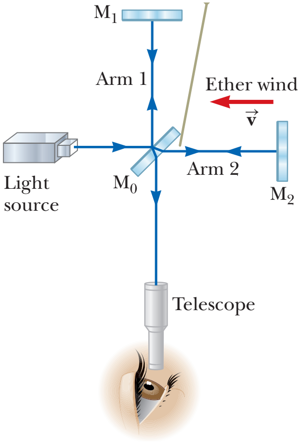
Current accepted value for the speed of light in a vacuum:

$$c = 299\,792\,458 \text{ m/s}$$

This agrees with the prediction of Maxwell's laws, which govern electromagnetism.

Light has needs no medium, but originally it was assumed that it must have a medium. The supposed medium was called the ether (or aether).

Michelson-Morely Experiment, 1887



IF there were an ether wind, the time taken for light to travel arm 2, t_2, would be different for arm 1, t_1.

$$\Delta t = t_2 - t_1 \approx \frac{Lv^2}{c^3}$$

Michelson-Morely Experiment

At different times of year, Earth's motion through the ether would be in different directions.

When the experiment was repeated over the course of a year, they expected to see a change in the value of the time difference Δt correlated with the time of year.

This is not what they saw. There was no substantial difference change with time of year - and $\Delta t = 0$ (to within experimental error).

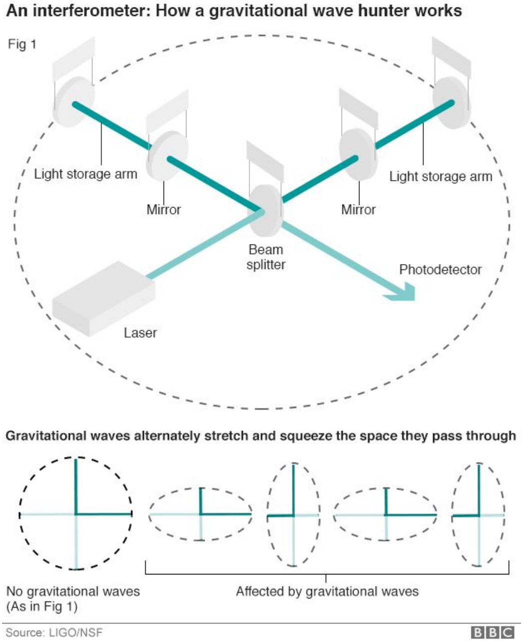
$\Rightarrow$ There is no ether. Light travels at the same speed in all frames.

Laser Interferometer Gravitational-Wave Observatory (LIGO)

Two miles-long interferometers where constructed in Hanford, Washington, and in Livingston, Louisiana.

[1]The LIGO Livingston Observatory in Louisiana. Caltech/MIT/LIGO Lab

Detecting Gravitational Waves



Laser Interferometer Gravitational-Wave Observatory (LIGO)

On Sept 14, 2015, both interferometers observed the same pattern of lengthening and contraction in the arms of their interferometers at basically the same time.

They concluded that the source of the waves was the merger of two black holes.

This was the first confirmed detection of gravitational waves.

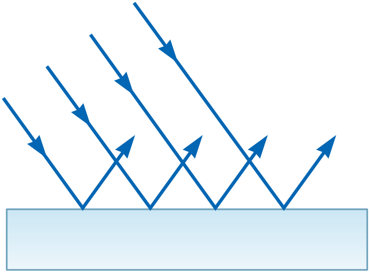
Just earlier this summer (June 1), LIGO has confirmed a third blackhole collision 3 billion light years away detected on Jan 4, 2017.

Behavior of Light: Reflection

Just as pulses on strings can be reflected from a fixed or free end of the string, light can be reflected from a surface when there is a sudden change of material.

When the surface is smooth, we see specular (mirror-like) reflection. If the incoming rays are parallel, so are the reflected rays.

Specular reflection:

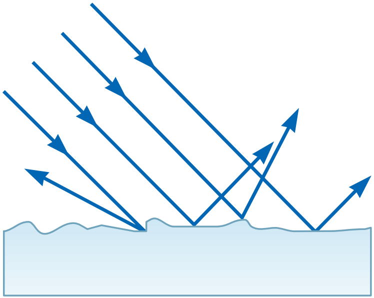


[1] Figure from Serway & Jewett, page 1062.

