Reflection – Refraction - Diffraction

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2 Reflection, Refraction, and Diffraction

Light that impinges on an object may be absorbed by the object, reflected from its surface or transmitted through it. Light transmitted through a material is usually refracted (bent) as it enters the material. Light that is not absorbed, must either be reflected, or transmitted, or both. Light that strikes a sharp edge of an object is bent around the edge in a process know as diffraction (Figure 1).

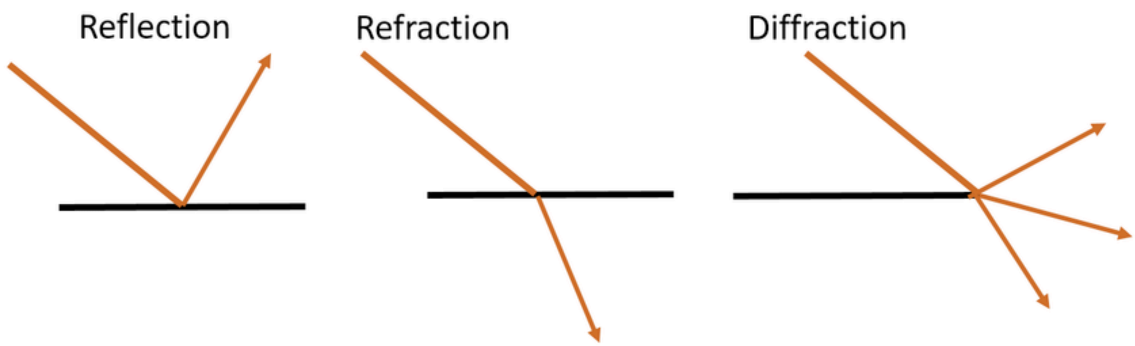


Figure 1 Reflection, Refraction, Diffraction (source: ResearchGate)

2.1 Wave – Particle Duality of Light

In a later chapter we will talk about the wave - particle duality of light. Light acts like a wave (Figure 2) when propagating from one place to another. When interacting with matter, light behaves like a massless particle, called a photon, that travels at the speed of light. The energy E_p of a photon is

$$E_p = h\,c/\lambda = hf$$

where

h = Planck's constant = $6.62607015 \times 10^{-34}$ joules per hertz

c = the speed of light in a vacuum = 299,792,458 meters per second

λ = wavelength of the light in meters

f = the frequency of the light in Hertz $[f = c/\lambda]$

The important observation about this equation is that both Planck's constant h and the speed of light in a vacuum c are constants. A photon always travels at the speed of light

c. It can not slow down or speed up. This will become important later. Wavelength λ is the only non-constant variable in the above equation. If a photon looses energy its wavelength λ must increase. A photon of blue light ($\lambda = 460\ nm$) that looses energy will change to a longer wavelength of light, perhaps red light with a wavelength $\lambda = 700\ nm$. That is

$$blue\ light - energy \rightarrow red\ light$$

Also note in the above equation that a photon's frequency of oscillation is $f = 1/\lambda$. Consequently, the frequency of a photon decreases as it looses energy.

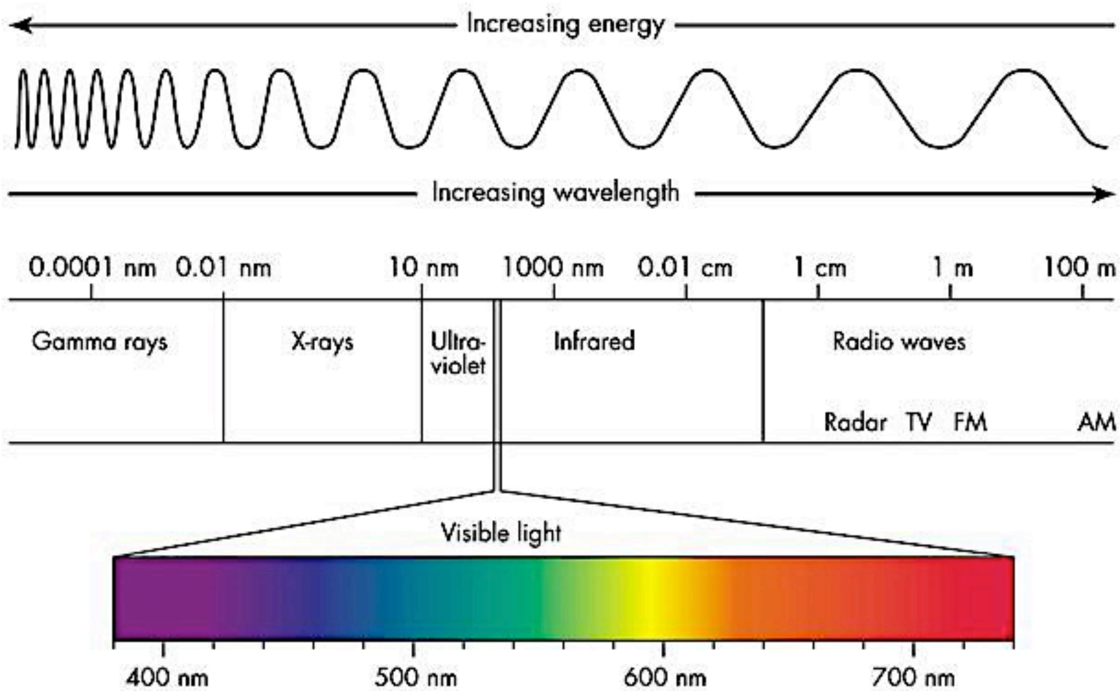


Figure 2 The spectrum of light, i.e. electromagnetic radiation (source: Cyberphysics)

2.2 Absorption

The energy of electrons within an atom and the energy of molecules can only exist at specific energy levels determined by quantum mechanics and chemical bonds. An electron can absorb a photon only if the photon's energy is equal to that necessary to jump the electron from one allowed energy level to an other allowed level. The photon will not be absorbed if its energy is anything else.

The same is true for molecules. For example, the energy of a molecule is the sum of its molecular vibration and rotational energies. Molecular absorption occurs only when the energy of a photon is equal to that required to change a molecule's vibration or rotational energy from one permitted level to an other.

Vibrational transitions occur when the molecule vibrates at a different frequency or in a different way than normal. Diatomic molecules such as O_2 and N_2 can only vibrate back and forth along the chemical bond that binds them together. More complicated molecules vibrate back and forth, as nuclei move toward and away from each other, and also by bending. Rotational transitions occur when a molecule changes its rate of rotation.

An electron which absorbs a photon becomes excited jumping to a higher energy level. Usually the electron falls back to its original ground state (its lowest energy level) relatively soon, emitting a photon in the process. The energy of the emitted photon is the same as the one originally absorbed. This energy is generally at ultraviolet to visible wavelengths.

Molecules also tend to fall back to their ground state energy levels. A molecule can return to its ground state by radiating a photon or transferring its excess energy to an other molecule through a collision. Radiated photons are typically in the near to mid infrared wavelengths for vibrational energy and far infrared to radio wavelengths for rotational energy. Thus near to mid infrared light is needed to change the vibrational energy of a molecule since the wavelength of light absorbed is equal to that of the photons later radiated. Far infrared to radio wavelengths are needed to change the rotational energy of molecules. Collisions between molecules happen frequently, usually resulting in the transfer of energy from one molecule to an other. Consequently, the energy absorbed from a photon is often transformed into thermal energy (heat) through molecular collisions.

Another possibility also exists. A molecule can break apart if the energy of the absorbed photon is greater than that of the chemical bond holding the molecule together. In the case of an atom, the energy of the absorbed photon can cause an excited electron to break free from its parent atom transforming the atom into a positive ion.

2.3 Interaction of Light With Materials

Light that is not absorbed by an atom's electrons can interact with those electrons in a different way. The sinusoidal electric field of a light wave (Figure 3) exerts a force on a atom's electrons causing them to vibrate back and forth. The vibrating electrons temporarily absorb energy from the light wave. Light does not interact with molecules in this way since molecules are far too massive, on the order of 20,000 times more massive than an electron.

The vibrating electrons re-radiate the absorbed energy as wavelets of light at the same frequency, but not necessarily the same direction or phase as the original light wave. A vibrating electron produces a sinusoidal magnetic field which in turn produces an orthogonal sinusoidal electric field creating a wavelet of light.

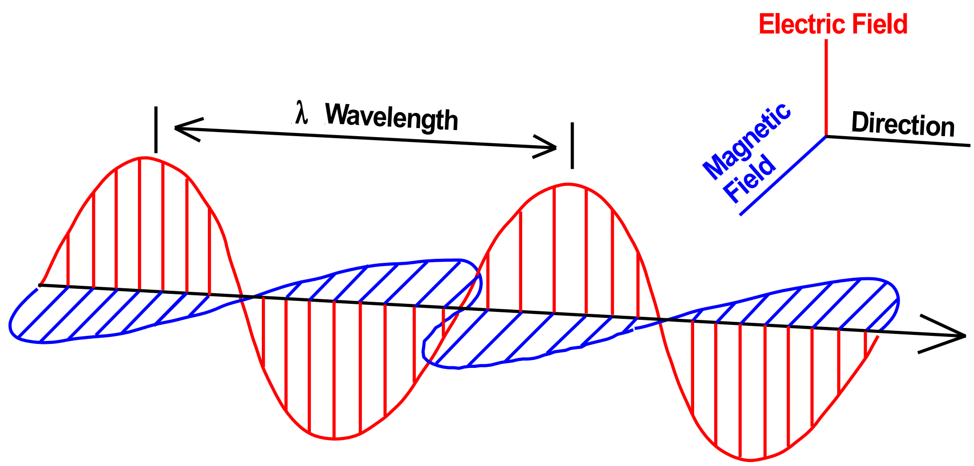
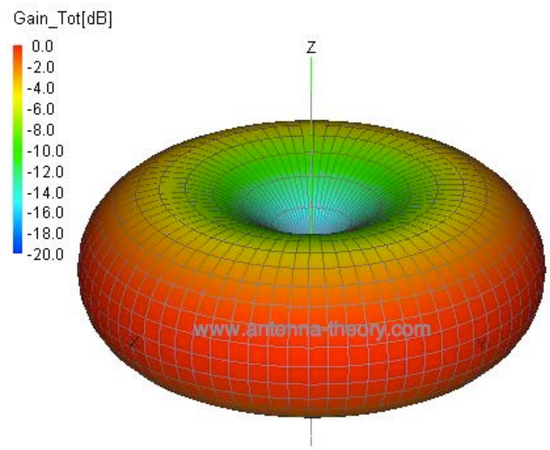


Figure 3 A light wave consist of sinusoidal orthogonal electric and magnetic fields oscillating in directions perpendicular to the direction of light travel (source: author)

The radiation pattern of a vibrating electron is the same as that of a radio wave radiated from a dipole antenna located in outerspace. This pattern is shown in Figure 4. The pattern of a radio wave radiated by an antenna close to ground level (mounted on top of a 32 foot pole for example) is distorted from that shown in Figure 4 by reflections of the radio wave from the ground's surface.

