MEDICAL UNIVERSITY – PLEVEN
FACULTY OF MEDICINE

DIVISION OF PHYSICS AND BIOPHYSICS

LECTURE 12

THE PHYSICS OF VISION

Refraction and lenses. Image formation by the eye. Common vision defects. Simple optical instruments. Color vision

The human eye is sensitive to electromagnetic waves in a certain narrow frequency range.

Such waves are called "light" or "visible light" to distinguish them from the wide range of EM.

REFRACTION AND LENSES

In free space, light travels in straight lines at the speed $c = 3 \times 10^8$ m/s. When it enters a transparent medium such as glass, or even air, it travels at a slower speed.

The propagation speed is a property of the medium in which it is traveling, as in the case of the other types of traveling waves.

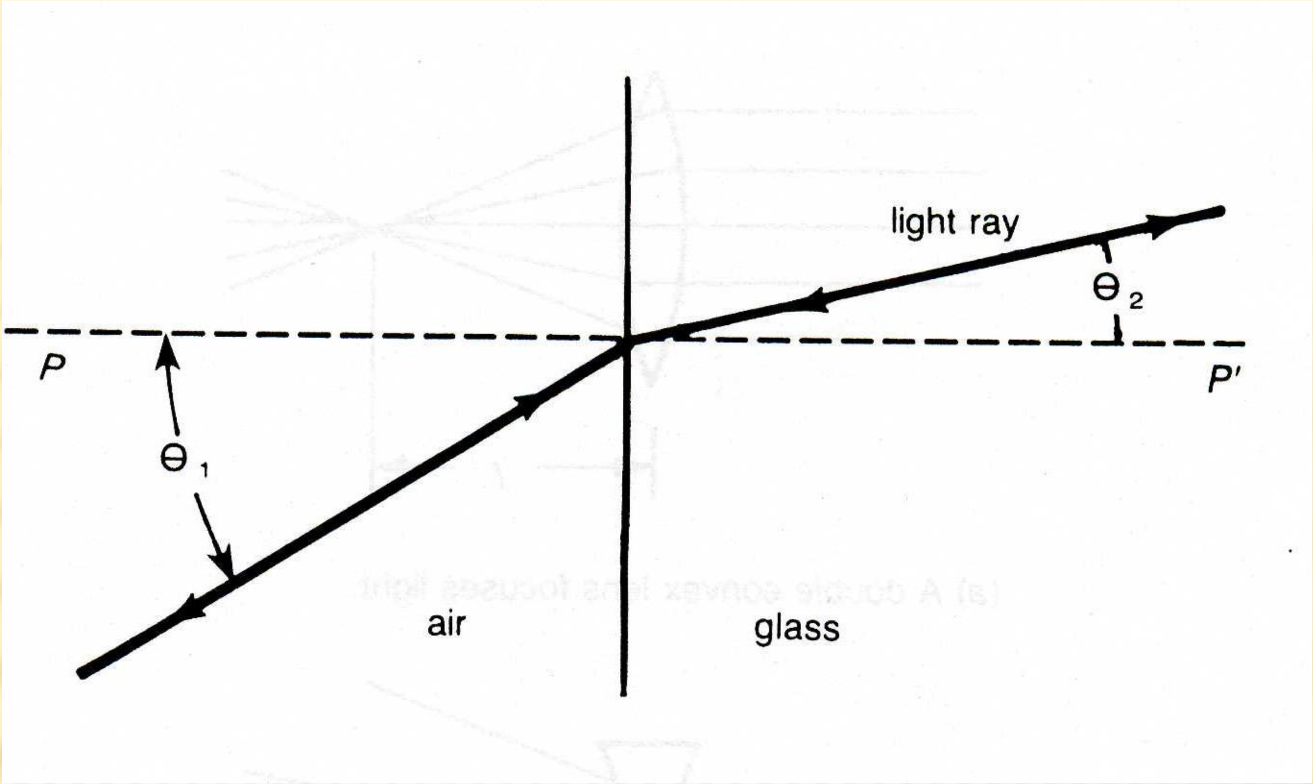
Light may either increase or decrease in effective speed as it crosses an interface between two different media.

If the propagation speed is ⊥ to the boundary, no visible effect accompanies the change in speed.

If it strikes the boundary at an angle other than 90º, the direction of a ray of light will be changed as it passes from one medium to the other.

Def. The "bending" of light rays at interfaces where the speed of light changes is referred to as refraction.

Instead of using **v** directly, the optical properties of substances are specified in terms of the **index of refraction, n.**



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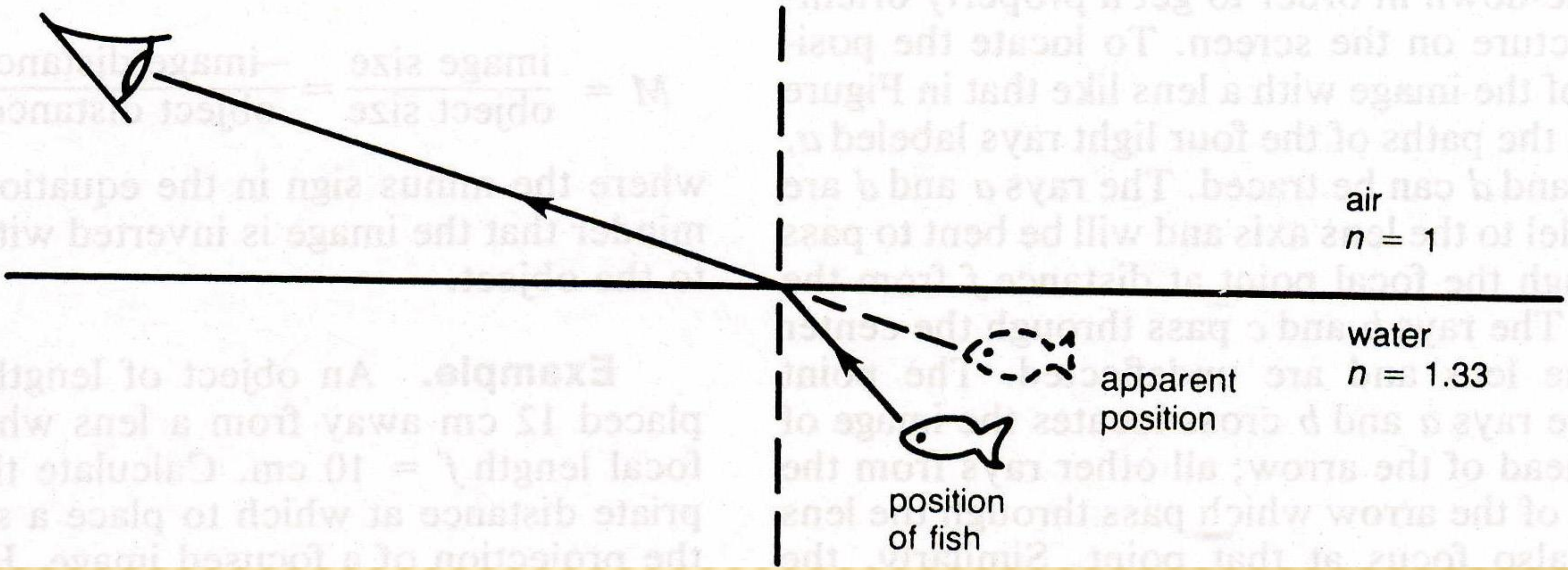
$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}}$$

Since the speed of light in all material media is less than the free space speed, $n \geq 1$.

