National Academy of Opticianry

# Continuing Education Course

Approved by the American Board of Opticianry and the National Contact Lens Examiners

# The Basics of Light, Refraction & Reflection

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## Course Description

This course will introduce the basics of light. Included in discuss will be two light theories, the principles of refraction (the bending of light) and the principles of reflection.

## Learning objectives/outcomes

At the completion of this course, the participant should be able to:

- Discuss the differences of the Corpuscular Theory and the Electromagnetic Wave Theory
- Have a better understanding of wavelengths
- Explain refraction of light
- Explain reflection of light

## Optical Theory

In this module, we will be discussing the optical theory of light, discussing both visible light as well as Invisible light. Light is comprised of both visible and invisible light. As a matter of fact, "Visible" light makes up a very small percentage of light.

## Understanding Light

Optics is the scientific study of the behavior of light, and covers reflection, refraction, diffraction and interference, as well as polarization of light.

Clinically, light is how we see. It transports visual impressions. Technically it is a form of radiant energy. It stimulates receptor cells on the retina, which in turn transmits impulses to the brain allowing us to see. In addition, light is essential for life on earth.

Interestingly enough, there are two theories of light that coexist, simply because facts that are unexplained in one theory are explained in the other. Neither is complete, but neither is totally incorrect as well. Therefore the two theories of light that we will be discussing are the Corpuscular Theory and the Electromagnetic Wave Theory.

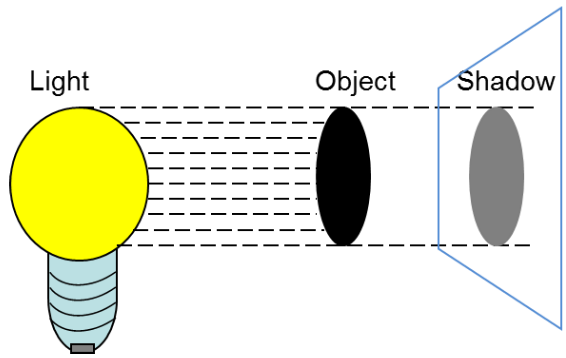
For example, the corpuscular theory (sometimes referred to as the particle theory) explains how we get heat from light, while the electromagnetic wave theory explains a behavior of light called interference.

Although we won't be discussing the Quantum Theory of Light, just for inclusion, let us say that it is more mathematical than Maxwell's equations, and is similar to the corpuscular theory of Newton, except that instead of describing light as particles, light is composed of 'packets of energy' or photons. The energy of the photon determines the color.

### Corpuscular Theory of Light

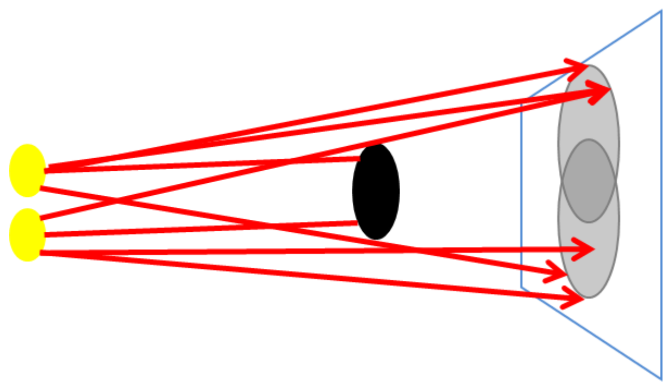
Originally introduced by Pythagoras and later elaborated on by Sir Isaac Newton, the corpuscular theory of light states that light consists of tiny particles or bundles of corpuscles, which are emitted by the light source and gathered in (absorbed) by the eye allowing for a visual experience.

We use this theory to describe reflection. It also explains how light can be used to create electrical energy and to used to describe reflection, as well as rainbows.
The Corpuscular Theory can explain shadows, in that the tiny particles of light will be stopped by an object and unobstructed particles will continue on, forming a shadow.




**Indistinct Shadow**

If light from two separate sources fall on the same object, two shadows overlap resulting in an indistinct shadow.



**Electromagnetic Wave Theory**

The Electromagnetic Wave Theory explains that light travels in a series of waves moving outward from a light source. The electromagnetic wave theory explains how a rainbow is formed, how light is dispersed when it passes through a prism, and how a telescope works.