In Figure 4, the back and forth motion of the vibrating electron is in the vertical direction along the z axis running through the pattern's "donut hole". In the horizontal direction, perpendicular to the electron's motion, the radiation is equal in all directions as illustrated by the azimuth graph in Figure 4. The elevation graph shows that maximum radiation also occurs perpendicular to the electron's direction of movement (at 0^o elevation). However, like a dipole antenna, significant radiation also occurs at greater elevation angles up to about 60^o. Above 60^o the radiation pattern forms a deep null along the direction of electron motion. With the exception of the deep null, a vibrating electron radiates significant energy in all directions. Most of this radiation is cancelled out by destructive interference from the radiation of neighboring vibrating electrons. However, the destructive interference is not complete. The neighboring electrons also interfere constructively producing a resulting light wave traveling in a particular direction.

The absorption re-radiation process takes time causing the phase of the re-radiated waves to lag behind the original light wave. The total light traveling through a material is the sum of the partially attenuated original wave plus all of the phase delayed re-radiated wavelets producing a resulting wave of the same amplitude but traveling in a slightly different direction from the original light wave. That is, the light wave bends as it enters the material. The contributions from the phase delayed wavelets also causes the observed speed of light through the material to be less than the speed of light in a vacuum.



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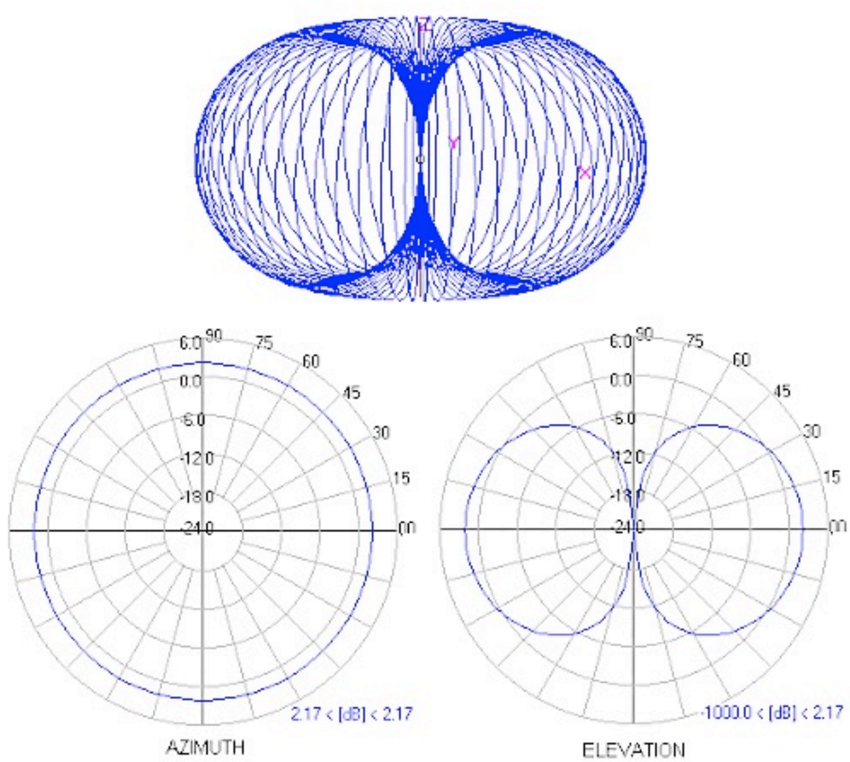

Figure 4 Radiation pattern of a vibrating electron (source: astrosurf)

Slowing in the observed speed of light as it travels through a material is easily understood from the particle nature of light. Photons of light travel unimpeded through the empty vacuum of space. However, within a material photons are continuously colliding with the material's molecules and atoms impeding photon motion. As a result of these collisions, the observed speed of light through a material is less than that through a vacuum. However, it is important to note that the speed of an individual photon through the empty space between molecules and atoms is still c the speed of light in a vacuum. It is the zigzag path of photons through a material that cause its observed speed to be less than c. An extreme example of this occurs within the Sun. Because of constant collisions and scattering, photons follow a chaotic zigzag path through the Sun's radiation zone as they travel from the core to the Sun's surface. In fact, it takes light (photons) around 170,000 years to travel through the radiation zone, a distance of 522,000 km, (Figures 5 and 6).

The speed of light through the radiation zone is

$$v = \frac{522{,}000{,}000\ meters}{(170{,}000\ yr)(365\ days/yr)(24\ hr/day)(60\ min/hr)(60\ sec/min)}$$

$$v = \frac{522{,}000{,}000\ meters}{5.36\ x\ 10^{12}} = 0.000097\ meters\ per\ second$$

far different than the nearly 300 hundred million meters per second speed of light through a vacuum !

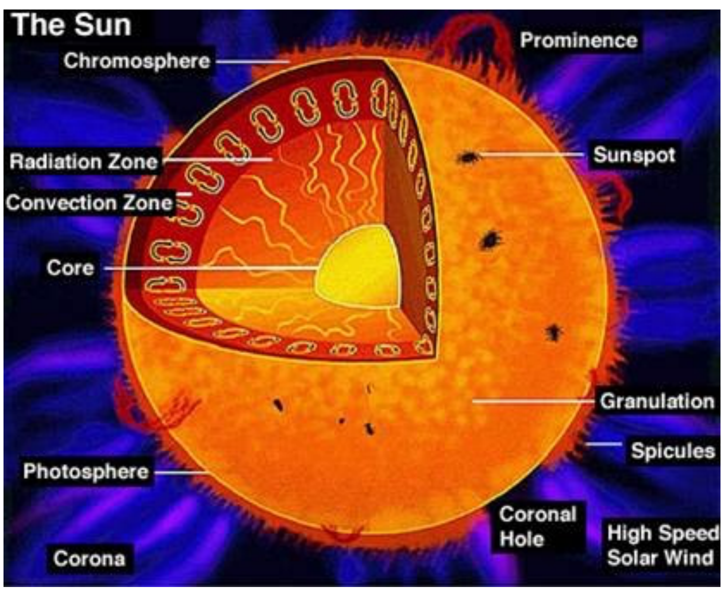

Figure 5 The Sun (credit: NASA's Cosmos – ase.tufts.edu)

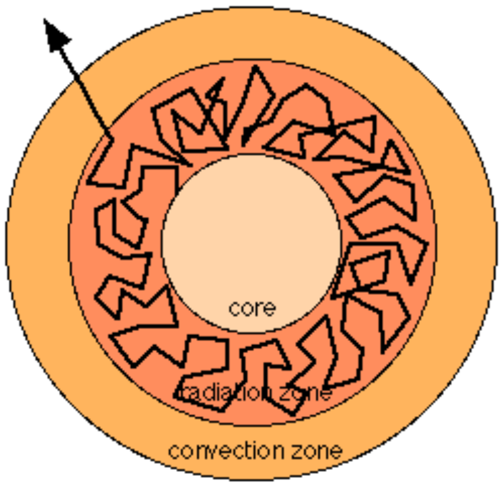

Figure 6 Chaotic zigzag path of photons through Sun's radiation zone
(source: http://solar.physics.montana.edu)

The optical density of a material refers to its ability to slow the observed speed of light passing through it. An optically dense materials slows the observed speed of light more than a material that is less optically dense. Note that physical density of a material is its mass per unit volume which is different from its optical density.

Reflection is the result of light interacting with electrons at the material's surface. The wavelets of light re-radiated at the surface radiate in all directions. Some of the wavelets radiate into the material. Other wavelets radiate back into the medium from which the light originally came creating reflected light. The amount of light reflected is that remaining after absorption of light in the material and transmission through it.

2.4 Reflection

Reflection occurs when a light wave encounters a smooth surface that does not absorb the light's energy. For example, the surrounding scenery is clearly reflected in a lake provide the surface of the lake is perfectly smooth. However, the reflected light will be scattered in all directions producing a blurry image if the surface of the lake is rough, as illustrated in Figure 7.

Smooth lake surface Rough surface

Figure 7 Reflections from the surface of water (source: olympus-lifescience.com)

Greek mathematician and scientist Euclid (~ 325 – 265 BC) was one of the first to study the phenomena of reflection around 300 BC. He documented his results in a book titled Optica. From his book it is known that he worked with polished metal spherical and parabolic mirrors in addition to plane mirrors (refer to the appendix introduction for more details).

