Chapter 26

The Refraction of Light: Lenses and Optical Instruments

Light travels through a vacuum at a speed $c = 3.00 \times 10^{8}\ \mathrm{m/s}$

Light travels through materials at a speed less than its speed in a vacuum.

DEFINITION OF THE INDEX OF REFRACTION

The index of refraction of a material is the ratio of the speed of light in a vacuum to the speed of light in the material:

$$n = \frac{\text{Speed of light in vacuum}}{\text{Speed of light in the material}} = \frac{c}{v}$$

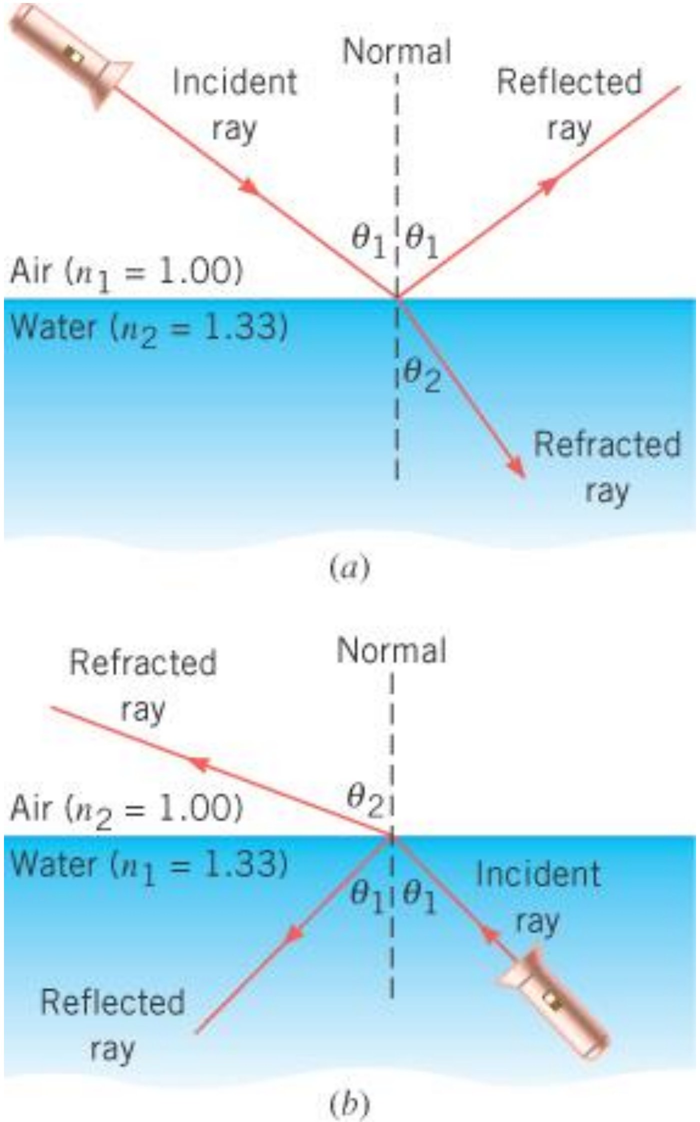
26.1 The Index of Refraction

Table 26.1 Index of Refraction[a] for Various Substances

Substance	Index of Refraction, n
Solids at 20 °C	
Diamond	2.419
Glass, crown	1.523
Ice (0 °C)	1.309
Sodium chloride	1.544
Quartz	
Crystalline	1.544
Fused	1.458
Liquids at 20 °C	
Benzene	1.501
Carbon disulfide	1.632
Carbon tetrachloride	1.461
Ethyl alcohol	1.362
Water	1.333
Gases at 0 °C, 1 atm	
Air	1.000 293
Carbon dioxide	1.000 45
Oxygen, O_2	1.000 271
Hydrogen, H_2	1.000 139

[a] Measured with light whose wavelength in a vacuum is 589 nm.

SNELL'S LAW



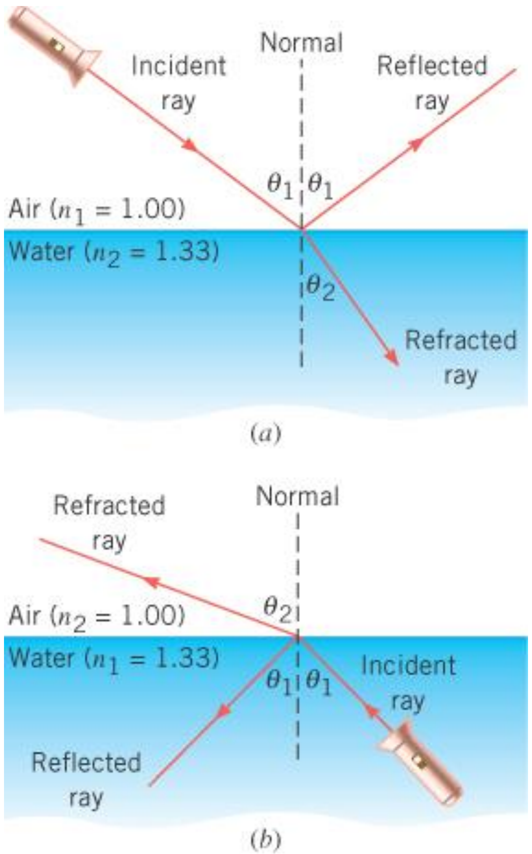
SNELL'S LAW OF REFRACTION

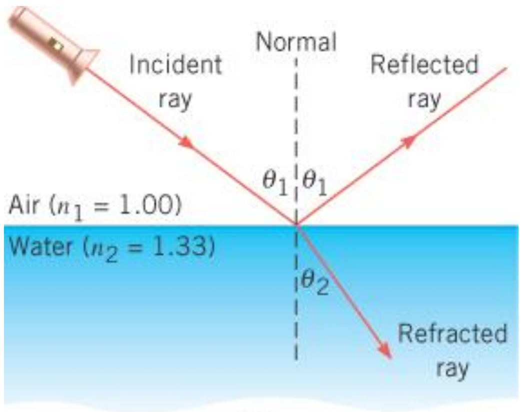
When light travels from a material with one index of refraction to a material with a different index of refraction, the angle of incidence is related to the angle of refraction by

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

Example 1 Determining the Angle of Refraction

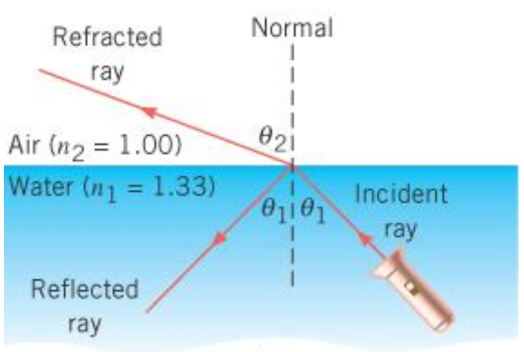
A light ray strikes an air/water surface at an angle of 46 degrees with respect to the normal. Find the angle of refraction when the direction of the ray is (a) from air to water and (b) from water to air.





(a) $$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2} = \frac{(1.00)\sin 46^\circ}{1.33} = 0.54$$

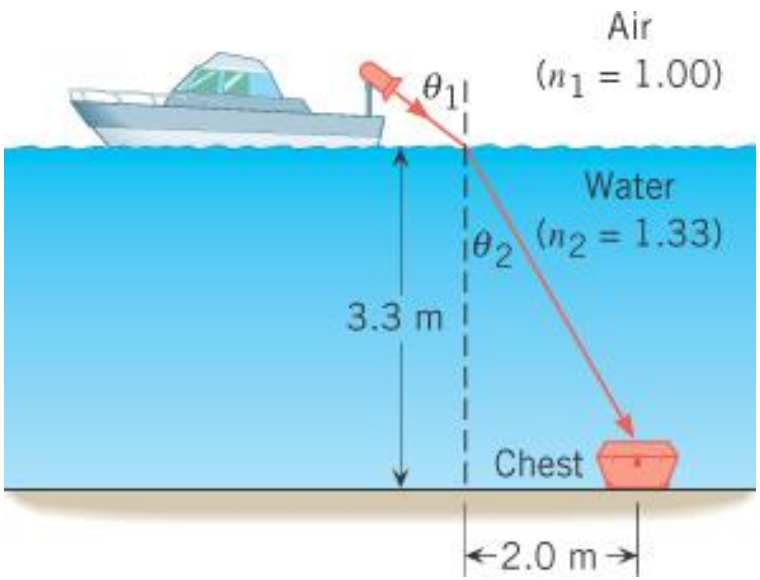
$$\theta_2 = 33^\circ$$



(b) $$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2} = \frac{(1.33)\sin 46^\circ}{1.00} = 0.96$$

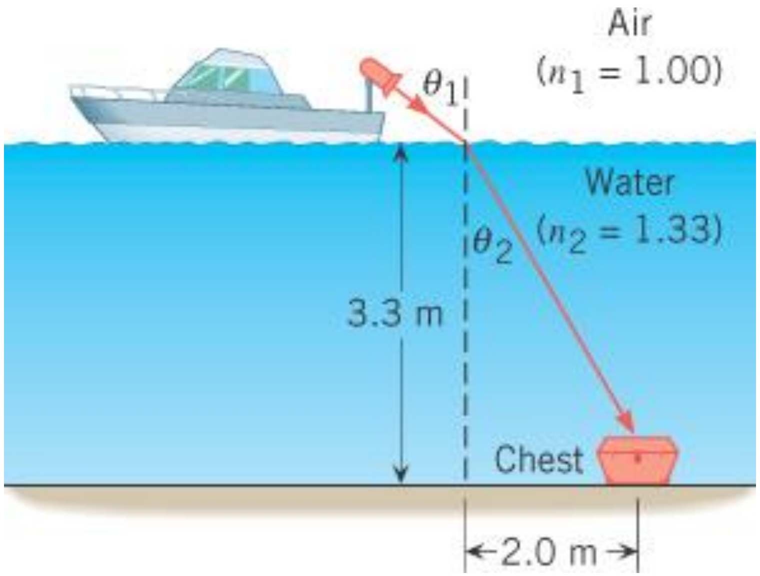
$$\theta_2 = 74^\circ$$

APPARENT DEPTH



Example 2 **Finding a Sunken Chest**

The searchlight on a yacht is being used to illuminate a sunken chest. At what angle of incidence should the light be aimed?



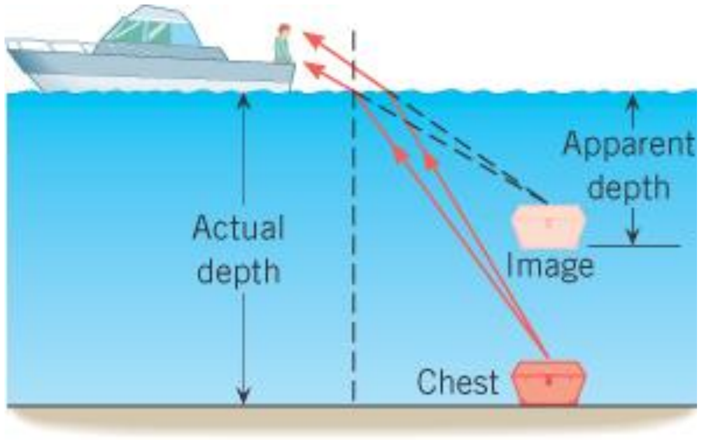
$$\theta_2 = \tan^{-1}(2.0/3.3) = 31^\circ$$

$$\sin\theta_1 = \frac{n_2 \sin\theta_2}{n_1} = \frac{(1.33)\sin 31^\circ}{1.00} = 0.69$$

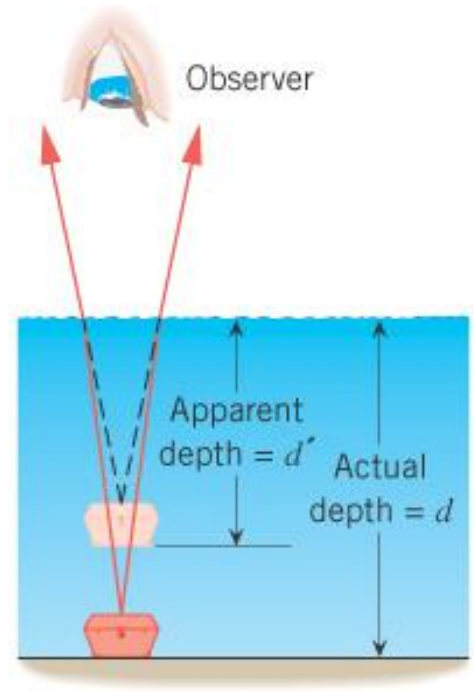
$$\theta_1 = 44^\circ$$

Apparent depth, observer directly above object

$$d' = d\left(\frac{n_2}{n_1}\right)$$



(a)