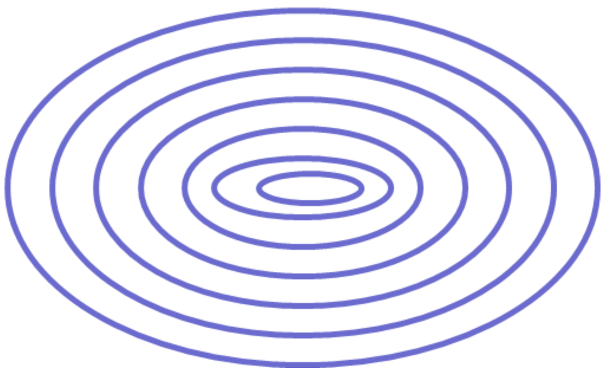
Begun as the Wave Theory of Light proposed by Huygens in 1678, this theory describes light as waves that move out/spread out from the source that generates light. Each color is a different wavelength. Supernumerary bows are explained by assuming that light is a wave.

James Clark Maxwell elaborated on the Wave Theory and describes light as having electric and magnetic properties--electromagnetic waves. It is an improvement over the wave theory in that it explains how light is generated. Visible light is only one type of electromagnetic wave. This theory is very math intensive.

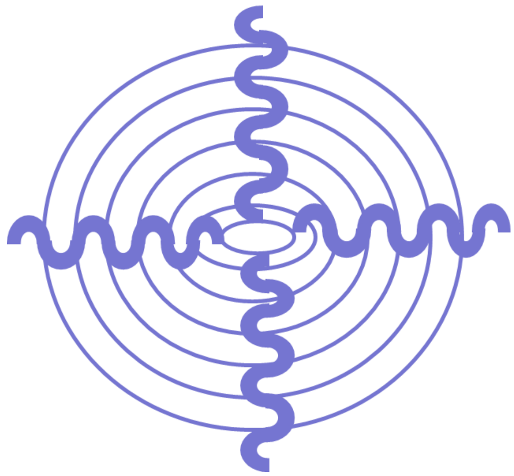
At first, it was thought that light might be some sort of wave motion that was a mechanical vibration of the ether (air). This idea finally allowed the electromagnetic wave theory to be brought into acceptance.

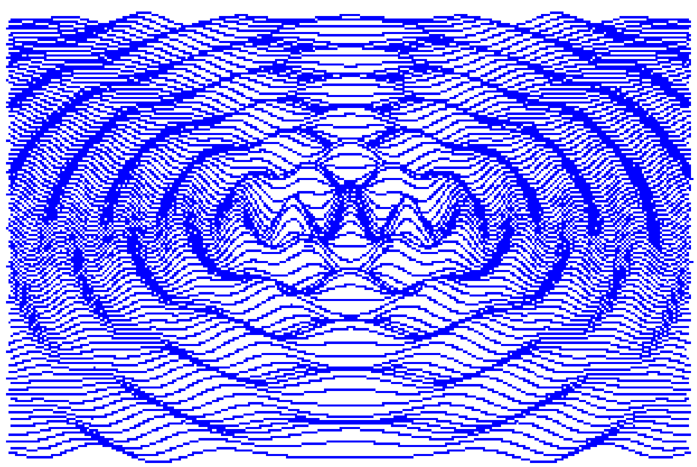
This is the theory that we use today to explain light. It describes the range of wavelengths. Wavelengths are expressed in nanometers (nm). As stated earlier visible light is only a small portion of the electromagnetic spectrum. On the short end are Gamma rays, X-Rays, Ultraviolet rays, and on the long end are Infrared, Radar, Radio, TV.

The Electromagnetic Wave Theory is the generally accepted theory used today. It is described as waves moving outward from the light source in concentric rings much like waves created by a pebble tossed in a pond. This theory also explains how white light is broken into its component parts when passing through a prism. The components colors are red, orange, yellow, green, blue, indigo, violet.



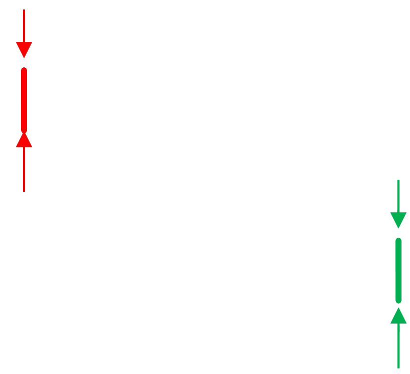
This example demonstrates how the waves travel or vibrate up and down and also travel outward from the center. This is called a transverse motion. Electromagnetic waves travel in much the same way when emitted from a light source.





***Wavelength***

Light is measured by its wavelength. Wavelengths are the distance between pulsations, either from crest to crest or trough to trough. It is the distance traveled forward by a wave as it goes through one complete vibration. Wavelengths are measured in nanometers (nm). A nanometer is one billionth of a meter. 0.000000001 m.