Since light travels faster in air than in water, the light is bent away from the vertical as it leaves the water.

If light reflected from a fish leaves the water and reaches your eye, the refraction at the surface changes the apparent position of the fish. The eye presumes that the direction to the object observed is along the direction of the light rays reaching the eye, so the fish appears to be closer to the surface.

This refraction makes deep, clear bodies of water appear deceptively shallow.


air
$n = 1$
water
$n = 1.33$
apparent
position
position
of fish

If parallel light rays strike an ideal convex lens, they will focus to a point at a fixed distance *f* **beyond** the lens. The distance f is called the focal length of the lens.

Parallel rays passing through a concave lens will diverge such that they appear to be emanating from a single point some distance *f* **behind** the lens. The length *f* is said to be the focal length of the concave lens, but it is given a negative sign.

It is customary to express **the focusing ability** of a lens in terms of *1/f*. This parameter is called the "strength" of the lens or lens power.

P in diopters [D] is defined as the reciprocal of the focal length expressed in m.

A lens which focuses parallel light rays to a point 10 cm past the lens has P=10 D.

A lens which causes parallel light rays to diverge so that they appear to be coming from a point - 20 cm behind the lens has P= - 5 D.

Converging lenses can be used to form real images of an object. For example, the lens in a slide projector can be used to form an enlarged image of a slide on a distant screen.

!!! The real image is inverted; this is why the slide must be placed in the projector upside-down in order to get a properly oriented picture on the screen.

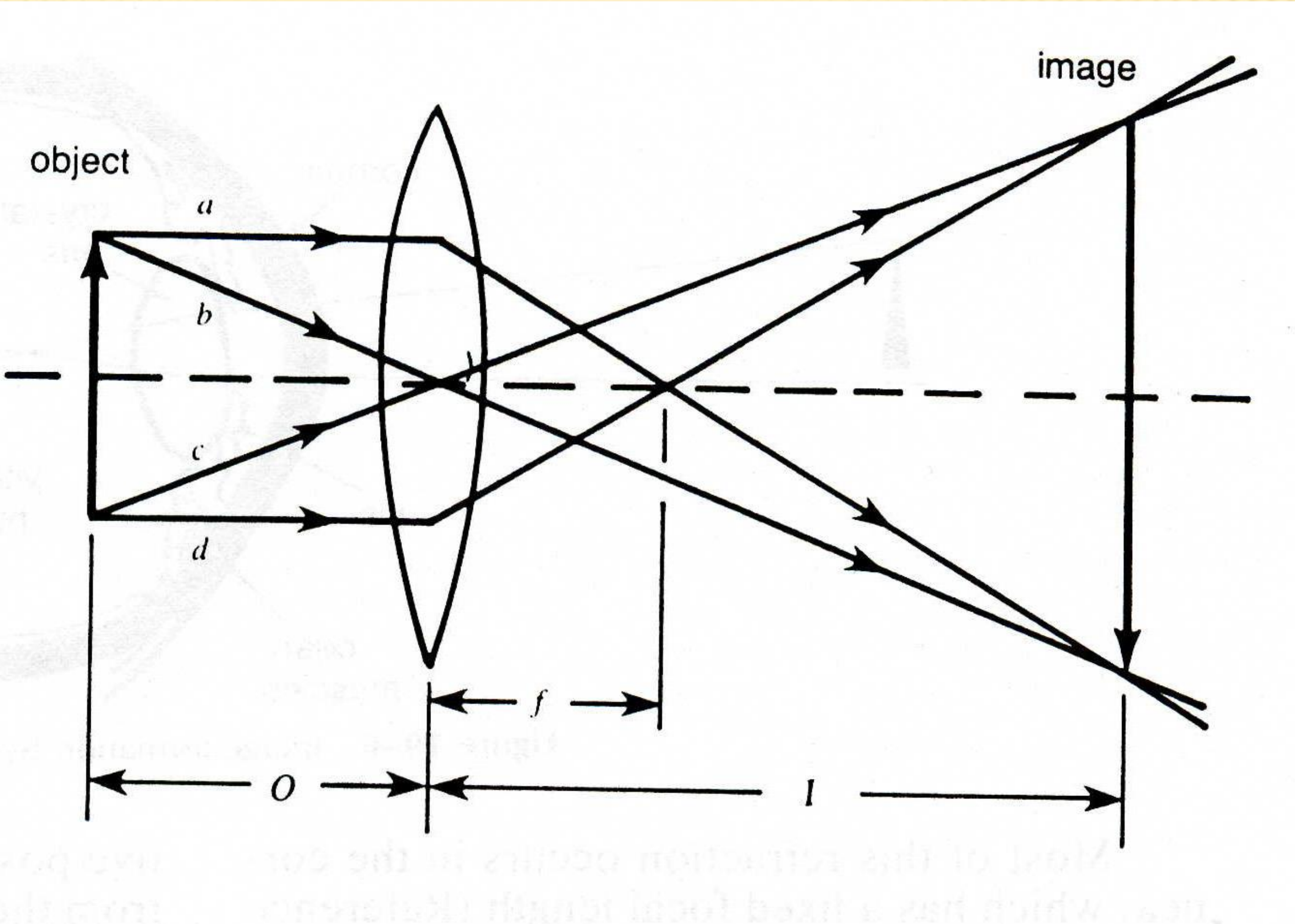


image
object
a
b
c
d
f
O
I

The distance, u, from the object to the lens and the distance, v, from the lens to the projected image are related by the equation

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

The equation is rigorously true only for an idealized thin lens, but it is good approximation.