Reflection

When the surface is rough, we see diffuse reflection. Even when the incoming rays are parallel, the reflected rays are not.

Diffuse reflection:



Why does reflection of light happen?

Incident light is composed of oscillating electromagnetic fields.

This causes oscillating polarizations of individual atoms or molecules (the distribution of their electron clouds change).

The atoms or molecules act like tiny dipole antennas that re-emit electromagnetic waves.

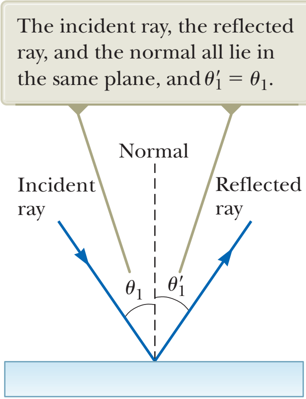
These re-emited waves are the reflected rays.

Metals make particularly good mirrors because the electrons in a metal are free to flow: they form better antennas.

Law of Reflection

For (specular) reflection, the angle made by the incident (incoming) ray with respect to the normal to the surface is equal to the angle made by the reflected ray with the normal:

$$\theta_i = \theta_r$$



Law of Reflection Question

Quick Quiz 35.1[1] In the movies, you sometimes see an actor looking in a mirror and you can see his face in the mirror. It can be said with certainty that during the filming of such a scene, the actor sees in the mirror:

(A) his face
(B) your face
(C) the director's face
(D) the movie camera

Boris Karloff as Frankenstein's monster.

[1]Serway & Jewett, page 1062.

Law of Reflection Question

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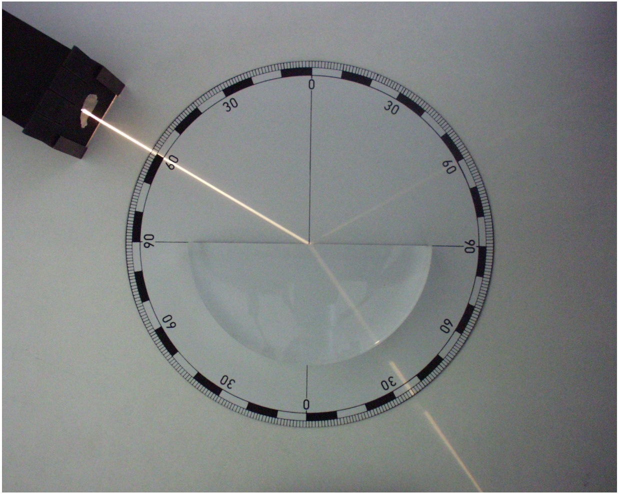
Behavior of Light: Refraction

When light rays pass from one material into another, they are often observed to bend.



[1]Image from Wikipedia, by Zátonyi Sándor.