*Frequency*

Frequency is the number of times a wave vibrates in one second. A cycle is defined as one complete vibration of a wave, and hertz is the number of cycles per second. One kilohertz is equal to 1000 hertz.

*Velocity*

Velocity is the speed at which a wave travels forward.

*Light*

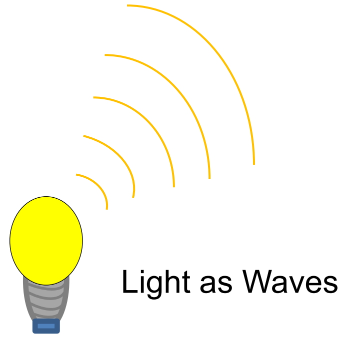
OK, let's put this together a little. First of all, light diverges from a source in waves. These form wavelengths. Both wavelengths and frequency are important in determining the measurement of light. The relationship of wavelength and frequency determines the velocity or speed of light. Finally, the formula for determining the speed of light is:

*Velocity = Wavelength X Frequency*

So, if a wave vibrates 10 times each second and travels forward one meter each time, its velocity is 10 meters per second.

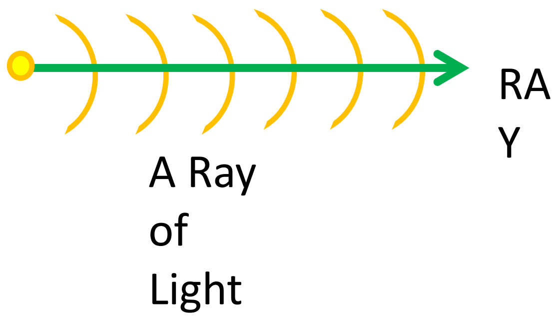
The velocity of all EM radiation is the same in air. Therefore, the velocity or speed of light in air (with an index of refraction of 1.0) is 186,000 miles per second. Light travels through space at this speed but slows down when traveling through various transparent materials. How much slower is dependent on the density of the material. The more dense the material, the slower the light travels. This will be discussed later in the OCPP.

Light travels outward from its source in waves. In the illustration below, light is traveling from a point source, e.g., a light bulb moving as a series of waves traveling in all directions equally. We draw it as a series of concentric circles.

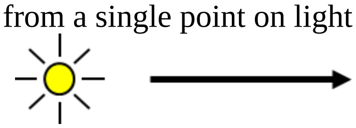



*Rays, Pencil, Beam*

If we picked one direction and drew an imaginary line at any given point, perpendicular (at right angles) to those waves, that imaginary line would be called a ray. This ray denotes the path of the waves or the path taken by one photon. Therefore, a ray of light shows the path in which light is traveling.

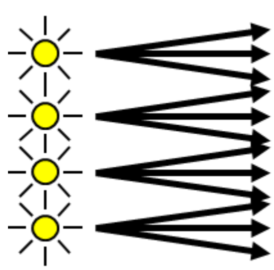



A ray is a single band of light from a single point on light source.



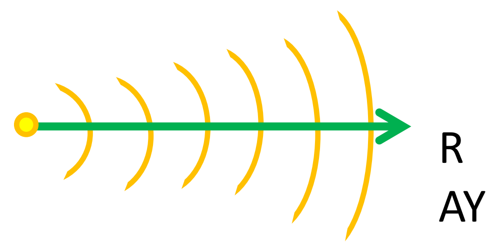
A pencil is a group of rays emanating from a single point on a light source.

A beam is a group of pencils emanating from all points on light source.

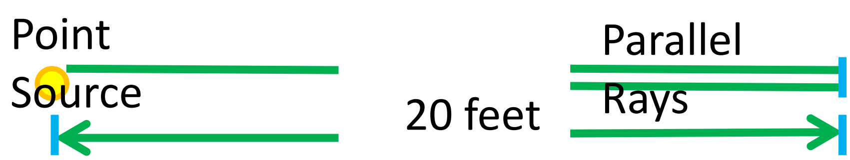


A ray is used almost exclusively, but remember the ray is representing the movement of a wave front of light. What is happening to that one ray is also happening to a larger part of that wave front.

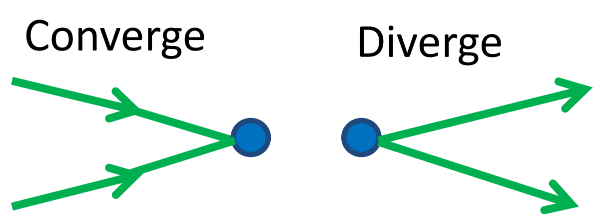
Rays may travel any distance. Imagine the rays of light coming from the sun. They are in fact representing wave fronts which are almost no longer curved, and the rays therefore are practically parallel.




