Physics
Unit 6: Waves
(EM Waves)

Notes

Electromagnetic Waves

Electromagnetic (EM) Waves

Electromagnetic (EM) waves (aka electromagnetic radiation) are a different type of wave that can travel through vacuum *or* a physical medium. EM waves transfer radiant energy

These are all examples of EM waves:

- Radio waves sending music to your car
- Microwaves heating your food
- The heat you feel putting your hand over a charcoal grill
- The light you see
- The x-rays the doctor uses to examine your bones

Wave-Particle Duality

So, is light a wave or a particle?

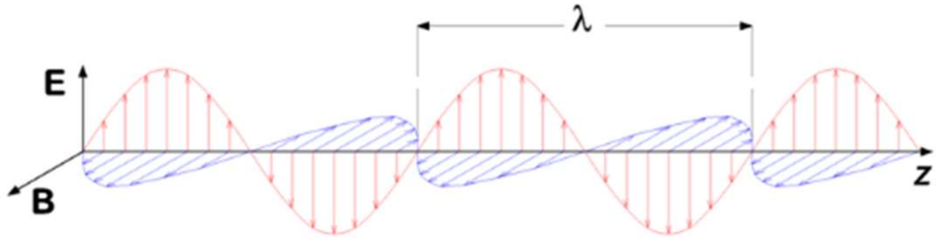
The answer: **BOTH!**

Light (and all EM waves) follows the wave-particle duality, meaning it exhibits characteristics of both waves and particles.

Wave Model of EM Waves

EM waves are simultaneously oscillating perpendicular electric and magnetic fields that carry radiant energy through vacuum or a physical medium

- Changing electric fields generate magnetic fields, and vice versa



Particle Model of EM Waves

EM waves are massless particles called **photons**

Photons are small packets of energy (quanta)

Photon Energy

The energy of a photon is given by the following equation:

$$E = hf$$

E = energy of photon (J)
h = Planck constant, 6.63×10^{-34} J·s
f = frequency (Hz)

Higher frequency (lower wavelength) EM waves have more energy

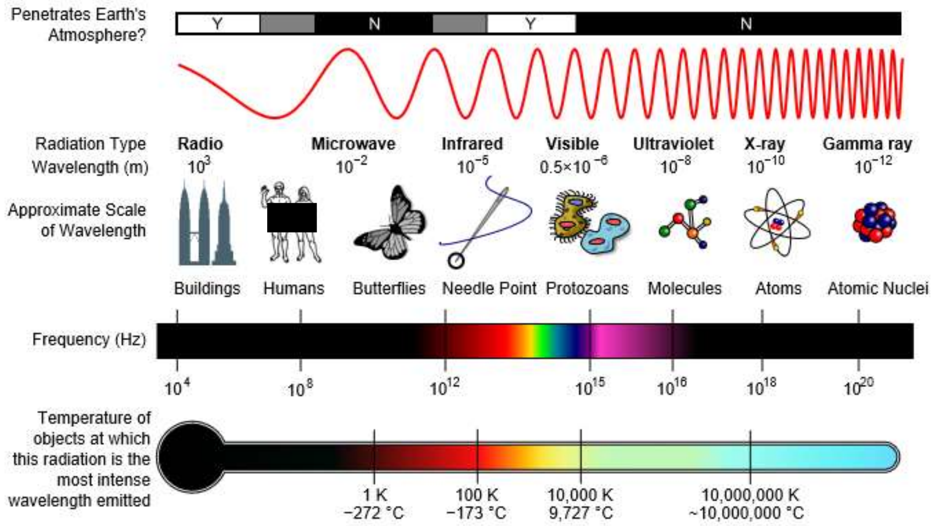
Electromagnetic Spectrum

EM waves occur in a wide range of frequencies called the **electromagnetic spectrum**

We divide this range of frequencies into seven named ranges of frequencies:

- Radio
- Microwave
- Infrared
- Visible
- Ultraviolet
- X-rays
- Gamma ray

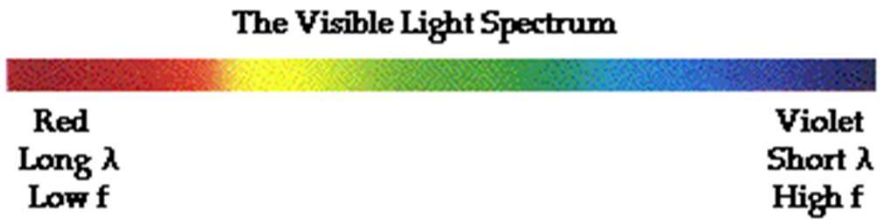
Increasing frequency
Decreasing wavelength
Increasing energy



Increasing energy

EMR Spectrum

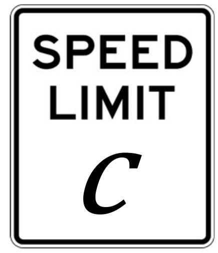
EMR	Wavelengths (λ)
Gamma	$1\text{x}10^{-13}$ to $1\text{x}10^{-12}$ m
X-Ray	$1\text{x}10^{-12}$ to $1\text{x}10^{-9}$ m
Ultraviolet	$1\text{x}10^{-9}$ to $4\text{x}10^{-7}$ m
Visible	$4\text{x}10^{-7}$ to $8\text{x}10^{-7}$ m
Infrared	$8\text{x}10^{-7}$ to $1\text{x}10^{-5}$ m
Microwaves	$1\text{x}10^{-5}$ to $1\text{x}10^{-2}$ m
Radio waves	$1\text{x}10^{-2}$ to 20 m



Red **O**range **Y**ellow **G**reen **B**lue **I**ndigo **V**iolet

ROYGBIV

Speed of Light in Vacuum



$$c = 3.00 \times 10^{8}\ \text{m/s}$$

Speed of light

In vacuum, all forms of EM waves move at the speed of light ($\mathbf{3.00 \times 10^{8}}$)

- Upper most speed limit in the universe—no matter or energy can travel faster than the speed of light.
- In one second, light travels the same distance as 7.5 times the distance around the Earth's equator.
- 1 light year = distance light travels through space in 1 calendar year. 1 LY = 9,460,000,000,000 km.
- 8.33 minutes for sunlight to travel from sun to the earth.

