PHYS 270 – SUPPL. #15
Ray Optics

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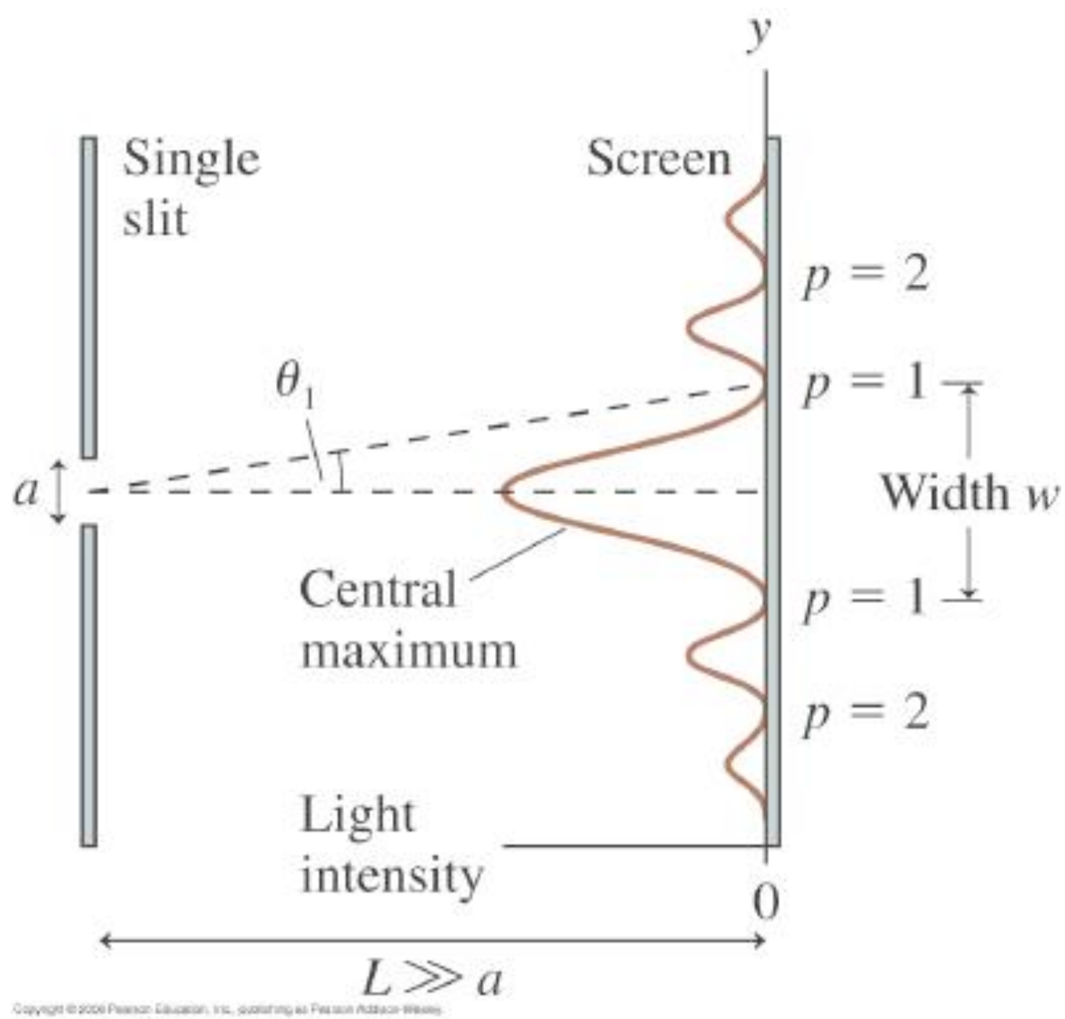
MARCH 29, 2011