Around 60 AD Heron of Alexandria (~ 10 – 75 AD) showed by geometrical methods that light reflected from a flat polished mirror takes the shortest possible path from the object (the light source) to the mirror and finally to the observer. Using this result, he concluded that the angle of reflection from the mirror (Figure 8) must equal the angle of incidence on the grounds that this would yield the shortest path. Due to the absorption and re-radiation of light by the material's electrons, light actually reflects from a smooth flat surface in all directions. However, most of the reflections are cancelled out through destructive interference resulting in the angle of the observed reflection being equal to the angle of incidence.

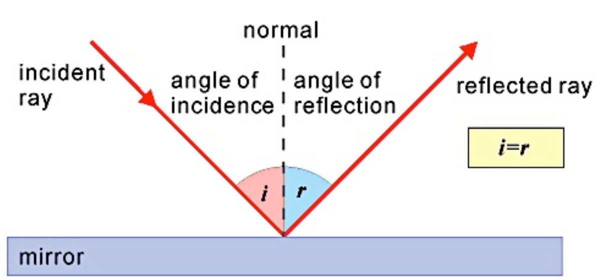

Figure 8 Angle of Incidence equals angle of Reflection (source: Quizlet.com)

It is believed that Muslim mathematician, astronomer, and physician al-Haytham (~965 – 1040), also known as Alhazen, was the first to achieve a detailed understanding of light. Among his many accomplishments, el-Haytham carefully verified the earlier results from Euclid and Heron of Alexandria that light travels in straight lines and, when reflected, the angle of incidence equaling the angle of reflection. Furthermore, al-Haytham made the important observation that the angle of reflection is in the same plane as the angle of incidence. (Refer to the appendix introduction for more details)

As alluded to above, reflection of light can be categorized into two types:

- Specular reflection, and
- Diffuse reflection.

Specular reflection is defined as light reflected from a smooth surface such that the angle of incidence equals the angle of reflection. In contrast, diffuse reflection is produced by light scattered in all directions from a rough surface. There are far more occurrences of diffuse reflection in daily life than specular reflection. The difference between specular and diffuse reflection is illustrated in Figure 9

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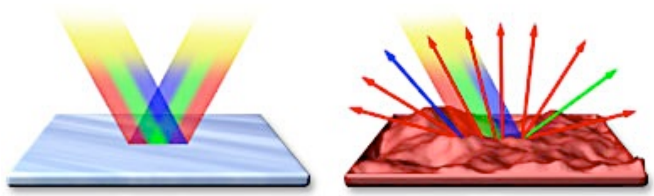


Specular Reflection Diffuse Reflection

Figure 9 Specular and diffuse reflection (source: olympus-lifescience.com)

The mirror surface on the left side of Figure 9 reflects all components of white light equally, including red, green, and blue wavelengths. However, the rough reddish surface absorbs all wavelengths with the exception of red which it reflects in all directions from its rough surface.

It is largely through diffuse reflection that we see nonluminous objects around us (people, cars, houses, animals, trees, mountains, etc.). The color of an object is the color, or wavelength of light, that the object reflects. When standing in sun light a red shirt appears red because the shirt absorbs all wavelengths in the solar spectrum with the exception of red which it reflects. It took people nearly two thousand years to understand this! Around 450 BC Greek philosopher Empedocles (~ 492 – 432 BC) claimed that sight was the result of light emitted from our eyes that bounced off objects and back into our eyes permitting us to see an object's size, shape and color. For 1,400 years this was the accepted theory of vision. Finally, around 1,000 AD al-Haytham proved conclusively that instead sight is the result of light reflecting off objects and then entering ours eyes.

There are two conditions required for specular reflection to occur:

1. A smooth reflecting surface is needed. That is, the average depth of surface irregularities must be substantially less than the wavelength of the incident light. Polished mirrors reflect very well. If the reflecting surface is rough, diffuse reflection will occur with light reflecting in more or less all directions.

2. The size of the reflecting surface must be much larger than the wavelength of the incident light. If this condition is not met, the incident light will again be scattered in all directions.

Reflections occur easily from a polished metal surface. The outer electrons in metal atoms are loosely held. Consequently, these electrons easily escape from their parent atoms creating a sea of free electrons throughout a metal object.

The sinusoidal electric field of a light wave (Figure 10) induces an electrical current in the free electrons at the metal's surface in the same way that a radio wave induces a current in a receiving antenna. The oscillating current in turn radiates a reflected light wave in the same way that an alternating current in a transmitting antenna radiates a radio wave. Most of the reflected light is cancelled out through destructive interference with the incident light wave. However, some of the incident and reflected light interfere constructively forming a reflected light beam whose angle of reflection is the same as the angle of incidence. The light's sinusoidal magnetic field generally is not involved in this process.

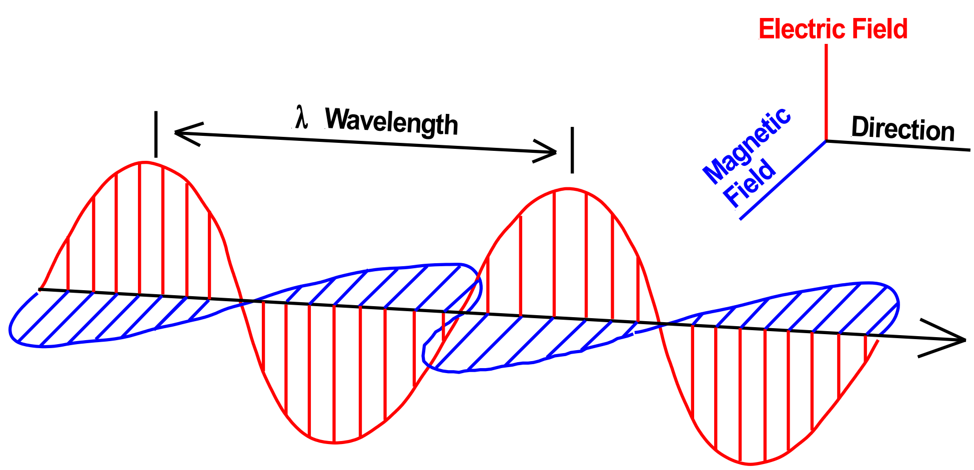


Figure 10 A light wave consist of sinusoidal orthogonal electric and magnetic fields oscillating in directions perpendicular to the direction of light travel (source: author)

The conclusion reached by Heron of Alexandria and others that the angle of reflection equals the angle of incidence can be demonstrated analytically. In Figure 11 light is emitted by a source at Point A, is reflected off a plane mirror, and arrives at Point B.

Let the perpendicular distance from the mirror to A and to B be the distance d with the shortest distance between the two points being D. Assume that light takes the path shown by the two red arrows. In this figure, the angle of incidence $\angle Ad$ is not necessarily equal to the angle of reflection $\angle dB$. The length of the path from A to the mirror to B is equal to

$$L = (x^2 + d^2)^{1/2} + ((D - x)^2 + d^2)^{1/2}$$

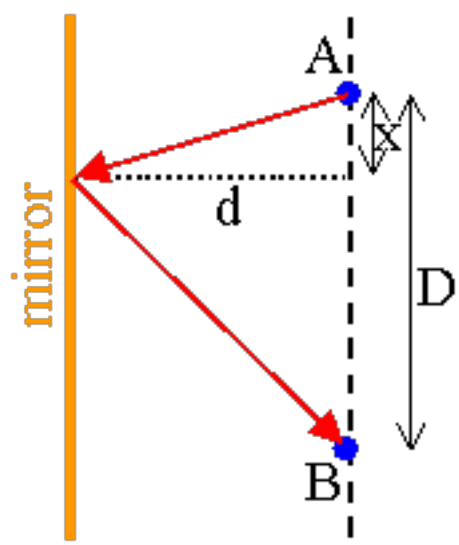


Figure 11 Reflection of light from a plane mirror (source: electron9.phys.utk.edu)

To find the shortest path from A to the mirror to B, we differentiate L with respect to x and set the result equal to zero.

$$\frac{dL}{dx} = \frac{x}{\sqrt{x^2 + d^2}} - \frac{(D - x)}{\sqrt{(D - x)^2 + d^2}} = 0$$

$$\frac{x^2}{x^2 + d^2} = \frac{D^2 + x^2 - 2Dx}{D^2 + x^2 - 2Dx + d^2}$$

$$x^2(D^2 + x^2 - 2Dx + d^2) = (D^2 + x^2 - 2Dx)(x^2 + d^2)$$

$$x^2D^2 + x^2x^2 - (2Dx)x^2 + d^2x^2 = D^2x^2 + x^2x^2 - (2Dx)x^2 + D^2d^2 + x^2d^2 - (2Dx)d^2$$

After canceling equal terms on both sides (the color coded terms) we are left with

$$0 = D^2d^2 - (2Dx)d^2$$

$$2Dd^2x = D^2d^2$$

$$2x = D$$

$$x = \frac{D}{2}$$

The shortest path from A to the mirror to B is the one for which x = D/2, or equivalently, the one for which i = r . Thus the angle of incidence i $= \angle Ad$ equals the angle of reflection r = $\angle dB$.

2.5 Refraction

Refraction is a property of light that causes it to bend at the interface between two different media as illustrated in Figures 12 and 13.

The amount of bending depends on the angle of incidence. A beam of light traveling normal (perpendicular) to the interface will pass straight through the materials without any bending. The amount of bending increases as the angle of incidence increases, illustrated in Figure 14. In this figure assume that the light is originating in the glass material and traveling upward through the interface into air. Within the glass the angle of incidence between the normal and the red colored ray of light is very small, about 0.3^o. The ray is bent 5^o with respect to the normal as it enters the air. The angle of incidence of the blue colored ray of light is a little larger than that of the red ray, about 30^o. However, the blue ray is bent at an angle of 45^o when it enters the air, considerably more bending than that of the red ray. The amount of bending for the purple ray (angle of incidence ~38^o) is even more, etc.

