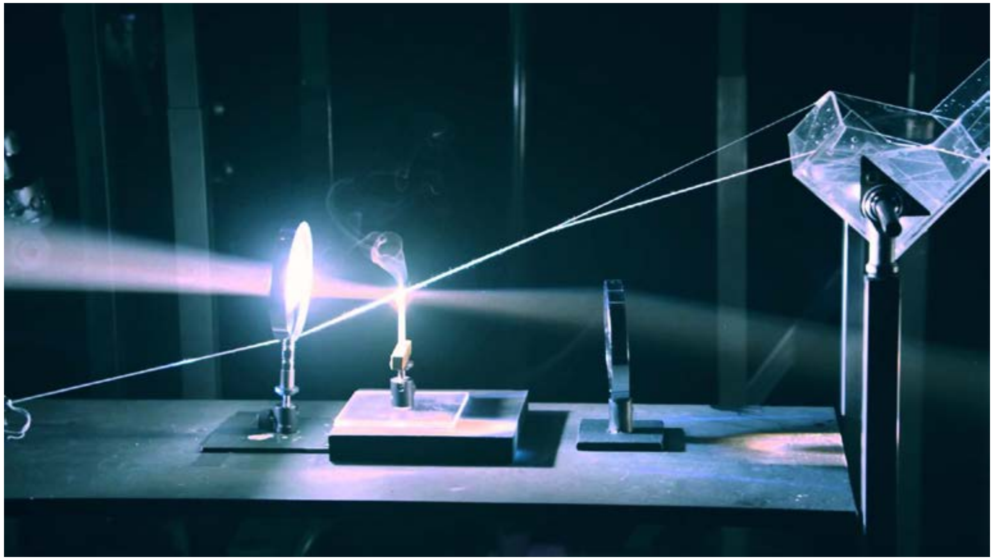
Optics

Optics is the branch of physics which involves the behavior and properties of *light*, including its interactions with matter and the construction of instruments that use or detect it.

Most optical phenomena can be accounted for using the classical ***electromagnetic description*** of light.

Complete electromagnetic descriptions of light are, however, often difficult to apply in practice. Practical optics is usually done using simplified models. The most common of these, ***geometric optics***, treats light as a collection of rays that travel in straight lines and bend when they pass through or reflect from surfaces.

Physical optics is a more comprehensive model of light, which includes wave effects such as diffraction and interference that cannot be accounted for in geometric optics.



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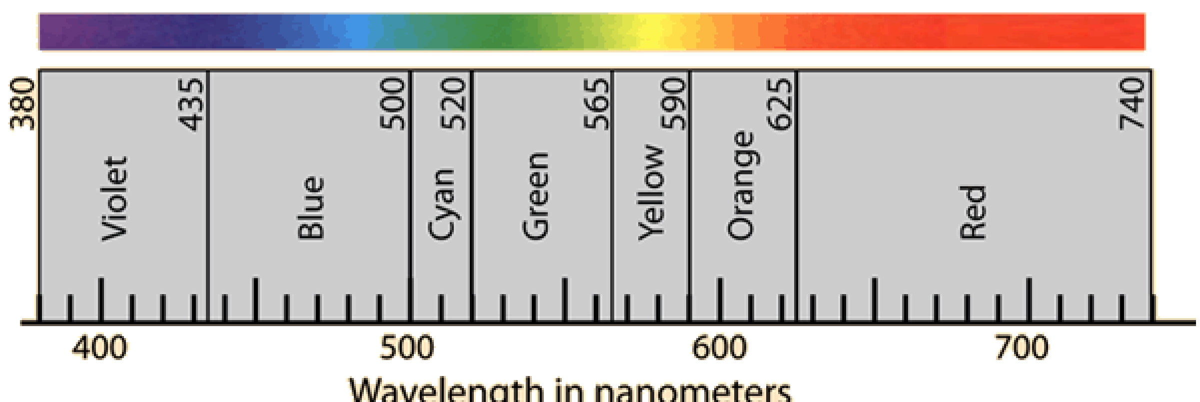
Spectral Colors

In a rainbow or the separation of colors by a prism we see the continuous range of spectral colors (***the visible spectrum***).

A spectral color is composed of a single wavelength and can be correlated with wavelength as shown in the chart below. It is safe enough to say that monochromatic light like the helium-neon laser is red (632 nm) or that the 3-2 transition from the hydrogen spectrum is red (656 nm) because they fall in the appropriate wavelength range. But most colored objects give off a range of wavelengths and the characterization of color is much more than the statement of wavelength. Perceived colors can be mapped on a chromaticity diagram.



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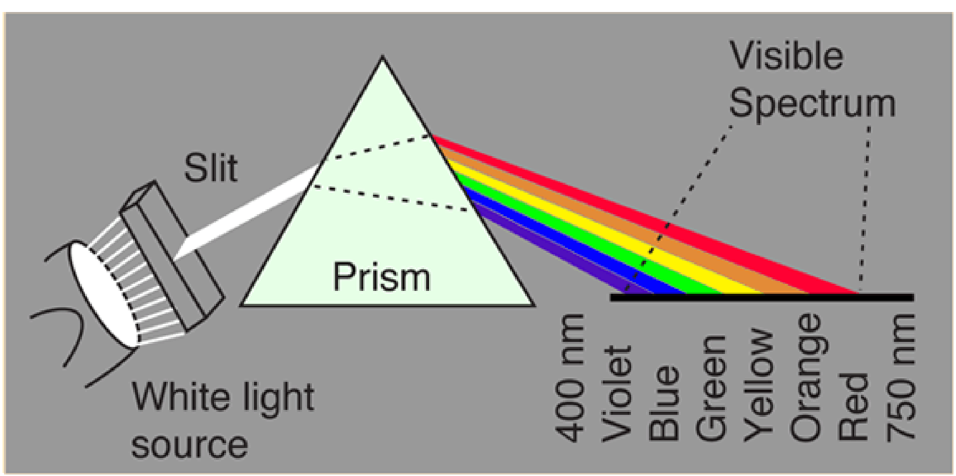
Color

It is common practice to define pure colors in terms of the wavelengths of light as shown. This works well for spectral colors but it is found that many different combinations of light wavelengths can produce the same perception of color.

Infrared	R	O	Y	G	B	I	V	Ultraviolet

This progression from left to right is from *long* wavelength to *short* wavelength, and from *low* frequency to *high* frequency light. The wavelengths are commonly expressed in nanometers (1 nm = 10^{-9} m). The visible spectrum is roughly from 700 nm (red end) to 400 nm (violet end). The letter I in the sequence above is for indigo - no longer commonly used as a color name.

The inherently distinguishable characteristics of color are ***hue***, ***saturation***, and ***brightness***.



White light, or nearly white light from the Sun, contains a continuous distribution of wavelengths. The light from the Sun is essentially that of a blackbody radiator at 5780 K.

The wavelengths (spectral colors) of white light can be separated by a dispersive medium like a *prism*. Even more effective separation can be achieved with a *diffraction grating*.

Propagation of Light

Visible light is a narrow part of the electromagnetic spectrum and in a vacuum all electromagnetic radiation travels at the speed of light:

$$c = 2.99792458 \times 10^8 m/s$$

In a material medium the effective speed of light is slower and is usually stated in terms of the index of ***refraction*** of the medium.

Light propagation is affected by the phenomena:

- ***refraction***,
- ***reflection***,
- ***diffraction***,
- ***interference***.

The behavior of light in optical systems will be characterized in terms of its ***vergence***.

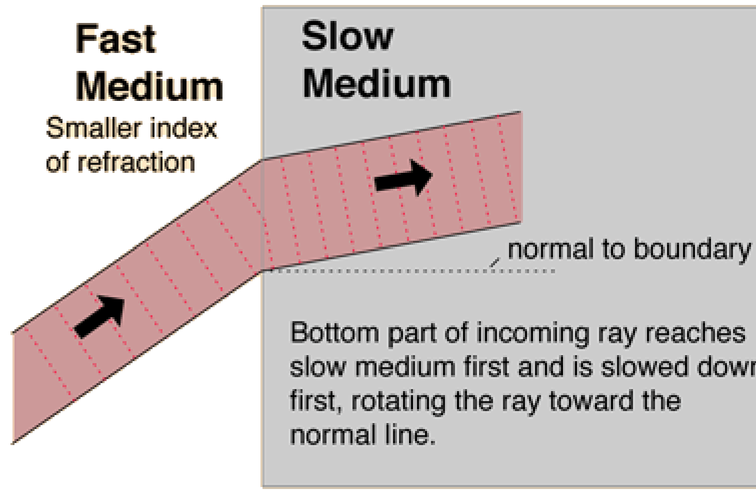
$$speed\ light\ \approx 3 \cdot 10^8 m/s$$

Refraction of Light

Refraction is the bending of a wave when it enters a medium where its speed is different.

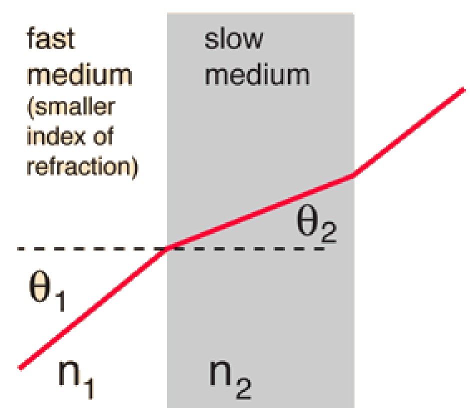
The refraction of light when it passes from a fast medium to a slow medium bends the light ray toward the normal to the boundary between the two media. The amount of bending depends on the indices of refraction of the two media and is described quantitatively by ***Snell's Law***.

As the speed of light is reduced in the slower medium, the wavelength is shortened proportionately. The frequency is unchanged; it is a characteristic of the source of the light and unaffected by medium changes.



Snell's Law relates the indices of refraction n of the two media to the directions of propagation in terms of the angles to the normal.