$$w = 2L\frac{\lambda}{a}$$

Most common situation, e.g. loudspeakers speakers – diaphragm and exit cone

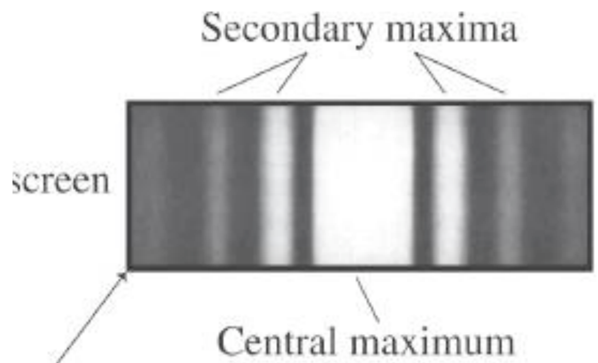
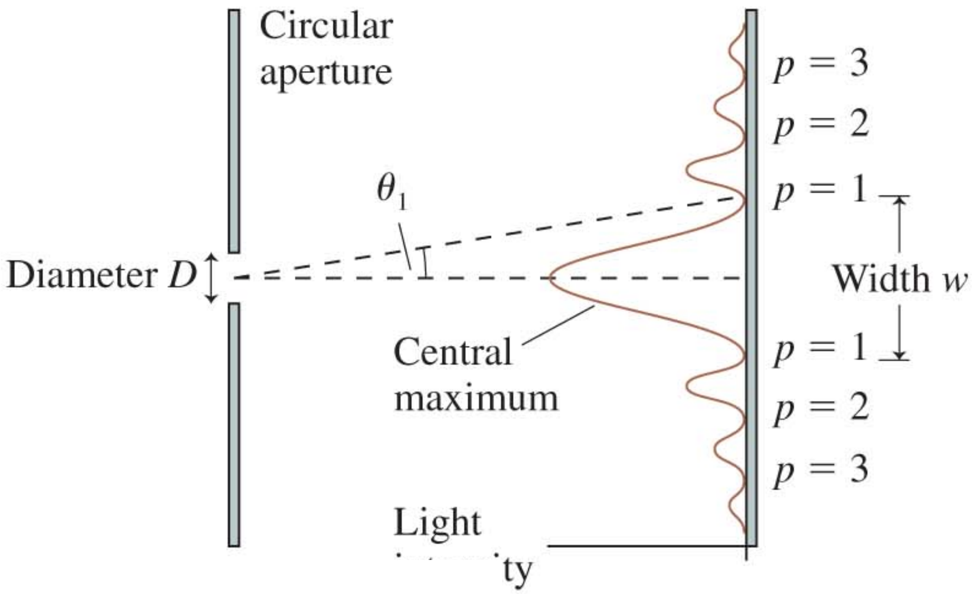
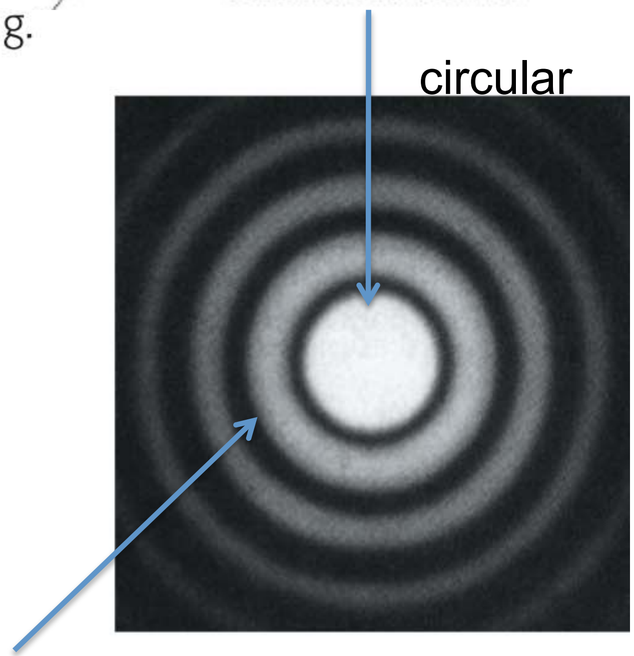


FIGURE 22.15 The diffraction of light by a circular opening.