Claudius Ptolemy (~ 85 – 165 AD) was one of the first to systematically study refraction and document his results. Ptolemy described a stick appearing to bend when partially immersed in a pool of water (similar to Figure 13), and accurately recorded the angles he observed. He discovered that water and glass have different angles of refraction. However, he was unable to mathematically describe the extent to which light refracts in passing from one medium to another.

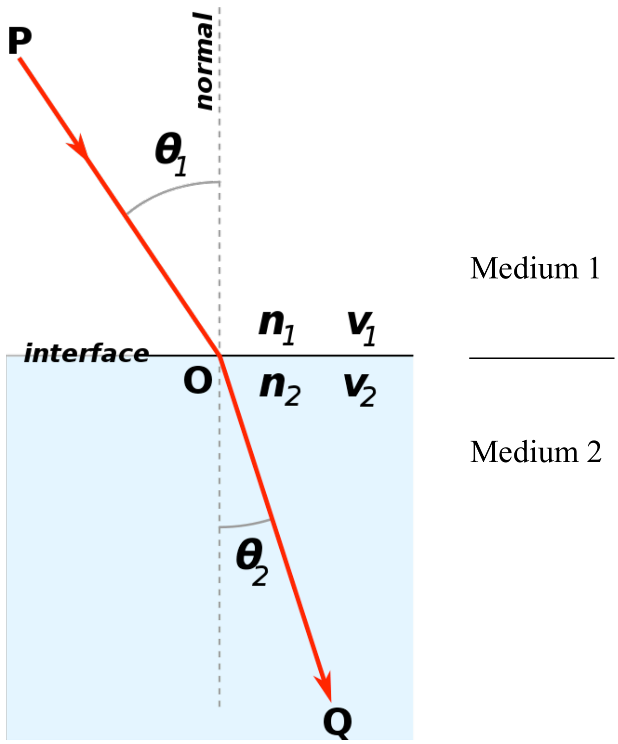


Figure 12 Refraction of a light ray (source: Wikipedia)

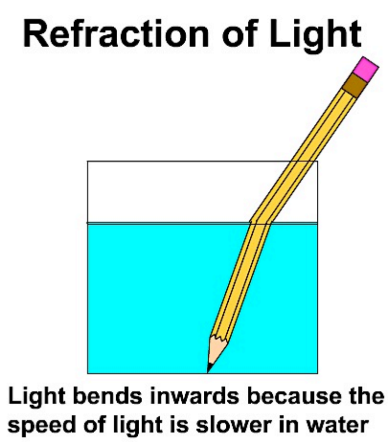


Figure 13 Pencil appears to bend in water (source: tonteraslight.blogspot.com)

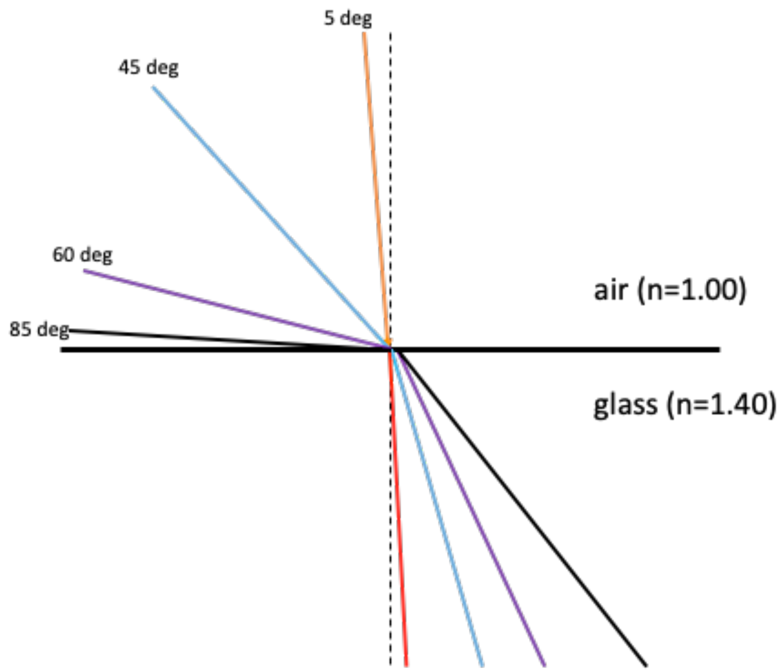


Figure 14 Degree of refraction (source: Quora)

2.5.1 Snell / Descartes Law of Refraction

English mathematician and astronomer Thomas Harriot (1560 – 1621) discovered the sine law of refraction for light in 1601. However, he did not publish his results. In 1621 Dutch astronomer and mathematician Willebrord Snell also discovered the sine law for refraction of light. But he didn't publish his results either. Finally, the sine law of refraction was published in 1637 by French mathematician and scientist Rene Descartes (1596 – 1650).

The Snell / Descartes law of refraction states that the amount by which light bends at the boundary between two media is given by

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

In this equation θ_1 is the angle of incidence with respect to the line perpendicular (normal) to the boundary as illustrated in Figure 12. The angle θ_2 is the angle of refraction. The refractive indices are n_1 for medium 1 and n_2 for medium 2 illustrated in Figure 12.

2.5.2 Huygens' Principles

In the 1670s Dutch scientist, Christiaan Huygens developed a number of theories explaining reflection, refraction, and diffraction. At the time the best scientists in the world had only a crude idea of what light, electricity and magnetism were. All of the great advances in the understanding of electro-magnetics by Coulomb, Franklin, Faraday, Henry, and others, culminating in Maxwell's integrated theory of electro-magnetics and light, were still more than a hundred years in the future. It is amazing that Huygens accomplished what he did using basically graphical techniques.

Huygens assumed that a wave front of light consisted of an infinite number of point sources. Light propagated from a point source as a spherical wavelet, illustrated in Figure 15. The radius of each wavelet was equal to the speed of light c multiplied by the time t since the wavelet was emitted by the point source. The infinite number of wavelets interfered with one an other with the result that they all canceled out *except* in the forward direction. In the forward direction the wavelets added constructively causing the wave front to move forward (to the right in the figure) from its position at time $t = 0$.

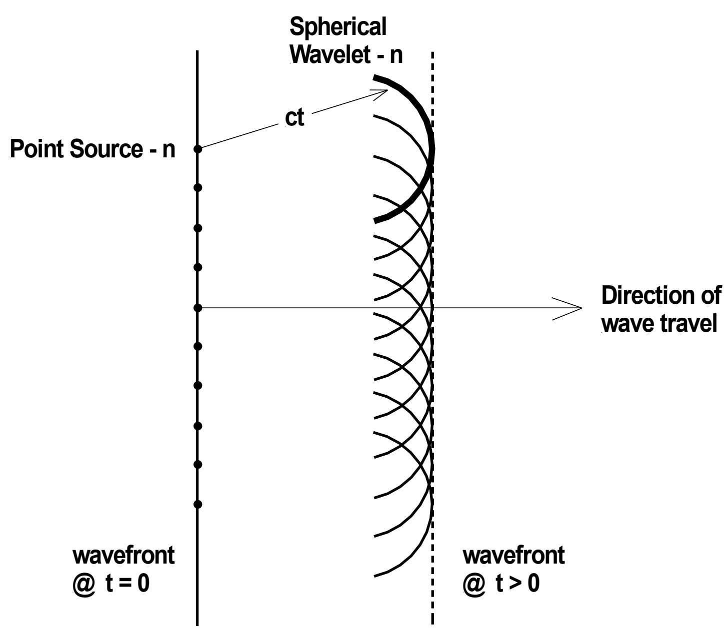


Figure 15 Huygens' Principle of Light (source: author)

With this simple model Huygens was able to explain the reflection, refraction, and diffraction of light.

Huygens proposed that the refractive index of a material was related to the speed at which light travels through the substance. Huygens suggested that light travels more slowly through materials having a higher refractive index. Based on this assumption, Huygens postulated that the refractive index n_m of a material is equal to the ratio of the speed of light in a vacuum to the speed of light in the material, specifically

$$n_m = \frac{c}{v_m}$$

where c is the speed of light in a vacuum (299,792,458 m/s) and v_m is the speed of light in the material. As an illustration, the refractive index of water is 1.333 which means that light travels 1.333 times slower through water than in a vacuum.

Actually, v_m is the phase velocity of light in a material. Phase velocity is the speed at which the crest or phase of a wave travels. Phase velocity is usually different from group velocity. Group velocity is the speed at which information, consisting of many different frequencies, travels through a medium, for example a pulse of light or the envelope of a modulated radio signal. Group velocity is also the speed at which the power carried by the wave travels. Group velocity and phase velocity are the same only in the vacuum of outer space.

Variations in the speed of light from one material to another was in fact the basis of Huygens wave theory of refraction. Huygens envisioned a wavefront to be like a line of soldiers marching along (Figure 16)

The soldiers on the left end of the line slow down as they encounter swampy terrain (yellow region in Figure 16), while the rest of the line (those in the gray region) continue marching along at their original speed. The difference in speed causes the line of soldiers to gradually bend toward the normal.

The same concept is illustrated in Figure 17. In this case the figure illustrates oblique wavefronts of light encountering the interface between air and glass. That part of a wavefront that has entered the glass slows down traveling at a speed of v_g instead of its original speed in air of v_a . In time t the wavefront in the glass covers a distance of

$$A\ to\ C = v_g\, t$$

That part of the wavefront that is still traveling through air continues at its original speed of v_a and in time t covers the much larger distance B to D. That is

$$B\ to\ D = v_a\, t$$

Consequently the wavefront is forced to bend toward the normal.