Speed of Light	
Vacuum:	300,000,000 m/s
Air:	299,000,000 m/s
Water:	225,000,000 m/s
Glass:	200,000,000 m/s
Diamond:	124,000,000 m/s

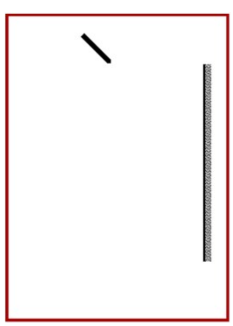
Fastest ↓ Slower

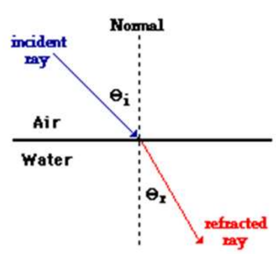
- More dense medium (solids) = move slower
- Less dense medium (gases) = move faster
- Through a vacuum (space) = fastest

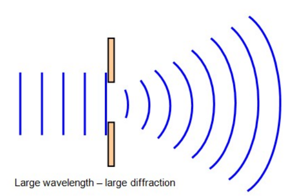
EM Wave Phenomena

EM waves exhibit three phenomena when they encounter a boundary or an obstacle:

1. Reflection
2. Refraction
3. Diffraction







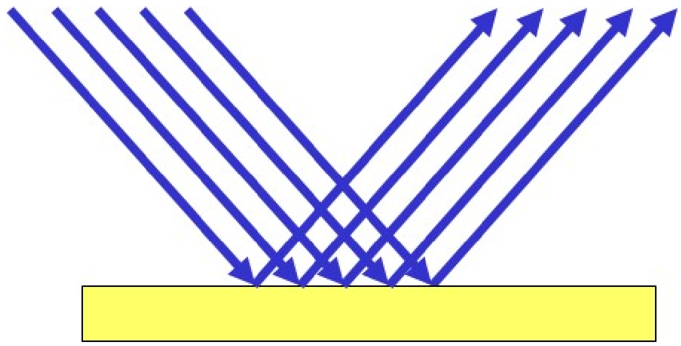
Reflection

Reflection: the redirection of waves (and particles) when they collide with a surface or boundary.

- All waves reflect: light, sound, seismic
- ONLY Direction changes
- Frequency, wavelength, and wave speed remain constant.
- Reflection happens in straight lines from the boundary.

Incident rays (Incoming)
Light or sound waves coming from the source

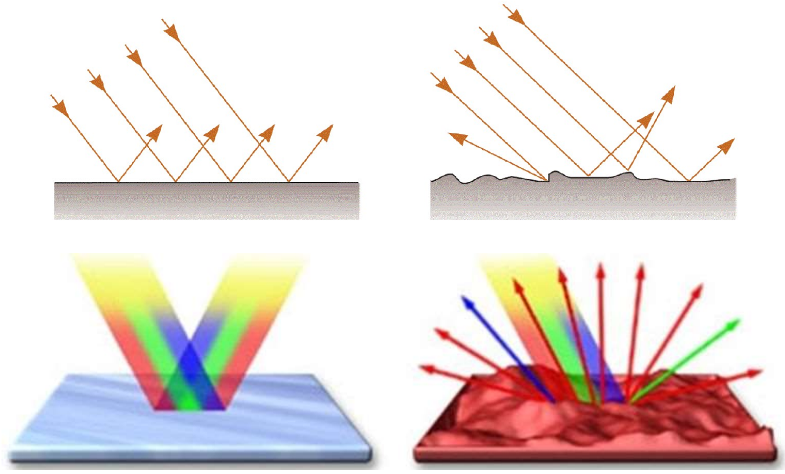
Reflected rays (Outgoing)
Light or sound waves after reflection from surface



Reflective surface or boundary

Perfect reflection: (specular reflection) The parallel rays of light reflect from the smooth surface.

Diffuse reflection: Rays of light are reflected in different directions by irregular or rough surfaces.

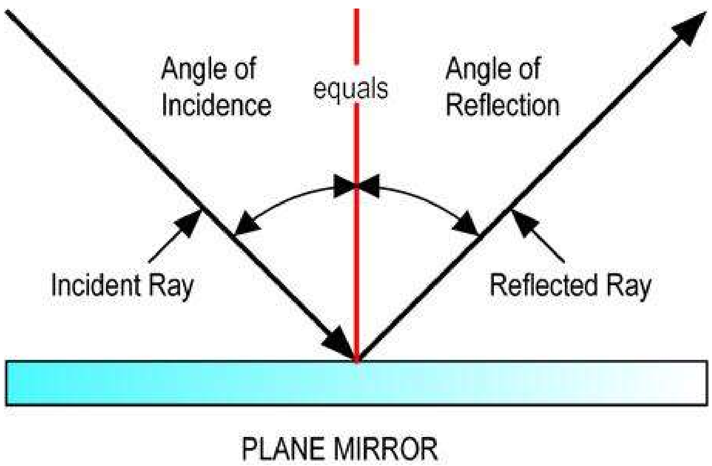


Perfect reflection from smooth, glassy surfaces will produce the **virtual image** on that surface.

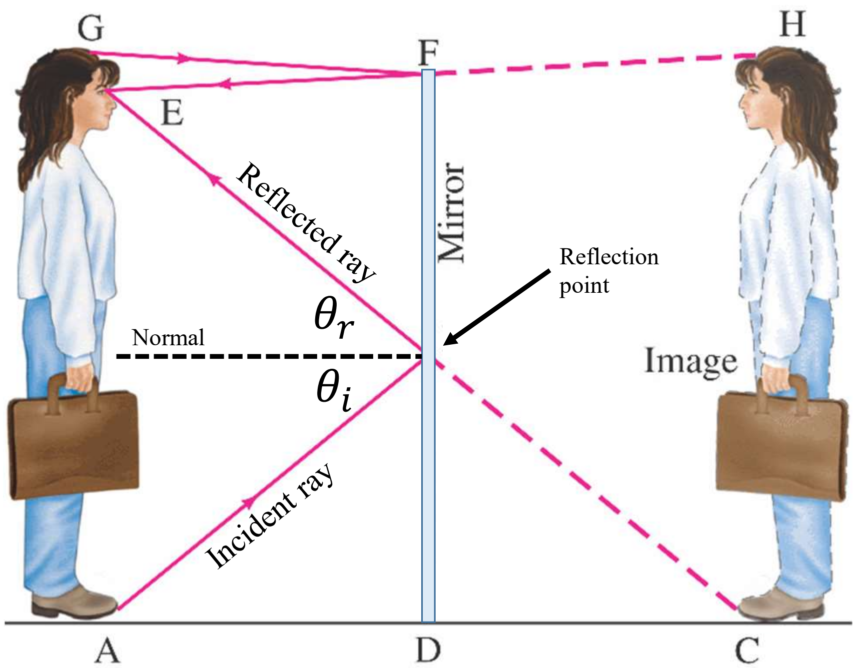
Light waves reflected from the surface are parallel.

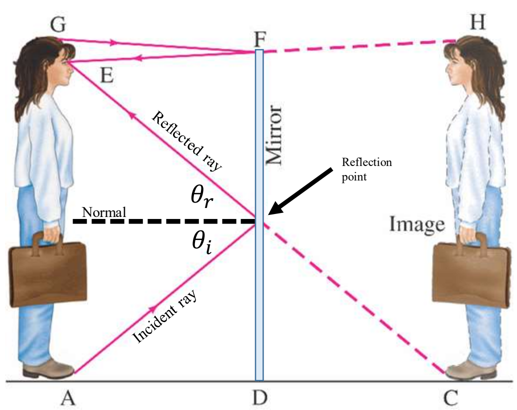
Diffuse reflection from rough, irregular surfaces will not produce a crisp **virtual image** on that surface.

Light waves reflected from the surface are multidirectional and not coherent.