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



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Index of Refraction of Light

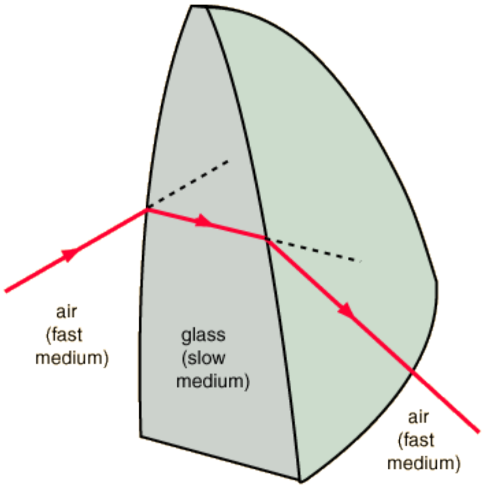
The index of refraction is defined as the speed of light in vacuum divided by the speed of light in the medium.

index of refraction

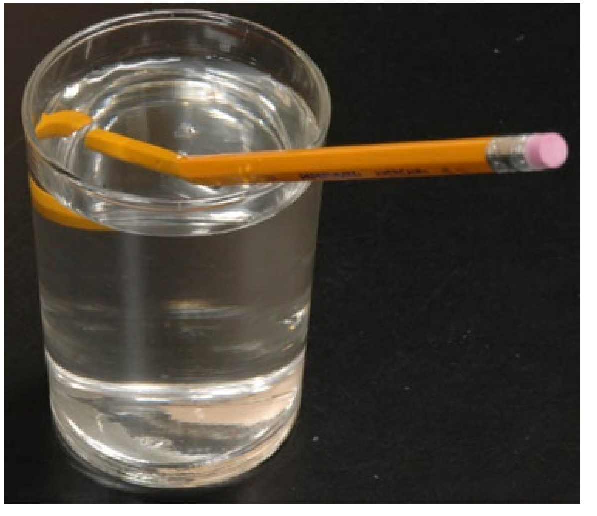
$$n = \frac{c}{v}$$

velocity of light in vacuum

velocity of light in the medium



Refraction of Light by Water



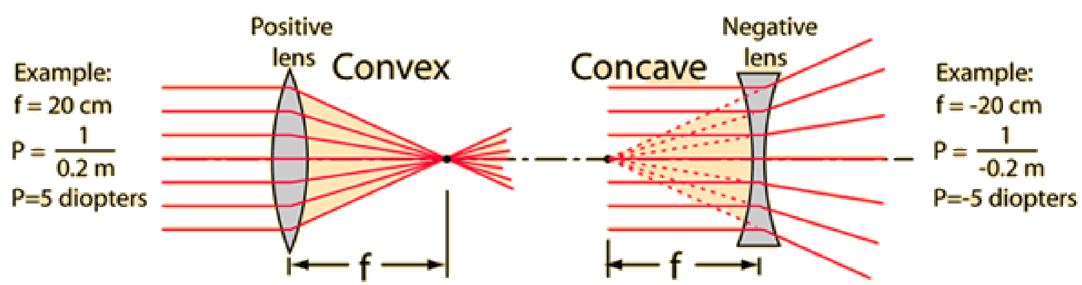
Light entering or exiting a water surface is bent by refraction. The index of refraction for water is 4/3, implying that light travels 3/4 as fast in water as it does in vacuum.

Refraction at the water surface gives the "broken pencil" effect shown above. Submerged objects always appear to be shallower than they are because the light from them changes angle at the surface, bending downward toward the water.

Principal Focal Length

For a thin double convex lens, refraction acts to ***focus*** all parallel rays to a point referred to as the ***principal focal point***. The distance from the lens to that point is the principal ***focal length*** *f* of the lens.

For a double concave lens where the rays are diverged, the principal focal length is the distance at which the back-projected rays would come together and it is given a negative sign.



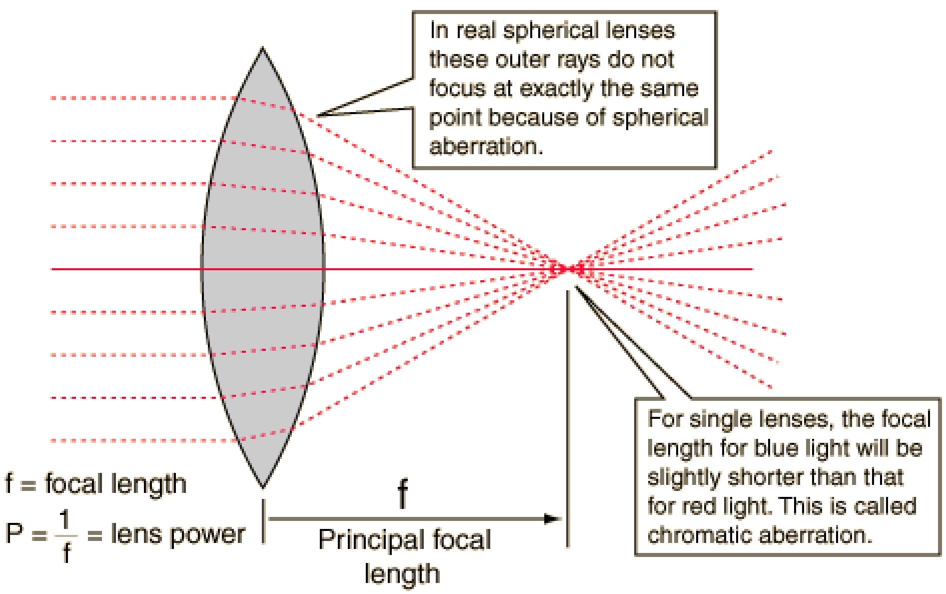
The lens strength in ***diopters*** is defined as the *inverse of the focal length in meters*.

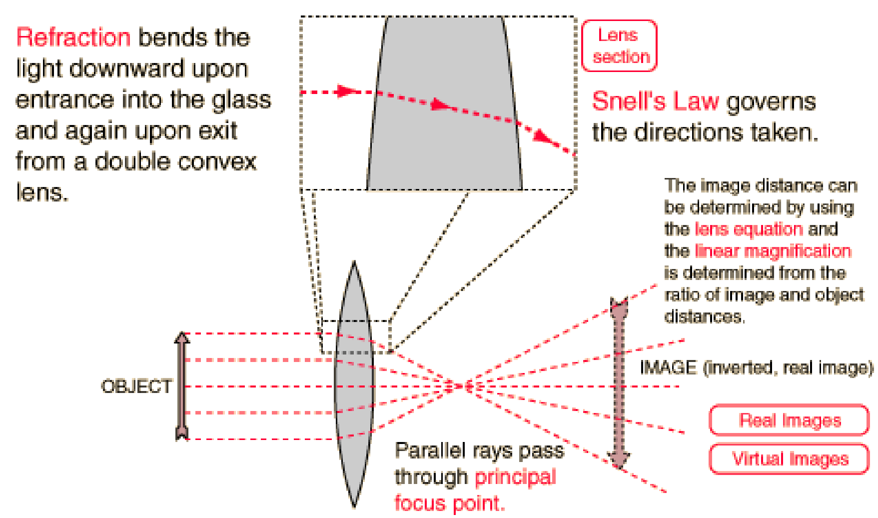
For a thick lens made from spherical surfaces, the focal distance will differ for different rays, and this change is called ***spherical aberration***. The focal length for different wavelengths will also differ slightly, and this is called ***chromatic aberration***.

The ***principal focal length*** of a lens is determined by the index of refraction of the glass, the radii of curvature of the surfaces, and the medium in which the lens resides.

Focal Length and Lens Strength

The most important characteristic of a lens is its principal ***focal length***, or its inverse which is called ***the lens strength*** or lens "***power***". Optometrists usually prescribe corrective lenses in terms of the lens power in ***diopters***. The lens power is the inverse of the focal length in meters: the physical unit for lens power is 1/meter which is called ***diopter***.

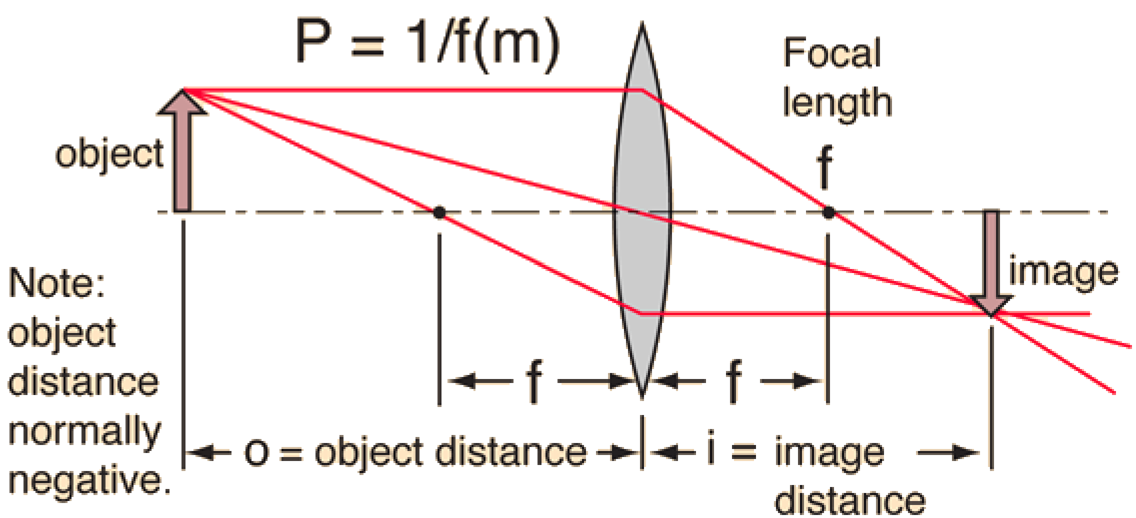




Thin Lens Equation

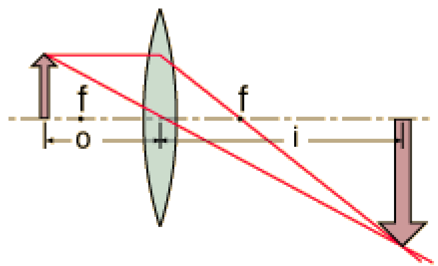
$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$

$$\frac{1}{\text{object distance}} + \frac{1}{\text{image distance}} = \frac{1}{\text{focal length}}$$



Magnification: Transverse &Angular

The linear magnification or ***transverse magnification*** is the ratio of the image size to the object size. If the image and object are in the same medium it is just the image distance divided by the object distance.



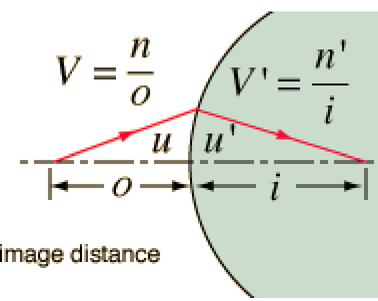
$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$ Lens equation

Linear magnification:

$$M = \frac{-i}{o} = \frac{h'}{h}$$

If the media are different on the two sides of the surface or lens, the magnification is not quite so straightforward. It can be variously expressed as

$$M_T = \frac{V}{V'} = \frac{nu}{n'u'} = \frac{ni}{n'o}$$



V = vergence o = object distance i = image distance

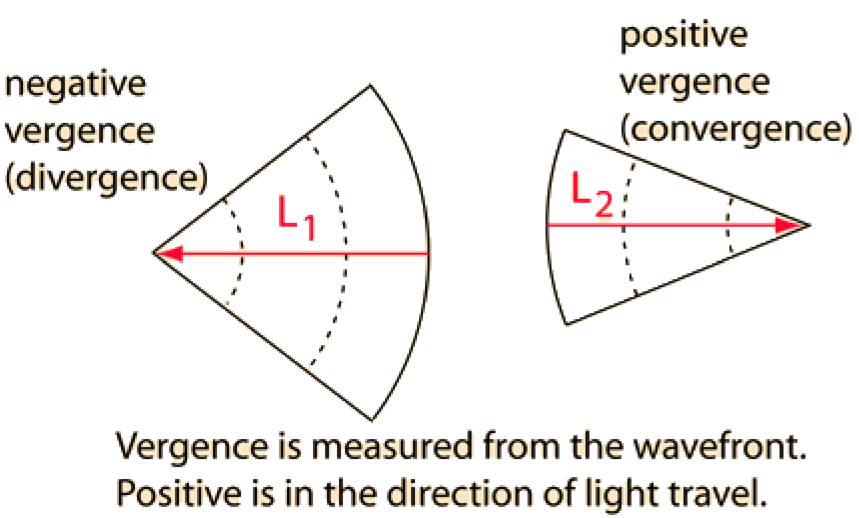
In this equation V is the ***vergence***, n is the index of refraction, and u is used for the angle.