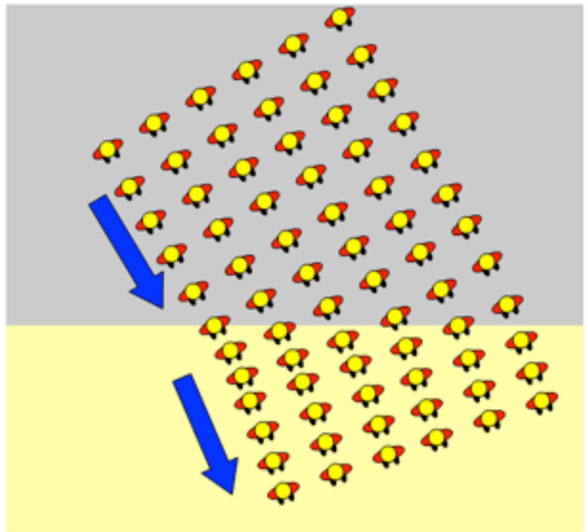


Figure 16 Huygens concept of refraction (source: esfsciencenew)

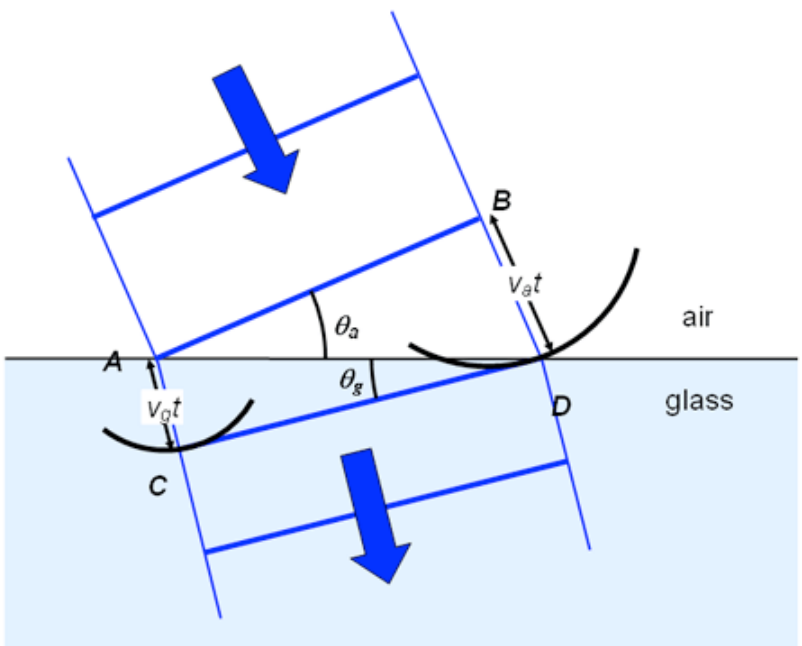


Figure 17 An illustration of refraction (source: resourcefulphysics.org)

If the blue arrows in Figure 17 are reversed, that is light traveling through the glass and into air, the wavefronts bend away from the normal as the light beam enters air. Specifically, that part of the wavefront that has entered the air travels at the much faster speed v_a covering the relatively larger distance D to B while the other end of the wavefront is still in the glass traveling at the much slower speed of v_g.

In more general terms, light bends toward the normal when passing from a material with a low refractive index to one with a higher index ($n_1 < n_2$) , as illustrated in Figure 18. In the reverse direction, light bends away from the normal when passing from a high refractive index material to a material with smaller index ($n_1 > n_2$).

Huygens theory of refraction was initially rejected by the majority of seventeenth and eighteenth century scientists who lacked the ability to accurately measure the speed of light. It appeared to them that the speed of light was the same regardless of the material through which it passed. 150 years after Huygens' death the speed of light was measured accurately enough to prove that Huygens theories were correct.

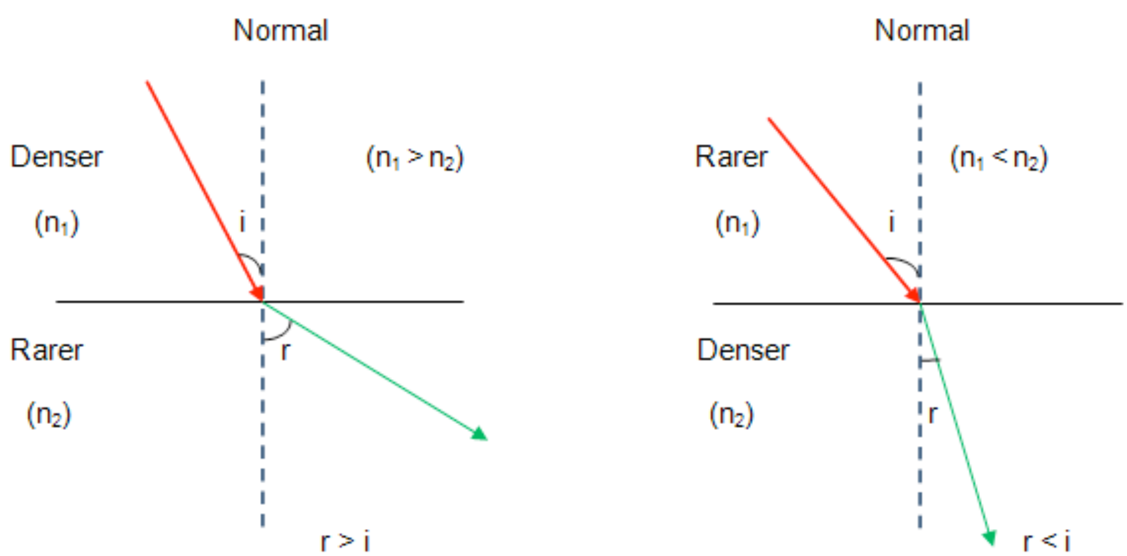
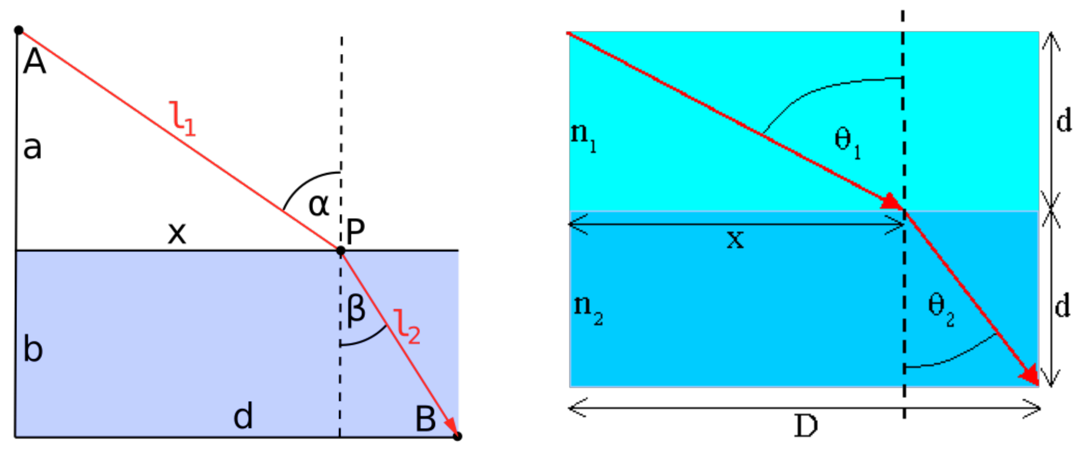


Figure 18 Bending toward and away from a line normal to boundary
(source: http://buphy.bu.edu)

2.5.3 Deriving Snell's Law

Snell's Law can be derived using Fermat's principle of least time. Given an object (light source) at point A in medium 1 (Figure 19a), and an observer at point B in medium 2, the refraction point P is that which minimizes the time taken by light to travel the path APB.



(a) (b)

Figure 19 Deriving Snell's law (source: electron9.phys.utk.edu)

Assume that light propagates from point A to point B across the boundary between medium 1 and medium 2 in Figure 19b

For the path shown in the figure the time required is

$$t = \frac{\sqrt{x^2 + d^2}}{c/n_1} - \frac{\sqrt{(D-x)^2 + d^2}}{c/n_2}$$

Setting dt/dx = 0 we obtain

$$\mathrm{n}_1 \frac{\mathrm{x}}{\sqrt{\mathrm{x}^2 + \mathrm{d}^2}} = \mathrm{n}_2 \frac{\mathrm{D} - \mathrm{x}}{\sqrt{(\mathrm{D} - \mathrm{x})^2 + \mathrm{d}^2}}$$

In this equation

$$\frac{\mathrm{x}}{\sqrt{\mathrm{x}^2 + \mathrm{d}^2}} = \sin\theta_1$$

and

$$\frac{\mathrm{D} - \mathrm{x}}{\sqrt{(\mathrm{D} - \mathrm{x})^2 + \mathrm{d}^2}} = \sin\theta_2$$

yielding Snell's Law

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

2.5.4 Speed of Light and Wavelength as a Function of Refractive Index

Snell's law of refraction can be written in two equivalent forms

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

and

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{n_1}{n_2} = \frac{v_2}{v_1}$$

The refractive index n_m for a medium is the factor by which the observed speed of light (v_m) in the medium is reduced relative to the speed of light in a vacuum ($v_0 = c$). Specifically

$$v_m = \frac{c}{n_m}$$

Similarly, the wavelength of light traveling through a medium (λ_m) is shorter than the wavelength of light in a vacuum (λ_0), that is

$$\lambda_m = \frac{\lambda_0}{n_m}$$

However, frequency f equals

$$f = \frac{v}{\lambda} = \frac{v_m}{\lambda_m} = \frac{\frac{c}{n_m}}{\frac{\lambda_0}{n_m}} = \frac{c}{\lambda_o}$$

so the frequency of light (its color) does not change as the light passes from one medium to another. For example, the color of an object in air is the same as its color in water as illustrated in Figure 20. It is only the velocity and wavelength of the light that changes.