The distance of six meters (20 feet) is a long enough distance to effectively produce parallel rays, as if they were coming from infinity.




Now rays may be parallel, may come together (converge), or move apart (diverge) This vergence of rays (light) will be the basis for which we will study the action of rays (light) on flat or curved surfaces. Vergence is described in diopters and distance is described in meters.

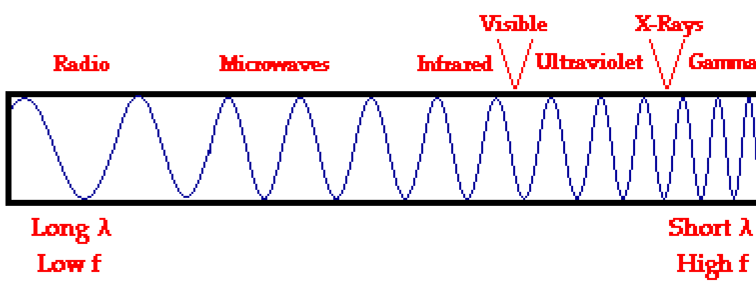



***Wavelength & Color***

In this section, we will be discussing wavelength and color.  We will include both visible and invisible light, and the qualities of light.  Visible light is a combination of different colors that have differing wavelengths.  They create the visible spectrum.

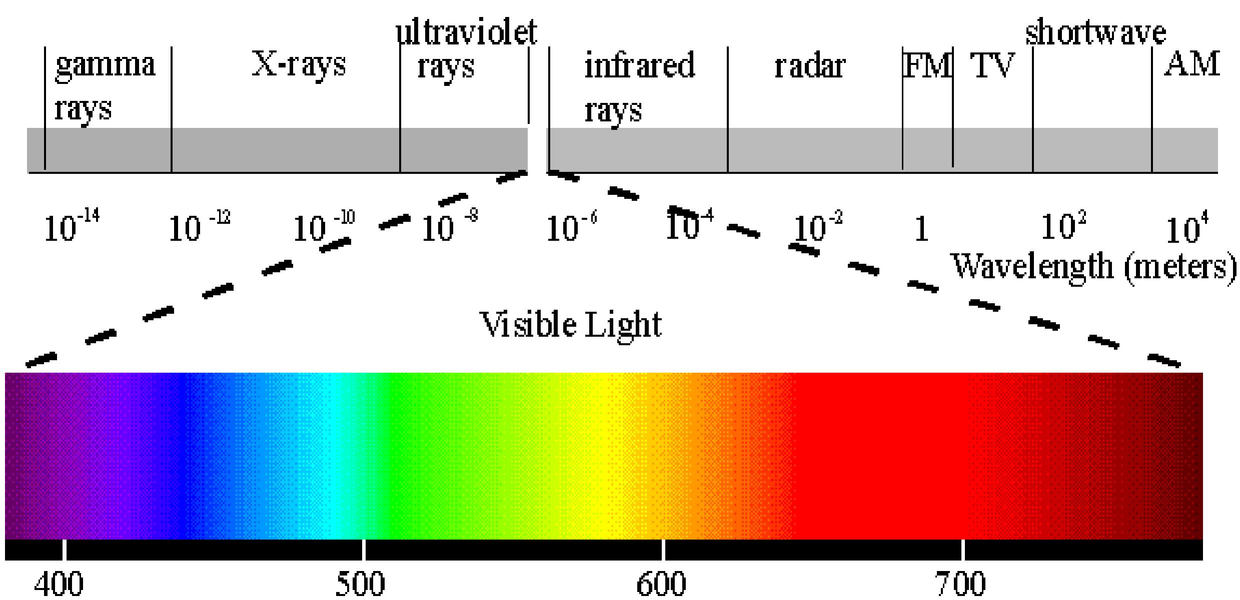
**Electromagnetic Spectrum**

Electromagnetic waves exist with an enormous range of frequencies. This continuous range of frequencies is known as the electromagnetic spectrum. The entire range of the spectrum is often broken into specific regions. The subdividing of the entire spectrum into smaller spectra is done mostly on the basis of how each region of electromagnetic waves interacts with matter. The diagram below depicts the electromagnetic spectrum and its various regions. The longer wavelength, lower frequency regions are located on the far left of the spectrum and the shorter wavelength, higher frequency regions are on the far right. Two very narrow regions within the spectrum are the visible light region and the X-ray region. You are undoubtedly familiar with some of the other regions of the electromagnetic spectrum.