Vergence

The vergence of light is defined by

$$vergence = V = n/L$$

where n is the index of refraction of the medium and L is the distance in accordance with the Cartesian sign convention. The standard use of vergence expresses the distance L in meters, so the unit of vergence is m-1, often called "diopters".

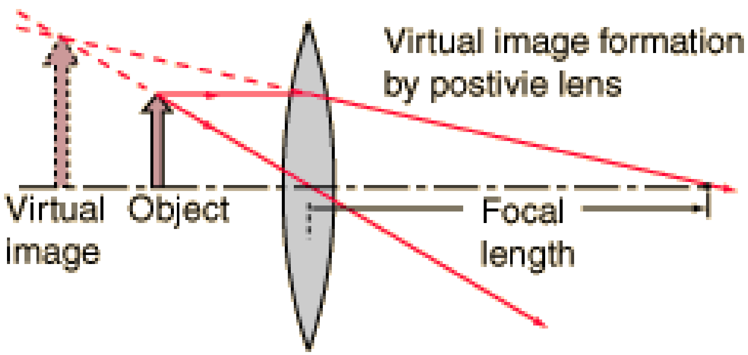


Since the distance L_1 is measured from the wavefront and light is traveling left to right, it is a negative distance and the vergence is negative (divergent). L_2 is positive since it is directed to the right from the wavefront (convergent).

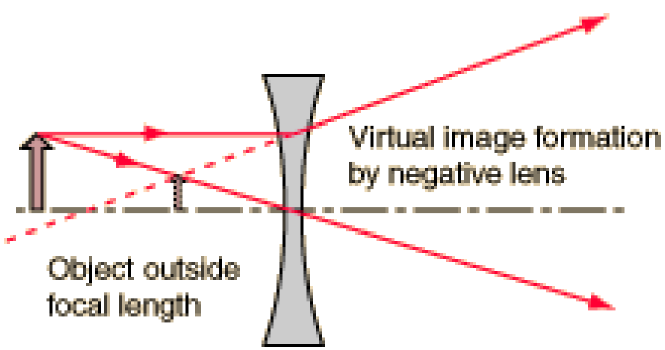
The change in vergence when the light encounters a refracting surface is equal to the ***power*** of the surface P_s:

$$V + P_S = V'$$

Virtual Image Formation



A ***virtual image*** is formed at the position where the paths of the principal rays cross when projected backward from their paths beyond the lens. Although a virtual image does not form a visible projection on a screen, it is no sense "imaginary", i.e., it has a definite position and size and can be "seen" or imaged by the eye, camera, or other optical instrument.



A reduced virtual image if formed by a single negative lens regardless of the object position. An enlarged virtual image can be formed by a positive lens by placing the object inside the principal focal point.

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Ray Diagrams for Lenses

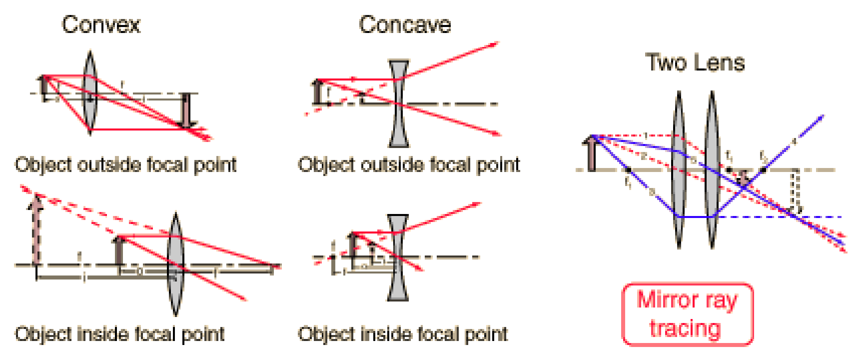
The image formed by a single lens can be located and sized with three principal rays. Examples are given for converging and diverging lenses and for the cases where the object is inside and outside the principal focal length.

The "***three principal rays***" which are used for visualizing the image location and size are:

1. A ray from the ***top*** of the object proceeding ***parallel to the centerline*** perpendicular to the lens. Beyond the lens, it will pass through the principal focal point. For a negative lens, it will proceed from the lens as if it emanated from the focal point on the near side of the lens.

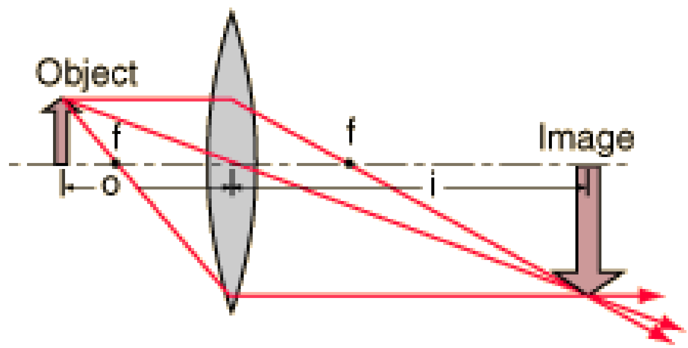
2. A ray through the ***center*** of the lens, which will be ***undeflected***. (Actually, it will be jogged downward on the near side of the lens and back up on the exit side of the lens, but the resulting slight offset is neglected for thin lenses).

3. A ray through the ***principal focal point*** on the near side of the lens. It will proceed ***parallel to the centerline*** upon exit from the lens. The third ray is not really needed, since the first two locate the image.

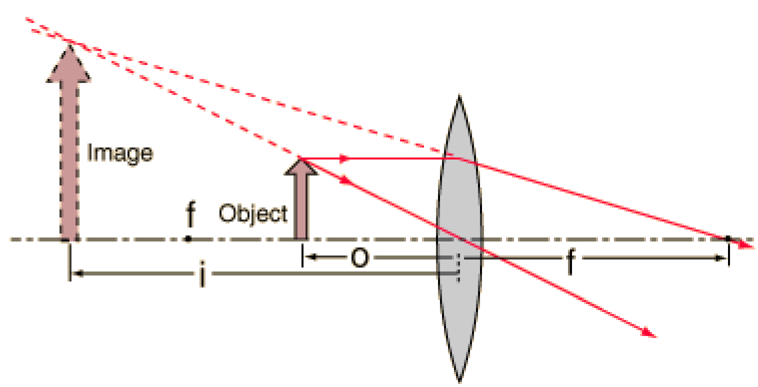


Ray Diagrams for Convex Lenses

For an object outside the focal point, a real inverted image will be formed.



For an object inside the focal point, a virtual erect image will be formed.



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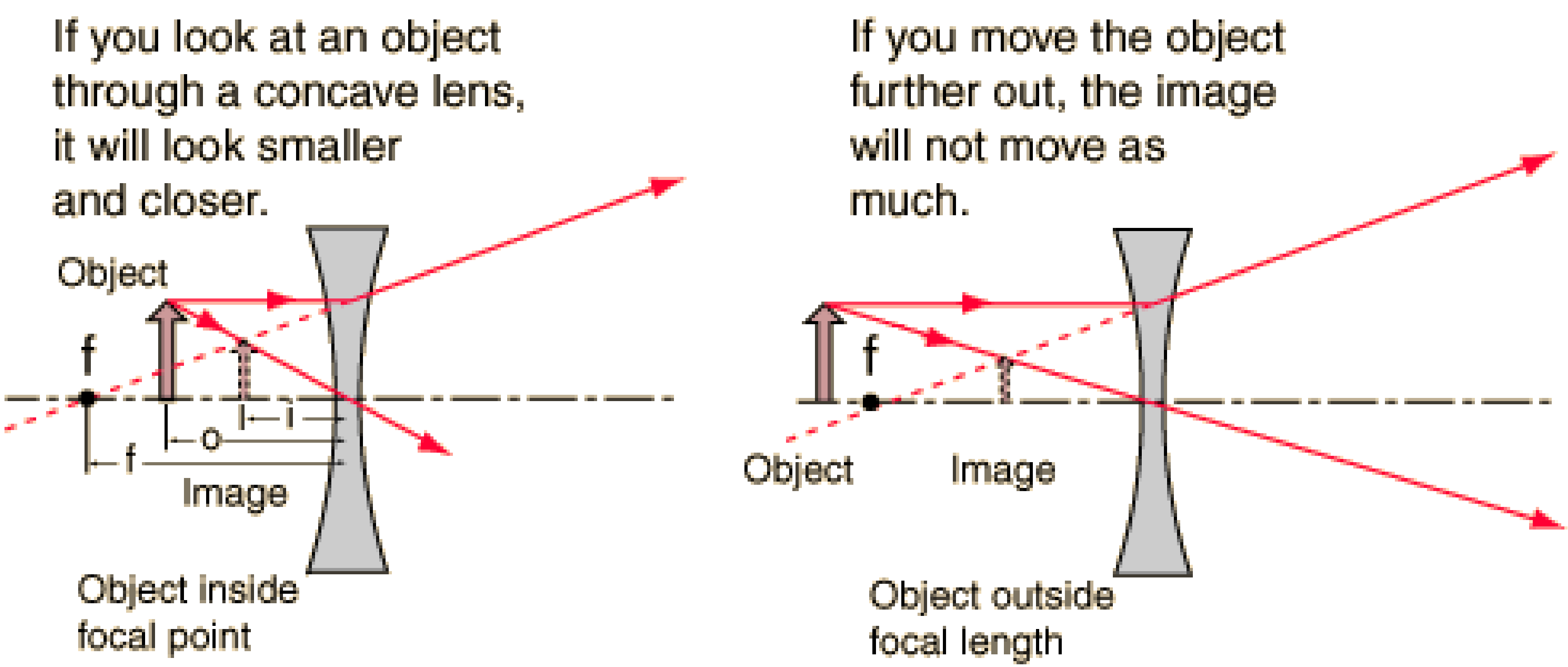
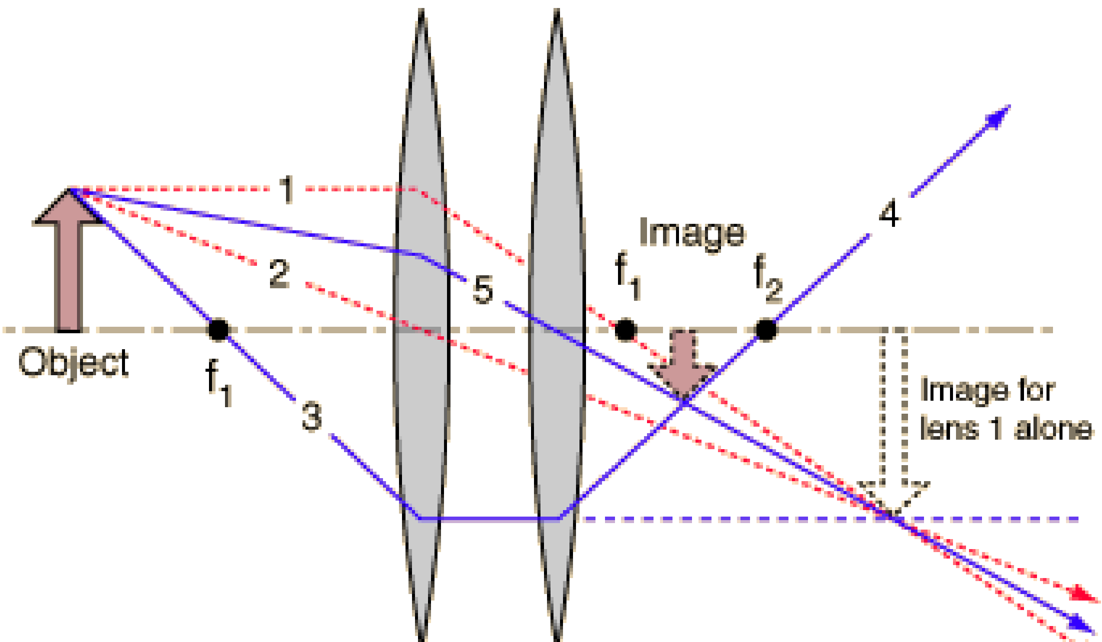
Ray Diagrams for Concave Lenses