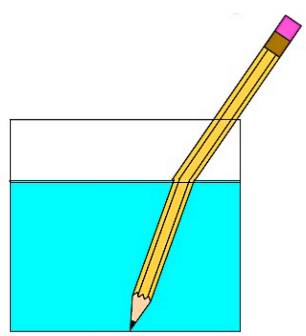


Figure 20 Refraction does not change the color of an object (source: tonteraslight.blogspot.com)

The index of refraction in a vacuum, n_0, is one since

$$n_0 = \frac{c}{v_0} = \frac{c}{c} = 1 \quad because\ \ v_0 \equiv c$$

Most gases at standard temperature and pressure have refractive indices close to 1 because of their low density. However, nearly all transparent solids and liquids have refractive indices above 1.3. For example, plastics generally have refractive indices of 1.3 to 1.7.

The refractive indices for many different types of material are shown in the table below. These values are measured at the yellow doublet D-line of sodium with a wavelength of 589 nanometers as is conventionally done. These indices can be much different for different wavelengths of light, for example higher in infrared light.

Material	Index of Refraction	State	Conditions
Vacuum	1		(by definition)
Helium	1.000036	Gas	(0°C and 1 atm)
Hydrogen	1.000132	Gas	(0°C and 1 atm)
Air	1.000277	Gas	(at STP*)
Air	1.000293	Gas	(0°C and 1 atm)
Carbon Dioxide	1.001	Gas	(0°C and 1 atm)
Liquid Helium	1.025	Liquid	(at -270°C)
Water Ice	1.31	Solid	(at 0°C)
Water	1.330	Liquid	(at 20°C)
Acetone	1.36	Liquid	(at 20°C)
Ethanol	1.361	Liquid	(at 20°C)
Kerosene	1.39	Liquid	(at 20°C)
Corn Oil	1.47	Liquid	(at 20°C)
Glycerol	1.4729	Liquid	(at 20°C)
Acrylic Glass	1.490–1.492	Solid	(at 20°C)
Benzene	1.501	Liquid	(at 20°C)
Crown Glass (pure)	1.50–1.54	Solid	(at 20°C)
Plate Glass (window glass)	1.52	Solid	(at 20°C)
Sodium Chloride (table salt)	1.544	Solid	(at 20°C)
Amber	1.55	Solid	(at 20°C)
Polycabonate	1.60	Solid	(at 20°C)
Flint Glass (pure)	1.60–1.62	Solid	(at 20°C)
Bromine	1.661	Liquid	(at 20°C)
Sapphire	1.762–1.778	Solid	(at 20°C)
Cubic Zirconia	2.15–2.18	Solid	(at 20°C)

Material	Index of Refraction	State	Conditions
Diamond	2.417	Solid	(at 20°C)
Silicon	3.42–3.48	Solid	(at 20°C)
Germanium	4.05–4.01	Solid	(at 20°C)

Selected refractive indices at λ=589 nm (source: Wikipedia)

2.5.5 Refractive Indices Less Than One

Some media have an index of refraction which is less than 1. These atypical media include plasmas such as the Earth's ionosphere.

Ionospheric electron density increases with altitude until a region of maximum density is reached somewhere near the middle of the ionosphere, as shown in Figure 21. From that point on the electron density decreases with altitude until the ionosphere disappears far above the Earth.

Since the ionospheric index of refraction $n_i < 1$, a radio wave is bent away from the normal as it travels from air $n_a \approx 1$ into the ionosphere $n_i < n_a$. The ionosphere's index of refraction becomes smaller as electron density increases. That is, the index of refraction at the bottom of the ionosphere n_{ib}, where there is little ionization, is greater than the ionospheric index of refraction n_{ic} in the highly ionized central region of the ionosphere, leading to the relationship

$$n_{ic} < n_{ib}$$

Consequently, a radio wave not only bends away from the normal when it enters the ionosphere, it continues to bend further and further away from the normal as it travels upward into the heavily ionized central region of the ionosphere. If a radio wave bends far enough (if it bends more than 90^{o} from the normal) it will in fact begin traveling back to Earth as illustrated by the red trace in Figure 21. As it does so it encounters decreasing levels of ionization causing the index of refraction n_i to increase from its minimal value in the ionosphere's central region. Traveling from a region of a low index of refraction to one with a higher refractive index cause the radio wave to bend toward the normal. In other words, the radio wave straightens out and travels to the distant Station B in Figure 21.

From this analysis it is clear how a radio wave can penetrate the ionosphere and be lost to outer space. The electron density of the ionosphere decreases with altitude from the middle to the upper edge of the ionosphere. At the upper edge ionization disappears all together. Consequently, the index of refraction must increases with altitude in the upper ionosphere until it reaches a value of one at the top of the ionosphere where ionization disappears and the vacuum of space begins. If n_{it} is the index of refraction at the top of the ionosphere then

$$n_{ic} < n_{it}$$

and

$$n_{it} \approx 1$$

A radio wave propagating through the upper ionosphere (blue trace in Figure 21) is continuously traveling from a region of low to a region of higher refractive index. Consequently, the radio wave is bent toward the normal, away from Earth and into outer space. A radio wave that penetrates the densest part of the ionosphere can never return to Earth. It is lost to outer space.

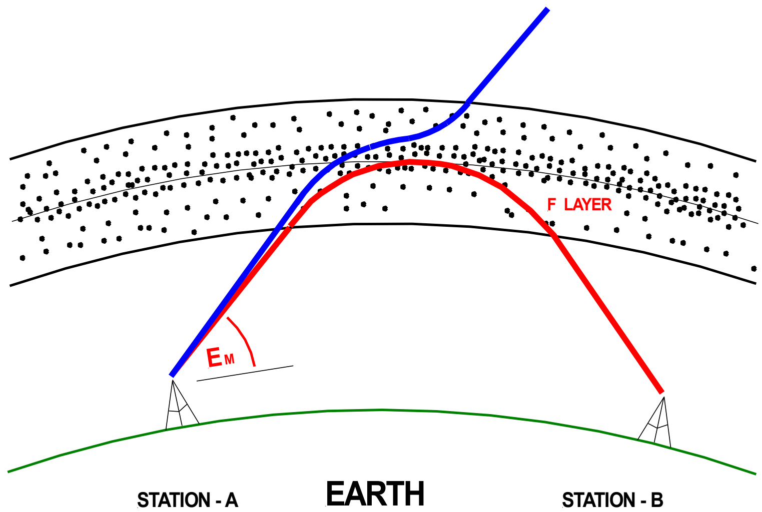


Figure 21 Ionosphere causes radio waves to be bent back to Earth (source: author)

An index of refraction less than 1 implies that the phase velocity of light v_m can travel faster than the speed of light. Since

$$v_m = \frac{c}{n_m} \quad if \;\; n_m < 1 \quad then \;\; v_m > c$$

How is this possible? Phase velocity is simply the speed at which the crest of a light wave travels. Since the wave crest does not carry any information or any of the wave's power, it can travel faster than the speed of light. However, the group velocity of a modulated light beam carrying information, such as video content, plus the power associated with the wave is prevented by Einstein's theory of relativity from traveling faster than the speed of light. Likewise, all material objects are prevented from traveling faster than the speed of light.

This phenomena can actually be observed by watching waves at the beach. In Figure 22 waves are approaching the shore at an oblique angle. The speed of an approaching wave is its group velocity, that is the speed associated with the movement of water as the wave passes. When the wave impacts the beach, the peak of the wave appears to race along the shoreline at a speed much fast than that of the wave itself. The difference in speed can be quite impressive, with the wave's phase velocity being considerably greater than its group velocity.

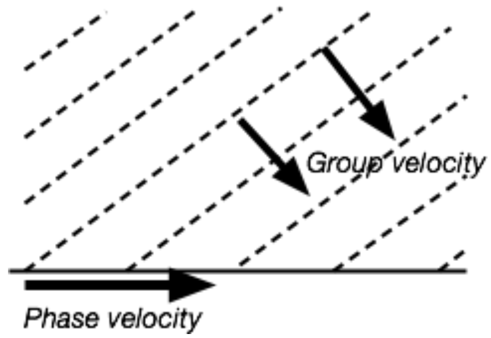


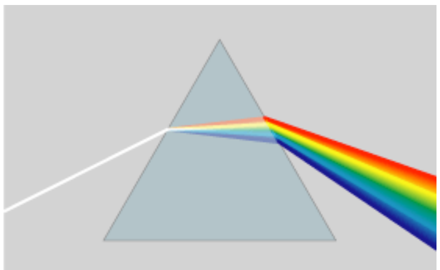
Figure 22 Phase velocity vs group velocity (source: Quora)

The phase velocity of light in most materials is less than c. However, it can exceed c in metals and in plasmas such as the ionosphere. Plasmas and metals both contain large quantities of free electrons which are no longer bound to the material's atoms. Only in empty space are the phase and group velocities identical, both being equal to c.

2.5.6 Dispersion

The refractive index of a material varies with the wavelength of light traveling through the material. Thus the index of refraction n is a function of wavelength $n(\lambda)$.

This property is called dispersion. Dispersion causes prisms and water droplets to separate white light into its constituent spectral colors (Figure 23). It also causes the focal length of lenses to vary with wavelength causing chromatic aberrations which often need to be corrected in imaging systems. It was the chromatic aberration present in refracting telescopes that first lead Newton to suspect that white light was not pure.




Light refracting through a prism and through water droplets forming a rainbow of colors

Figure 23 Dispersion of light (source: Wikipedia)

The degree to which the refractive index varies with wavelength is given by Cauchy's equation which, in its most common form, is

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}$$

where A, B, C, etc., are coefficients determined by the material through which the light is passing.

For visible light, the refractive indices for most transparent materials (air, glass, etc.) generally increase as the wavelength of light becomes shorter. This is called normal dispersion. The wavelength of blue light is shorter than that of red light. Consequently, the index of refraction of blue light n_{blue} is greater than that of red light n_{red} , causing blue light to be bent more than red as it passes through a prism.

$$n_{blue} > n_{red}$$

This is clearly apparent in Figure 23.