Law of reflection: For planar reflective surfaces, the angle of incidence equals the angle of reflection. (all waves)



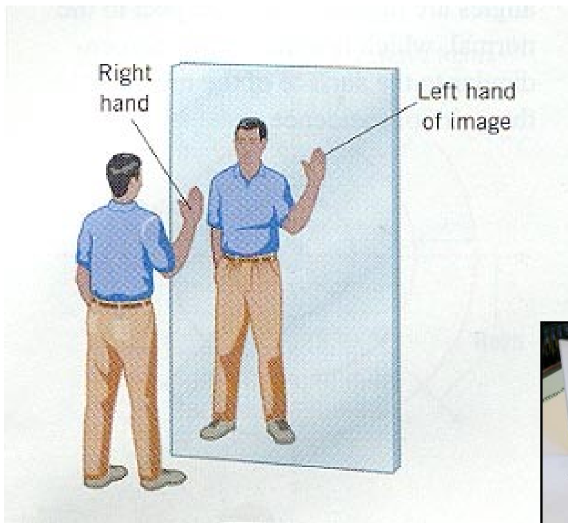


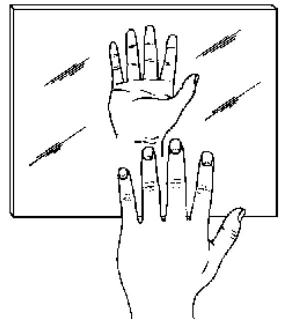
Because of the law of reflection, light reflects from the surface of the mirror's surface (reflection) at the same angle at which it strikes the mirror's surface (incident)

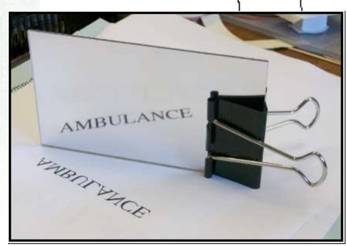
The **reflection point** in the mirror is where the girl must look to see the body part in the virtual image. The reflection point is the midpoint on the mirror between her eye and the body part.

Example: To see her ankle, she must look at the mirror at ½ the distance (midpoint) between her eye and her ankle.

Virtual images in mirrors and reflective smooth surfaces display Left-Right Reversal and Symmetry Reversal.

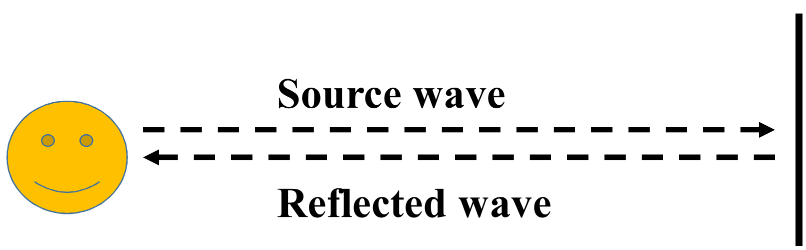






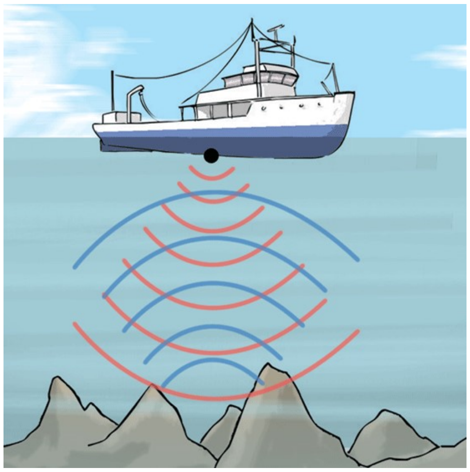
Reflection of Sound

Echo: Reflection of sound waves from a surface.



- Sound is emitted, travels through the medium, reflects from the boundary, and returns to the source.
- The sound wave travels 2-times the physical distance between the source and the reflective boundary.

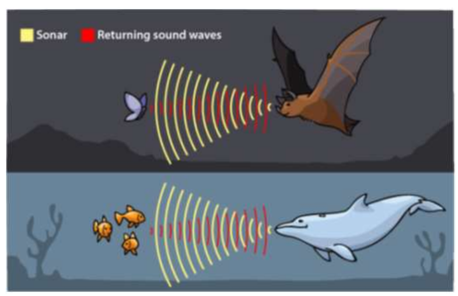
SONAR (Sound navigation and ranging)
Pulses of sound waves are sent by a source (ship, aircraft) through the water, the sound waves impact objects (seafloor, submarines, ships), and the echo returns to the sender.



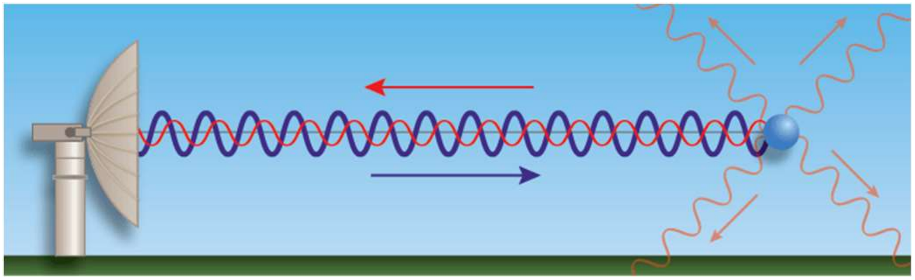
The longer the time interval between the original pulse and the return of the echo, the greater the distance between the source and the object.

The shorter the time interval between the original pulse and the return of the echo, the shorter the distance between the source and the object.

Echolocation
Bats and dolphins use pulses of ultrasound sound waves for hunting prey.



Ultrasound imaging.
Ultrasound sound waves reflect off of the internal organs and unborn baby, the echo returns to the receiver where the image is created.



RADAR (Radio waves)

- Radio waves travel at the speed of light (300,000,000 m/s).
- They are emitted from an antenna or dish, they travel through air or space, reflect off of objects, and return to the receiver.
- This happens in under 1 second.
- Identification of how far and how fast aircraft and weather phenomena move.

Refraction

Speed of Light in Different Media

- Light in a vacuum travels at *c* (3.00×10^8 m/s)
- Light in a physical medium will travel at a lower speed
- The **optical density** of a medium refers to how slowly light travels in that medium
  - The more optically dense, the slower light moves
- Optical density is measured with a value called the **index of refraction**

Index of Refraction

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

n = index of refraction (no unit)
c = speed of light in a vacuum (3.00×10^8 m/s)
v = speed of light in the medium (m/s)

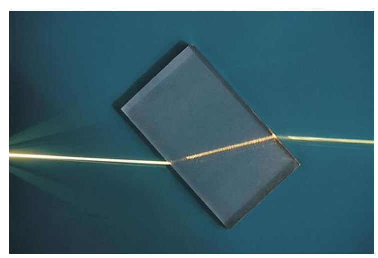
Note:
- Index of refraction is always ≥ 1
- Higher index of refraction means slower light in the medium