The ray diagrams for concave lenses inside and outside the focal point give similar results: an erect virtual image smaller than the object. The image is always formed inside the focal length of the lens.



Ray Diagram for Two Lenses

1. The principal rays 1 and 2 are used to determine the location of the of the image for lens 1 alone.



2. Ray 3 through f_1 will approach lens 2 parallel to the axis and will project through focal point f_2, forming one principal ray (4) for the final image.

3. Back projecting from the single lens image through the center of lens 2 will define the second needed ray (5) since that ray will be undeflected.

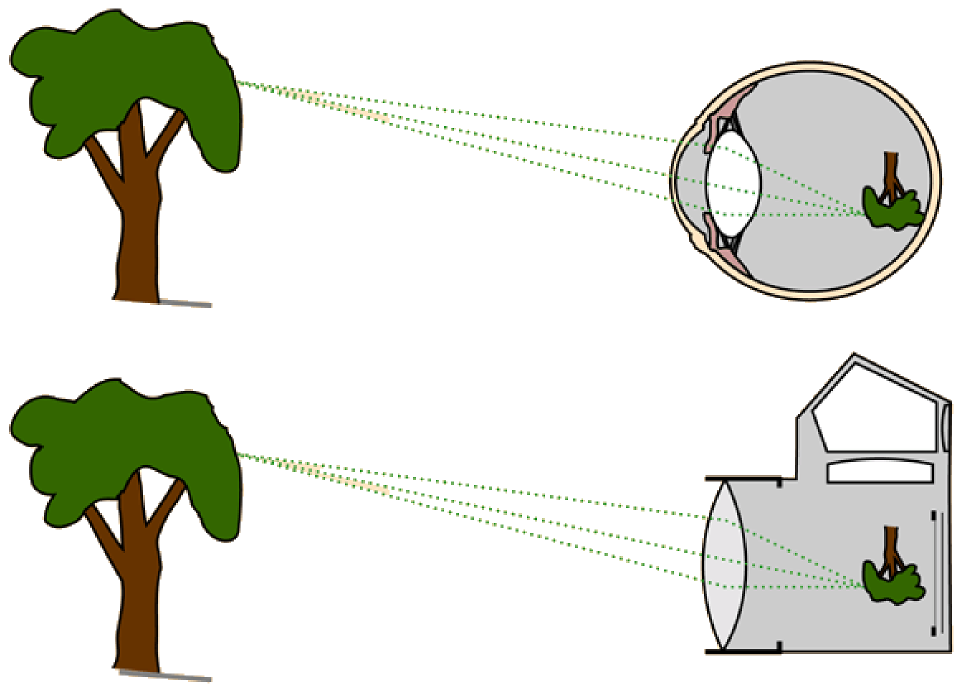
Refraction and the Eye

Most of that refraction in the eye takes place at the first surface, since the transition from the air into the ***cornea*** is the largest change in index of refraction which the light experiences. About 80% of the refraction occurs in the cornea and about 20% in the ***inner crystalline lens.***

While the inner lens is the smaller portion of the refraction, it is the total source of the ability to accommodate the focus of the eye for the viewing of close objects. For the normal eye, the inner lens can change the total focal length of the eye by 7-8%.

Common eye defects are often called "refractive errors" and they can usually be corrected by relatively simple compensating lenses.

Images are formed in a camera by refraction in a manner similar to image formation in the eye. However, accommodation to image closer objects is done differently in the eye and camera.



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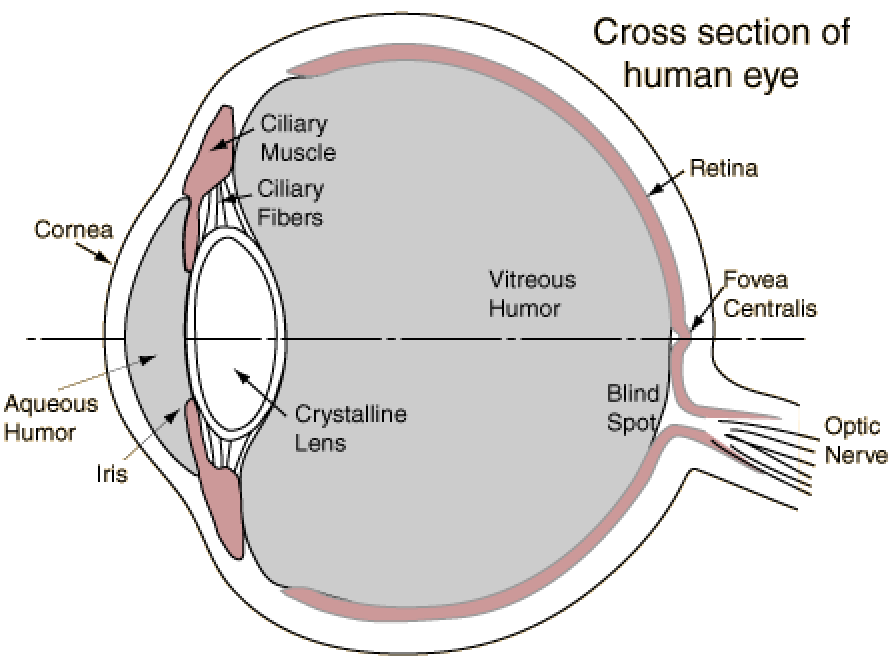
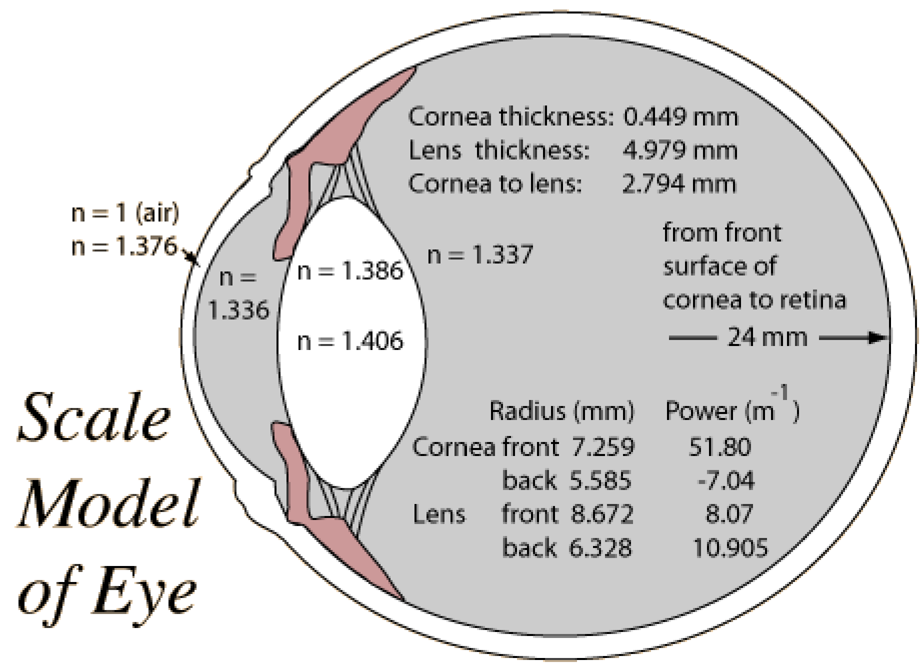
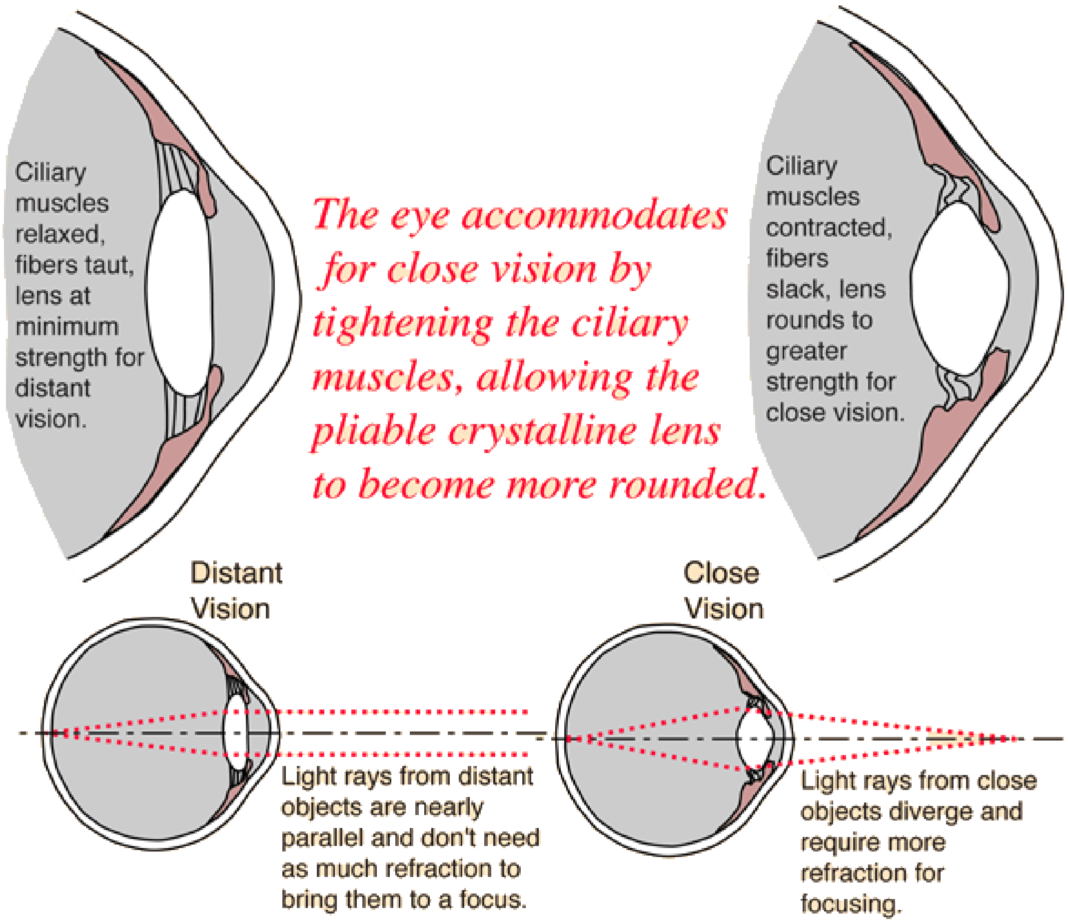
Eye