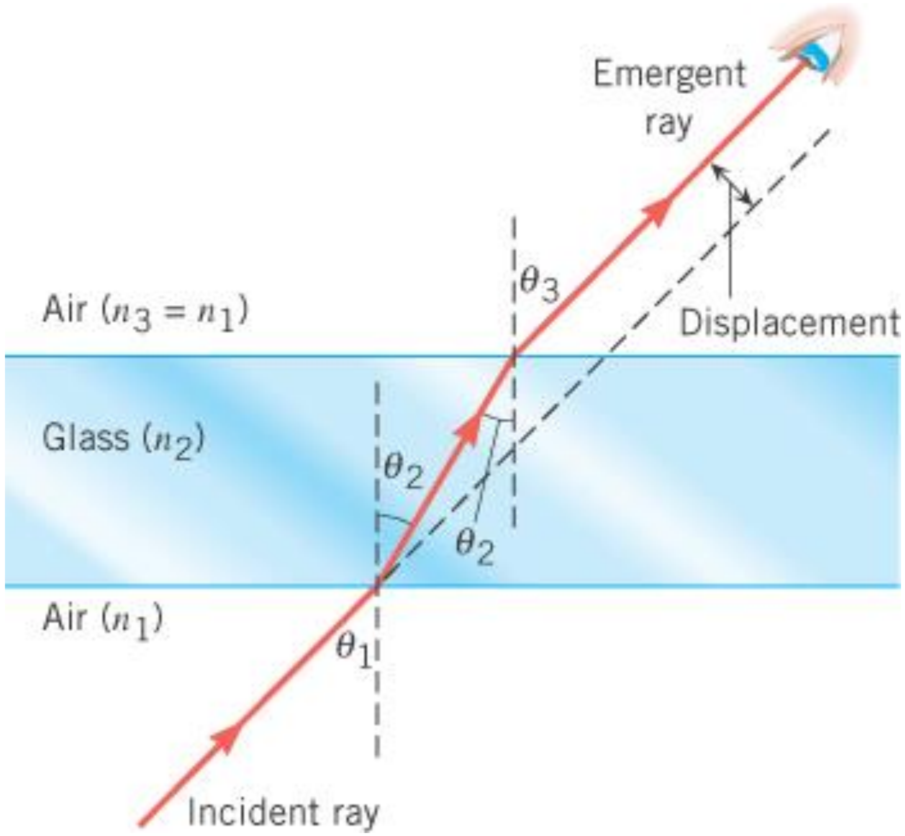


(b)

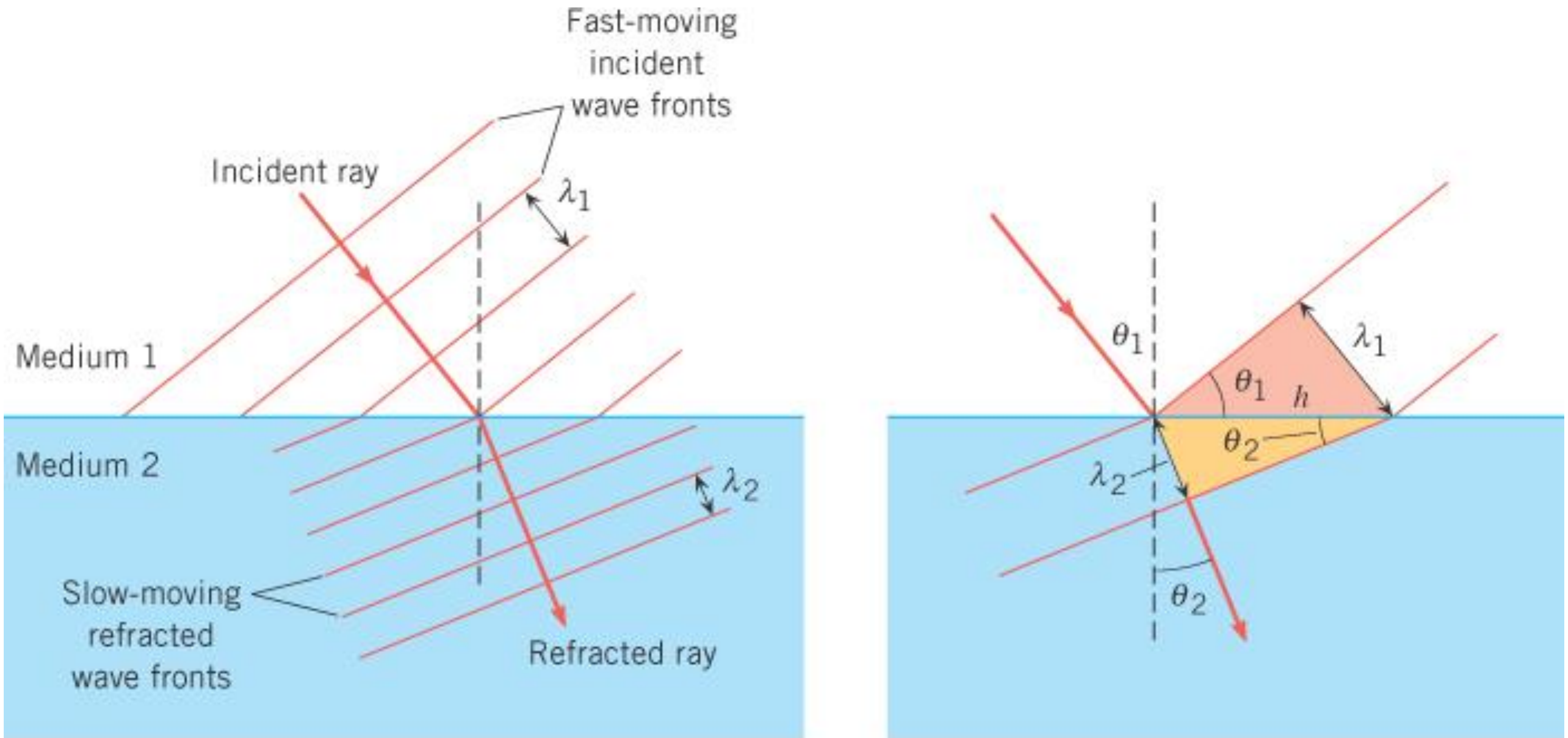
Conceptual Example 4 On the Inside Looking Out

A swimmer is under water and looking up at the surface. Someone holds a coin in the air, directly above the swimmer's eyes. To the swimmer, the coin appears to be at a certain height above the water. Is the apparent height of the coin greater, less than, or the same as its actual height?

THE DISPLACEMENT OF LIGHT BY A SLAB OF MATERIAL



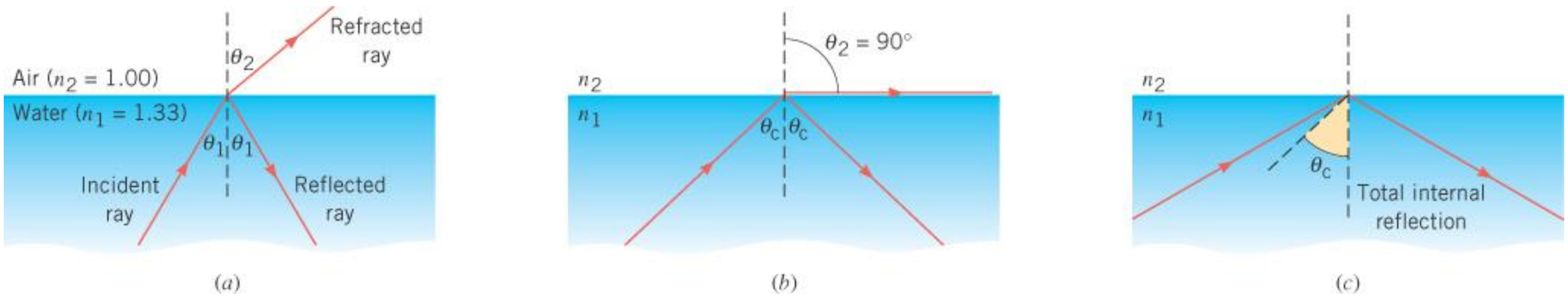
THE DERIVATION OF SNELL'S LAW



(a) (b)

26.3 Total Internal Reflection

When light passes from a medium of larger refractive index into one of smaller refractive index, the refracted ray bends away from the normal.

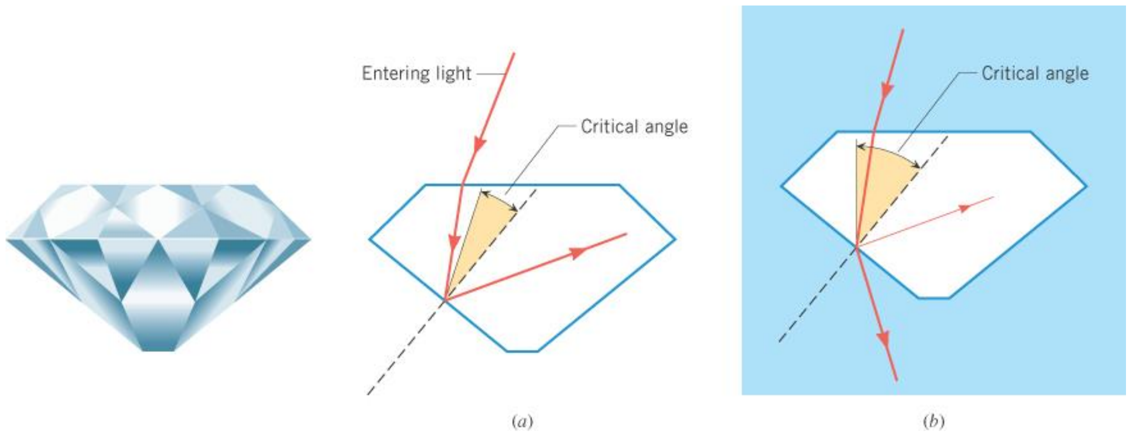


Critical angle

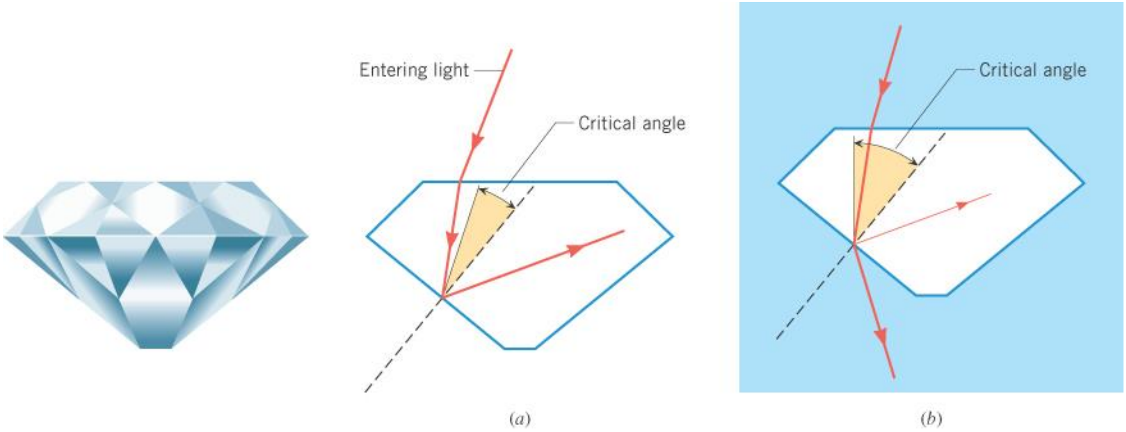
$$\sin\theta_c = \frac{n_2}{n_1} \qquad n_1 > n_2$$

Example 5 Total Internal Reflection

A beam of light is propagating through diamond and strikes the diamond-air interface at an angle of incidence of 28 degrees. (a) Will part of the beam enter the air or will there be total internal reflection? (b) Repeat part (a) assuming that the diamond is surrounded by water.



26.3 *Total Internal Reflection*

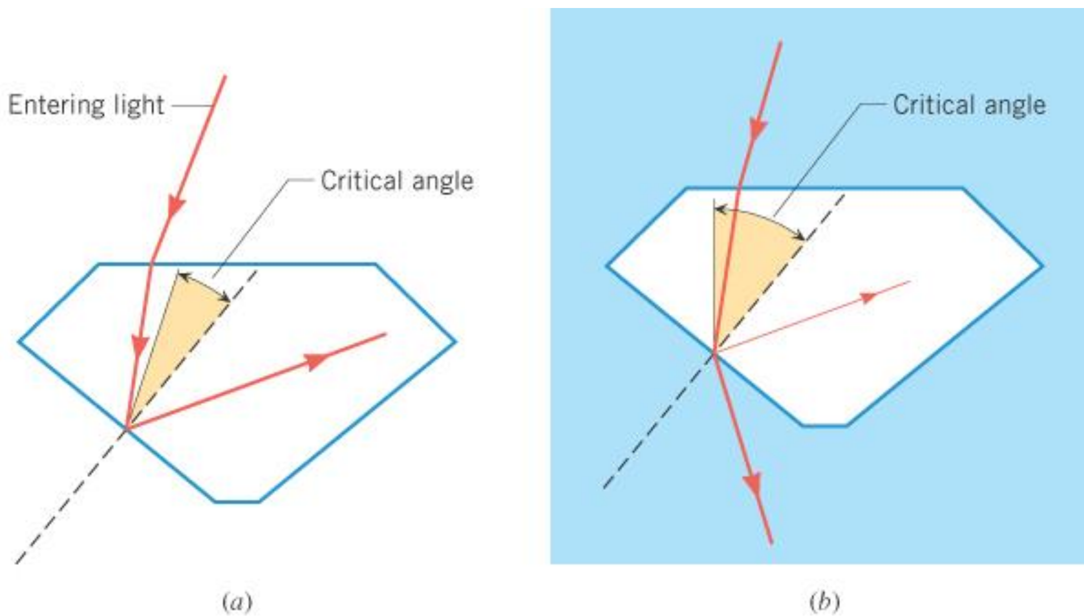


(a) $$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.00}{2.42}\right) = 24.4^\circ$$