The magnification, M, achieved is equal to the ratio of the image distance to the object distance:

$$\mathbf{M} = \frac{\textbf{image size}}{\textbf{object size}} = -\frac{\mathbf{v}}{\mathbf{u}}$$

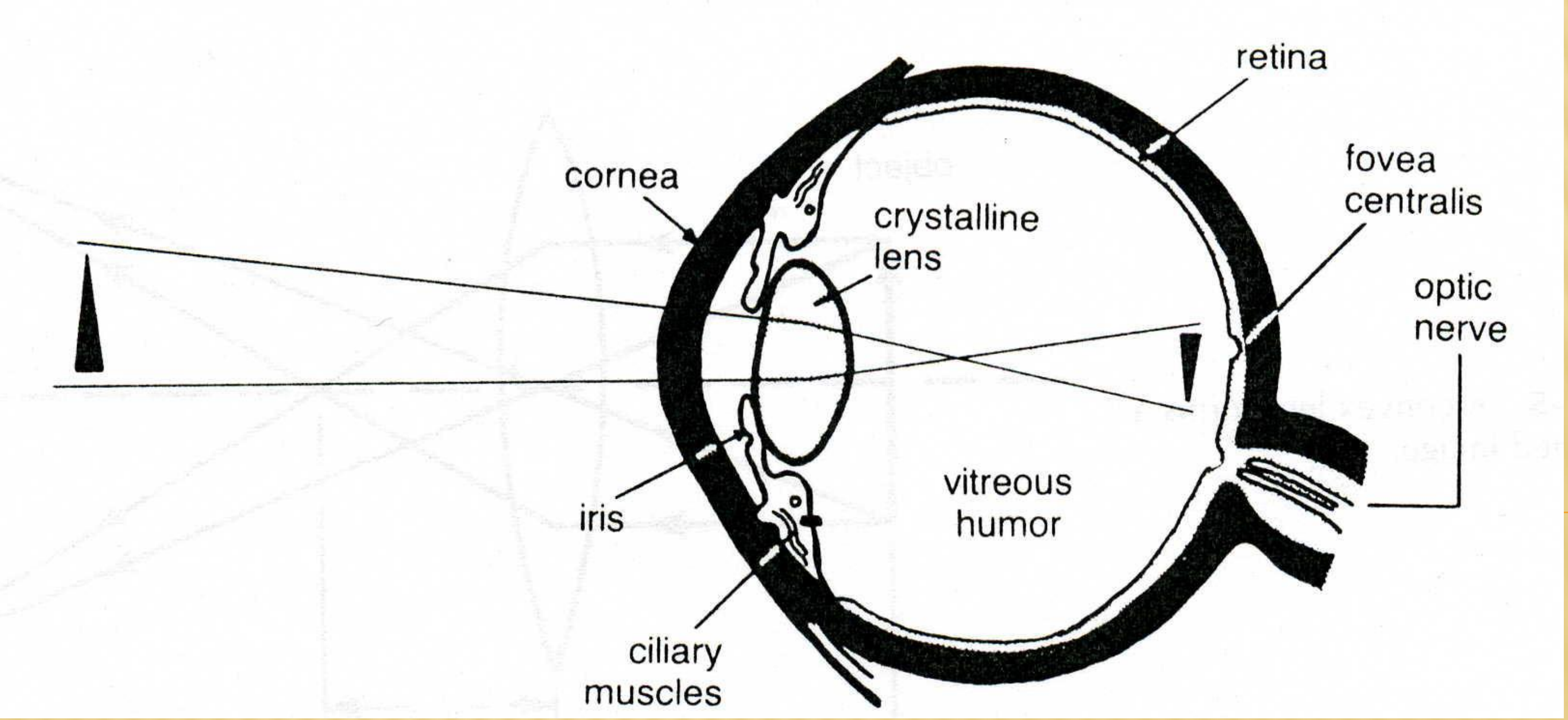
IMAGE FORMATION BY THE EYE

When light from an object strikes the eye, it passes through the cornea; the crystalline lens and the transparent vitreous humor to form an image on the retina. The nerve endings in the retina transmit electrical impulses to the brain via the optic nerve.

The image formation is accomplished by refraction in the cornea and crystalline lens; a focused real image is formed on the retina. Most of the refraction occurs in the cornea, which has a fixed focal length.

The crystalline lens is adjustable to provide for accommodation of the focus of the eye for objects at different distances. It is accomplished by changing the shape of the crystalline lens to alter its focal length.

A ring of muscles called the ciliary muscles surrounds this crystalline lens; when these muscles are relaxed, the lens is held in a strained position by ciliary fibers - the normal eye is focused upon a distant object.



To focus on a closer object, a "stronger" lens is required to form the image. The ciliary muscles contract, loosening the ciliary fibers and allowing the crystalline lens to take on a more rounded shape. This shortens **f** of the crystalline lens and increases its refracting capability.

Although the eye is a two-lens system, it is instructive to consider a simplified model in which the two lenses (cornea and crystalline lens) act together as a single lens to form images on the retina.

The effective position of this single lens is about 2.2cm from the retina in the average human eye.

When the object viewed is at a large distance from the eye, the image is formed near the focal length of the lens.

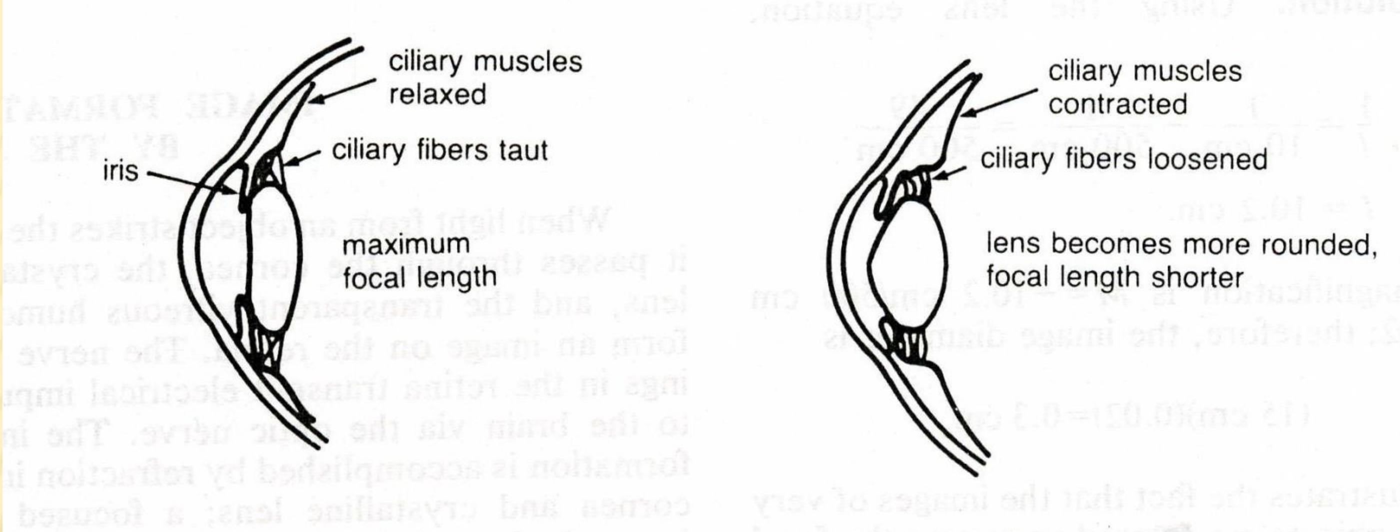
If the object distance is infinite, then from lens equation it can be seen that the image distance is exactly equal to the focal length. Therefore, the effective focal length of the eye when viewing distant objects must be about 2.2 cm, the distance to the retina. Therefore, P=45 D.