Cross section of human eye
Ciliary Muscle
Ciliary Fibers
Retina
Cornea
Vitreous Humor
Fovea Centralis
Aqueous Humor
Crystalline Lens
Blind Spot
Optic Nerve
Iris

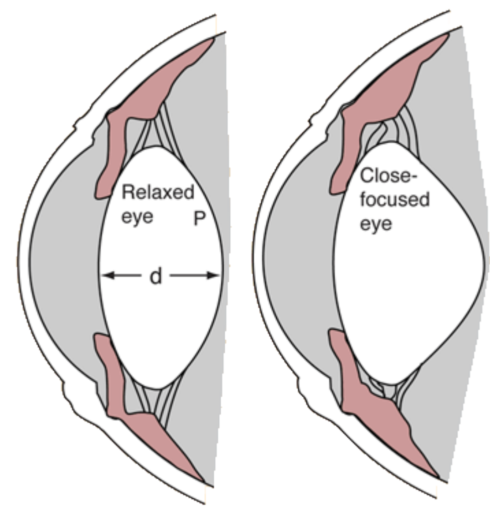

Scale Model of Eye
n = 1 (air)
n = 1.376
n = 1.336
n = 1.386
n = 1.406
n = 1.337
Cornea thickness: 0.449 mm
Lens thickness: 4.979 mm
Cornea to lens: 2.794 mm
from front surface of cornea to retina
24 mm
Radius (mm) Power (m^{-1})
Cornea front 7.259 51.80
back 5.585 -7.04
Lens front 8.672 8.07
back 6.328 10.905

Accommodation



Accommodation is the process of adjusting the focus distance of an optical instrument to the object which is to be viewed.

When the eye is relaxed and the interior lens is the least rounded, the lens has its maximum focal length for distant viewing . As the muscle tension around the ring of muscle is increased and the supporting fibers are thereby loosened, the interior lens rounds out to its minimum focal length..



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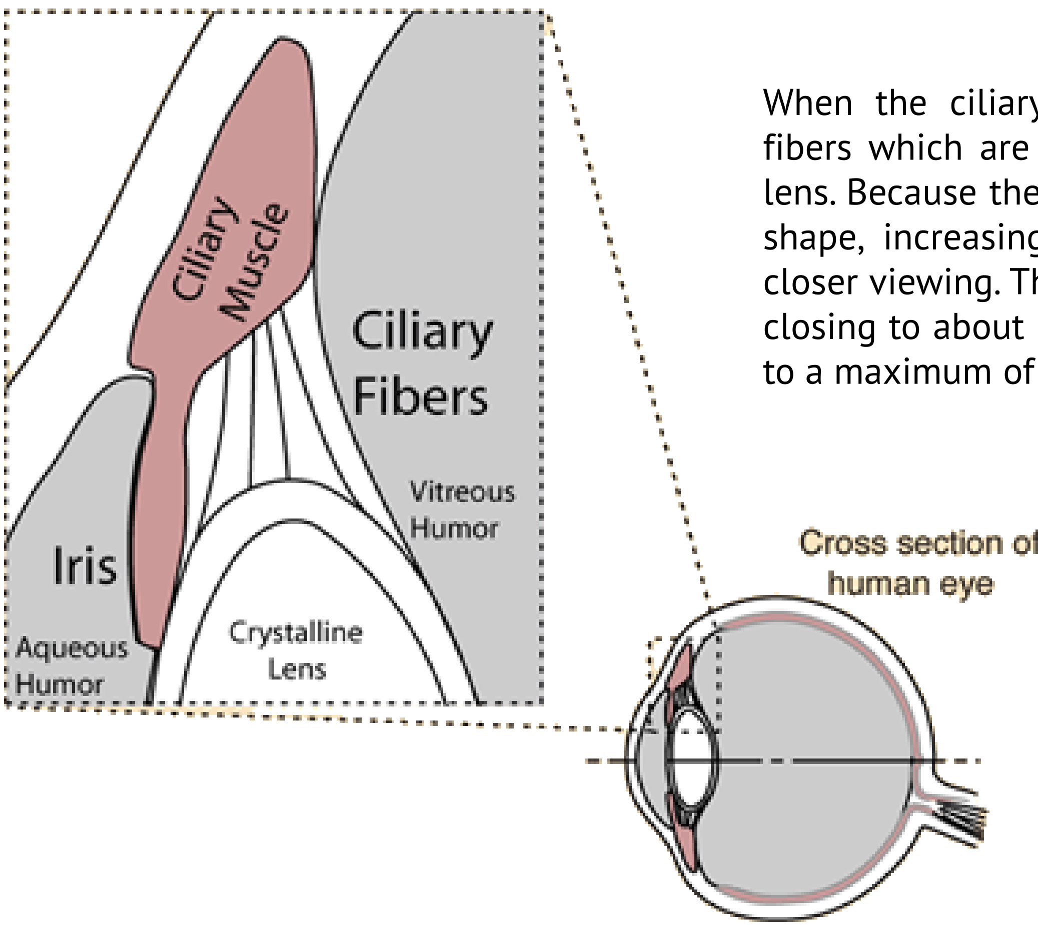
Accommodation



When the ciliary muscles contract, they loosen the ciliary fibers which are attached to the envelope of the crystalline lens. Because the lens is pliable, it relaxes into a more curves shape, increasing it's refractive power to accommodate for closer viewing. The iris serves as the aperture stop for the eye, closing to about 2mm in diameter in bright light and opening to a maximum of about 8mm in dim light.

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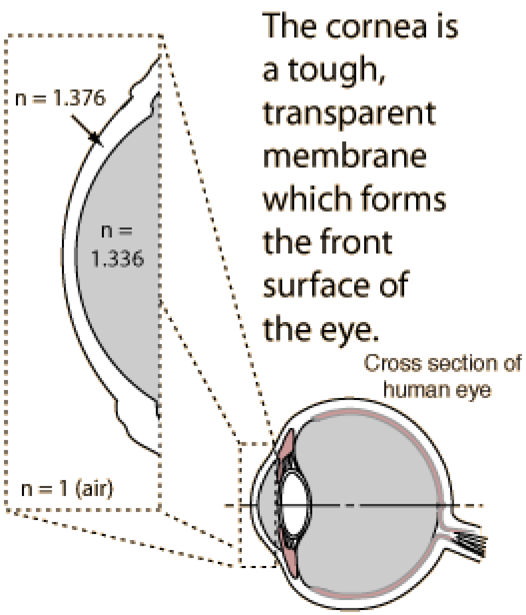
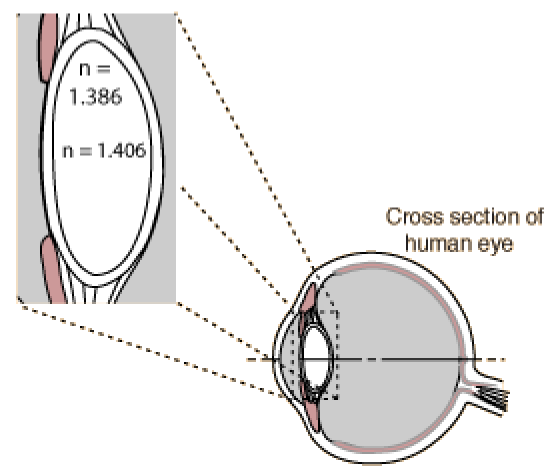
The Cornea



The cornea represents the strongest part of the refracting power of the eye, providing about 80% of the power of the system. The index of refraction of the cornea is about 1.376. Rays pass from the cornea into the watery fluid known as the aqueous humor which has an index of refraction of about 1.336, so most of the refraction is at the cornea-air interface.

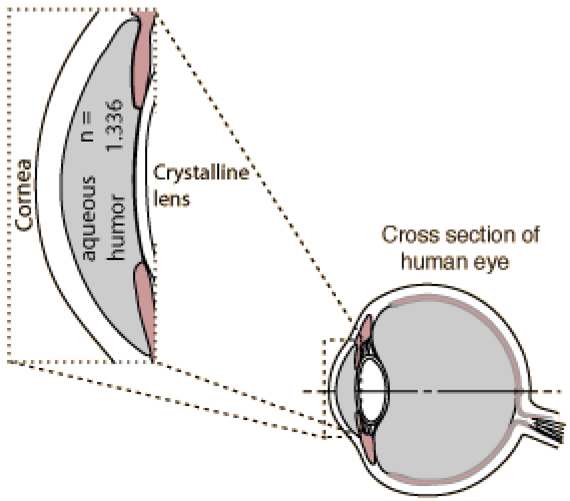
Crystalline Lens



About 9mm in diameter and 4 mm thick, the ***crystalline lens*** provides perhaps 20% of the refracting power of the eye. Hecht likens it to a tiny transparent onion with some 22,000 fine layers. The index ranges from about 1.406 at the center to about 1.386 in outer layers, making it a gradient index lens. It is pliable, and changes shape to accomplish accommodation for close focusing.

The term ***cataract*** is used to describe the condition of clouding or darkening of this lens.