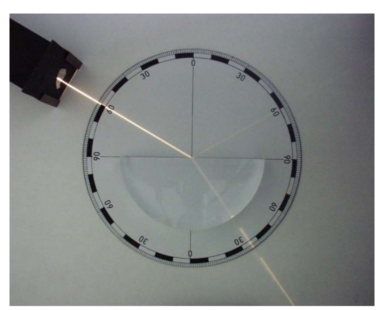
Material	n
Vacuum	1
Gases at 0 °C and 1 atm	
Air	1.000 293
Helium	1.000 036
Hydrogen	1.000 132
Carbon dioxide	1.000 45
Liquids at 20 °C	
Water	1.333
Ethanol	1.36
Olive oil	1.47
Solids	
Ice	1.31
PMMA (acrylic, plexiglas, lucite, perspex)	1.49
Window glass	1.52[11]
Polycarbonate (Lexan™)	1.58[12]
Flint glass (typical)	1.62
Sapphire	1.77[13]
Cubic zirconia	2.15
Diamond	2.42
Moissanite	2.65

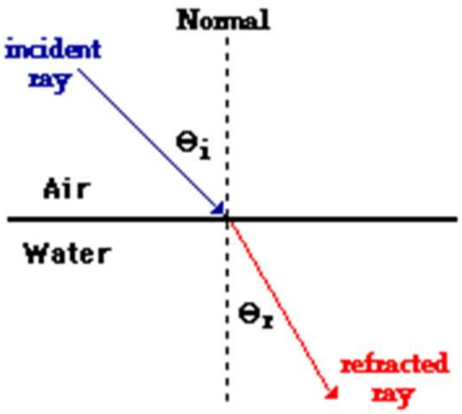
Refraction

- For two media in which there are different speeds of light (i.e. different indices of refraction), when light crosses the boundary between one medium and the other, the path of the light will bend

- This bending is called **refraction**







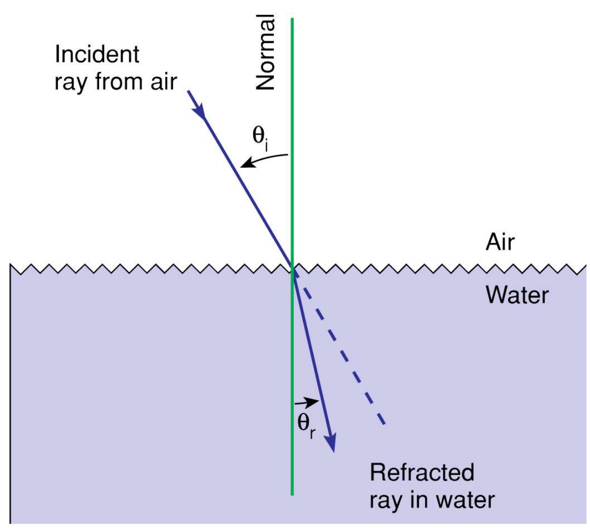
θ_i = angle of incidence

θ_r = angle of refraction

In this case, light passes through a boundary from **air into water**
- Light goes from higher to lower speed
- Light bends toward the normal

Faster wave speed
Greater angle

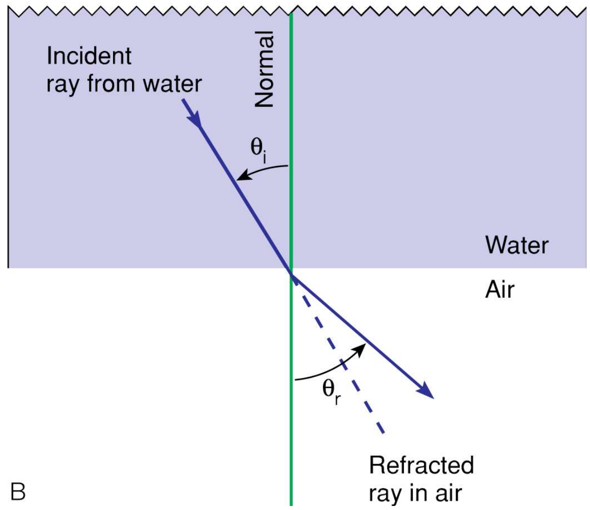
Slower wave speed
Smaller angle

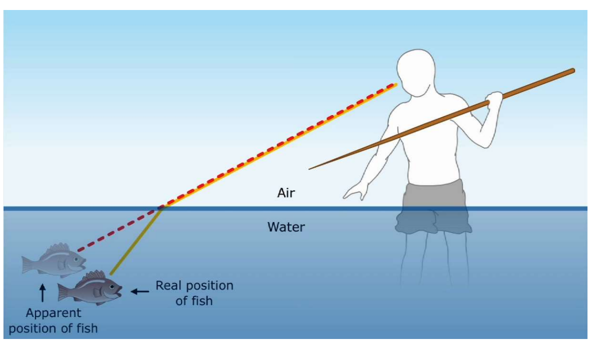


In this case, light passes through a boundary from **water into air**
- Light goes from lower to higher speed
- Light bends away from the normal

Slower wave speed
Smaller angle

Faster wave speed
Greater angle



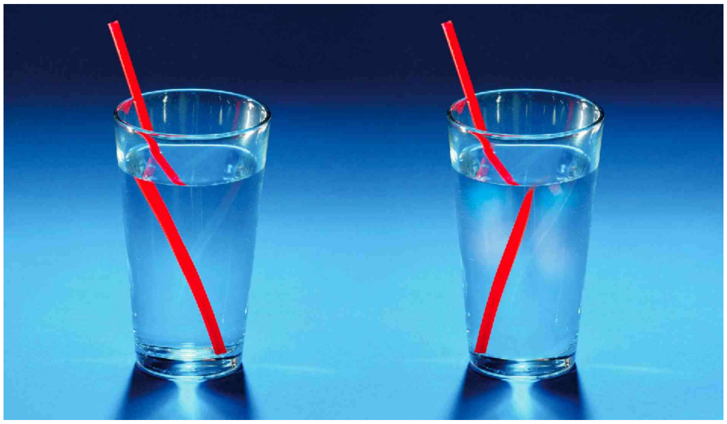


The fish's real position in the water and where the fisherman sees the fish are not in the same location.

Light reflects off of the fish. The light waves move through the water, pass into air, then move to the fisherman's eye.
- In the water, light is slower and closer to the normal.
- In the air, light is faster and away from the normal.

The light waves refract away from the normal as they pass from the boundary of water → air.

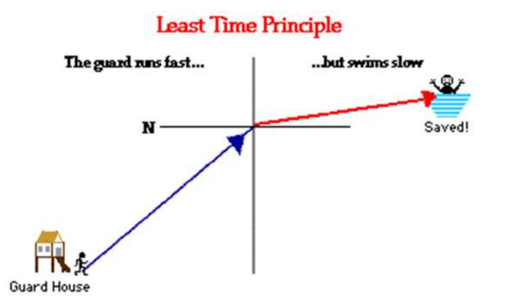
Water Mineral oil



The straws appear broken when viewed through the clear glass. The light is refracting from the liquid to glass, then from glass to air. The curvature of the glass changes the refraction angles more than a regular flat boundary.

Why does refraction occur?

- Fermat's Principle: the principle of least time



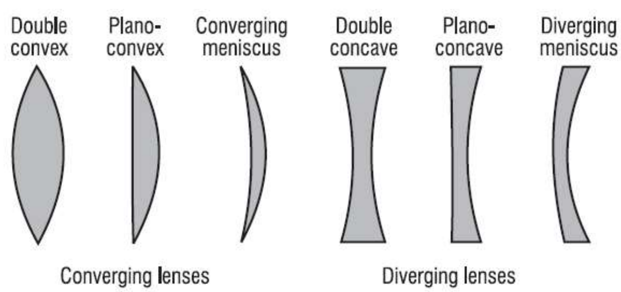
To reach the drowning swimmer in the least amount of time, the life guard must maximize the time spent running in the sand. Once reaching the sand-water boundary, the life guard turns and runs closer to the normal line.