When the object is closer to the eye, the image is formed at the position given by lens equation. Since the image distance is fixed, the focal length of the lens must change to produce a focused image on the retina.

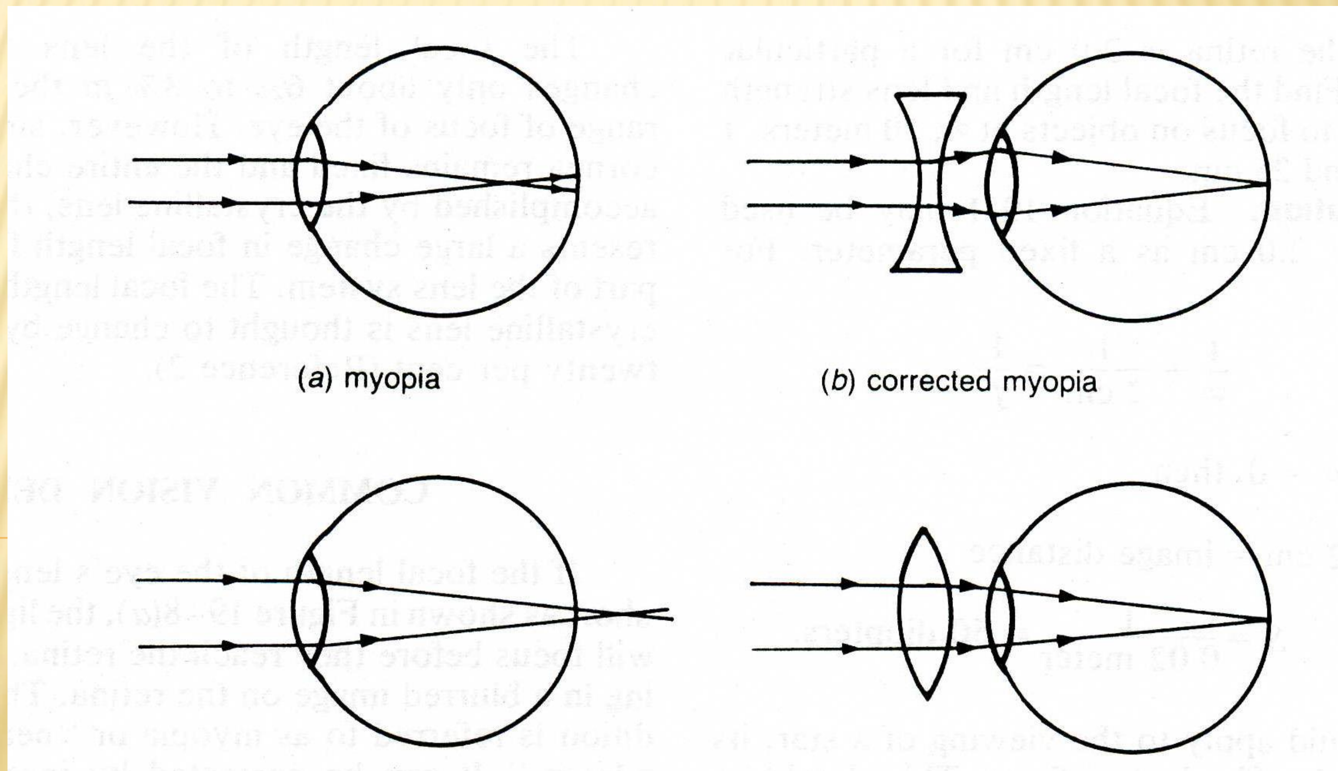
COMMON VISION DEFECTS

If the focal length of the eye's lens is too short, the light rays will focus before they reach the retina, resulting in a blurred image on the retina. This condition is referred to as myopia or "nearsightedness." It can be corrected by inserting a diverging or "negative" lens in front of the eye to cause the rays to diverge slightly before entering the eye.

If the focal length of the eye is too long (hyperopia or "farsightedness"), then the light would focus at a distance greater than the distance to the retina. A converging lens will correct this defect.