The reverse is true in material having an index of refraction less than 1, which is the situation in Earth's ionosphere. In this case, known as anomalous dispersion, refraction increases as wavelength becomes longer, causing long wavelength light to be refracted more than short wavelength light. This is clearly apparent in the refraction of radio waves in the ionosphere illustrated in Figure 24. Long wavelength 80 meter signals (3.5 MHz) are refracted more, bending back to Earth lower in the ionosphere, than short wavelength 20 meter signals (14.0 MHz). If a radio wave passes through the most dense part of the ionosphere without being refracted back to Earth (the 15 meter signal in Figure 24), it will be lost to outer space.

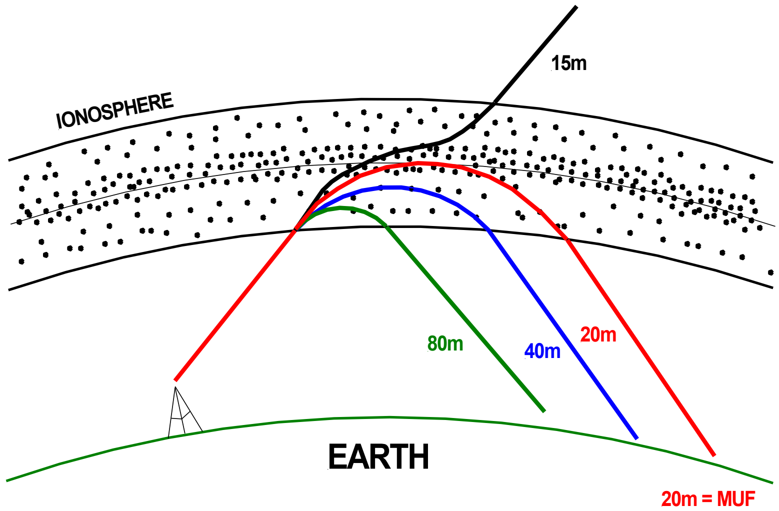


Figure 24 Anomalous dispersion in the ionosphere (source: author)

One of the serious problems resulting from dispersion is called group velocity dispersion. An information carrying signal is composed of many different frequency components. The velocity v_{f1} of a single frequency component is $v_{f1} = c/n_{f1}$ where n_{f1} is the index of refraction for that frequency as it travels through a material. Since each of the signal's frequency components has a different index of refraction n_{fm} they will all travel through the material at different speeds due to dispersion. The result is signal distortion, for example the widening of a signal pulse.

Consequently, dispersion management is extremely important in communication systems. If dispersion is too high in a fiber optic cable, a group of pulses representing a bit stream will spread in time, merge, and render the bit stream useless. This limits the cable length that a signal can be sent down without regeneration.

2.5.7 Total Reflection

Total reflection, illustrated in Figure 25, can occur when light travels from a material with a high index of refraction to one with a lower index of refraction, that is when

$$n_1 > n_2$$

The angle of refraction θ_2 depends on the angle of incidence θ_1. The angle of refraction can reach 90° ($\theta_2 = 90°$) if the angle of incidence becomes large enough. The angle of incidence for which this occurs is called the critical angle θ_c illustrated in Figure 25. A light wave will be completely reflected at the interface between two media, without ever entering Medium 2, if the angle of incidence is greater than the critical angle. This is called total reflection. Thus total reflection occurs when

$$\theta_1 > \theta_c$$

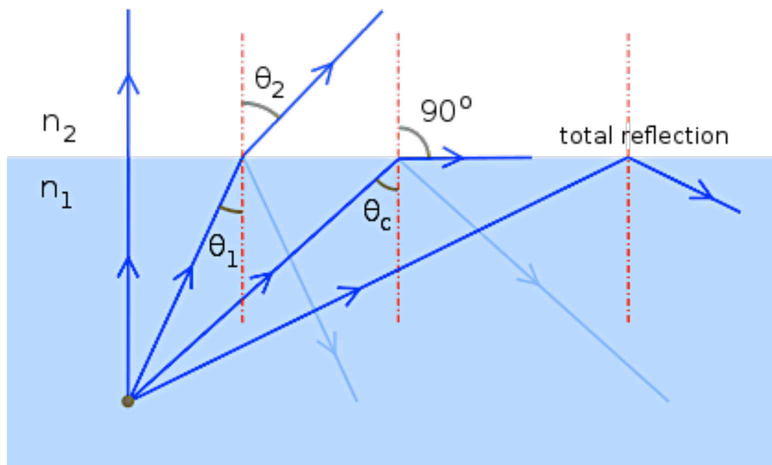


Figure 25 Total reflection (source: Wikipedia)

Total reflection for light entering air from water is illustrated in Figure 26.

Figure 26 Total reflection (source: W3spoint)

Total reflection is also the mechanism used to send light through a fiber optic cable as illustrated in Figures 27 and 28.

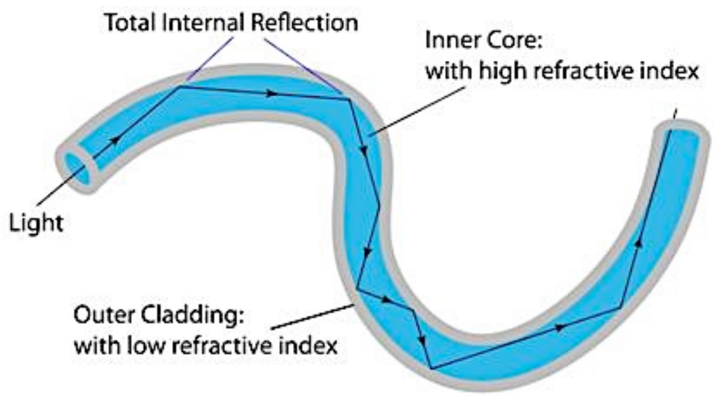


Figure 27 Fiber optic light transmission (source: todaystechnologyy)

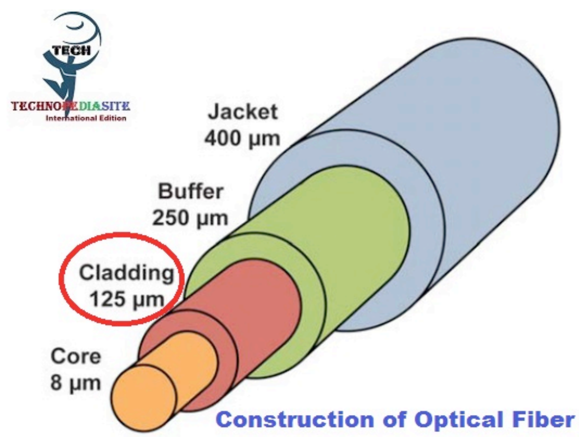


Figure 28 Construction of fiber optic cable (source: technopediasite)

2.6 Diffraction

Diffraction is a property of light that causes it to bend around sharp edges. In addition, diffraction causes light to spread out after passing through a small opening which is comparable in size to its wavelength.

Italian Jesuit priest, mathematician and physicist Francesco Maria Grimaldi (1618 – 1663) was the first to carefully study the diffraction of light. Since diffracted light seems to travel in different direction, Grimaldi named the phenomena diffraction meaning breaking up into pieces. Grimaldi showed that light spreads out and creates interference patters when it passed through a small hole. The results obtained by Grimaldi were published in 1665 after his death.

An intuitive understanding of diffraction is provided by Huygens' principles. As described earlier, Huygens assumed that the wave front of a propagating light wave consisted of an infinite number of point sources. Light propagated from a point source as a spherical wavelet, illustrated in Figure 29. The radius of each wavelet was equal to the speed of light c multiplied by the time t since the wavelet was emitted by the point source. The infinite number of wavelets interfered with one an other with the result that they all canceled out *except* in the forward direction. In the forward direction the wavelets added constructively causing the wave front to move forward (to the right in the figure) from its position at time t = 0.

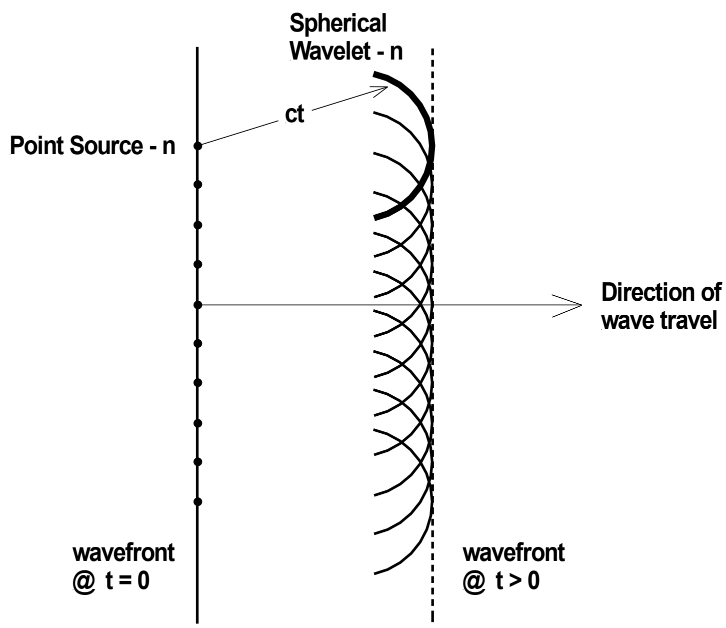


Figure 29 Huygens' Principle of Light (source: author)

In Figure 30 an incident light wave impinges on an opaque screen which contains a single pin hole a . The pin hole is one wavelength in diameter.

In accordance with Huygens principle, the wavefront approaching the screen is radiating wavelets of light from an infinite number of point sources along the wavefront. All but one of these wavelets is blocked by the screen. The one that is not blocked passes through the pin hole. This wavelet expands in a spherical manner, filling all space on the right side of the screen, since there are no other wavelets to interfere with it. The result is a complete diffraction pattern.