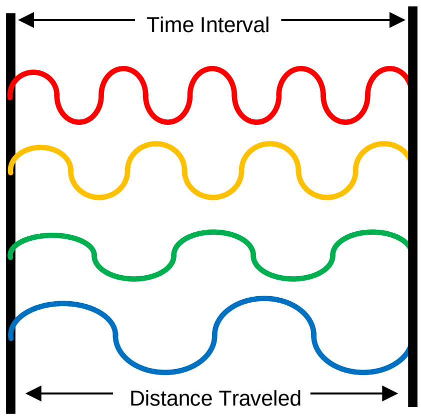



**Visible Spectrum**

The visible spectrum falls within that portion of the electromagnetic spectrum between 380 nanometers (nm) and 750 nanometers (nm). On the lower end of the visible spectrum in the invisible spectrum lies the UV rays, X-Ray and Gamma (Cosmic) rays. On the upper end, lie the infrared, radar, FM, TV, shortwave and AM Rays.



OK, since visible light is composed of colors, why don't we see the colors in the air around us? It's simple, in air, the different wavelengths travel outward from the source at the same speed…it's just the up and down motion (vibrations) that differ in frequency. Each light has traveled the same distance in the same amount of time, although maintaining its own velocity or vibration rate while traveling that distance. So until it hits something like a prism, to break it up into its components, all we will see is white light.




*Electromagnetic Radiation*

The approximate wavelengths of the visible spectrum including those just on either side are:

- Ultraviolet
- UVC: 200 - 275 nm Ozone Layer
- UVB: 275 - 330 nm Sunburn
- UVA: 330 – 380/400 nm Ocular Hazard
- Visible Light
- 380/400 - 750 ROY G BIV
- Infrared - Heat
- 750 - 1,000,000 nm

*Invisible Light*

Ultraviolet light is the high-energy invisible light that is divided into three categories, UV-A, UV-B and UV-C. UV-C ranging from 190nm to 280 nm is not thought to be of concern because it is filtered by the earth's ozone layer, however UV-A at 315 to 380 nm and UV-B at 280 to 315 nm can cause damage to the tissues of the body including the eye.

*High-Energy Visible Light*

Blue light or more accurately the blue and violet portion of the visible light spectrum is the high-energy visible light (HEV), which research is beginning to show is a contributing factor to age-related macular degeneration (AMD).

As we age, there is typically less antioxidant that protects our eyes and we lose more of the protective melanin pigment that is found in our skin and retina. The less pigment a person typically has (lighter complexions, light eye colors) the greater the exposure risk becomes.

## Refraction and Reflection

Now let's proceed with information on refraction and reflection.

*Index of Refraction*

Since the speed of light in air is 186,000 miles per second, we will use that number in determining how fast light travels through other mediums. When light travels through any substance other than air, it slows down according to the degree of the chemical composition (hardness) of the substance it is passing through. The important relationship of the speed of light in air to the speed of light in another substance (medium) is called the index of refraction. The index of refraction of a substance is a comparison of the speed of light in air to the speed of light in the transparent substance.

The formula for this relationship is:

$$n = \frac{\text{speed of light in air}}{\text{speed of light in the medium}}$$

In other words, the higher the index of refraction, the slower the speed of light in the medium, the more light is bent as it passes through the medium. On the other hand, the faster the speed of light in the medium, the less light is bent as it passes through the medium.

Let's use the formula. Let's say the peed of light in the medium is 124,165 miles per second. The formula becomes 186,000 divided by 124,165. n = 1.498, which is CR-39 plastic.

You can also find the speed of light through a medium by reversing the formula and dividing the index of refraction into the speed of light in air.

$$\text{Speed of light in a medium} = \frac{\text{speed of light in air}}{n}$$

Let's discuss rounding off for just a moment. If for instance we drop the 0.008 from 1.498 and use 1.49 (which some people do) as the index of refraction, it would seem that the speed of light through CR-39 would be 124,832 miles per second. If we round it up to 1.5, it would seem that the speed of light through CR-39 would be 124,000 miles per second. I believe in leaving the number carried out at least to the third decimal.