(*a*) distant vision (*b*) close vision

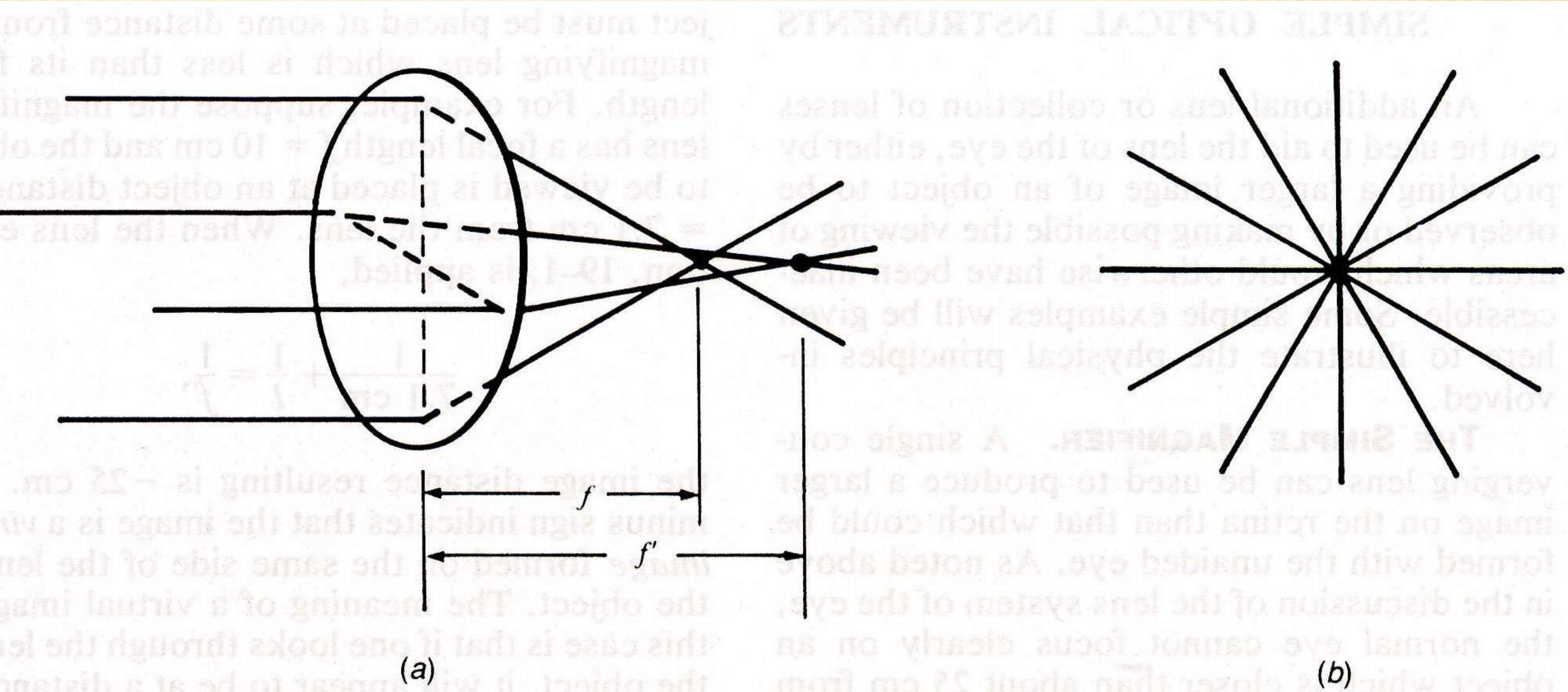

(*a*) myopia (*b*) corrected myopia

(*c*) hyperopia (*d*) corrected hyperopia

Up to this point it has been assumed that the lenses considered were symmetric and with ideal optical properties.

The common eye defect known as astigmatism occurs when the lens has different focal lengths for light rays striking it in different planes.

Light coming from a distant bright object such as a star will therefore not focus to a point behind the lens. If a screen were placed at distance f, the image would be a short bright line in the horizontal plane rather than a bright dot, since the light in the vertical plane is focused at that distance but that in the horizontal plane is not.

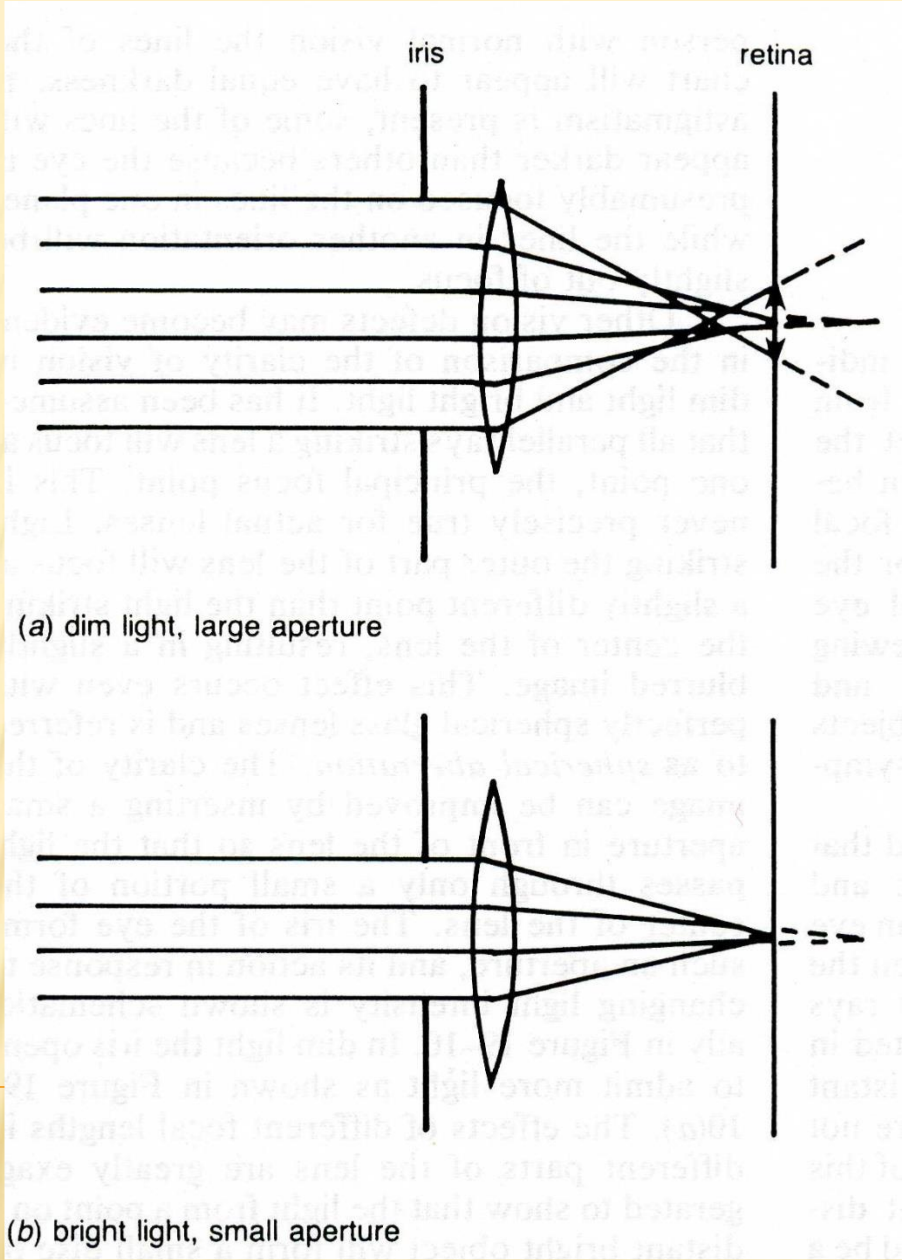


Astigmatism.

Other vision defects may become evident in the comparison of the clarity of vision in dim light and bright light.

It has been assumed that all parallel rays striking a lens will focus at one point, the principal focus point. This is never precisely true for actual lenses.

Light striking the outer part of the lens will focus at a slightly different point than the light striking the center of the lens, resulting in a slightly blurred image. This effect occurs even with perfectly spherical glass lenses and is referred to as spherical aberration.