Refraction

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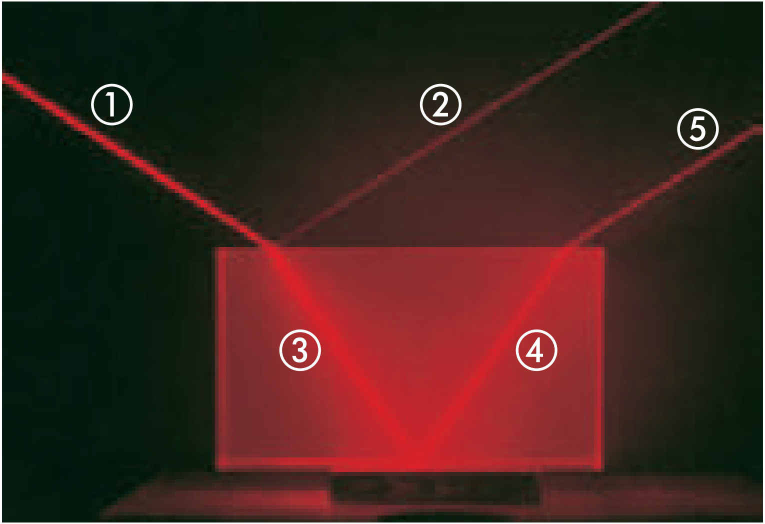
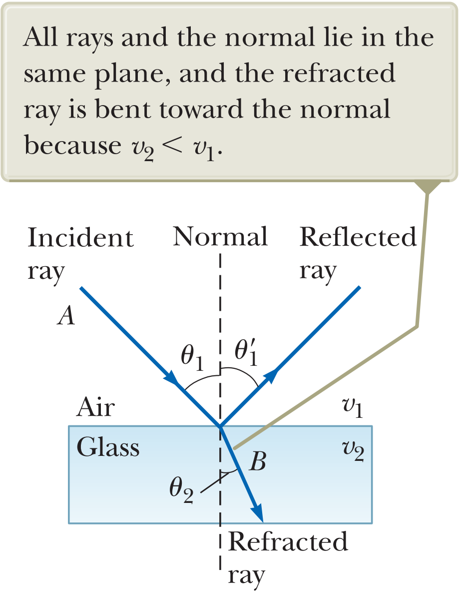
Refraction



Courtesy of Henry Leap and Jim Lehman

Refraction


All rays and the normal lie in the same plane, and the refracted ray is bent toward the normal because $v_2 < v_1$.
Incident ray
Normal
Reflected ray
A
θ_1
θ_1'
Air
v_1
Glass
v_2
B
θ_2
Refracted ray

Refraction

Why does this happen?

Foucault did his speed-of-light experiment in water (1850), and Fizeau (1851) went further, also investigating light *moving* water.

Both found visible light had a *slower* speed in water than in air. This agreed with the wave model of light. (But not the particle model!)

Refraction

If a wave enters a material where it moves more slowly, what happens?

1. the frequency cannot change – the source still "updates" the material about a new wave front every T seconds.

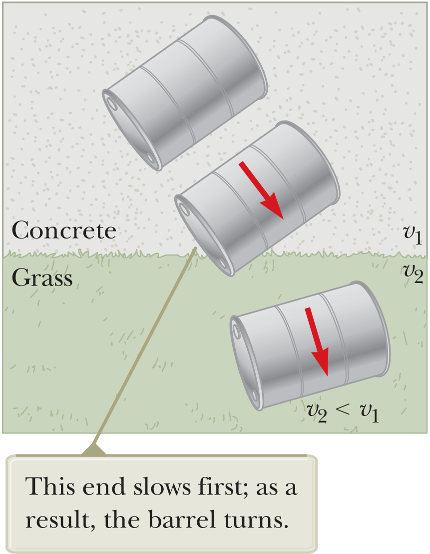
Refraction

If a wave enters a material where it moves more slowly, what happens?

1. the frequency cannot change – the source still “updates” the material about a new wave front every T seconds.
2. the **wavelength changes** ($v = f\lambda$)

When the wavefronts slow, they bend.

Refraction



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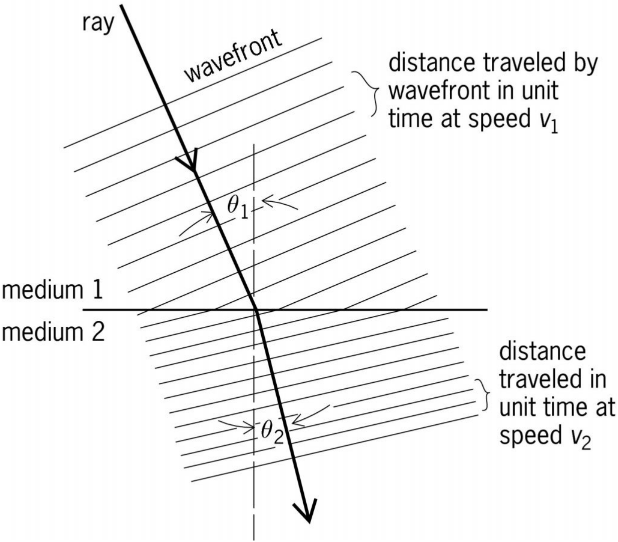
[1] Serway & Jewett, 9th ed, page 1066.