Aqueous Humor

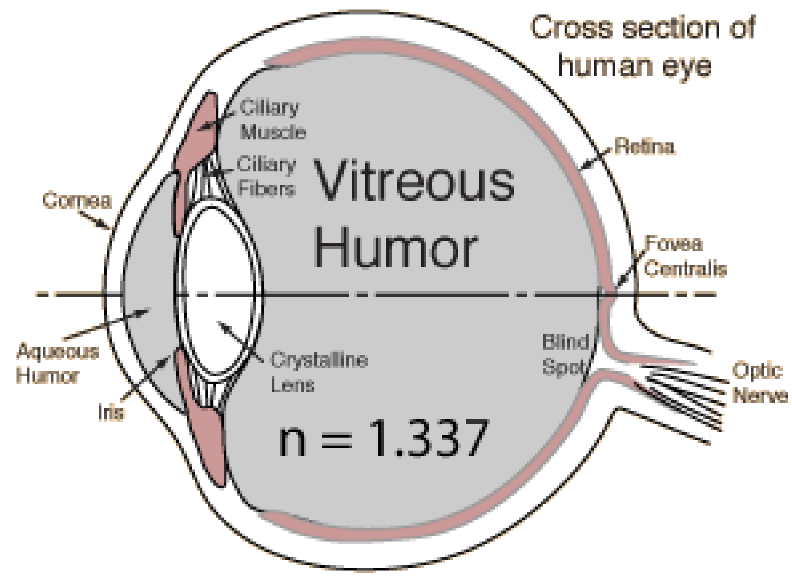


The anterior chamber of the eye is filled with the watery "***aqueous humor***" which has an index of refraction of about 1.336. It is positioned immediately behind the cornea. The larger chamber of the eye is filled with the gelatinous "vitreous humor", which has an index of refraction of about 1.337 .

Vitreous Humor

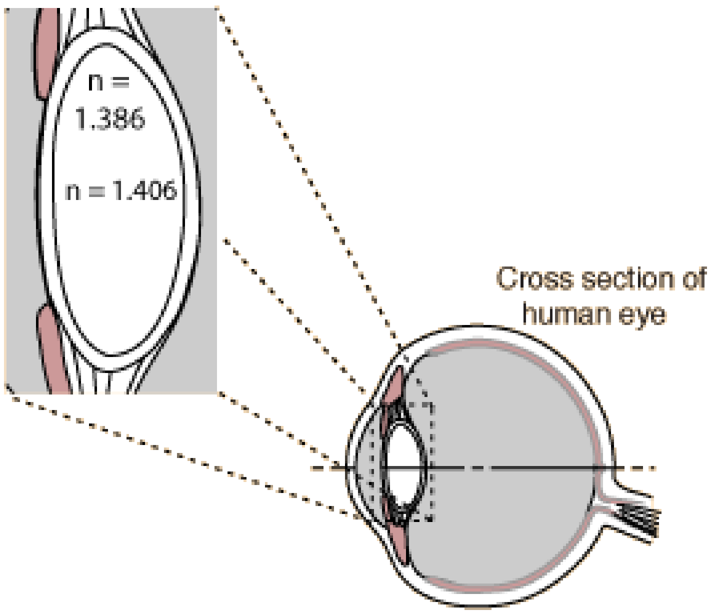
The large chamber of the eye is filled with the gelatinous "***vitreous humor***", which has an index of refraction of about 1.337 . The front chamber of the eye, immediately behind the cornea, is filled with the watery "aqueous humor" which has an index of refraction of about 1.336.

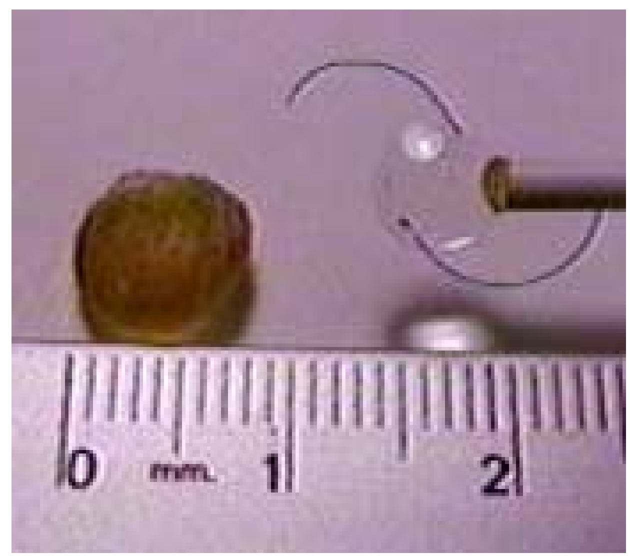
The index of refraction of both of the interior fluids of the eye are very close to that of water, n= 4/3 = 1.333 .



Cataracts

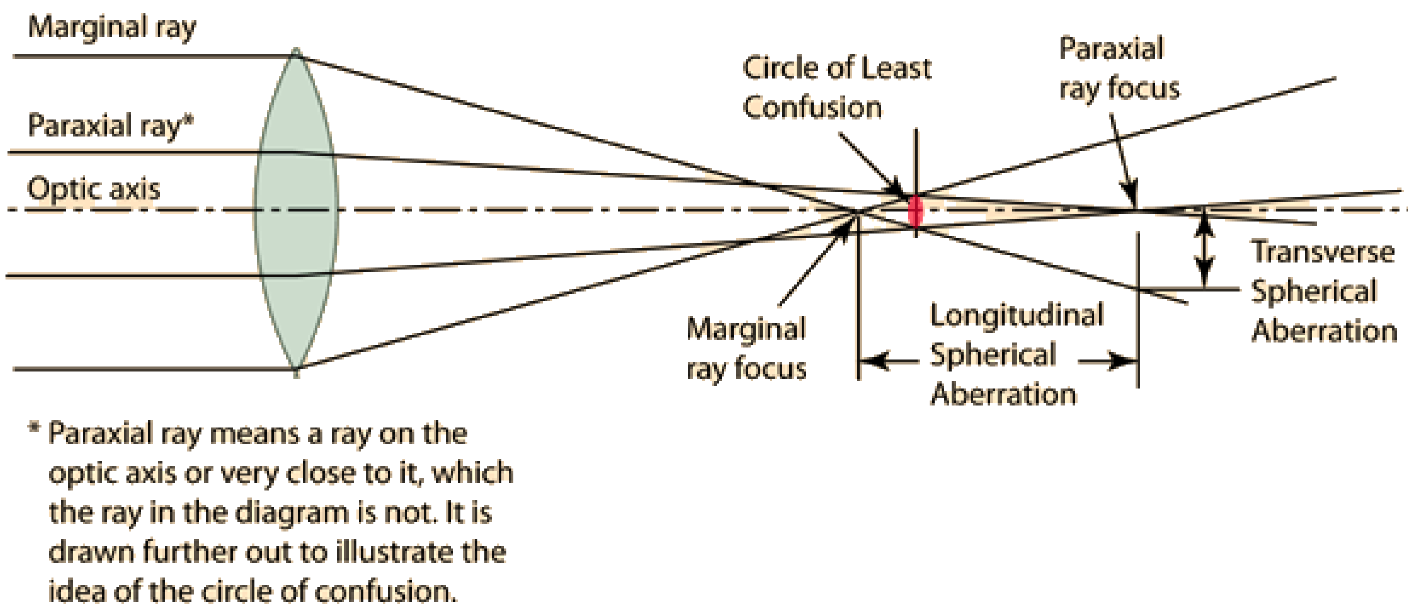
When the inner lens of the eye becomes *darkened* or *opaque*, the condition is called a ***cataract***. The lens may be surgically replaced with a plastic lens. This can have dramatic results in restoring vision to the eye. The implanted lens is of fixed focal length, so it is not capable of accommodation like the natural lens. This is usually not a major concern, because persons who develop cataracts after age 60 do not have much accommodation remaining anyway because the inner lens has become less pliable with age.





Aberrations

In an ideal optical system, all rays of light from a point in the object plane would converge to the same point in the image plane, forming a clear image. The influences which cause different rays to converge to different points are called ***aberrations.***



For lenses made with spherical surfaces, rays which are parallel to the optic axis but at different distances from the optic axis fail to converge to the same point. For a single lens, spherical aberration can be minimized by bending the lens into its best form. For multiple lenses, spherical aberrations can be canceled by overcorrecting some elements. The use of symmetric doublets like the orthoscopic doublet greatly reduces spherical aberration.

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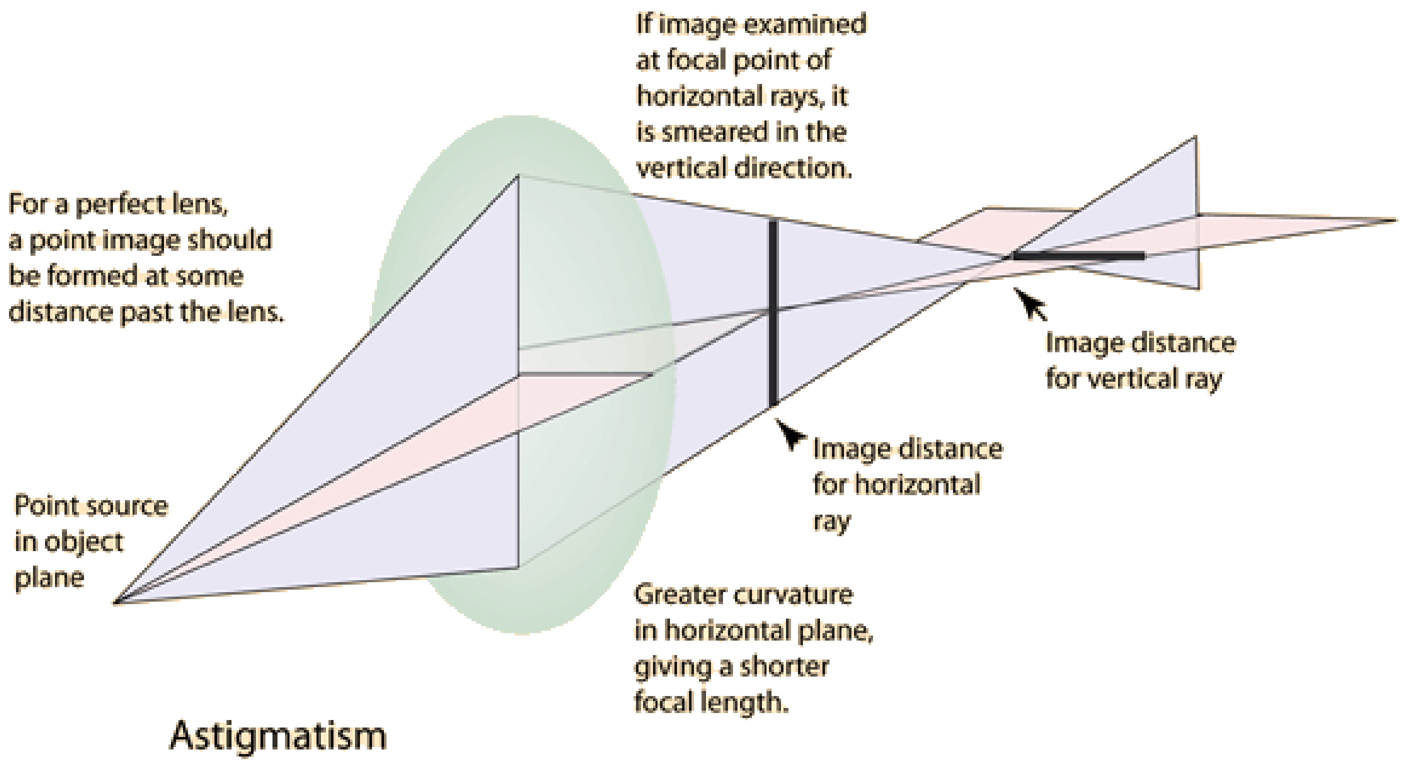
Astigmatism

The kind of astigmatism commonly encountered as a vision defect is a result of different lens curvatures in different planes. If the behavior of light from a point source object is examined, then for a perfect lens it should form a focused bright spot on the opposite side of the lens. But if the focal length of the lens is different for different planes of incident light, there will be no point where all the rays from the object reach a sharp focus.