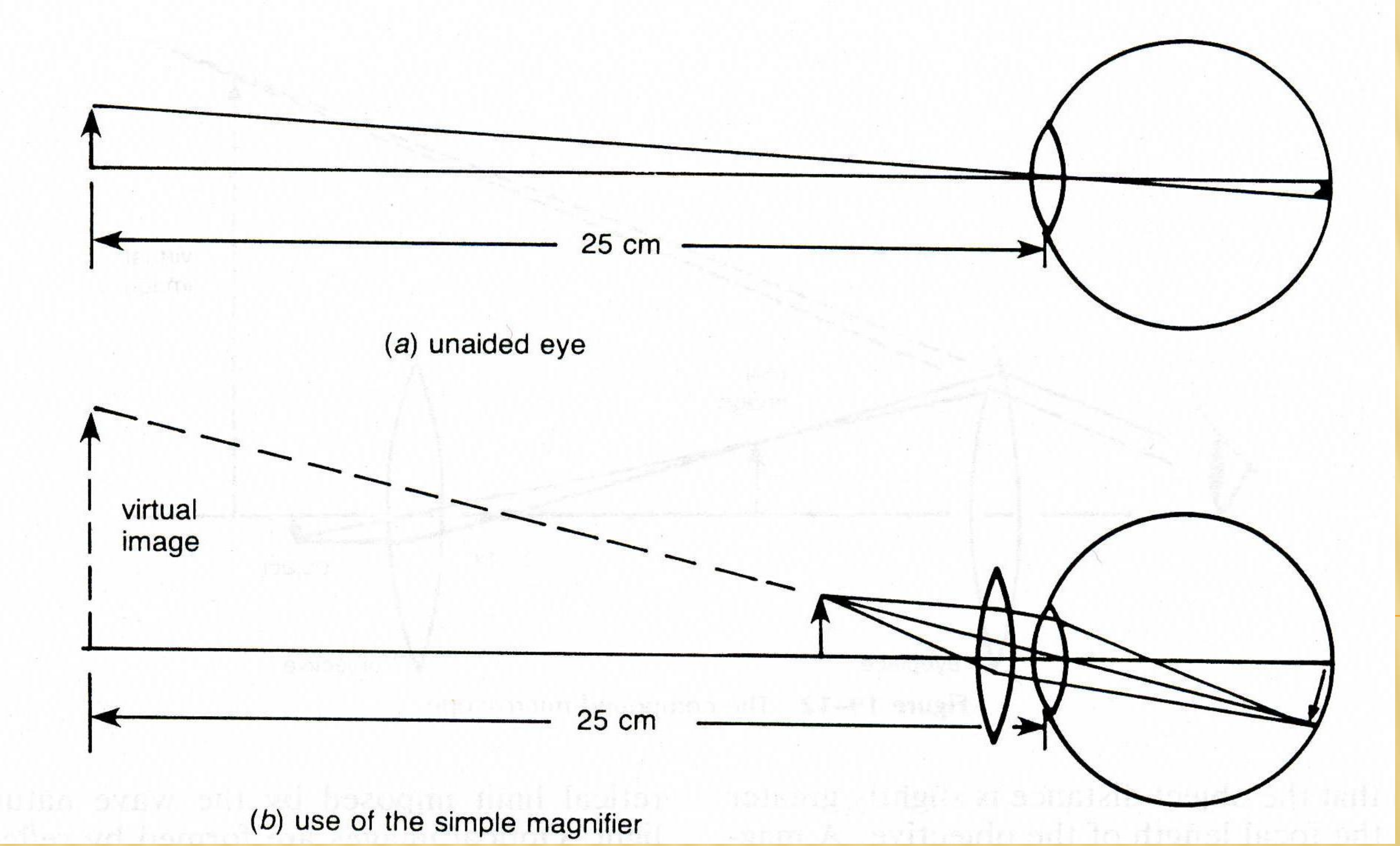
The effect of aperture size upon focusing.

The clarity of the image can be improved by inserting a small aperture in front of the lens so that the light passes through only a small portion of the center of the lens. The iris of the eye forms such an aperture. In dim light the iris opens to admit more light.

In bright light the aperture formed by the iris is smaller and the image is therefore sharper. The sharpness of the image is degraded by a wide iris opening, even for a perfectly symmetrical lens, and the effects of any lens defects are made more pronounced in dim light because more of the lens area is being used to form the image on the retina.

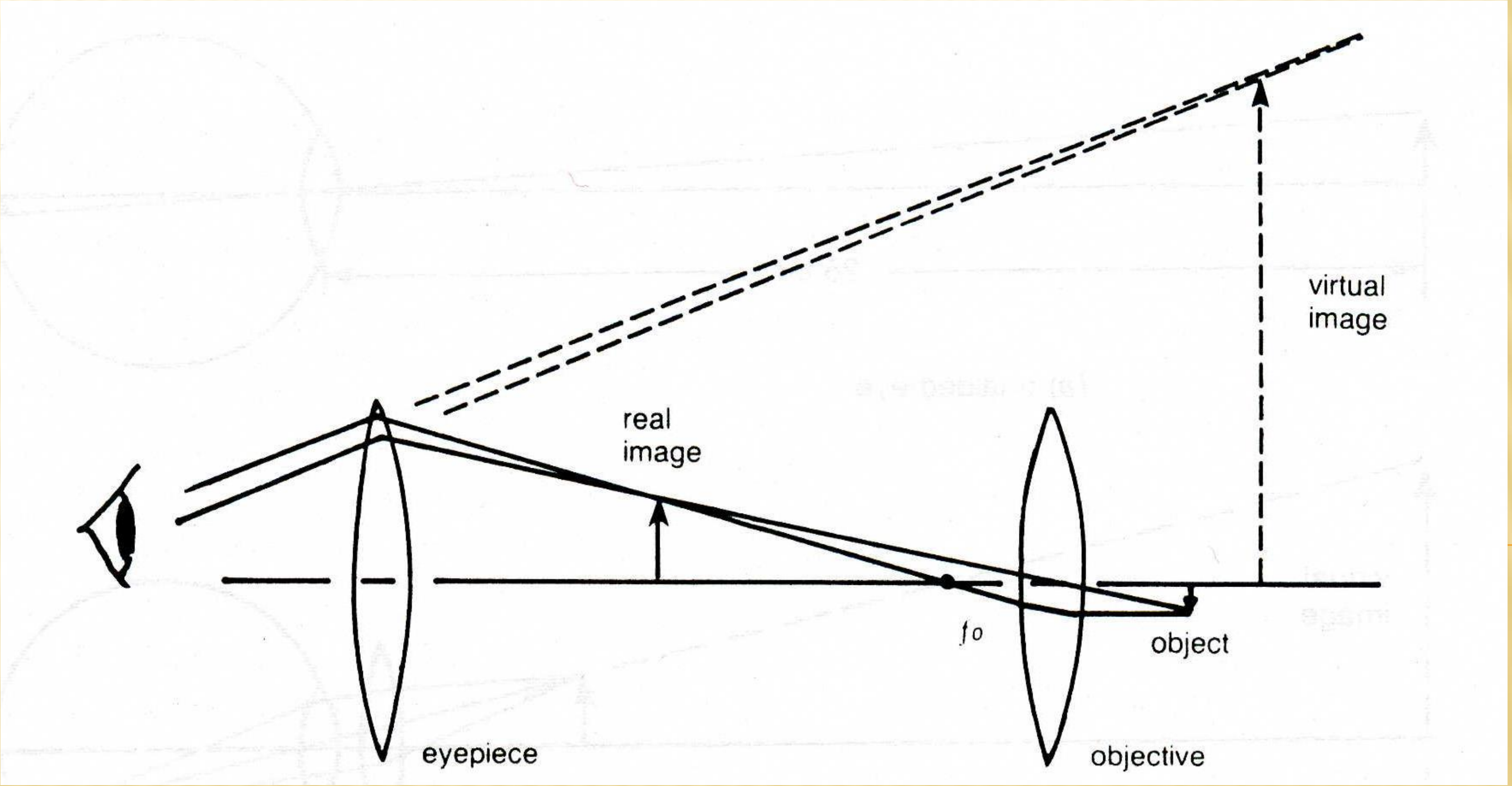
SIMPLE OPTICAL INSTRUMENTS

THE SIMPLE MAGNIFIER



THE COMPOUND MICROSCOPE

$$M = M_{objective} \times M_{eyepiece}$$



It could be assumed that M could be increased without limit by increasing the power of the microscope lenses. However, limits arise:

1. The images formed by a lens system are never perfectly "sharp" because of imperfections in the lenses, which results in a slight blurring or overlap of the images of two adjacent points on the object. Increasing the magnification beyond a certain power provides no new information.
2. The theoretical limit imposed by the wave nature of light. Optical images are formed by reflecting light from an object, but to be distinguished an object must be larger than λ of the light which is reflected from it.