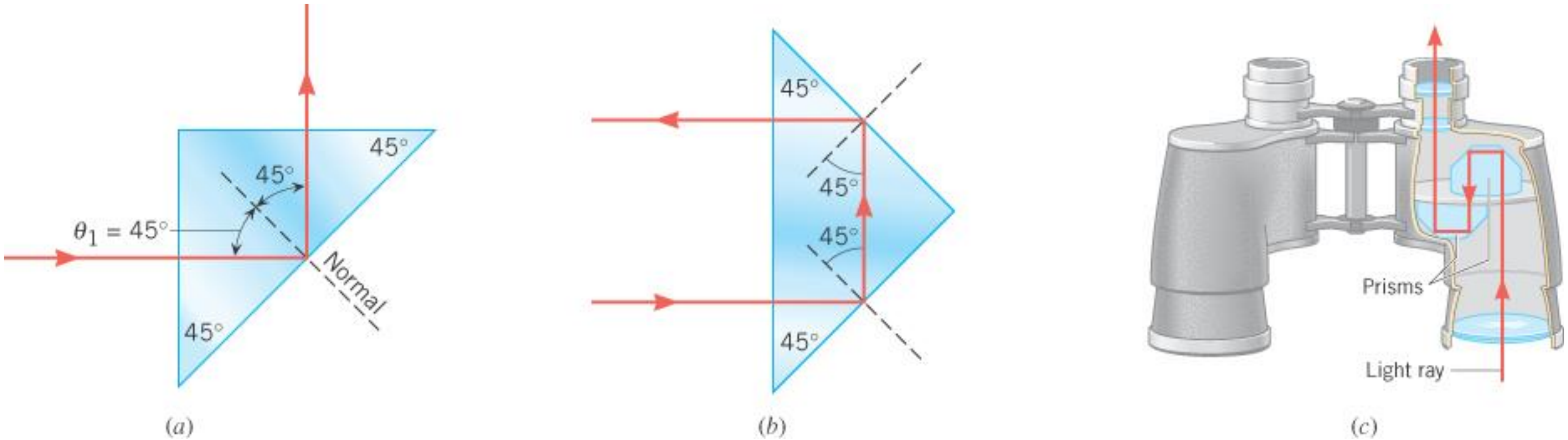
(b) $$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.33}{2.42}\right) = 33.3^\circ$$

Conceptual Example 6 The Sparkle of a Diamond

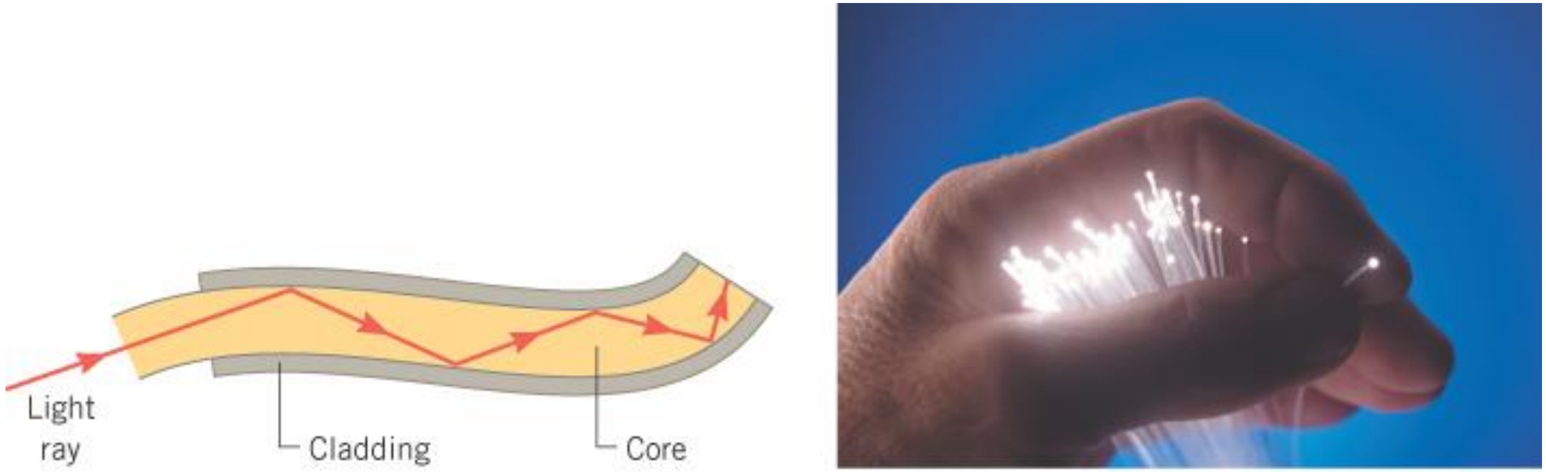
The diamond is famous for its sparkle because the light coming from it glitters as the diamond is moved about. Why does a diamond exhibit such brilliance? Why does it lose much of its brilliance when placed under water?



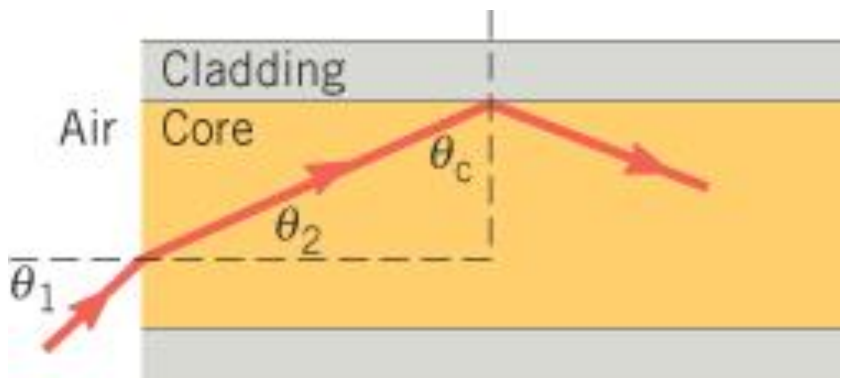
26.3 *Total Internal Reflection*



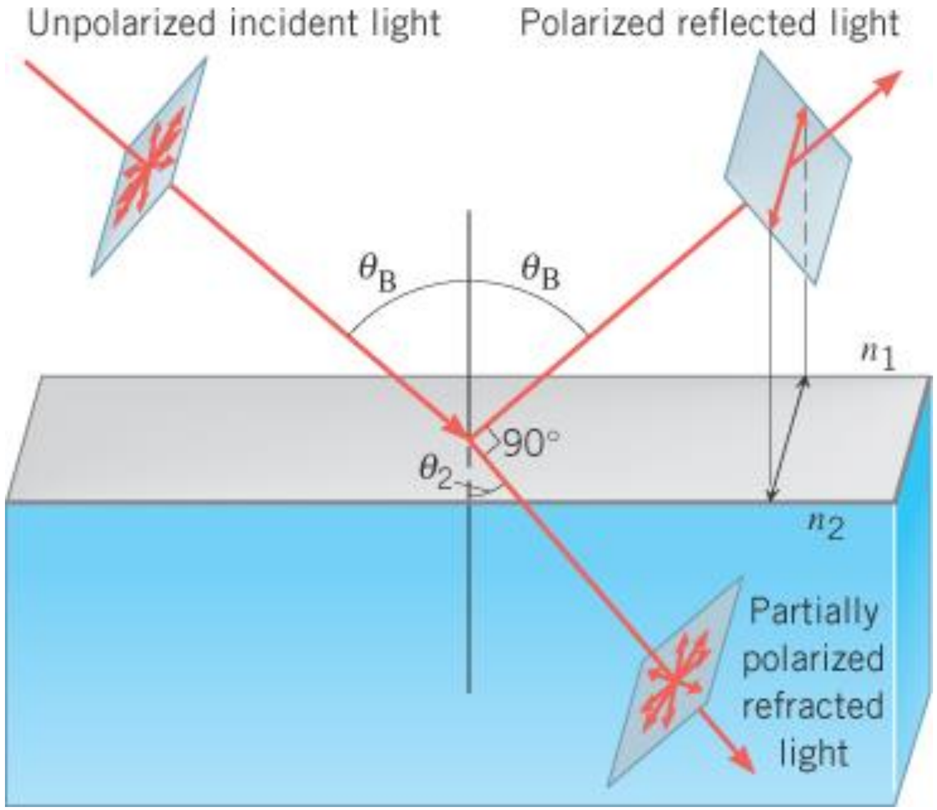
26.3 Total Internal Reflection



(a) (b)



26.4 Polarization and the Reflection and Refraction of Light



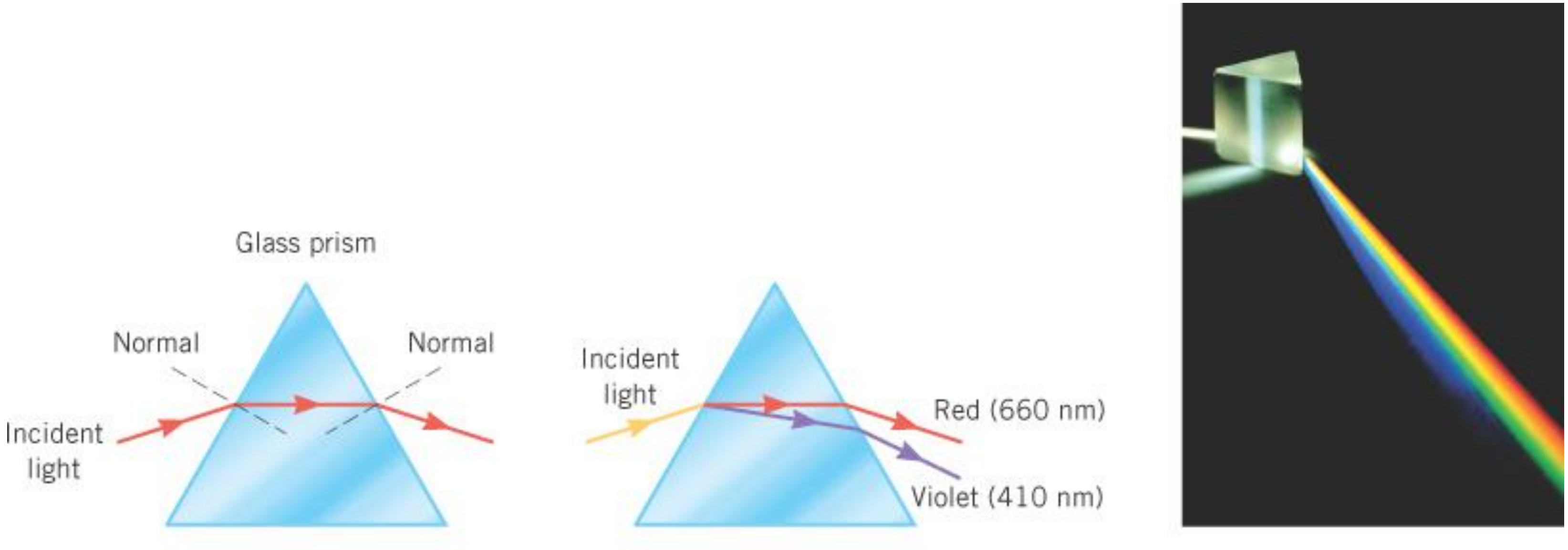
Brewster's law

$$\tan\theta_B = \frac{n_2}{n_1}$$

26.5 The Dispersion of Light: Prisms and Rainbows

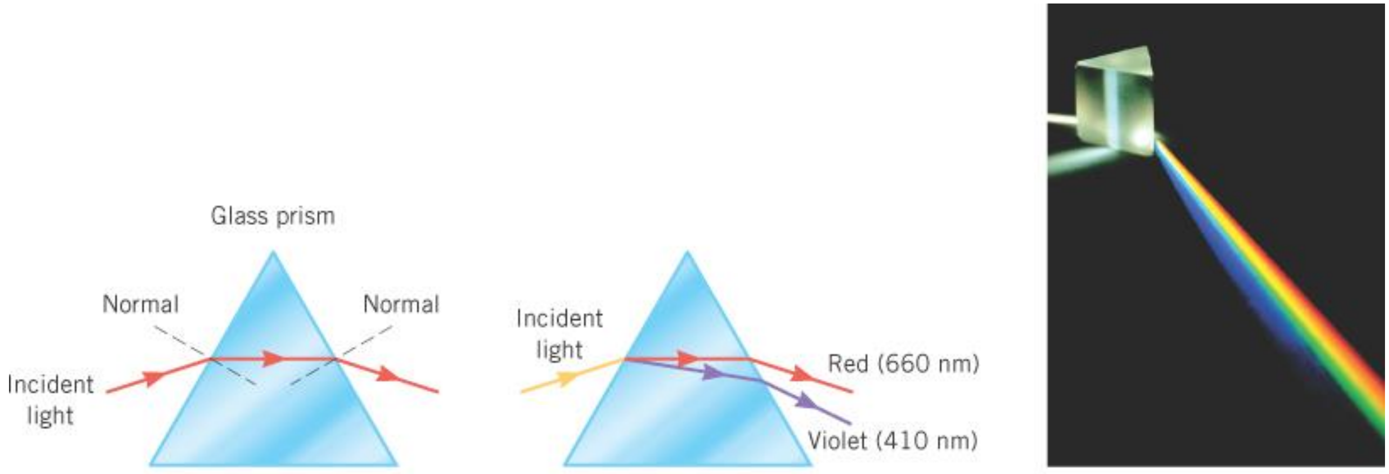
The net effect of a prism is to change the direction of a light ray.