Refraction



[1]McGraw-Hill Concise Encyclopedia of Physics. © 2002 by The McGraw-Hill Companies, Inc.

Refractive Index

Light *at a particular frequency* moves at different speeds in different materials.

Light interacts with the charges that constitute the material, and the net effect is a wave that moves more slowly.

Refractive index of a medium, n

$$n = \frac{c}{v}$$

where $v = \frac{\omega}{k}$ is the phase velocity of light with angular frequency ω in that material.

Snell's Law

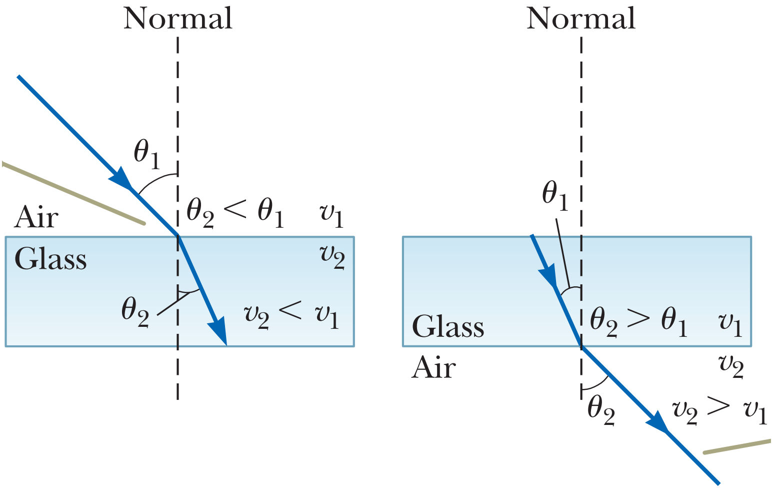
Snell's Law gives the relation between the angles of incidence and refraction and the refractive indices:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

[1] Willebrord Snell discovered this law experimentally.

Snell's Law and Refraction

If $n_1 < n_2$ the ray bends towards the normal, if $n_1 > n_2$ the ray bends away from the normal.



Dispersion

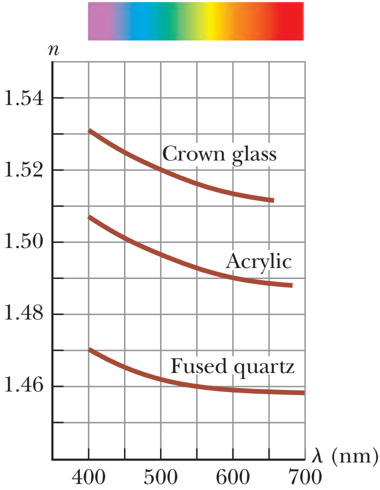
We have already said that the speed of light for a given frequency of light is different in different materials.

However, the speed of light is also different for different frequencies of light in *the same* material.

This means the refractive index is a function of frequency, $n(f)$.

Dispersion

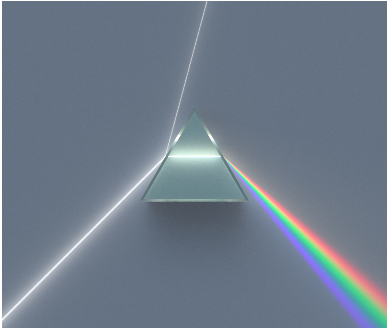
A plot of refractive index vs. wavelength for some kinds of transparent solids:

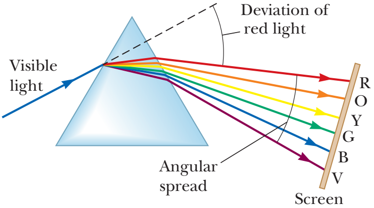


[1]Figure from Serway & Jewett, 9th ed, page 1072.

Prism Dispersion

All materials exhibit dispersion, to varying degrees, except the vacuum.