In limiting cases, the resolution of a microscope can be improved by using monochromatic blue or violet light sources, which have the shortest wavelengths in the visible spectrum.

If an object is small compared to the wavelength of light, however, it cannot be observed by a light microscope.

Many viruses are so small that they cannot be resolved by a light microscope. The increased magnification of an electron microscope is made possible by the shorter effective wavelength achieved.

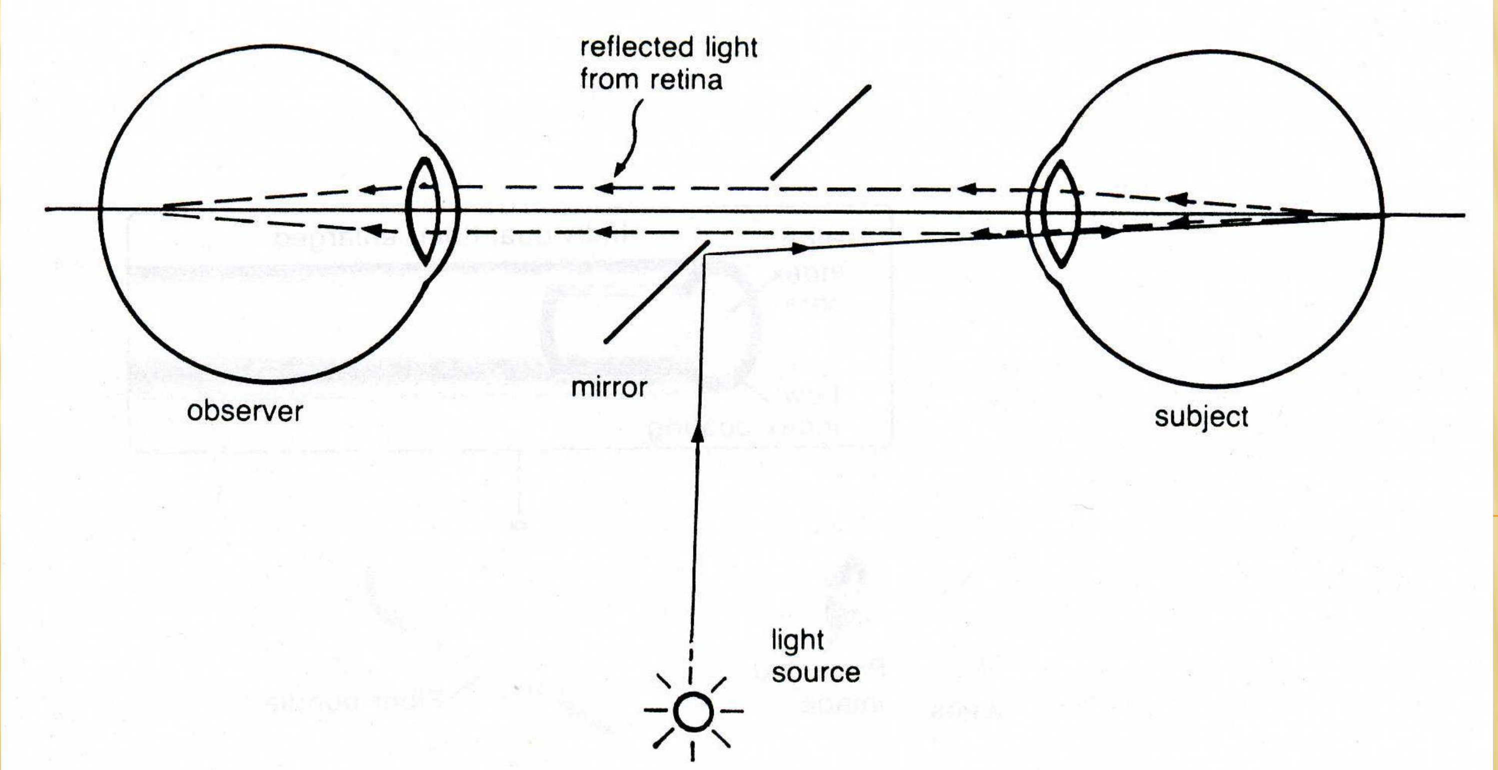
THE OPHTHALMOSCOPE - an instrument for viewing the retina of the eye.

In its simplest form it consists of a light source and a mirror with an aperture.

Light is reflected from the mirror into the subject's eye and illuminates the retina. If the subject's eye is normal and focused for viewing a distant object, then the focal length of the eye's lens will be at the retina.

Therefore, light rays reflected from a point on the retina will be rendered parallel by the eye's lens when passing out of the subject's eye, and these rays can be focused by the observer's eye to form a clear image of the retina.

The lens of the subject's eye is being used as a simple magnifier to provide an enlarged image of the retina for the observer. If the subject's eye is abnormal, correcting lenses may be added to bring the image of the retina into focus.



FIBER OPTICS. Complicated optical systems have been developed for bronchoscopes, cystoscopes, etc. for viewing the internal tracts of the body.

More recently, fiber optics probes have been developed which may supplant and improve upon such systems. Under the proper conditions, light will be transmitted through a thin fiber with very little loss.

If the path of the ray is perpendicular to the boundary, most of it will be transmitted, but if the direction is gradually changed so that it becomes more nearly parallel to the boundary, more and more of it will be reflected.

For a given type of boundary there is a certain critical angle, beyond which all the light is reflected from the boundary. If light enters the end of a small fiber, it will pass along the fiber by means of multiple internal reflections. A large bundle of such fibers constitutes a "light pipe" which transmits light even if the bundle is bent into tight curves and complicated shapes.

If an illuminated object is placed at one end of the bundle, an image of the object can be transmitted to the other end. Under conditions of total internal reflection, the light from adjacent fibers does not mix and each fiber transmits information about the luminosity of a localized area of the object - a "mosaic" image is formed.

A flexible bundle of fibers can easily follow the change of direction in an internal tract of the body.