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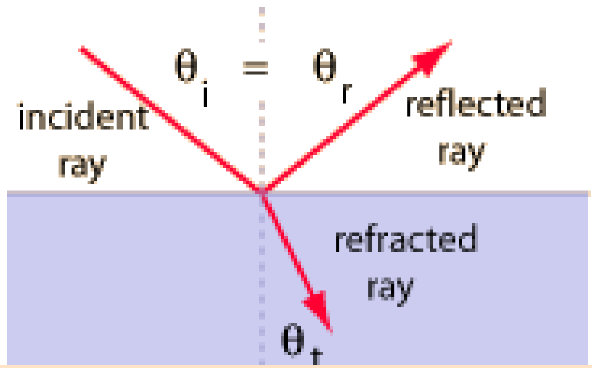
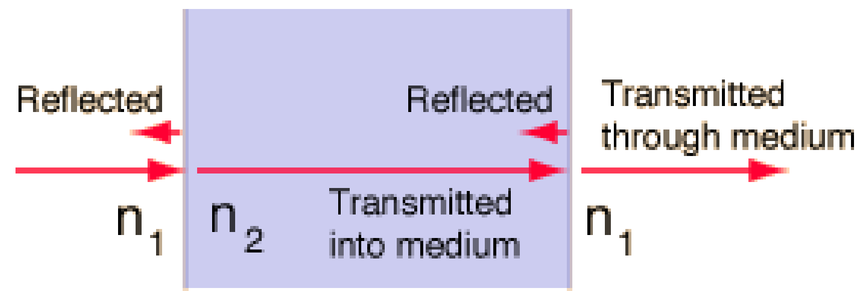
Reflection





the reflectivity is

Light incident upon a surface will in general be partially reflected and partially transmitted as a refracted ray. The fact that the angle of incidence is equal to the angle of reflection is sometimes called the "***law of reflection***".

The reflectivity of light from a surface depends upon the angle of incidence and upon the plane of polarization of the light. The general expression for reflectivity is derivable from Fresnel's Equations. For purposes such as the calculation of reflection losses from optical instruments, it is usually sufficient to have the reflectivity at normal incidence. This normal incidence reflectivity is dependent upon the indices of refraction of the two media.

For light from a medium of index n_1 normally incident upon a medium of index n_2 the reflectivity is:

$$R = \left[\frac{n_2 - n_1}{n_2 + n_1}\right]^2 \quad (\%)$$

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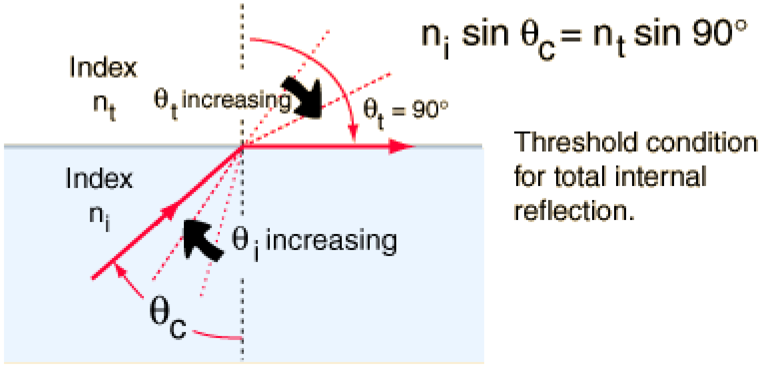
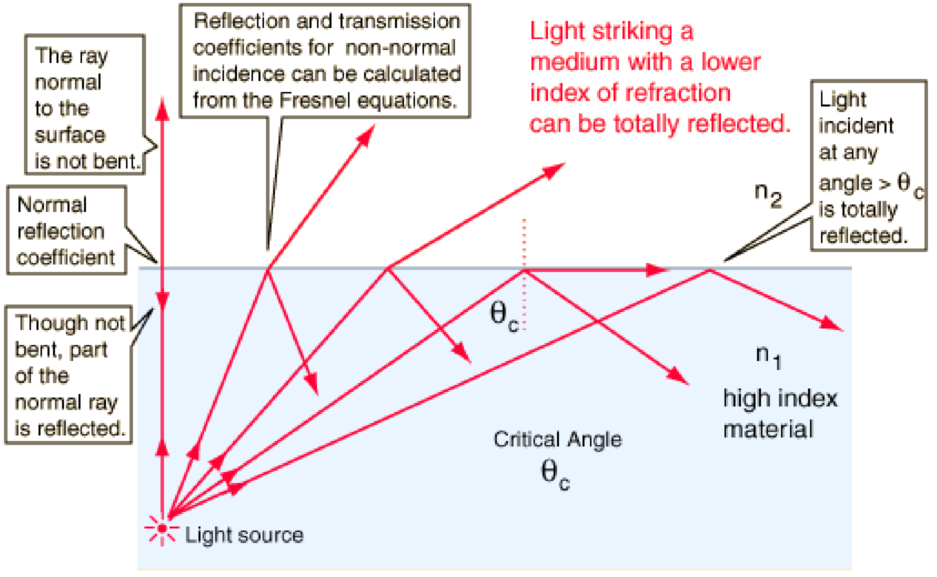
Total Internal Reflection

When light is incident upon a medium of lesser index of refraction, the ray is bent away from the normal, so the exit angle is greater than the incident angle. Such reflection is commonly called "***internal reflection***". The exit angle will then approach 90° for some ***critical*** incident angle ϑ_C , and for incident angles greater than the critical angle there will be ***total internal reflection***.





The critical angle can be calculated from Snell's law by setting the refraction angle equal to 90°. Total internal reflection is important in fiber optics and is employed in polarizing prisms.

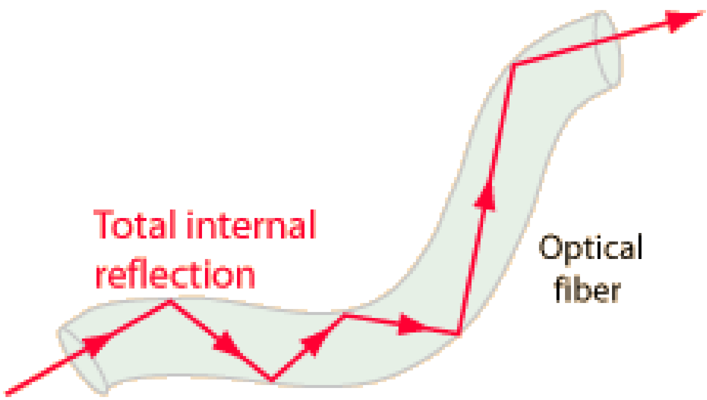
For *any angle* of incidence *less* than the *critical angle*, part of the incident light will be *transmitted* and part will be *reflected*.

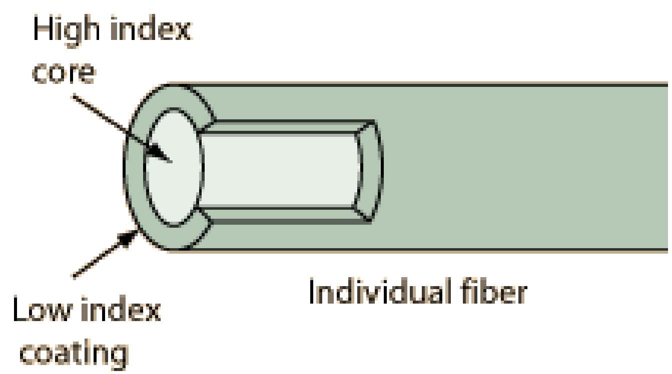
The normal incidence reflection coefficient can be calculated from the indices of refraction. For non-normal incidence, the transmission and reflection coefficients can be calculated from the Fresnel equations.

Fiber Optics

The field of fiber optics depends upon the total internal reflection of light rays traveling through tiny optical fibers.

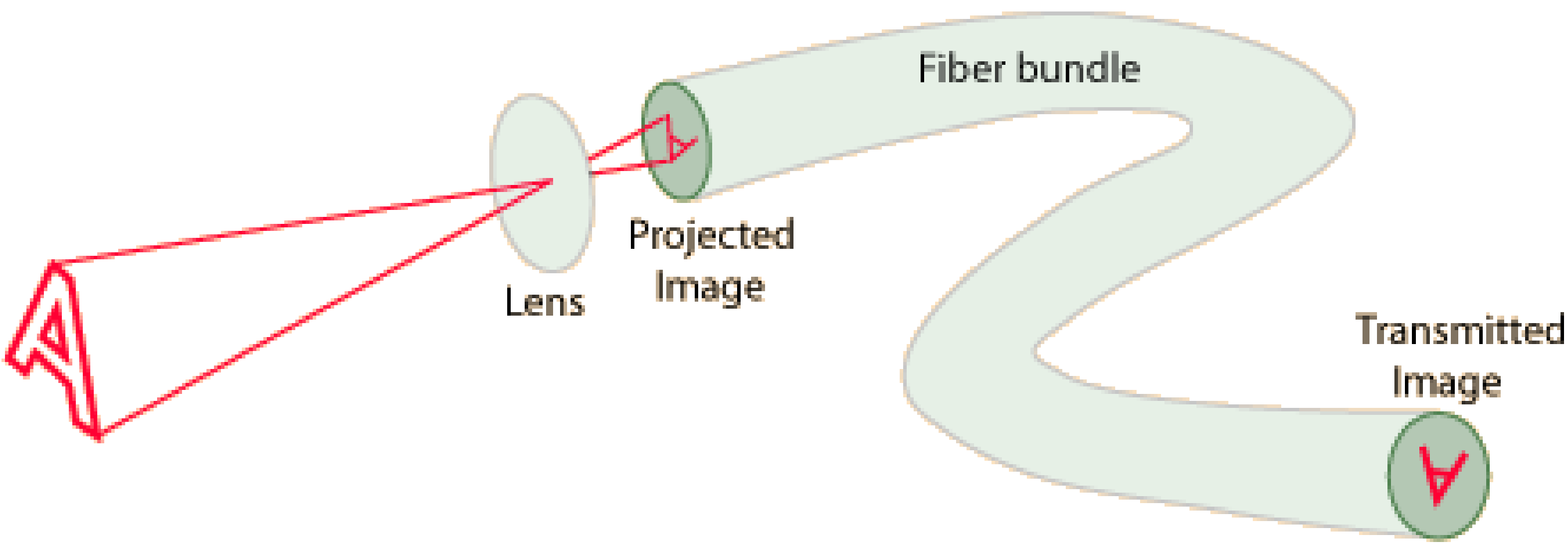
The fibers are so small that once the light is introduced into the fiber with an angle within the confines of the numerical aperture of the fiber, it will continue to reflect almost losslessly off the walls of the fiber and thus can travel long distances in the fiber. Bundles of such fibers can accomplish imaging of otherwise inaccessible areas.