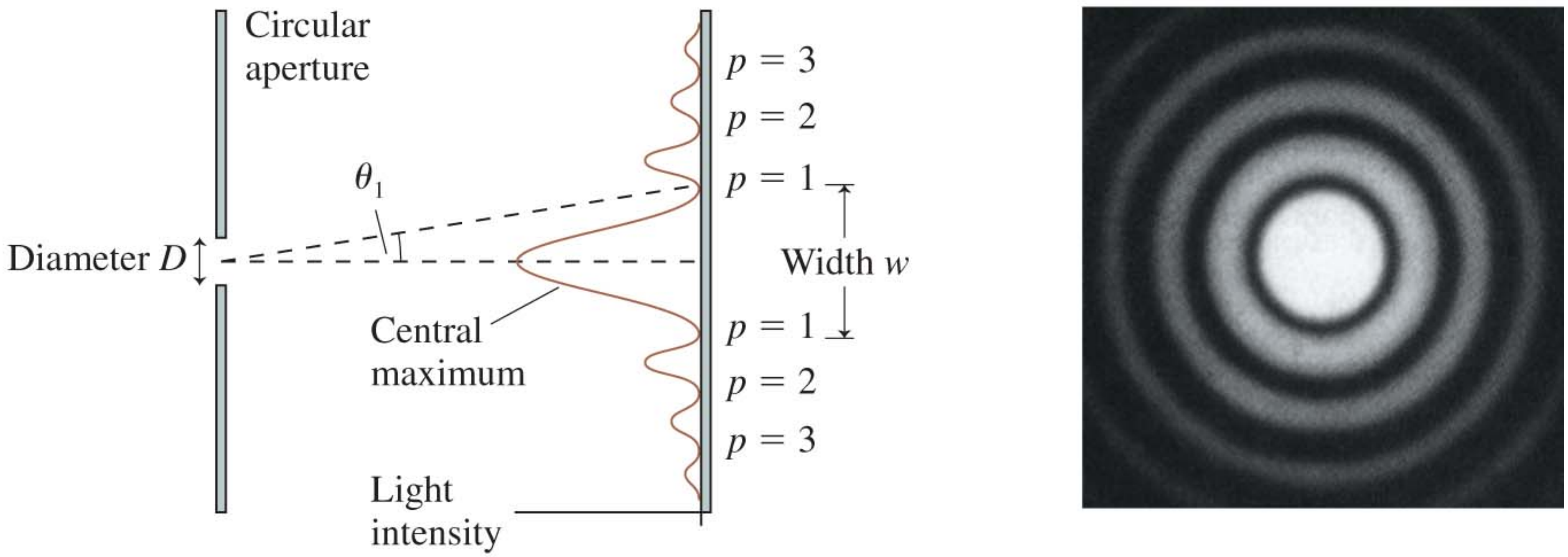


$$\theta_1 = \frac{1.22\lambda}{D}$$

Radians

$$w = 2y_1 = 2L\tan\theta_1 \approx \frac{2.44\lambda L}{D}$$

FIGURE 22.15 The diffraction of light by a circular opening.