Light can be passed down the outer fibers to illuminate the tract ahead of the bundle. Light reflected back through the central core of the bundle can provide a detailed image of the tract if the fibers are small enough. Fiber-optic bundles are now often used in gastroscopes and other medical optical instruments.

The flexible bundles may be manufactured with lengths in excess of 3 m, and some experimentation has been done with the transmission of laser light for cancer treatment and other therapeutic treatments in inaccessible areas.

COLOR VISION

When a beam of white light is passed through a prism, it is separated into colored bands by refraction.

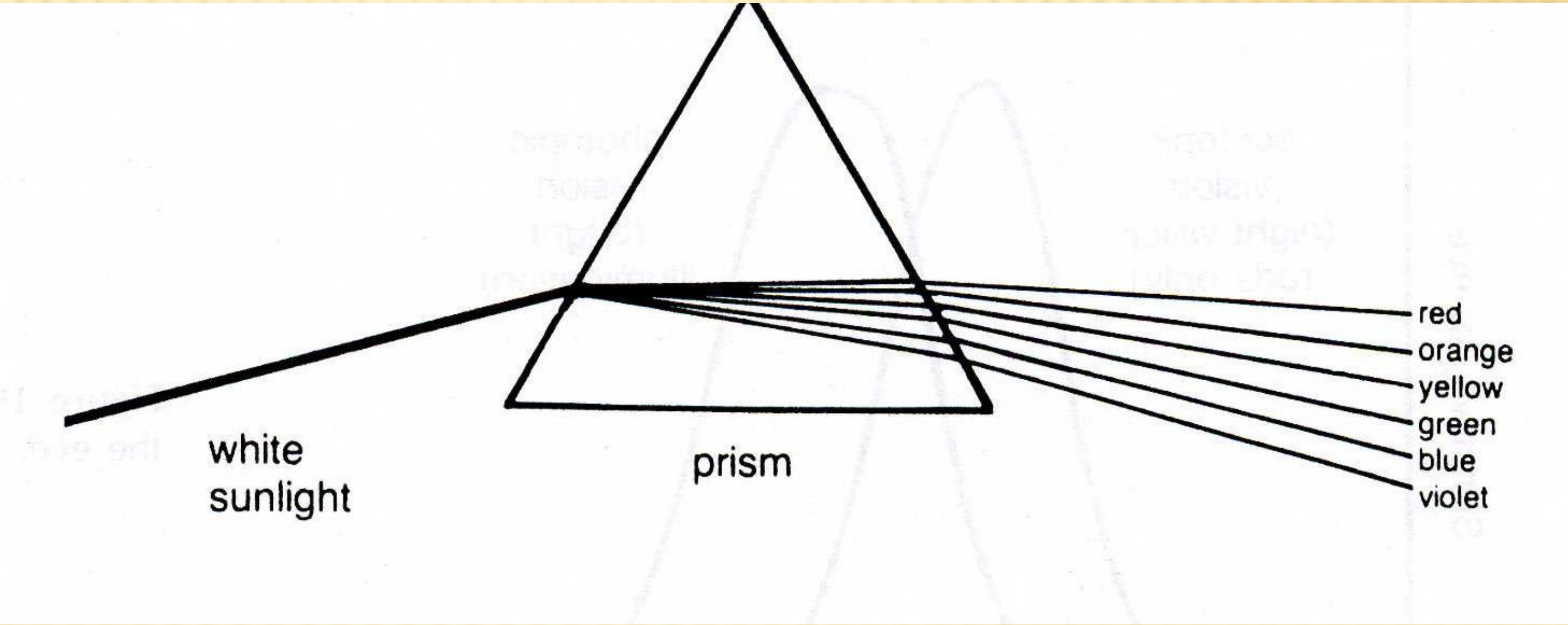
This separation occurs because **n=f(f)**, and therefore different frequencies are bent through different angles.

The prism serves to illustrate the fact that white light is composed of all the colors of the visible spectrum and color is associated with the frequency (or λ) .

The human eye is sensitive to EM waves in a small range of frequencies (3.9×10^{14} Hz - 7.9×10^{14} Hz). This range is referred to as light or "visible light" to distinguish it from infrared and ultraviolet light.

Since the frequencies of visible light are so large, it is common practice to use the wavelengths.

Using the general wave relationship $v = f\lambda$ with $v = 3 \times 10^8$ m/s, the wavelength range of visible light is from 3.8×10^{-7} to 7.7×10^{-7} m. This range is usually expressed in angstrom units (A), where $1\ A = 10^{-10}$ m.



Visible light:

colors	red	to	violet
f	3.9×10^{14} Hz	to	7.9×10^{14} Hz
λ	7700 A	to	3800 A

The retina of the eye contains two types of light-sensitive nerve endings commonly referred to as "rods" and "cones."

The cones are responsible for the ability to discriminate between colors. If light with λ=5000 A strikes the eye, most persons can identify the color as green. The eye can identify and discriminate many different colors in the rainbow spectrum.

No corresponding ability exists in the hearing of most persons. While relative pitches can be perceived, most persons do not have the ability to distinguish absolute pitches (frequencies).

The rods have little color discriminating ability. They are more numerous than the cones, typically about 130 million compared to 7 million cones.

The cones are more concentrated near a central spot on the retina called the fovea centralis, and the number of cones is very small in the extremities of the retina → color sensitivity is greatest when looking directly at an object, because the light rays from the object fall near the fovea centralis.

The color sensitivity associated with extreme peripheral vision is very slight, since the light falls on areas of the retina which are deficient in cones. This can be demonstrated by moving two objects of different color from a point directly in front of your eye to a point beside your head where they can just be seen. At this point the colors will be indistinguishable.

When the light intensity is low, vision occurs primarily by stimulation of the rods. A nerve cell requires a stimulus above a certain threshold to depolarize the cell and produce the "action potential," which in this case would carry the visual information to the brain.

The threshold for the rods is considerably lower than that for the cones. Since the rods are less concentrated near the direct vision part of the retina (fovea), the sensitivity of direct vision in dim light is less than the sensitivity of peripheral vision. The sensitivity of the rod vision or "night vision" is significantly decreased by a deficiency in vit A.

Dark-adapted vision (almost entirely rod vision) is referred to as "scotopic vision." It is most sensitive for light of λ =5100 A, which is in the green region. In bright light both rods and cones are active and the peak sensitivity occurs at about 5800 A, which is in the yellow region.

This light-adapted vision is referred to as "photopic vision. "

The difference in the wavelength associated with the peak sensitivity of the eye under bright and dim lighting conditions may be demonstrated by observing a red rose in twilight conditions.

When the light is bright (photopic vision), the red petals will appear much brighter than the surrounding green leaves. But as the light level falls, the relative brightness of the green leaves will increase. Under very dim light (scotopic or rod vision) the green leaves will often appear brighter than the red petals.