Lenses

How do we use refraction for useful purposes?

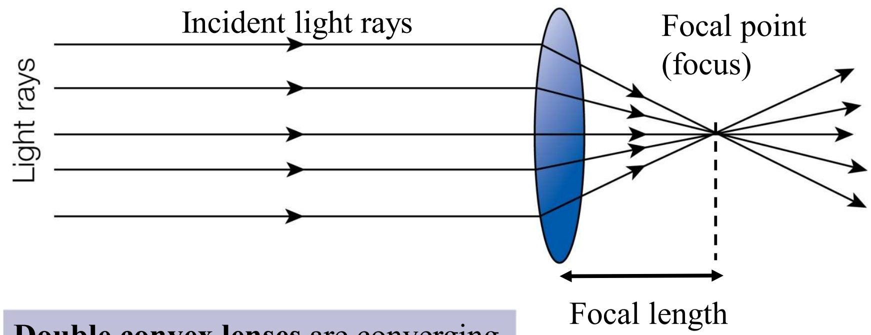
LENSES

Lenses are polished, curved pieces of transparent material (glass, plastic, quartz) that are used to transmit and focus light rays.

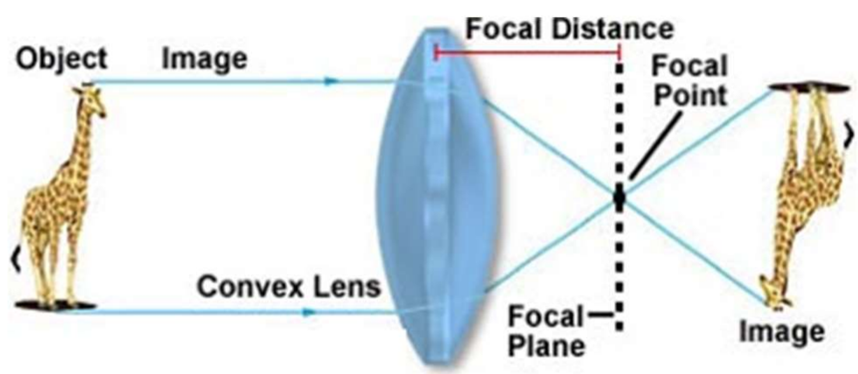


Light rays pass through the lens and refract. The shape of the lens determines the lens's function.

Converging lens: A lens that brings light rays together to a common focus—light rays cross. Converging lenses are used to enlarge images and to project real images on screens and flat surfaces.

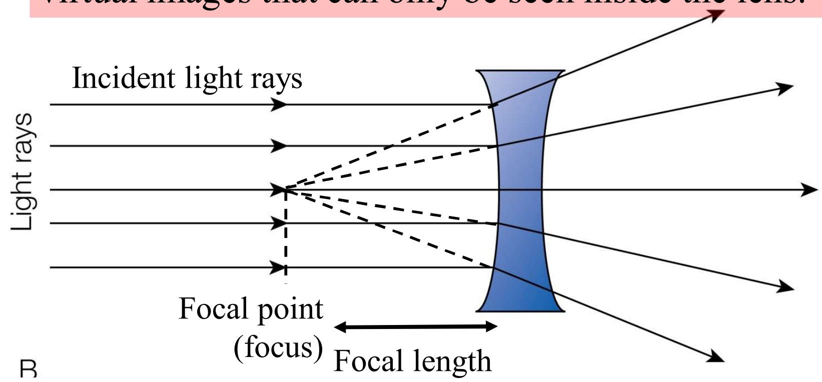


Double convex lenses are converging lenses. They bring light to a common focus on the other side of the lens.

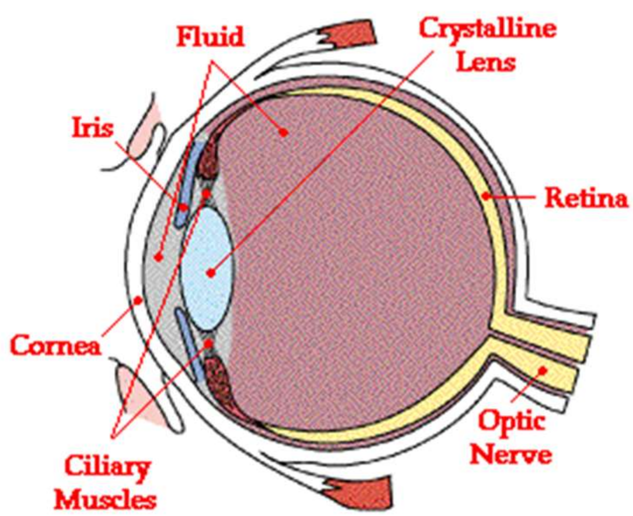


Notice that the image of the giraffe is inverted and left-right reversed. This happens because the light rays on the refracted side cross through each other at the focal point and continue to move away in straight lines.

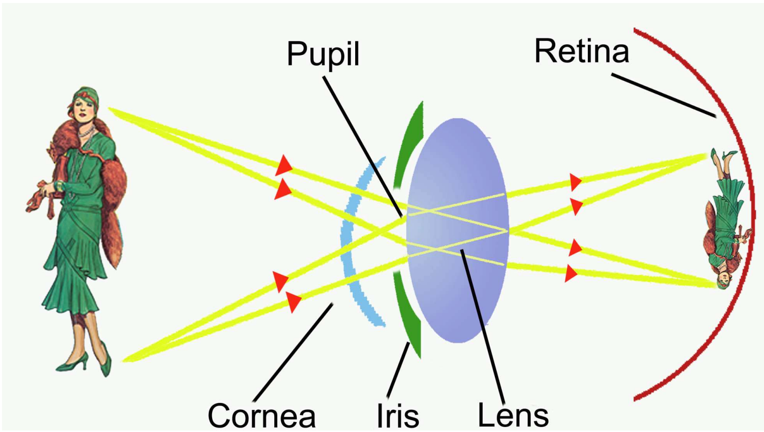
Diverging lens: A lens that spreads out light rays after passing through the lens. Diverging lenses produce virtual images that can only be seen inside the lens.



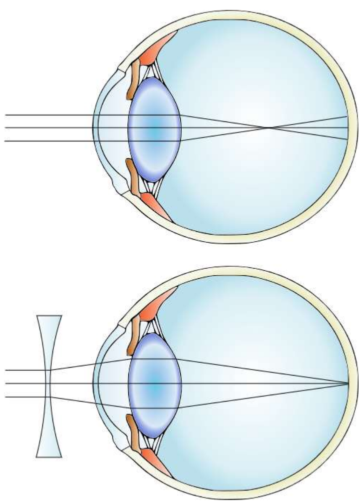
Double concave lenses are diverging lenses. They spread light rays out. The focal point is between the source and the lens.