Light rays corresponding to different colors bend by different amounts.



(a) (b) (c)

26.5 The Dispersion of Light: Prisms and Rainbows



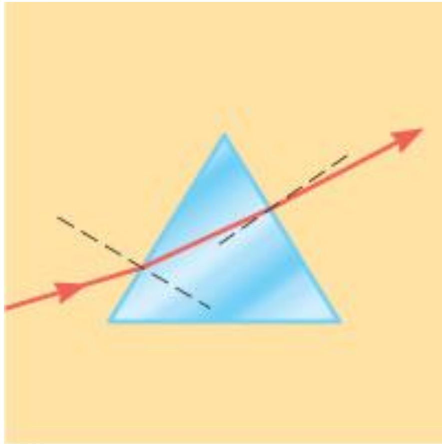
(a) (b) (c)

Table 26.2 Indices of Refraction n of Crown Glass at Various Wavelengths

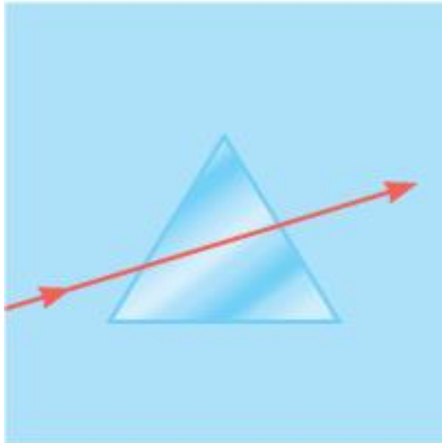
Approximate Color	Wavelength in Vacuum (nm)	Index of Refraction, n
Red	660	1.520
Orange	610	1.522
Yellow	580	1.523
Green	550	1.526
Blue	470	1.531
Violet	410	1.538

Conceptual Example 7 The Refraction of Light Depends on Two Refractive Indices

It is possible for a prism to bend light upward, downward, or not at all. How can the situations depicted in the figure arise?

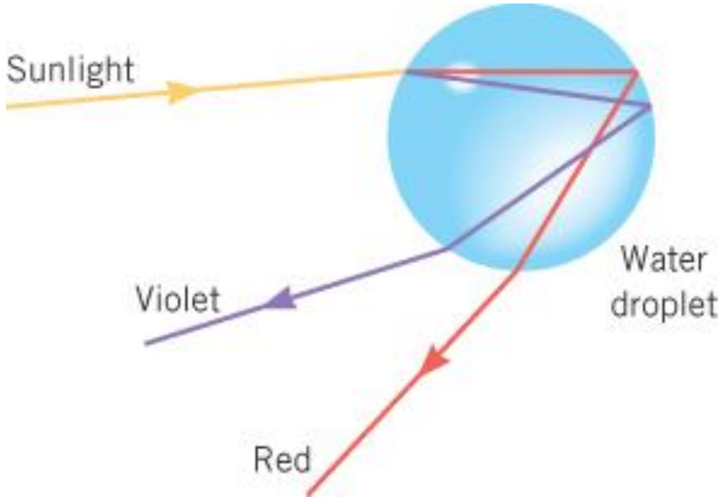


(a)



(b)

26.5 The Dispersion of Light: Prisms and Rainbows

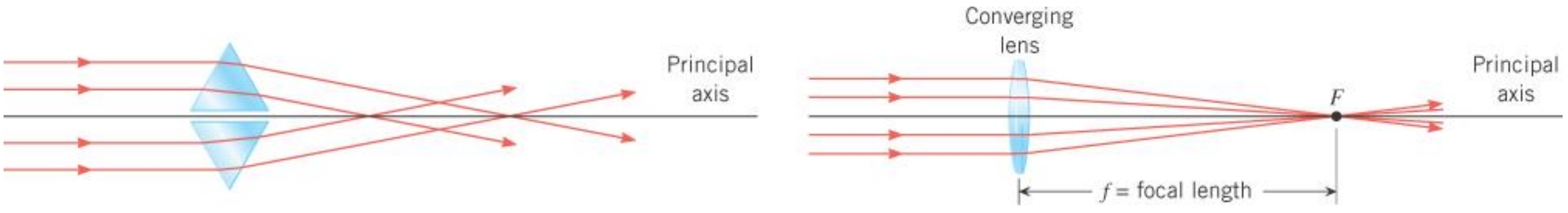


(a)

(b)

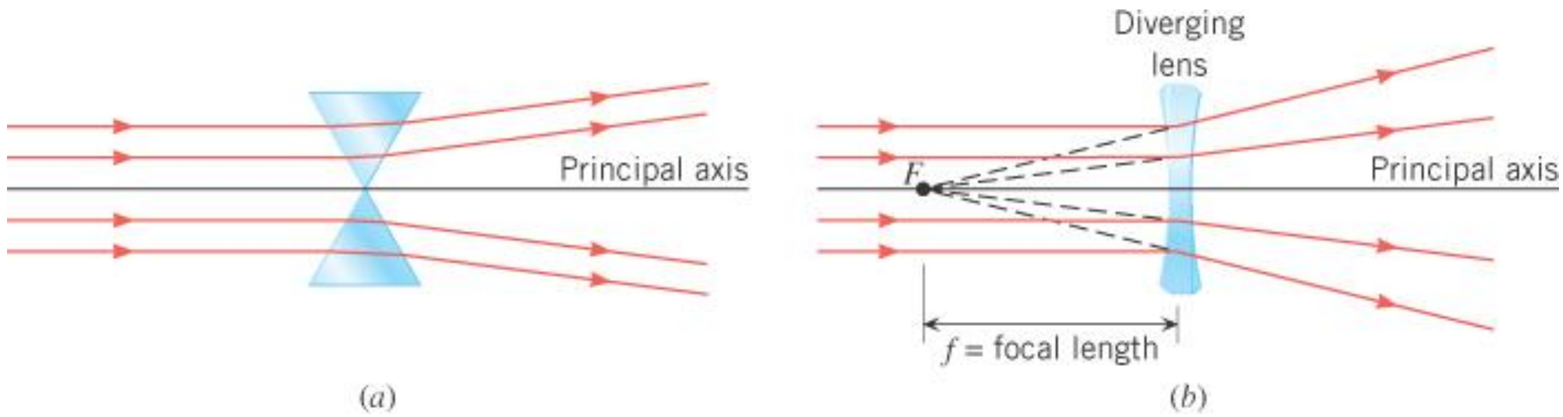
Lenses refract light in such a way that an image of the light source is formed.

With a converging lens, paraxial rays that are parallel to the principal axis converge to the focal point.

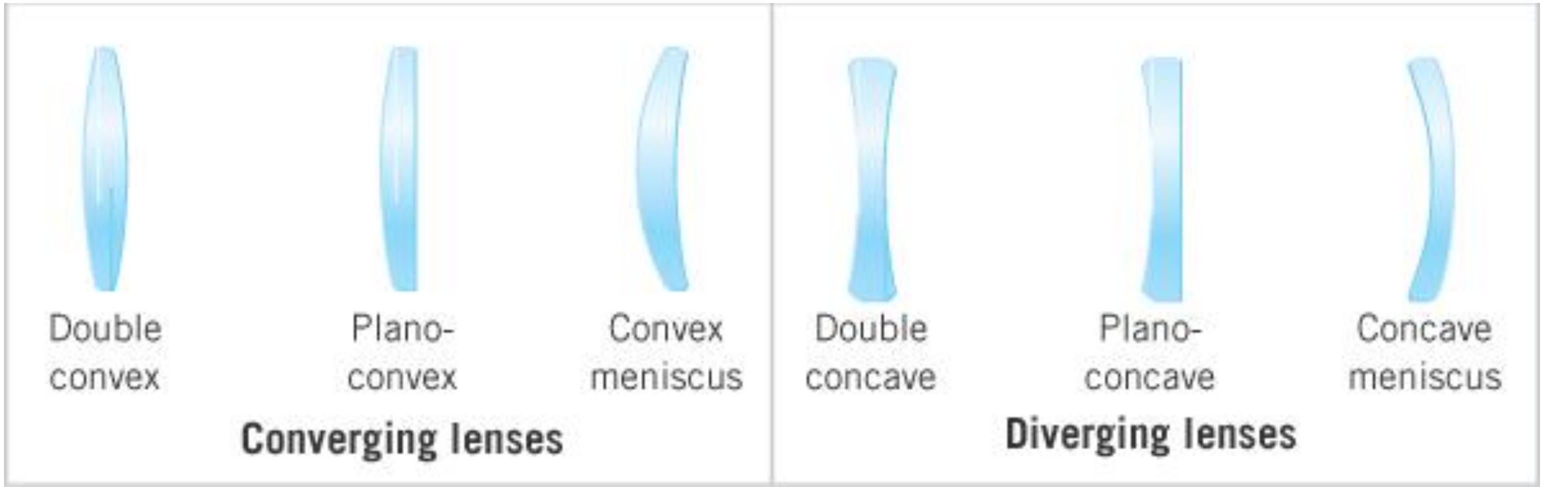


(a) (b)

With a diverging lens, paraxial rays that are parallel to the principal axis appear to originate from the focal point.



26.6 Lenses


Double convex
Plano-convex
Convex meniscus
Converging lenses
Double concave
Plano-concave
Concave meniscus
Diverging lenses