Fiber Optic Imaging

Fiber optic imaging uses the fact that the light striking the end of an individual fiber will be transmitted to the other end of that fiber. Each fiber acts as a light pipe, transmitting the light from that part of the image along the fiber. If the arrangement of the fibers in the bundle is kept constant then the transmitted light forms a mosaic image of the light which struck the end of the bundle.



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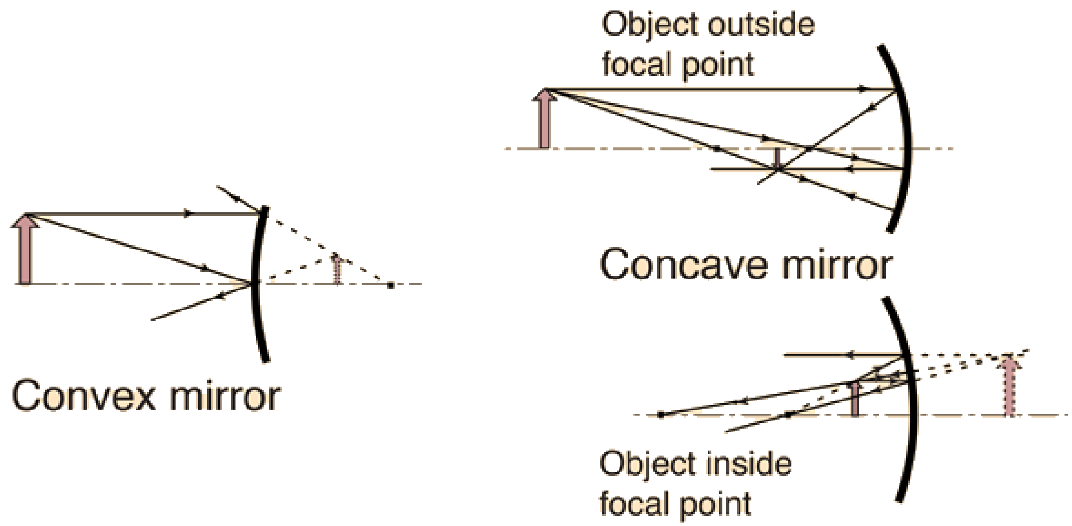
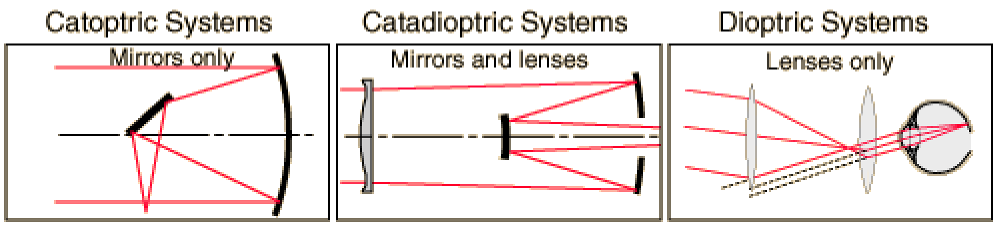
Mirrors in Imaging

Mirrors are used widely in optical instruments for gathering light and forming images since they work over a wider wavelength range and do not have the problems of dispersion which are associated with lenses and other refracting elements.



Mirrors are widely used in telescopes and telephoto lenses. They have the advantage of operating over a wider range of wavelengths, from infrared to ultraviolet and above. They avoid the *chromatic aberration* arising from dispersion in lenses, but are subject to other *aberrations*.



Instruments which use *only mirrors* to form images are called ***catoptric systems***, while those which use *both lenses and mirrors* are called ***catadioptric systems*** (dioptric systems being those with lenses only).

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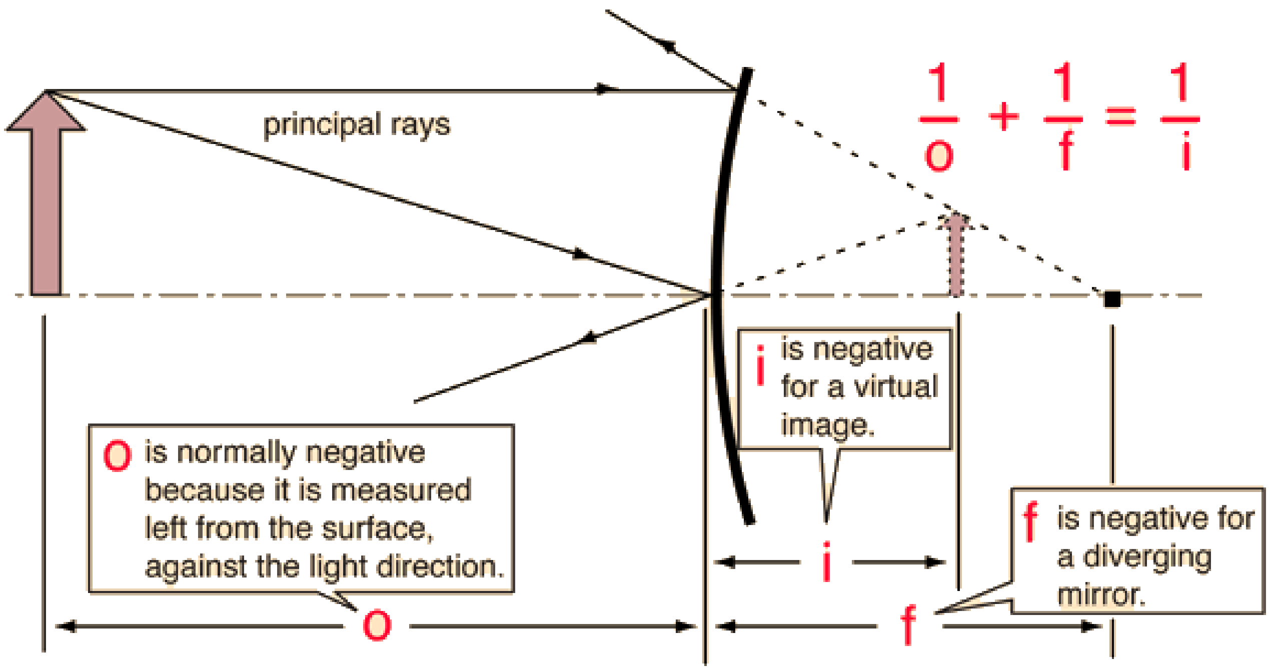
Convex Mirror Image

A convex mirror forms a ***virtual image***.



Using a ray parallel to the principal axis and one incident upon the center of the mirror, the position of the image can be constructed by back-projecting the rays which reflect from the mirror. The virtual image that is formed will appear smaller and closer to the mirror than the object.

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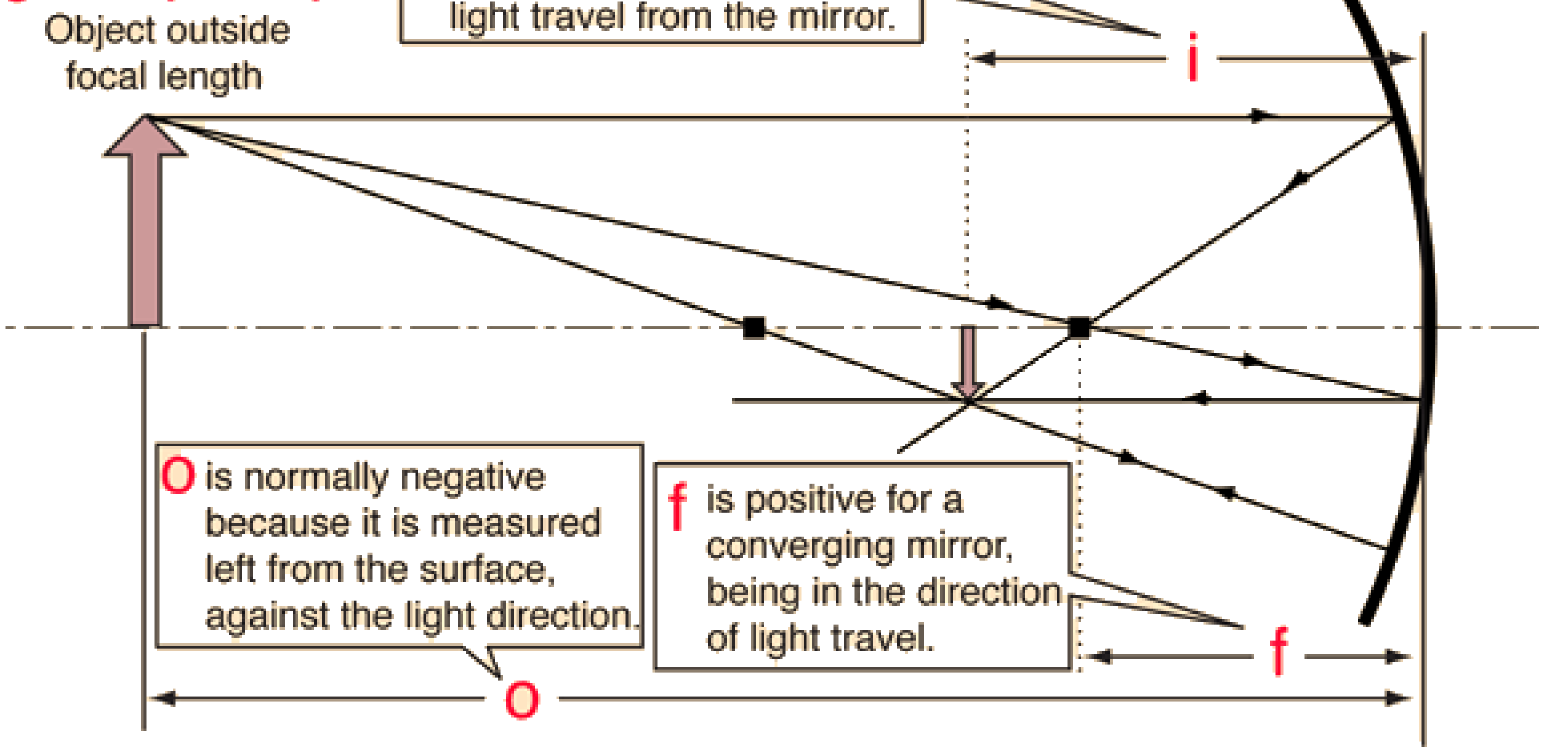
Concave Mirror Image

If the object is ***outside the focal length***, a concave mirror will form a ***real***, ***inverted*** image.

$$\frac{1}{o} + \frac{1}{f} = \frac{1}{i}$$



Concave Mirror Image

If an object is placed ***inside the focal length*** of a concave mirror, and ***enlarged virtual*** and ***erect image*** will be formed behind the mirror.