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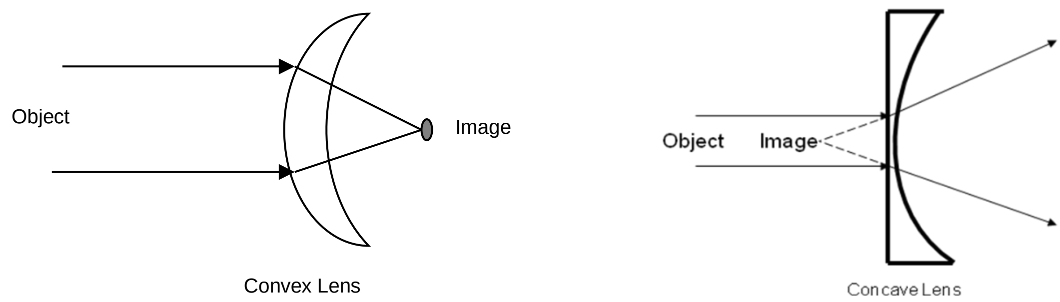
*Real Images*

Real images are formed when light rays pass through an optical medium and converge (come together) to a point.

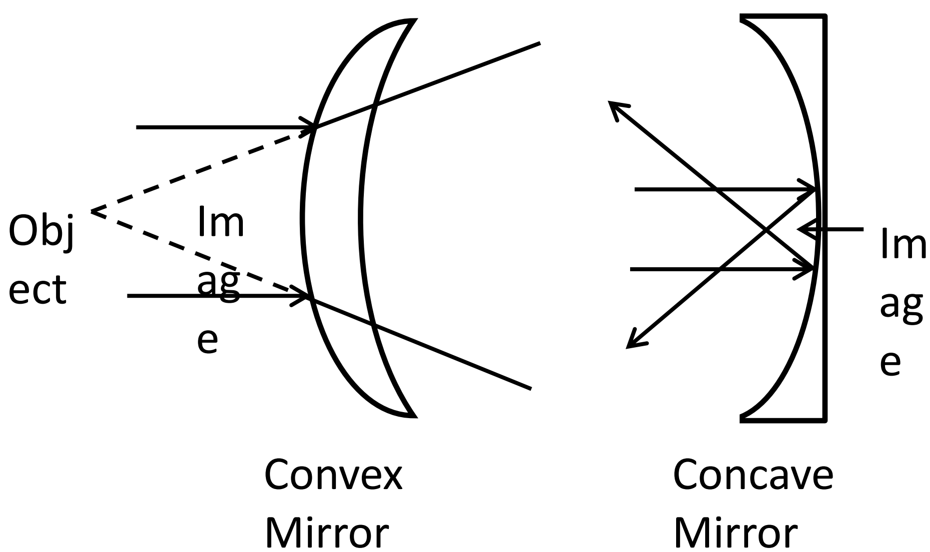
An example is when rays pass through a convex lens or concave mirror; they converge and form a real image.




*Virtual Images*

Virtual images are formed when light rays pass through an optical medium and diverge (spread apart).

An example is when rays pass through a convex mirror or concave lens; they diverge and form a virtual image.



**Dispersion**

Visible light is that light which is seen by the human eye, and is also referred to as white light. OK, Lets discuss how white light is broken up into its component parts. When visible (white) light passes through a prism, it is slowed down, bent and broken down into its component colors. This is defined as dispersion. The result of this is a rainbow resulting from the dispersion of the wavelengths. The colors in order from longest wavelength to shortest wavelength is red, orange, yellow, green, blue, indigo (which is sometimes left out) and violet. Remember ROY G BIV.

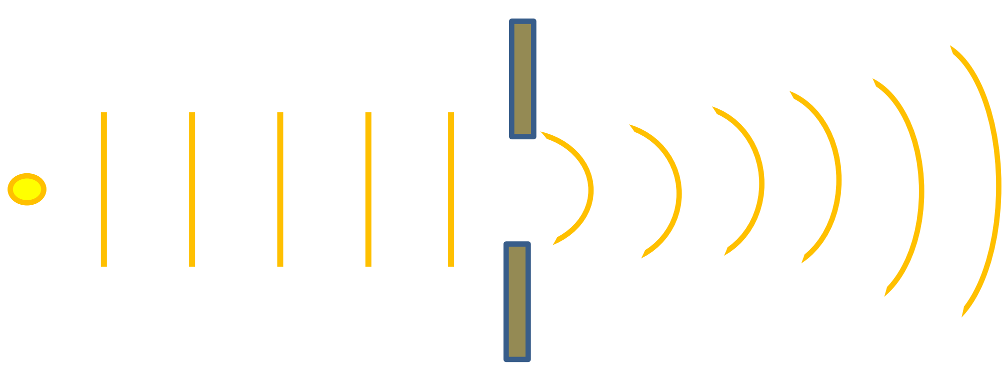
All colors travel at the same speed (velocity) in air, but slow down at different rates when passing through a denser medium (material). This is the reason that light appears colorless. Red is the longest wavelength and travels fastest and bends less. Violet is the shortest wavelength and travels the slowest and bends the most. Although there are variations of the wavelengths of the visible spectrum, they range from 380 nanometers (nm) to 750 nanometers (nm).