RAY DIAGRAMS

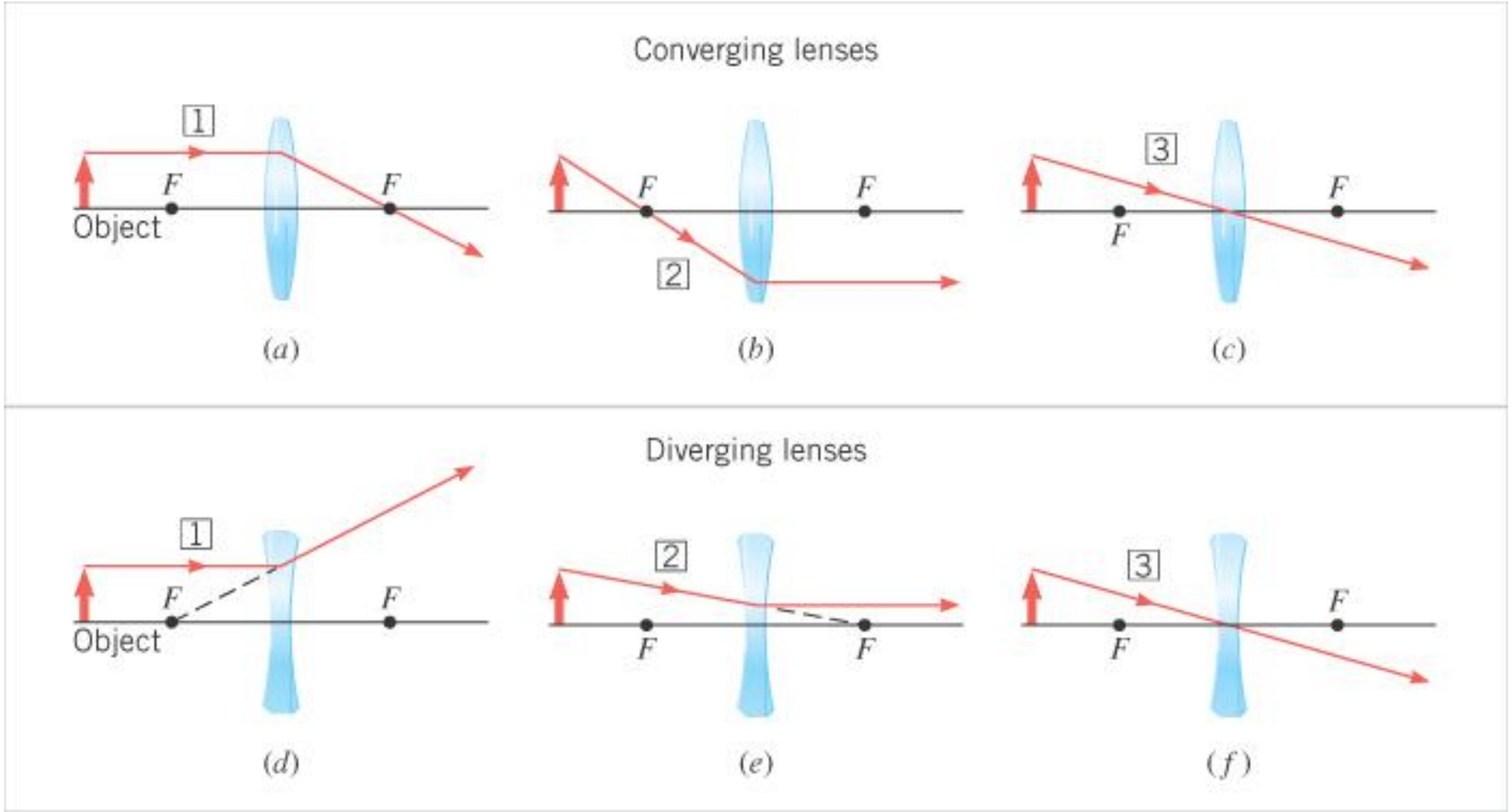
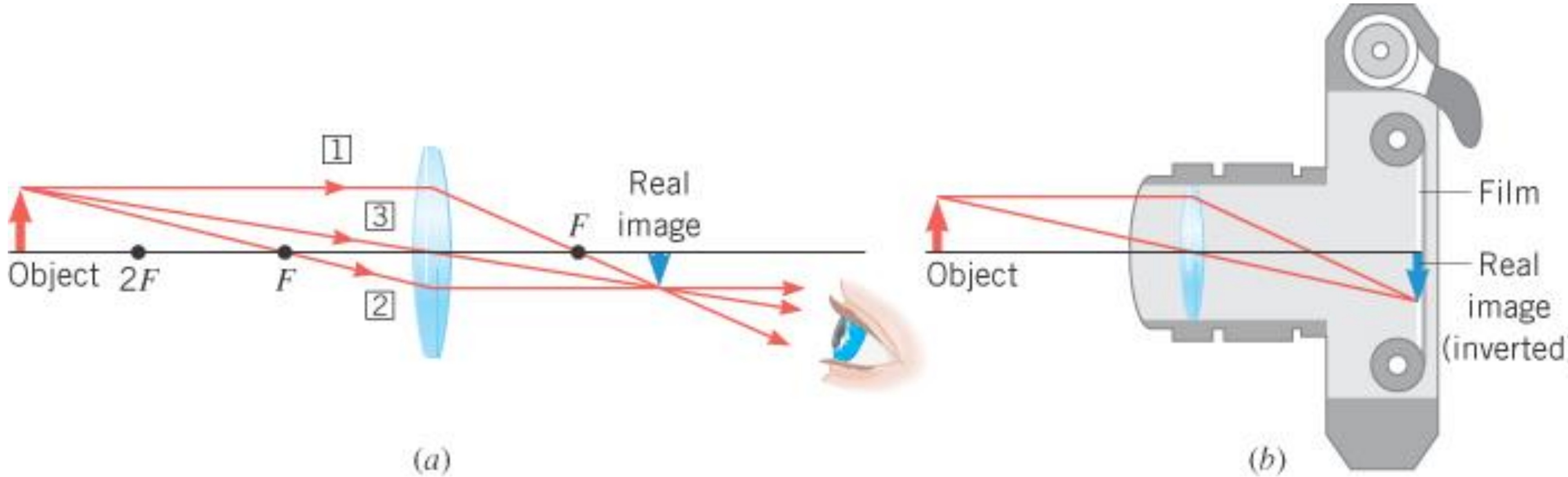
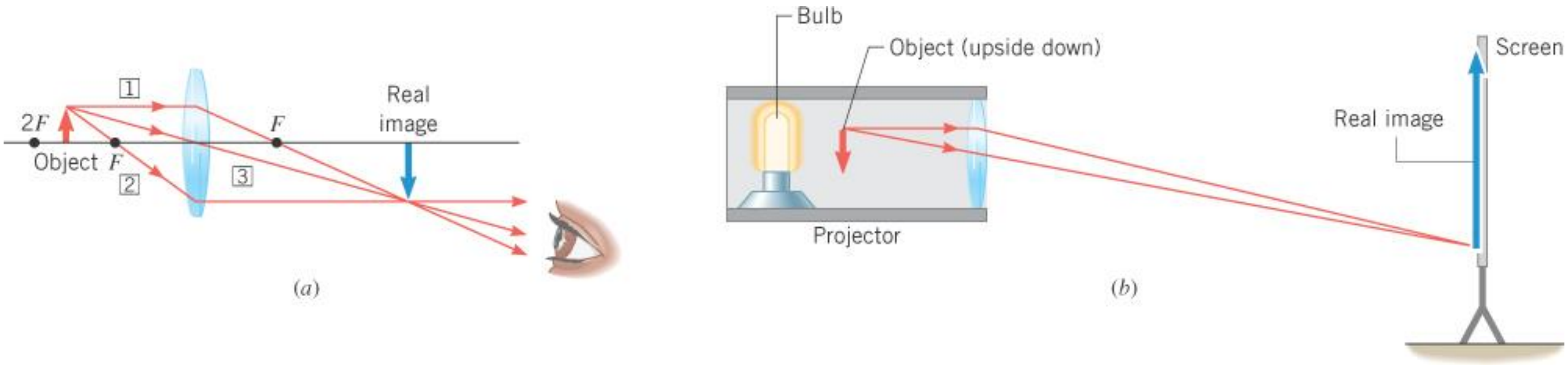


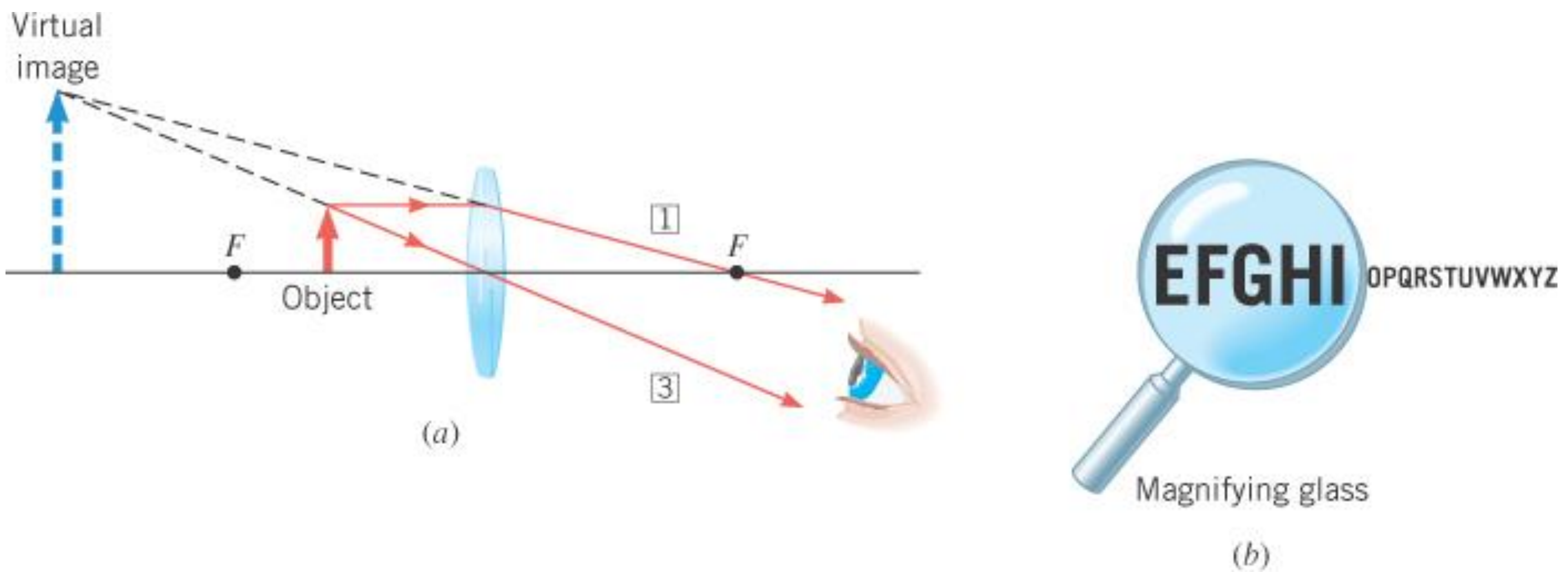
IMAGE FORMATION BY A CONVERGING LENS



In this example, when the object is placed further than twice the focal length from the lens, the real image is inverted and smaller than the object.

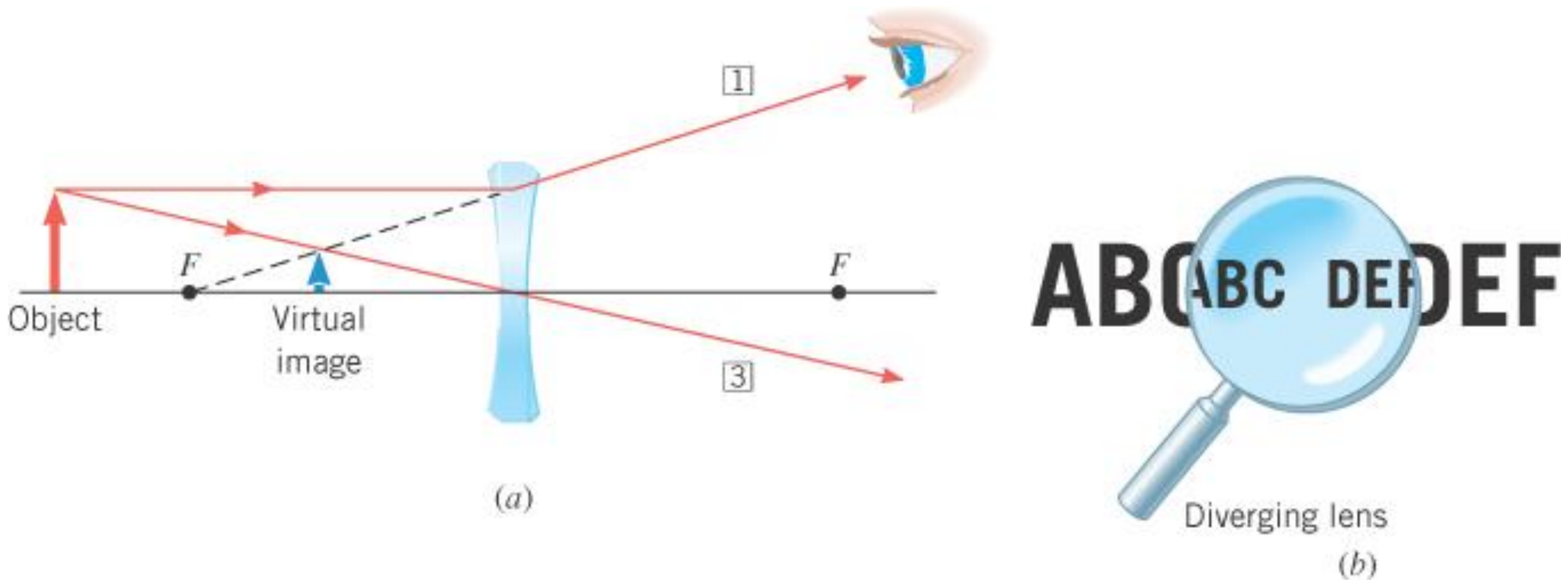


When the object is placed between F and 2F, the real image is inverted and larger than the object.



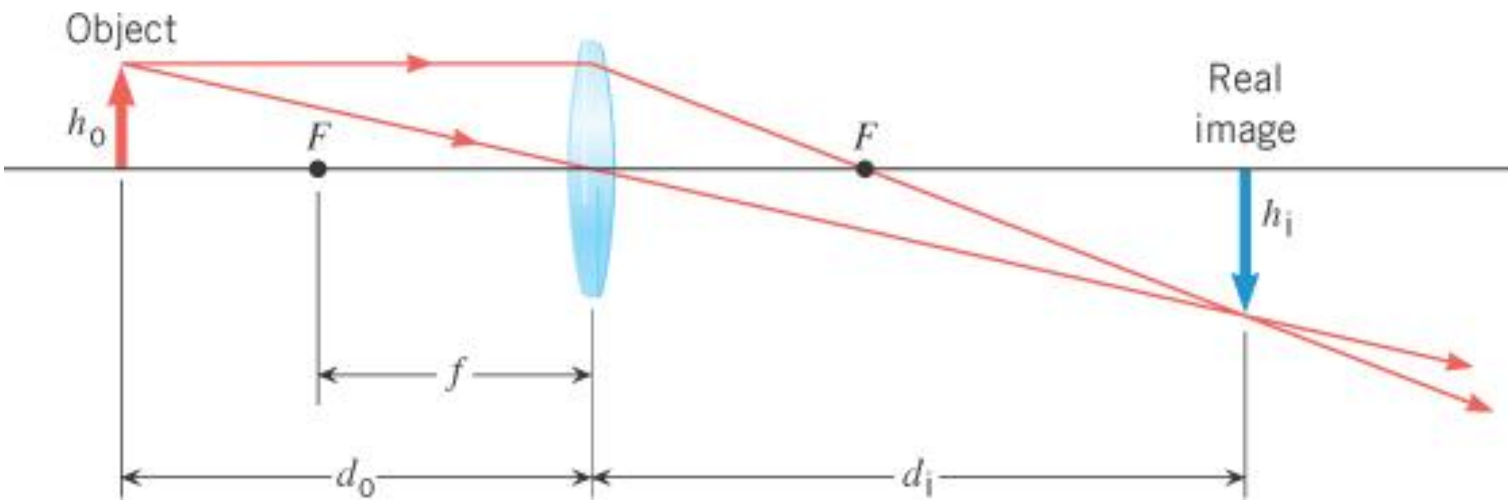
When the object is placed between F and the lens, the virtual image is upright and larger than the object.

IMAGE FORMATION BY A DIVERGING LENS



A diverging lens always forms an upright, virtual, diminished image.

26.8 The Thin-Lens Equation and the Magnification Equation



$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

Summary of Sign Conventions for Lenses

f is + for a converging lens.

f is − for a diverging lens.

d_o is + if the object is to the left of the lens.

d_o is − if the object is to the right of the lens.

d_i is + for an image formed to the right of the lens (real image).

d_i is − for an image formed to the left of the lens (virtual image).

m is + for an upright image.

m is − for an inverted image.