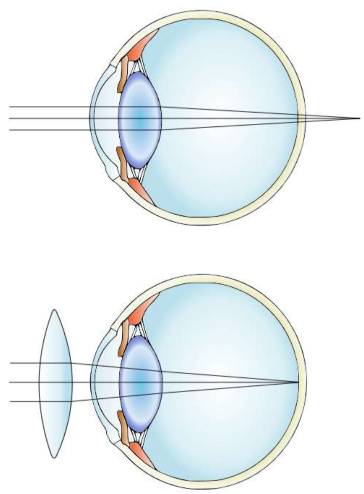
The anatomy of the human eye. Notice that the retina collects light as an upside down & inverted real image. The brain flips the image as it processes information to an upright mental picture.



Near-sightedness

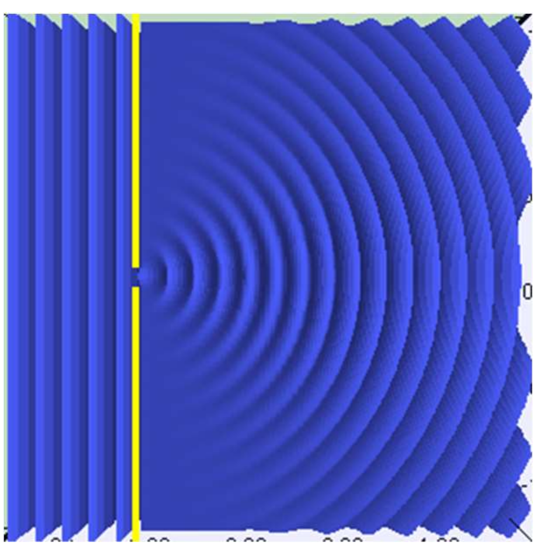


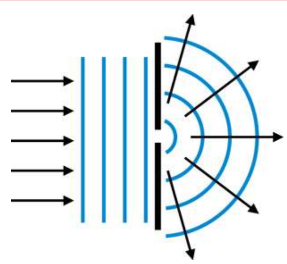
Far-sightedness



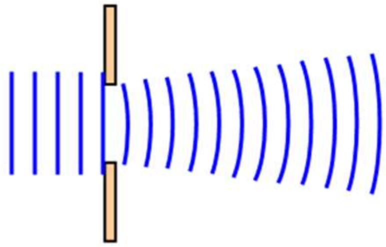
Diffraction

Diffraction: Waves spread out after passing through small openings or spread out around the edges of obstacles.

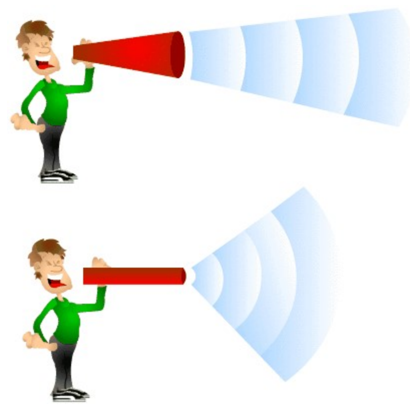


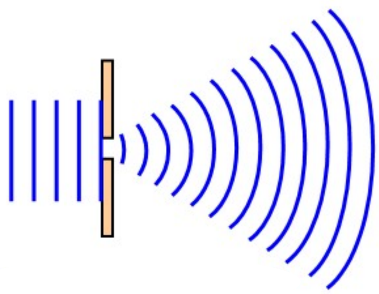


Waves with longer wavelengths and lower frequencies diffract more than waves with shorter wavelengths and higher frequencies.

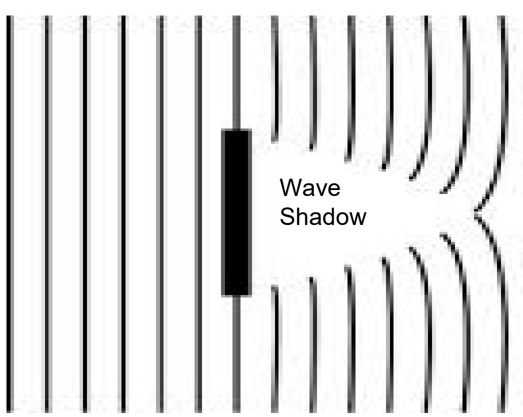


Waves passing through narrow openings diffract more than waves passing through wider openings.



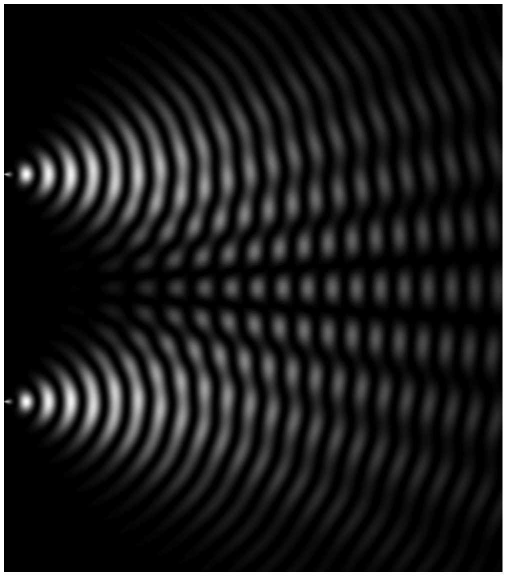


Waves passing around obstacles will diffract and eventually merge with some interference on the other side.

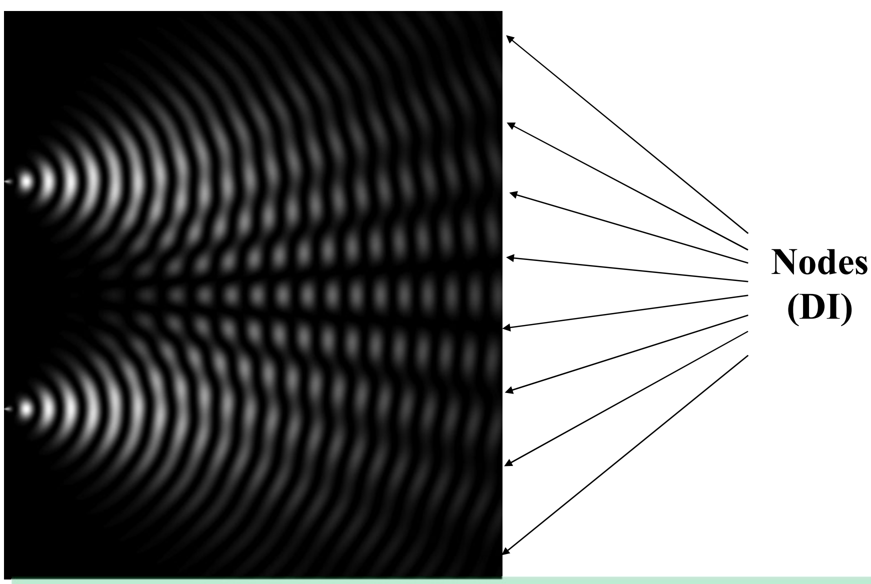


The **wave shadow** is the area "of calm" behind the obstacle not affected by the diffracting waves.