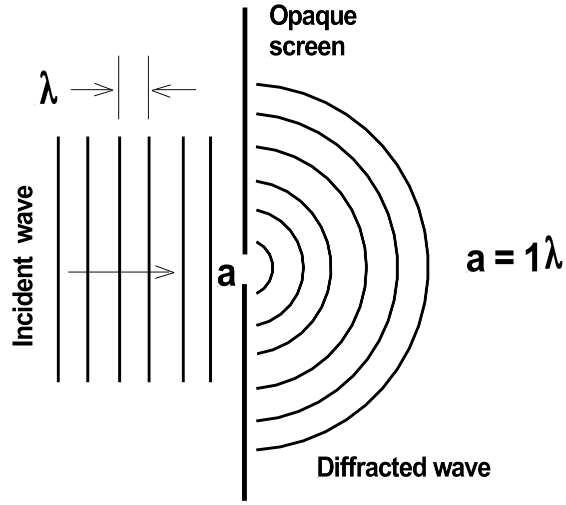


Figure 30 Diffraction through a pin hole 1λ in diameter (source: author)

In Figure 31 the pin hole is enlarged so that it is 3 wavelengths in diameter. The larger pin hole allows several wavelets to pass through. These wavelets interfere with each other on the right side of the screen forming a reduced refraction pattern.

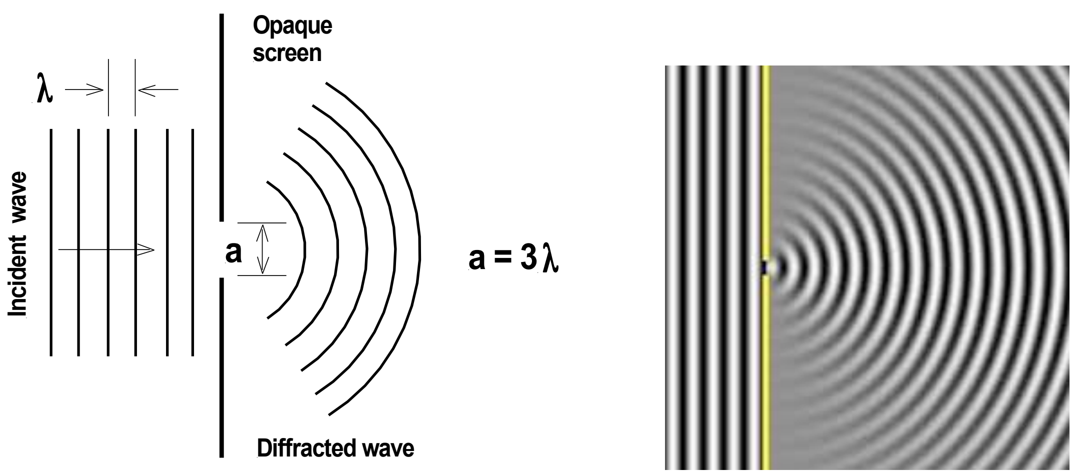


Figure 31 Diffraction through a pin hole 3λ in diameter (source: author)

In Figure 32 the pin hole is increased further in size to a diameter of 6 wavelengths, big enough to permit a large number of wavelets to pass through. All of these wavelets interfere with one and other creating even a smaller refraction pattern on the right side of the screen.

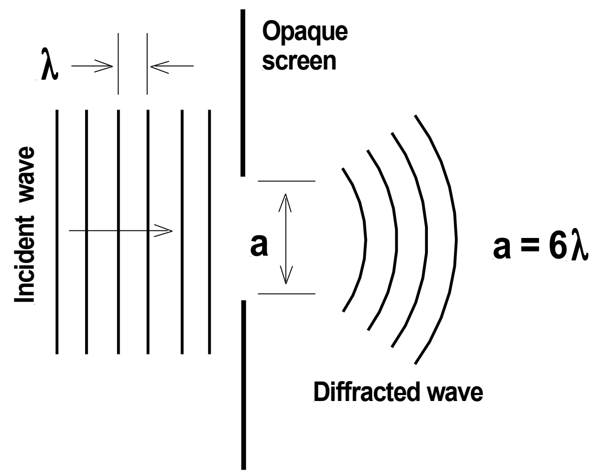


Figure 32 Diffraction through a pin hole 6λ in diameter (source: author)

In the last illustration, Figure 33, the hole is made so large that it is huge compared to a wavelength. In this case the diffraction effect completely disappears. The light wave simply passes through the hole as if the screen were not there.

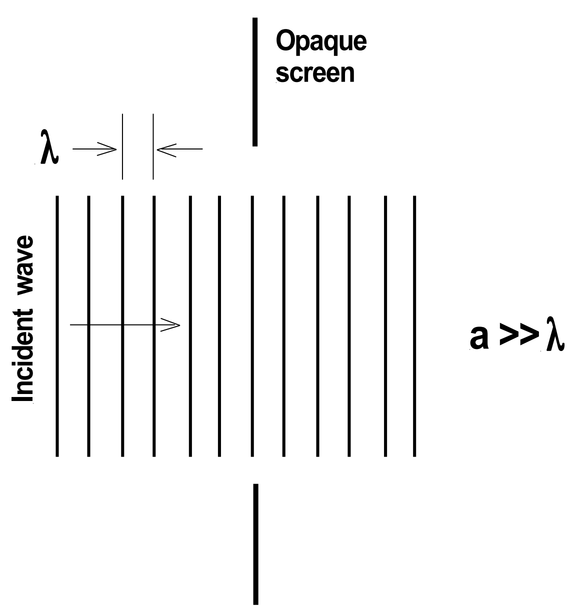


Figure 33 Diffraction through a large hole (source: author)

Diffraction of light around an object with sharp edges is illustrated in Figure 34. In this figure the bottom part of a wave front is removed by an obstacle. The top part of the wave continues on, unaffected, in the forward direction. As before, destructive interference between adjacent wavelets account for the wave's forward movement. However, destructive interference does not occur at the bottom of the wavefront because the lower part of the wavefront has been removed by the obstacle. Consequently, point sources of light at the bottom of the remaining wavefront propagate downward as well as straight ahead causing the light to bend around the obstacle.

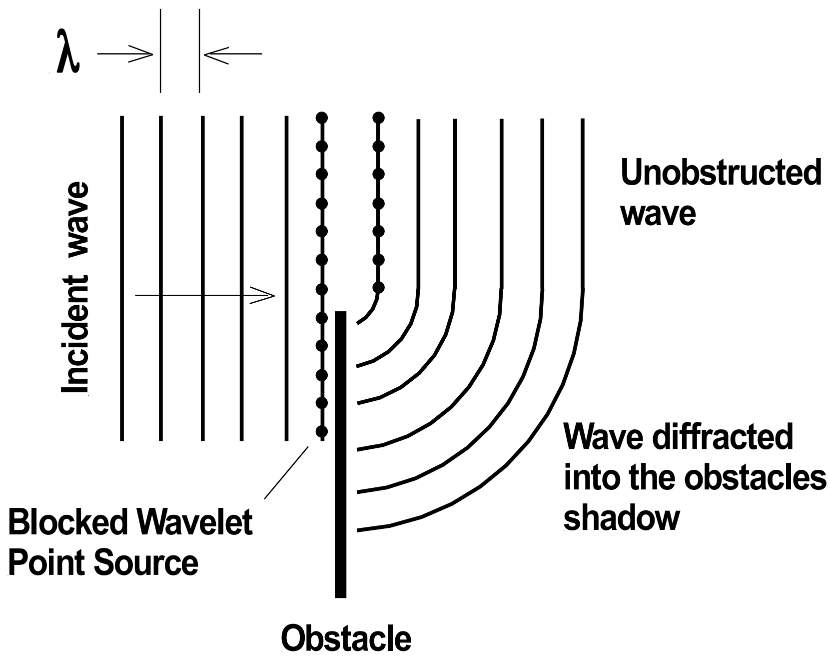


Figure 34 Diffraction of light around an obstacle (source: author)

Figure 35 illustrates the diffraction of a radio signal. In this figure a radio station is transmitting from the tower on the right side of the picture. A receiving station, the antenna on the left side of the figure, is in the shadow of a large hill and should not be able to hear the transmitted signal. The transmitted signal passes over the top of the hill and keeps on going in a straight line. However, some of the signal is diffracted downward by the hill top allowing the receiving station in the shadows to hear the transmission.

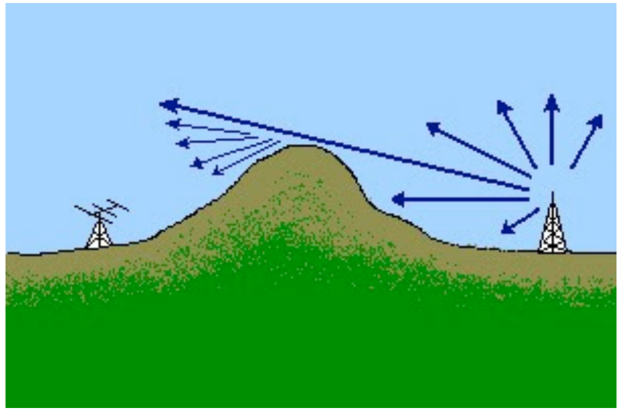


Figure 35 Diffracted radio signal (source: astrosurf)

Diffraction is a phenomenon of all types of waves. The picture in Figure 36 shows the diffraction of ocean waves through a small break in a sea wall. Diffraction is the reason that we can hear around corners. Sound waves travel from one room to another, spreading out through doorways and bending around the edge of buildings and other obstructions. Diffraction of radio signals by hills, buildings, and other structures are common occurrences at VHF frequencies and above. The diffraction of light is usually not noticeable because the wavelength of light is so short. However, light will diffract, as illustrated above, if an opening is extremely small or the edge of an object is sharp enough.

Figure 36 Diffraction of water waves (source: Verbcatcher Wikimedia)

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