Example 9 The Real Image Formed by a Camera Lens

A 1.70-m tall person is standing 2.50 m in front of a camera. The camera uses a converging lens whose focal length is 0.0500 m.
(a) Find the image distance and determine whether the image is real or virtual. (b) Find the magnification and height of the image on the film.

(a)

$$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o} = \frac{1}{0.0500\,\text{m}} - \frac{1}{2.50\,\text{m}} = 19.6\,\text{m}^{-1}$$

$$d_i = 0.0510\,\text{m}$$

real image

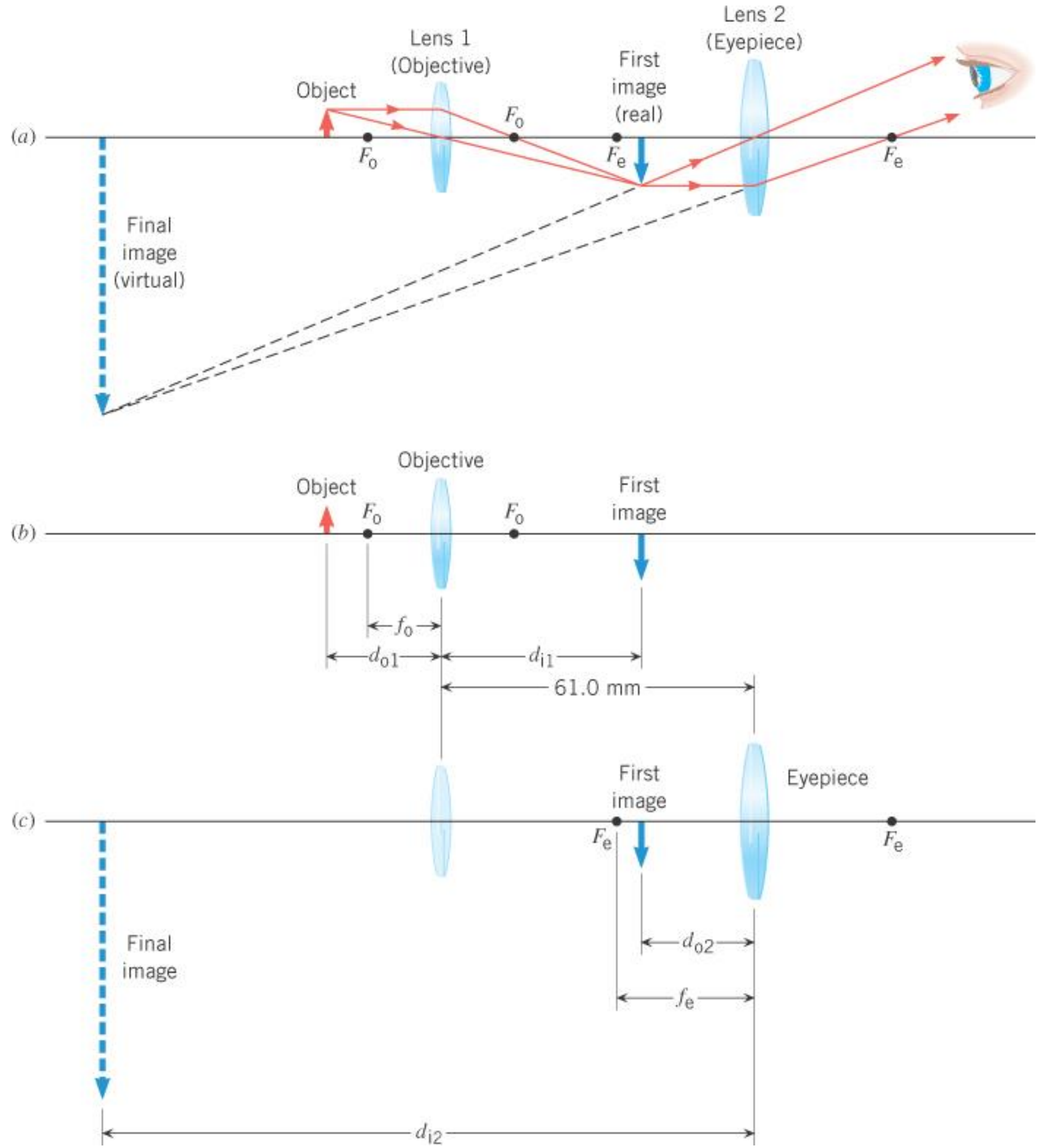
(b)

$$m = -\frac{d_i}{d_o} = -\frac{0.0510\,\text{m}}{2.50\,\text{m}} = -0.0204$$

$$h_i = m h_o = (-0.0204)(2.50\,\text{m}) = -0.0347\,\text{m}$$

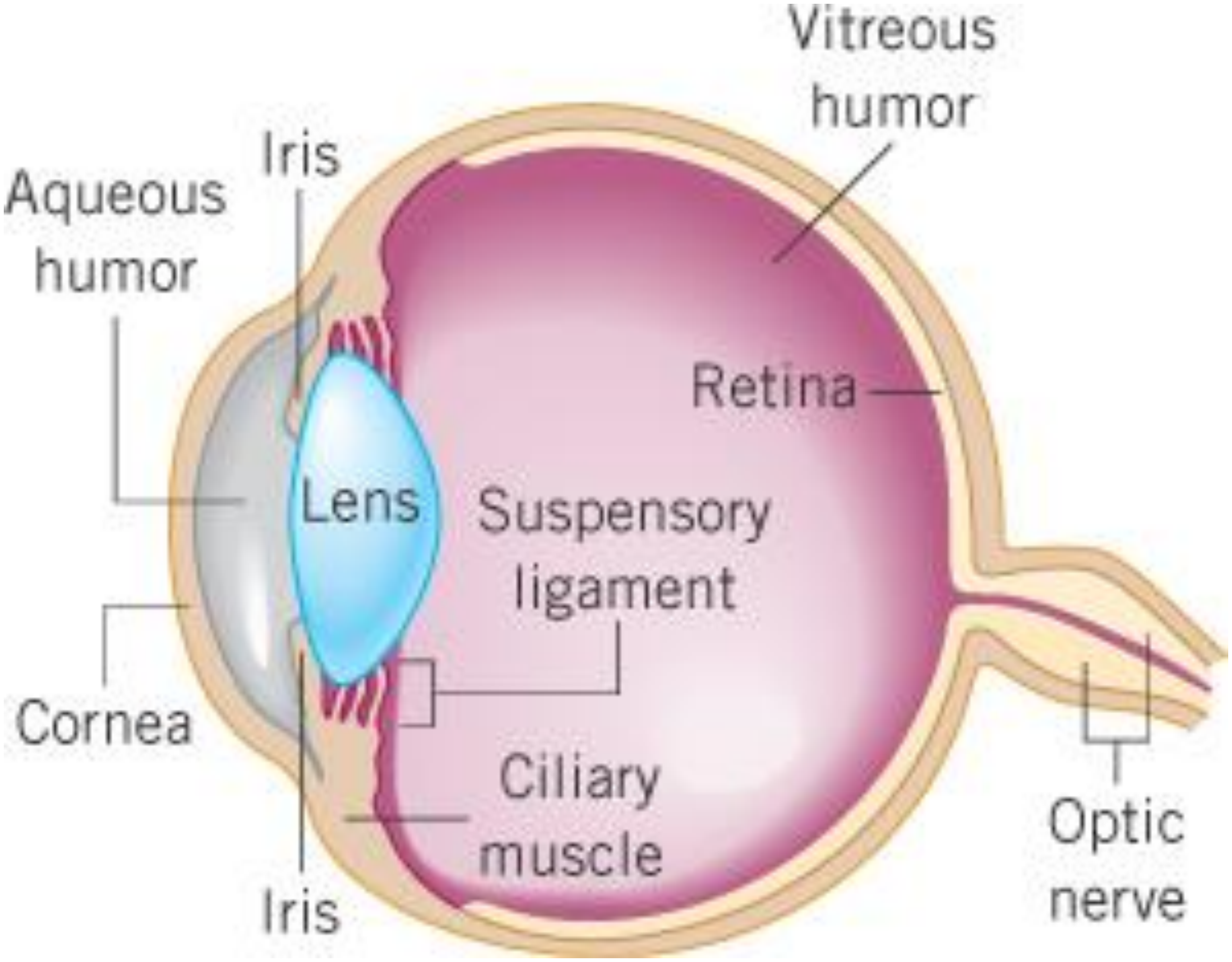
26.9 Lenses in Combination

The image produced by one lens serves as the object for the next lens.