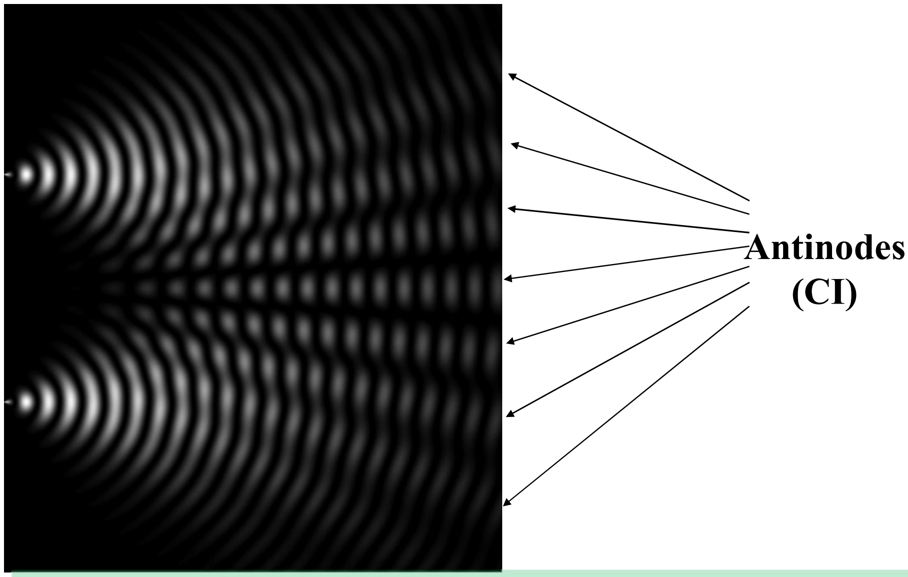
Diffraction interference patterns



If light or waves are emitted from multiple slits or openings, the overlapping waves will constructively and destructively interfere with each other to form the **diffraction interference pattern**.



The dark bands are **nodal lines**, the series of nodes cause by the local destructive interference by the successive overlapping waves from the two sources.



The light bands are the antinodes, the local constructive interference by successive overlapping of waves from the two sources.

Visible Light & Color

Luminous objects generate and emit their own visible light or white light. Stars, fire, and light bulbs are luminous. Those object generate and emit their light.



Emission: The release of radiant energy (EMR, visible light, photons) by matter. Light is given off (not reflected).

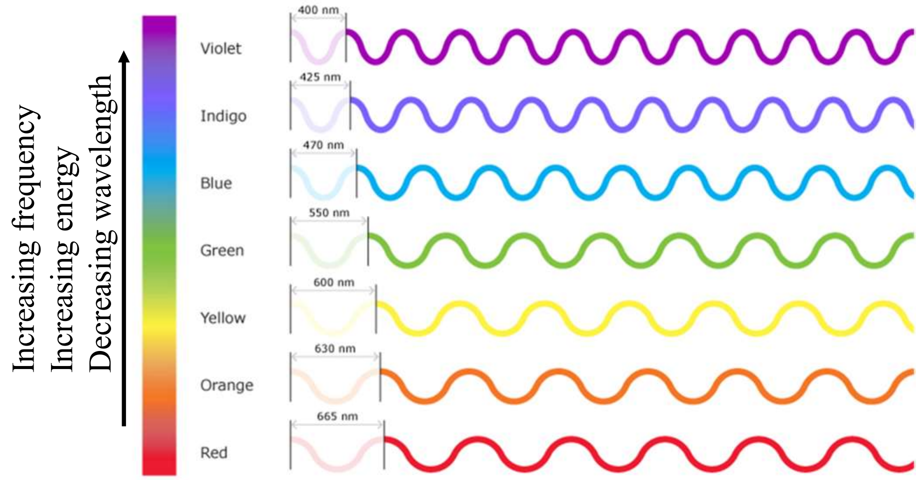




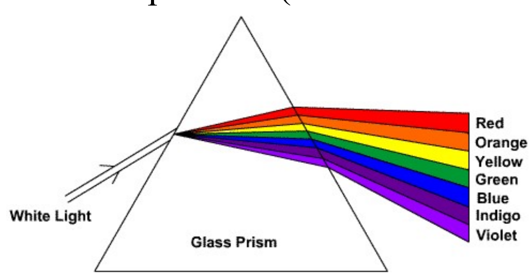
Incandescence: Objects have temperatures that are so hot that they emit visible light. (fire, surface of stars, incandescent light bulbs, forged metals).

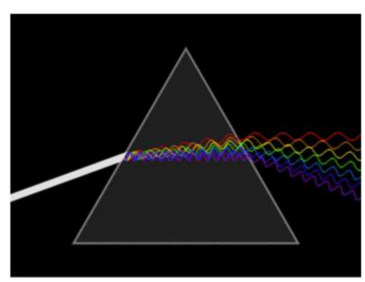
- Incandescence begins around 800 K (527ºC) as a pale red glow (like a metal poker in a fire).
- At much hotter temperatures, the color of incandescing matter changes from red to blue as temperature increases.

Visible Spectrum



White light: Total collection of all wavelengths of the visible spectrum (all colors ROYGBIV collectively).





Double refraction of white light through a prism yields the separation of the visible spectrum into bands of color.

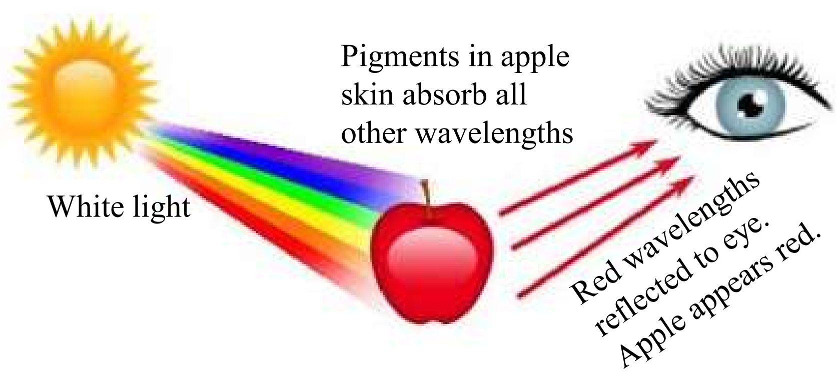
Shorter wavelengths (blues) refract more than longer wavelengths (reds).