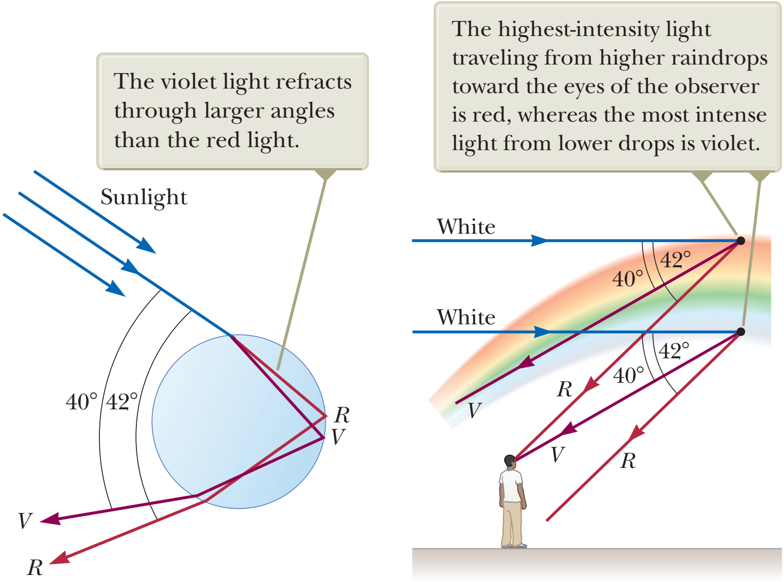




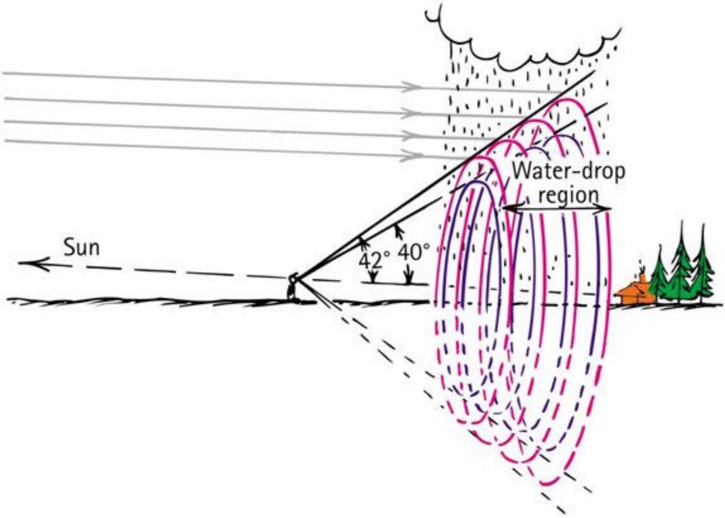
Each frequency has a different refractive index *n*, so each is refracted at a different angle.

[1] Left, Wikipedia by Spigget; right, Serway & Jewett, page 1083.

Dispersion in Rainbows



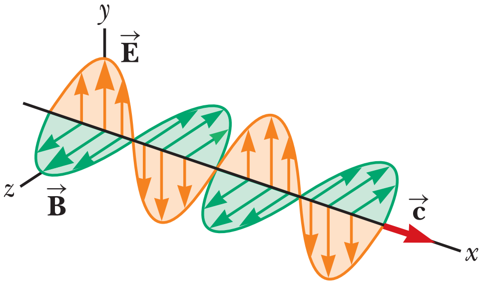
Dispersion in Rainbows



[1]Figure from Hewitt, page 496.

Polarization

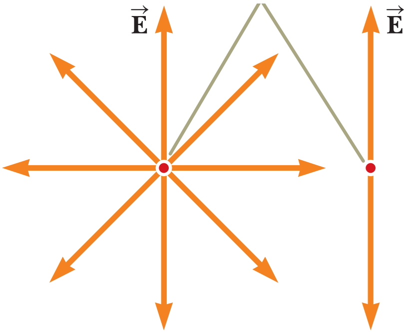
Light is composed of oscillation electric and magnetic fields.



In the diagram the E-field oscillates in the y-direction. The magnetic field must oscillate in perpendicular direction (here x) and the direction of propagation is z.

Polarization

We refer to the direction of oscillation of the E-field as the **polarization direction** of the light ray.



unpolarized light   vertically polarized light

Light can also be horizontally polarized or polarized in any other plane.