These are the approximate wavelengths of the visible spectrum.

- Red = 650 to 750 nm
- Orange = 590 to 650 nm
- Yellow = 560 to 590 nm
- Green = 500 to 560 nm
- Blue = 470 to 500 nm
- Indigo = = 445 to 470 nm
- Violet = 380 to 445 nm

***Diffraction***

Diffraction occurs when light is bent without entering another medium. An example would be light bending around a doorway into a dark room.



### *How Light Interacts With an Object*

When light interacts with an object, several things can happen. The object may transmit most or part of the light and would be considered transparent or translucent. If no light is transmitted, the object is considered opaque. Some light may be reflected. The color would depend upon how much light is reflected and the wavelengths. The light may be absorbed which would generate heat. To illustrate absorption generating heat, if the rays of the sun strike a black surface, such as asphalt, it is absorbed and the surface becomes hot. Finally, when light falls on an object, pressure is exerted on the object.

## Refraction

Refraction is defined as the "bending" of light as it passes obliquely between two different refractive mediums. A beam of light that enters a refractive medium perpendicularly is not refracted, but merely slowed down and the path of the beam is unchanged.

## Index of refraction

Index of refraction is a number comparison of the speed of light through a medium compared to speed of light in air. The speed of light in air is 1.0

We will be using the relative index of refraction, which is the speed of light in air. The absolute index of refraction would be the speed of light in a vacuum, (which is actually 1.000000, whereas the actual index of refraction of air carried out further is 1.000277) and won't be used for our purposes. So…the comparison will be with the speed of light in air which is 186,000 miles per second. The formula for determining the speed of light in a medium is:

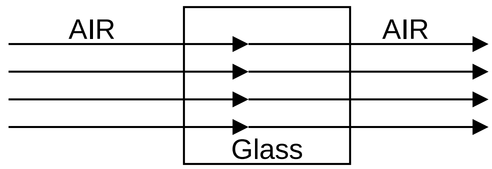
n represents the index of refraction.

$$n = \frac{\text{Speed of light in Air}}{\text{Speed of light in a Medium}}$$

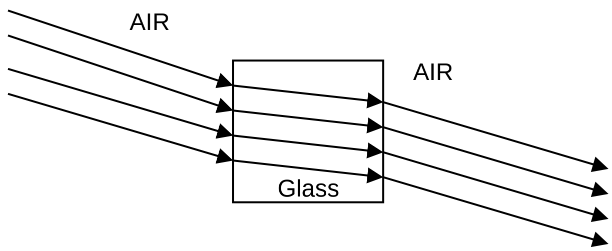
The higher the index of refraction means that rays passing through will be slowed more, and bent more, therefore, the higher indices slow light more and lower indices slow light less.

## Refraction

When a beam of light, moving through air, strikes a parallel piece of optical medium, two different things can happen. If the light strikes the surface at a perpendicular angle, it will merely be slowed down, and will travel through the medium on its original path.




If the light strikes the same surface (parallel piece of optical medium) at an oblique angle, it will be slowed down, bent, and will emerge slightly deviated from its original path.



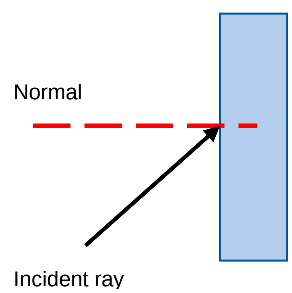

**Refraction Terminology**

Angle of incidence = The angle at which a ray strikes the surface and a line perpendicular to the surface, or "normal". Designated by "i"

Angle of refraction = The angle between the ray inside the glass and the line perpendicular to the surface. Designated by "r"

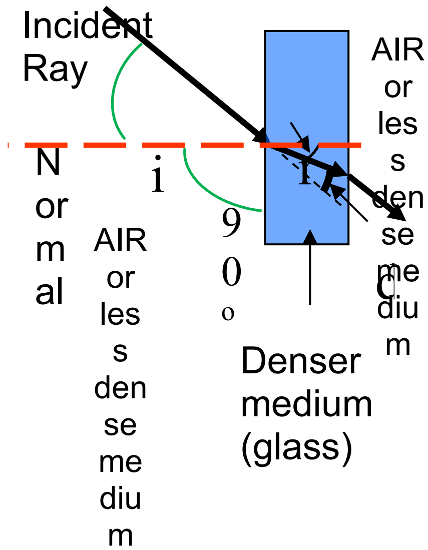
Angle of deviation = The angle from which the line would have extended with no deviation from where it actually extends. Designated by "d"

Normal = An imaginary line that is perpendicular to the refractive surface, located at the point of incidence




A refracted ray bends toward the Normal (perpendicular to the surface) when it enters a region where the index of refraction is greater and away from the Normal (perpendicular) when it enters a region where the index of refraction is smaller.