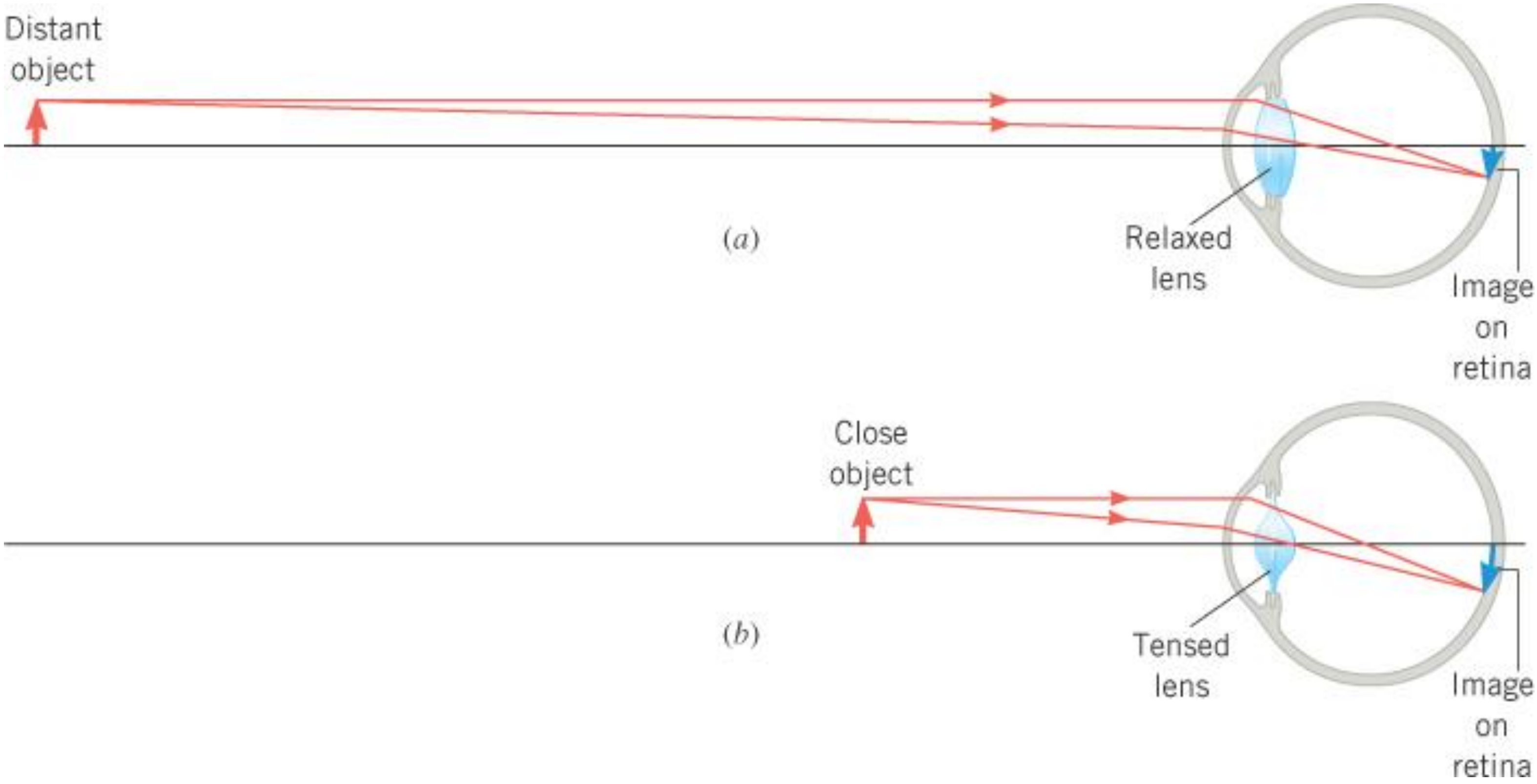


26.10 The Human Eye

ANATOMY

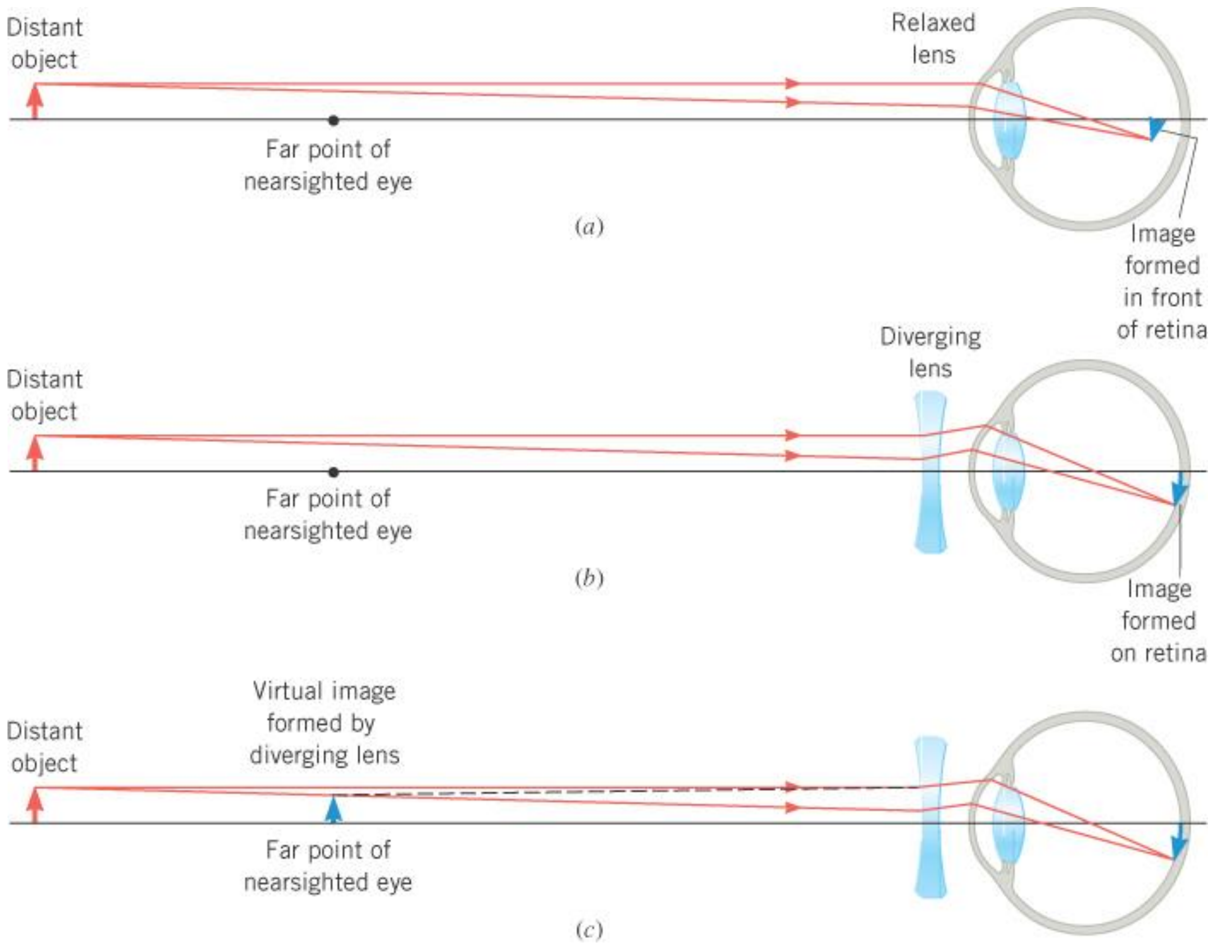


OPTICS



The lens only contributes about 20-25% of the refraction, but its function is important.

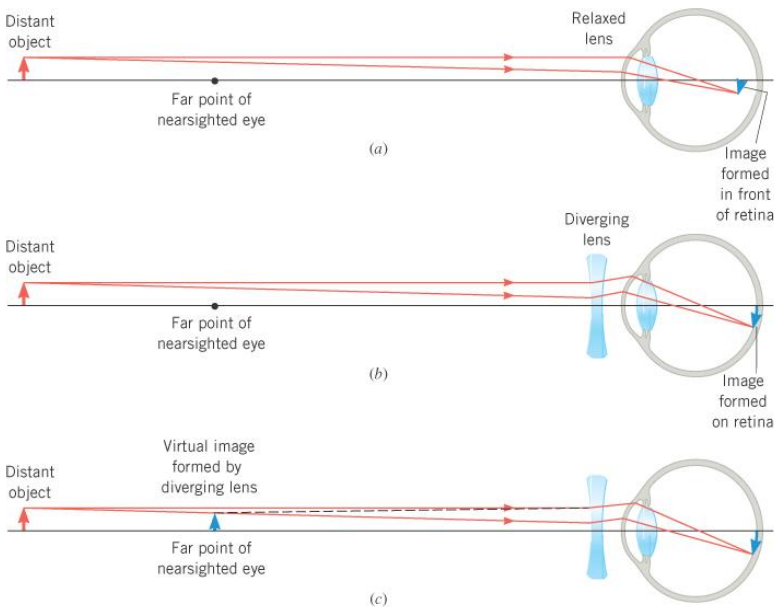
NEARSIGHTEDNESS



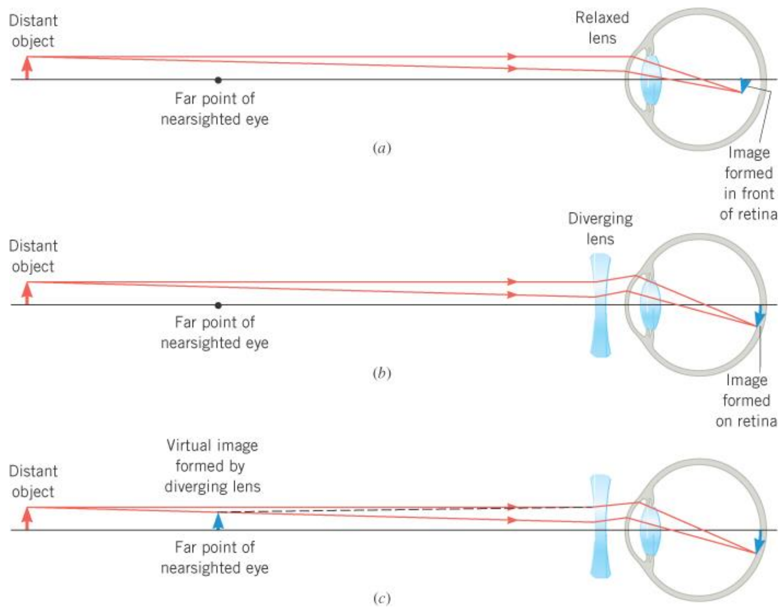
The lens creates an image of the distance object at the far point of the nearsighted eye.

Example 12 Eyeglasses for the Nearsighted Person

A nearsighted person has a far point located only 521 cm from the eye. Assuming that eyeglasses are to be worn 2 cm in front of the eye, find the focal length needed for the diverging lens of the glasses so the person can see distant objects.



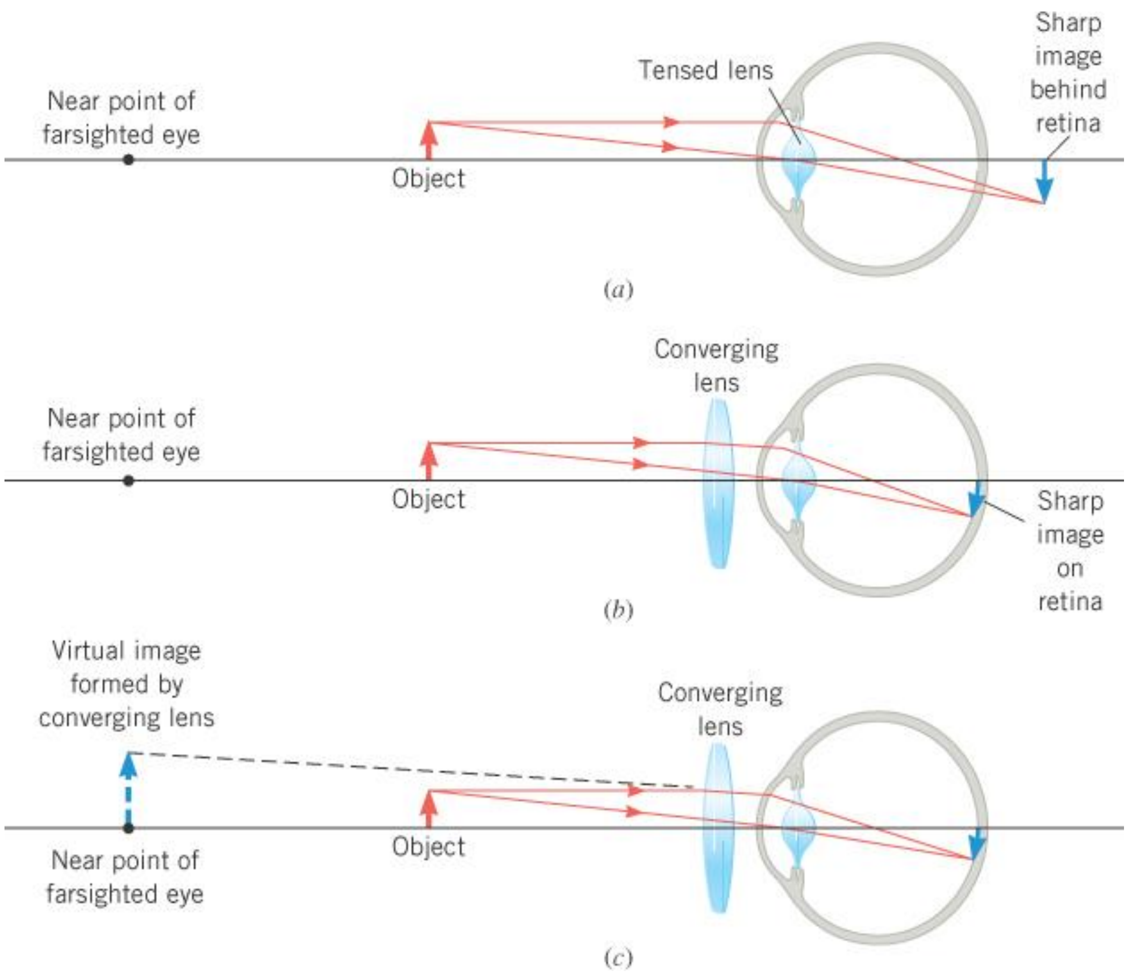
26.10 The Human Eye



$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{\infty} - \frac{1}{519\,\text{cm}}$$

$$f = -519\,\text{cm}$$

FARSIGNTEDNESS

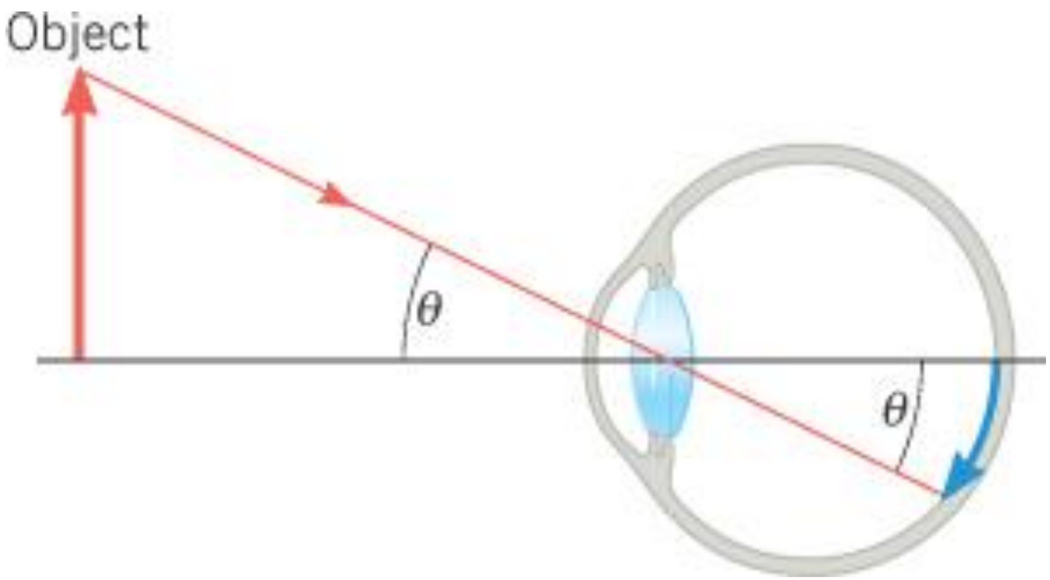


The lens creates an image of the close object at the near point of the farsighted eye.

THE REFRACTIVE POWER OF A LENS – THE DIOPTER

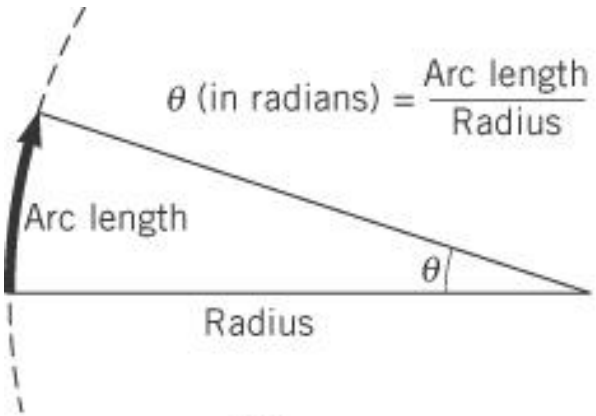
Optometrists who prescribe correctional lenses and the opticians who make the lenses do not specify the focal length. Instead they use the concept of ***refractive power.***

$$\text{Refractive power (in diopters)} = \frac{1}{f\,(\text{in meters})}$$

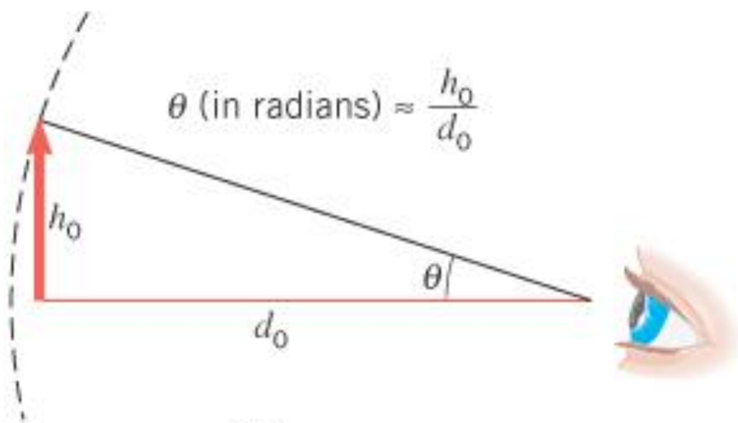


The size of the image on the retina determines how large an object appears to be.