It can also be **circularly polarized**, meaning the direction of oscillation of the E-field rotates as the ray propagates.

Creating Polarized Light: by Selective Absorption

When unpolarized light of a long wavelength is shone through a set of closely-placed vertical wires, it becomes polarized horizontally.

Any light ray with an electric field oscillation that is vertical causes a current in the wires. The energy is absorbed as the electron flow in the wire heats the wire.

The horizontally polarized light has no electric field oscillation vertically, so it passes through the wires without interacting with them.

For shorter wavelengths a material called *polariod* will do the same thing.

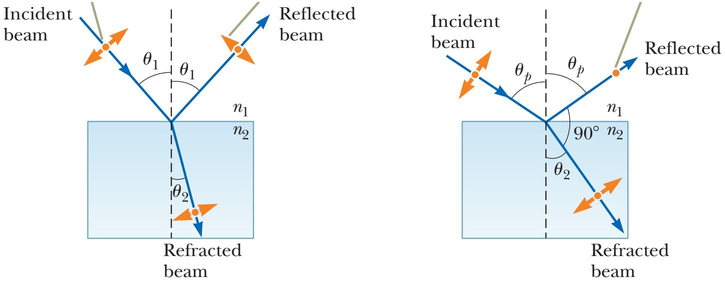
Creating Polarized Light: by Reflection

When light strikes a smooth surface of a transparent material, some light is reflected and some is transmitted.

Interestingly, the polarization of the transmitted beam is not the same as of the reflected beam!

If the incident ray is unpolarized, the transmitted and reflected rays will be partially polarized.

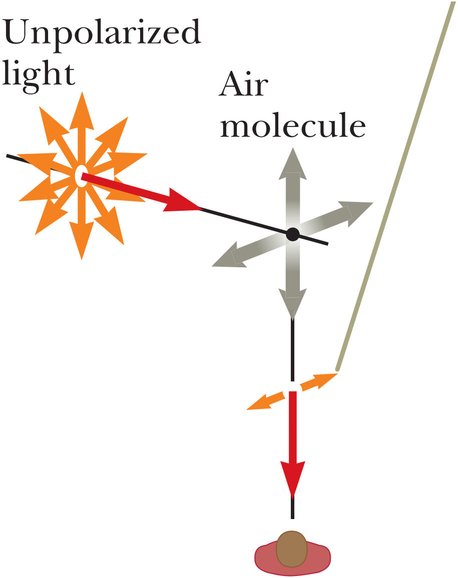
Creating Polarized Light: by Reflection



The dipoles in the surface cannot create a ray that has an E-field oscillating in the direction that the ray travels.

When the incident and reflected rays are perpendicular, the reflected ray is completely polarized parallel to the surface.

Creating Polarized Light: Scattering

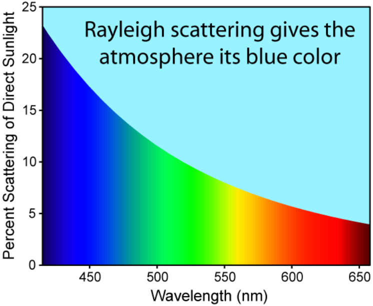


[1]Figure from Serway & Jewett, 9th ed, page 1180.

Why the Sky is Blue: Rayleigh Scattering

The amount (intensity) of the light scattered by small particles depends on the wavelength:

$$I \propto \frac{1}{\lambda^4}$$



shorter wavelength light is scattered more

opalescent glass

[1]Left, Robert A. Rohde, Wikipedia; right, user optick, https://www.flickr.com/photos/optick/112909824/

Summary

- interactions between electricity and magnetism
- light and the speed of light
- reflection and refraction
- polarization

Homework Hewitt,

- Ch 24, onward from page 437. Exercises: 21, 37
- Ch 25, onward from page 452. Exercises: 25, 39
- Ch 26, onward from page 484. Exer: 5, 7, 13; Probs: 1, 3, 7
- Ch 27, onward from page 484. Exercises: 1, 31, 33, 35
- Ch 29, onward from page 527. Exercises: 29, 35