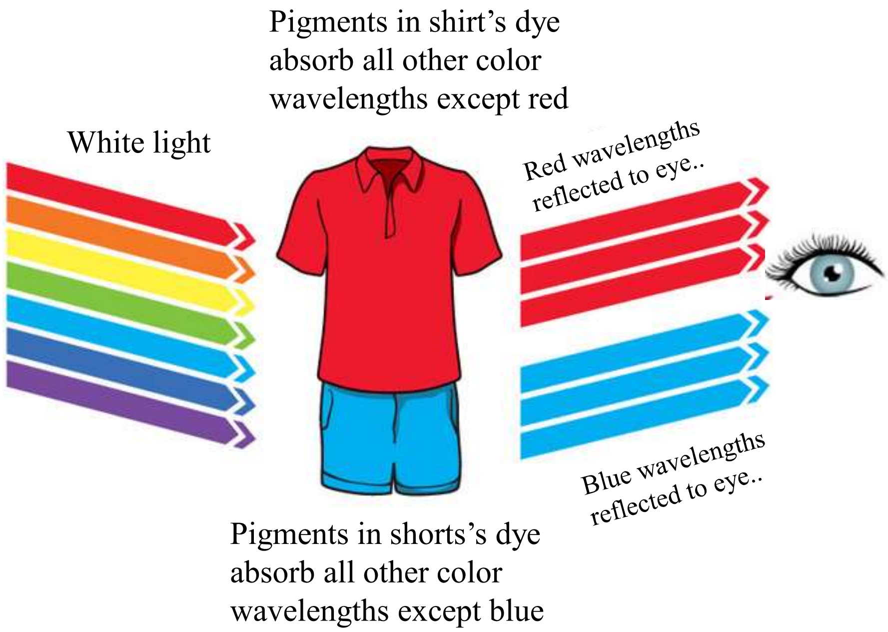
Pigments are chemical compounds that selectively absorb specific colors and reflect specific colors.

Pigments create **pure colors** of paint and dyes.

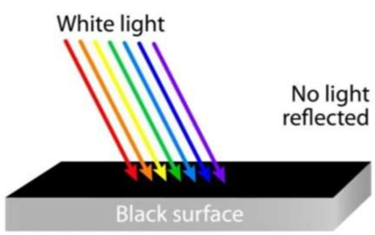
We see objects because of the light reflected off of the surface of objects to our eyes.

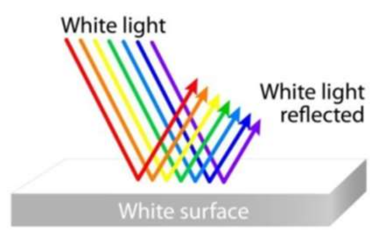
The pigments in the apple's skin selectively absorbs all wavelengths of the color spectrum except for red. Red wavelengths are reflected to the eye.





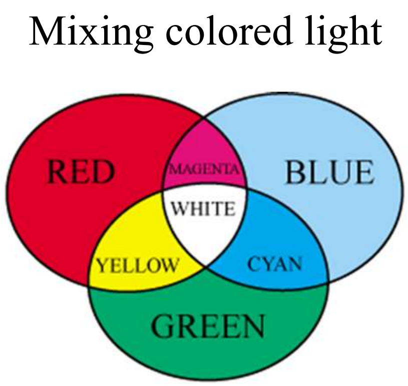
Black and White

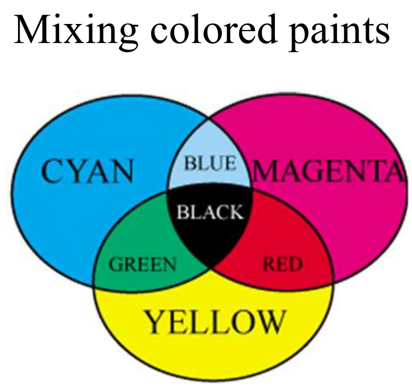




Objects appear as **black** when most or all wavelengths of colored light are absorbed by the surface and no light is reflected to the eye.

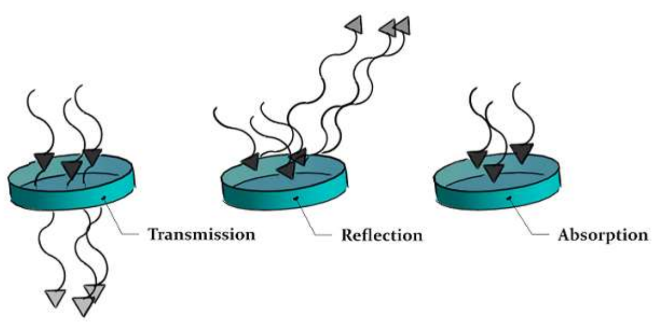
Objects appear as white when most or all wavelengths of colored light are reflected by the surface to the eye and no light is absorbed.





If all of the primary light colors are mixed, the result is white light.

If all of the primary hues of pigments are mixed, the result is black.



- **Transmission**: The property of matter that describes how light penetrates or passes through it.
- **Reflection**: The redirection of waves or light off of a surface or boundary of another material.
- **Absorbance**: The assimilation of radiant energy by a material.

Transparent: clear; allows light to pass through the material without distortion. Undistorted images can be seen through the material. (glass, still water, air)

Translucent: semi-clear; light will pass through the surface of the material, but the light will become distorted or blurred because of interference in the interior. (gems, silk, milk, clouds)

Opaque: light will not pass through the surface of the object.

Brightness of Light

What affects "how bright" light emitting objects appear?

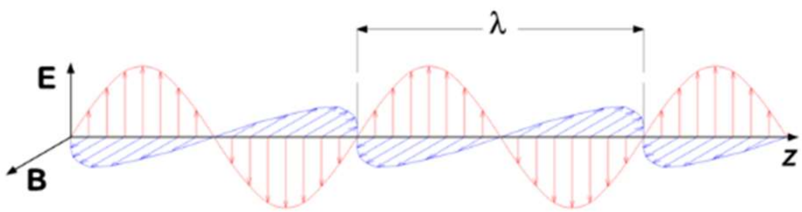
- **Luminosity**: the amount of light emitting power.
- **Distance**: how far away is the light emitting object from the observer.
- **Scattering**: are there clouds, haze, or suspended particles that may reduce the light in between the source and the observer.

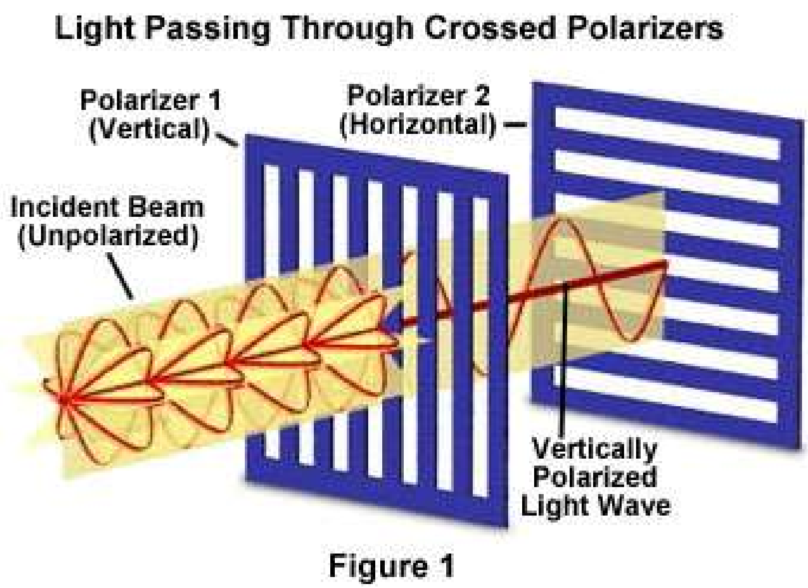
Polarization

Polarization

Polarized light means that the oscillating electric fields of a group of light waves are all aligned (for example, they all oscillate up and down)

Passing unpolarized light through a polarizer will produce polarized light





Uses for Polarizers

- Sunglasses (reducing glare)
- Photography
- 3D movie glasses
- Stress analysis