26.11 Angular Magnification and the Magnifying Glass



(a)



(b)

$$\theta\ (\text{in radians}) = \text{Angular size} \approx \frac{h_o}{d_o}$$

Example 14 A Penny and the Moon

Compare the angular size of a penny held at arms length with that of the moon.

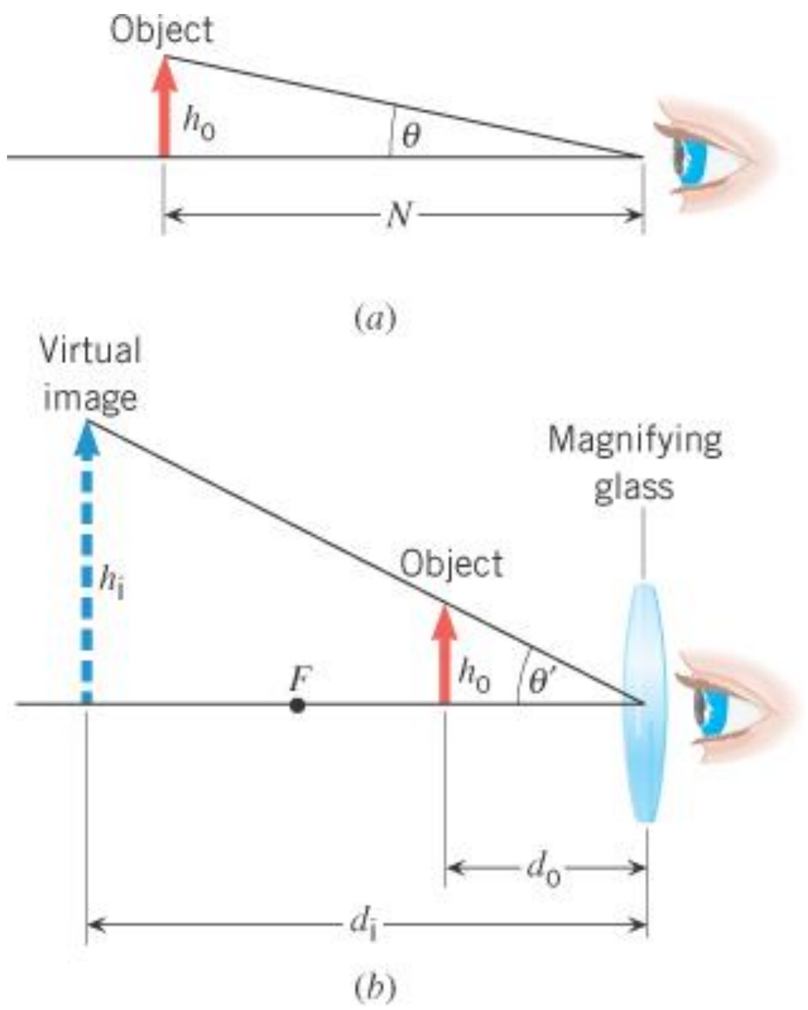
Penny

$$\theta \approx \frac{h_o}{d_o} = \frac{1.9\,\text{cm}}{71\,\text{cm}} = 0.027\,\text{rad}$$

Moon

$$\theta \approx \frac{h_o}{d_o} = \frac{3.5\times 10^{6}\ \text{m}}{3.9\times 10^{8}\ \text{m}} = 0.0090\,\text{rad}$$

26.11 Angular Magnification and the Magnifying Glass

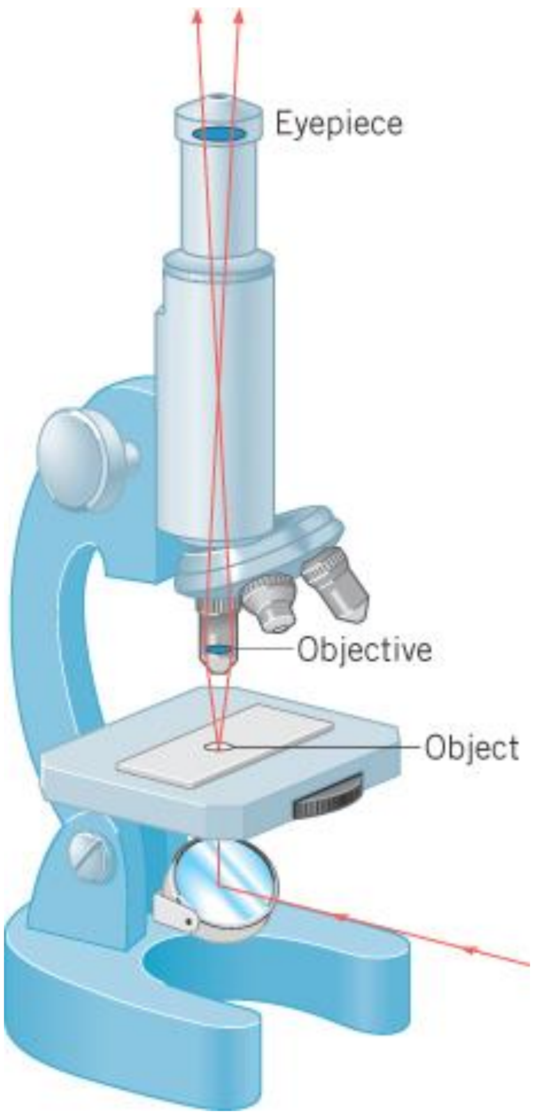


Angular magnification

$$M = \frac{\theta'}{\theta}$$

Angular magnification of a magnifying glass

$$M \approx \left(\frac{1}{f} - \frac{1}{d_i} \right) N$$

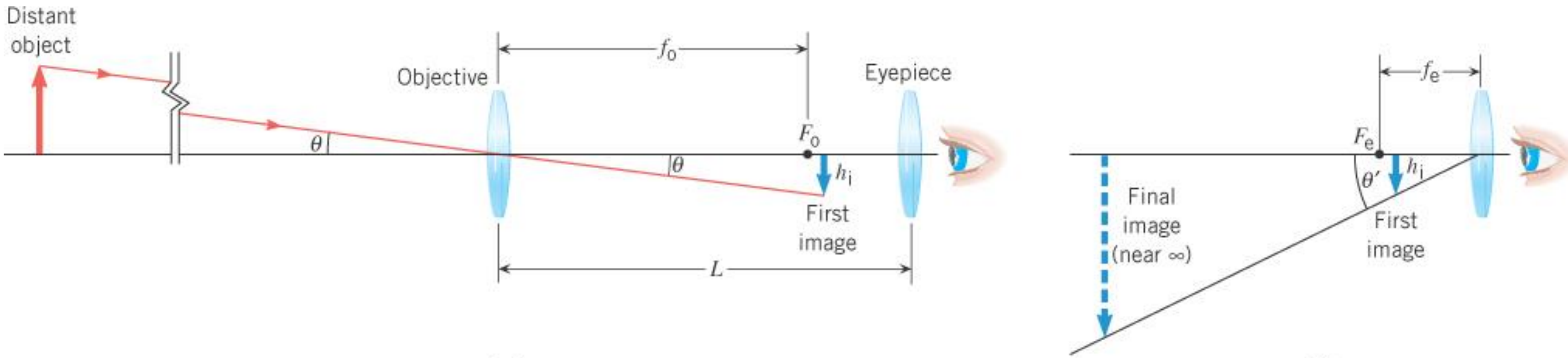


To increase the angular magnification beyond that possible with a magnifying glass, an additional converging lens can be included to "premagnify" the object.

Angular magnification of a compound microscope

$$M \approx -\frac{\left(L - f_e\right)N}{f_o f_e}$$

26.13 The Telescope

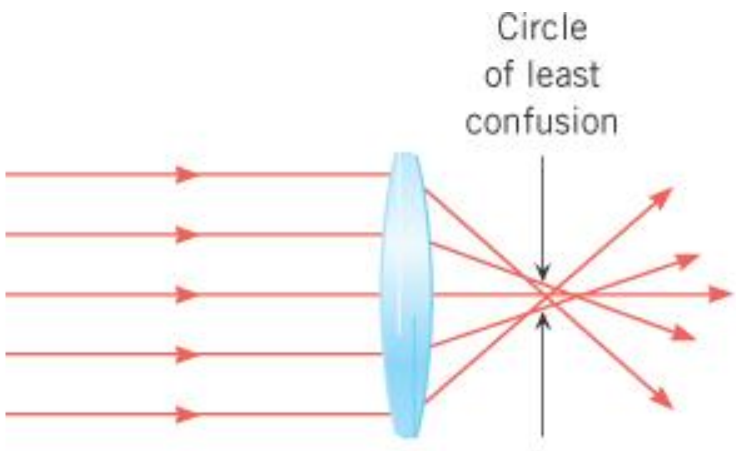


(a) (b)

Angular magnification of an astronomical telescope

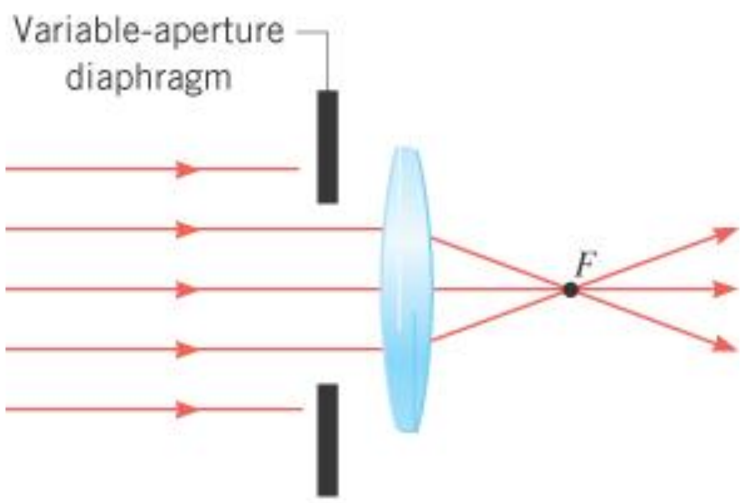
$$M \approx -\frac{f_o}{f_e}$$

26.14 Lens Aberrations



(a)

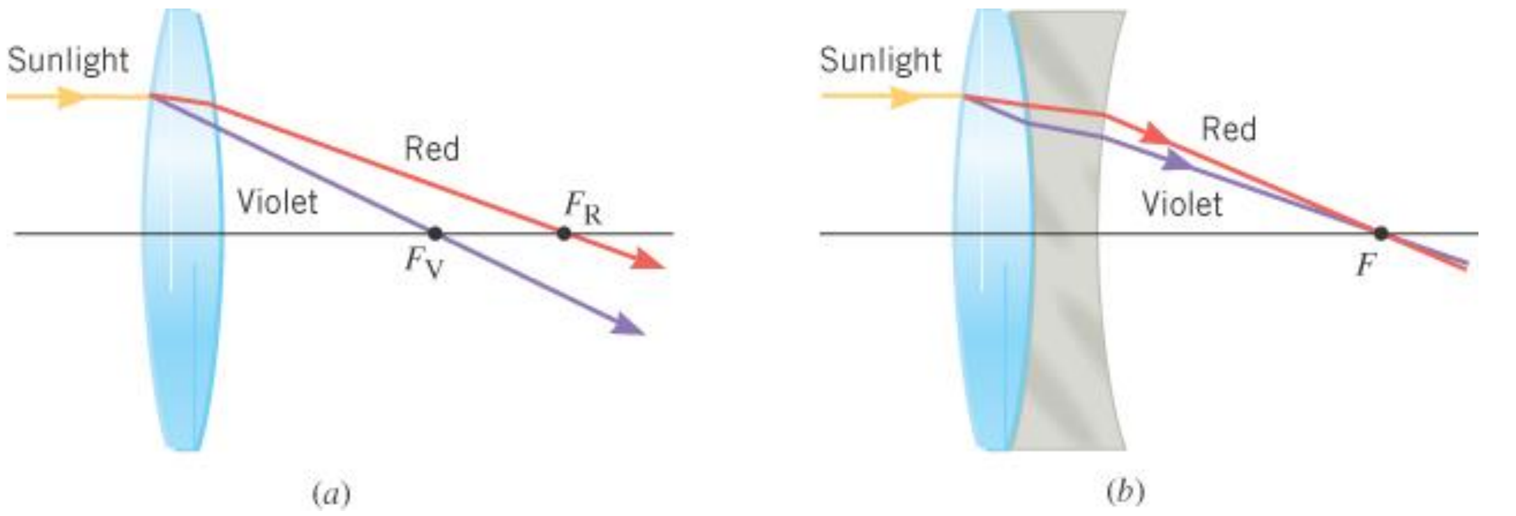
In a converging lens, spherical aberration prevents light rays parallel to the principal axis from converging at a single point.



(b)

Spherical aberration can be reduced by using a variable-aperture diaphragm.

26.14 Lens Aberrations



Chromatic aberration arises when different colors are focused at different points along the principal axis.