Variables are the refractive indices of the 2 mediums, the angle of incidence, and the curvature of the surface.




**Snell's Law**

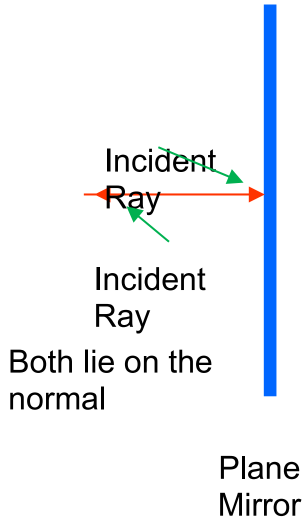
The formula for Snell's Law
$n_1 \sin i = n_2 \sin r$

The refractive index of the incident medium times the sine of the angle of incidence equals the refractive index of the refractive medium times the sine of the angle of refraction. Snell's Law describes the relationship between the angles and the velocities of the waves.

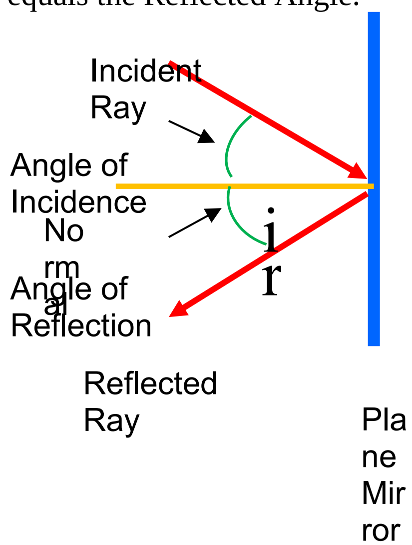
For simplicity purposes here, early in your training modules, we will say that simply stated, Snell's Law states that the angle of refraction plus the angle of deviation equals the angle of incidence.

*Reflection*

Unless interrupted, a single ray of light travels in a straight line. If it strikes a reflective object, the ray of light bounces back at a predictable angle. If it strikes a surface at a perpendicular line, it is reflected back on itself.

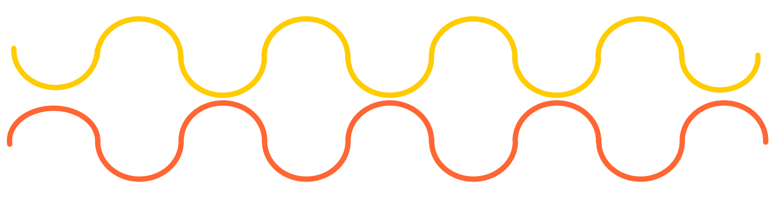



Both the Angle of Incidence and the Angle of Reflection are measured from the Normal. The Reflected Angle always equals the Reflected Angle.

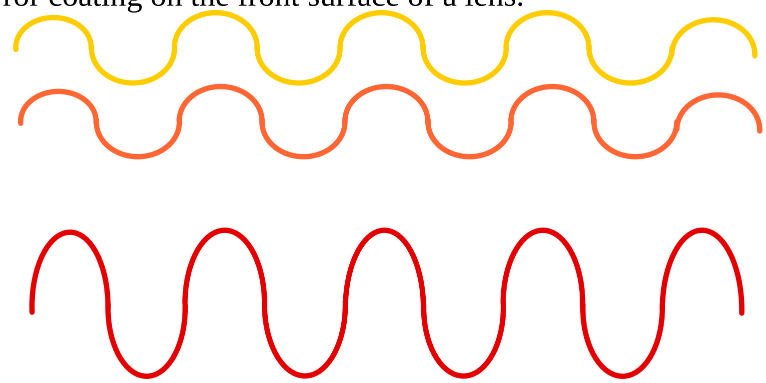



***Light – Reflection – Interference***

OK, so what happens if you have two waves that are moving in the same direction, but the crests are opposite or out of phase. They becoming destructive waves and cancel each other out. There would be no reflection. This is the principle of an AR coating.



Reflection is the result of light waves that are constructive by moving in the same direction and the crests are at the same place at the same time.  They are in phase. Therefore, they are compounding and result in a reflection.  An example would be when we apply a mirror coating on the front surface of a lens.



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