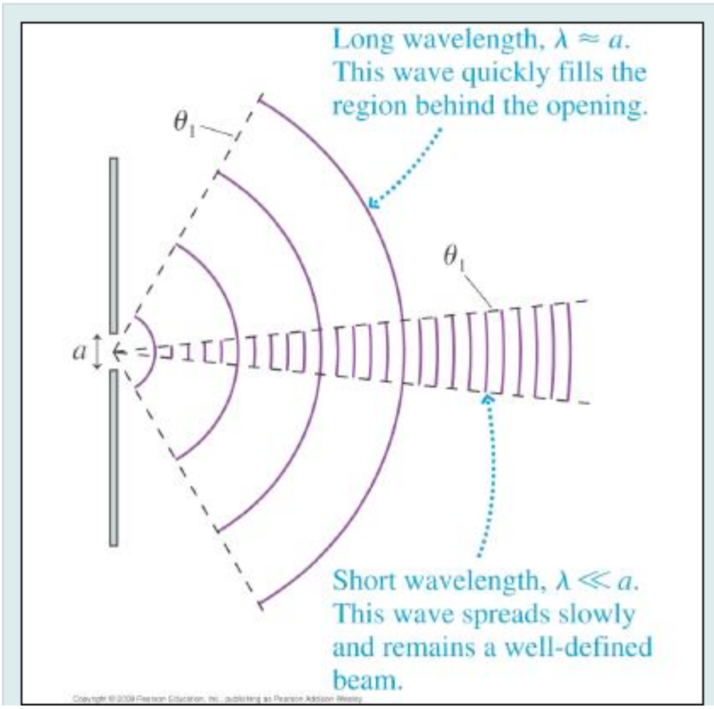


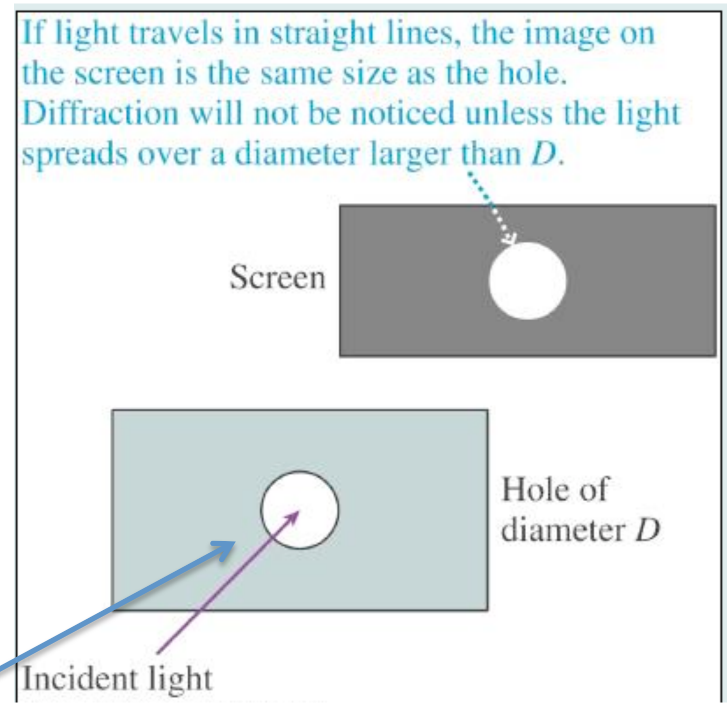
$$\theta_1 = \frac{1.22\lambda}{D}$$ Radians

$$w = 2y_1 = 2L\tan\theta_1 \approx \frac{2.44\lambda L}{D}$$

The diameter w of the diffraction pattern increases with distance L, showing that light spreads out behind the circular aperture, but it decreases if the size D of the circular aperture increases.

Wave vs. Ray Model





$$\theta = \sin^{-1}(\lambda / a)$$

w= D

$$2.44\lambda L / D = D$$

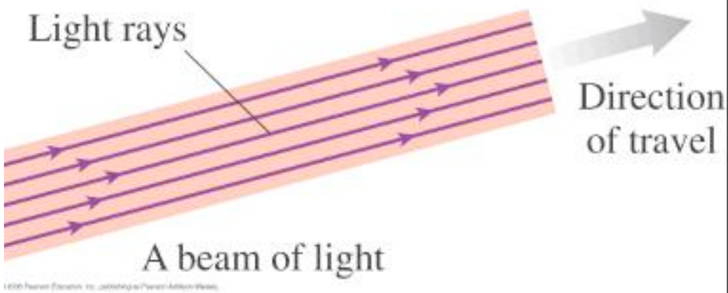
$$D_c = \sqrt{2.44\lambda L}$$

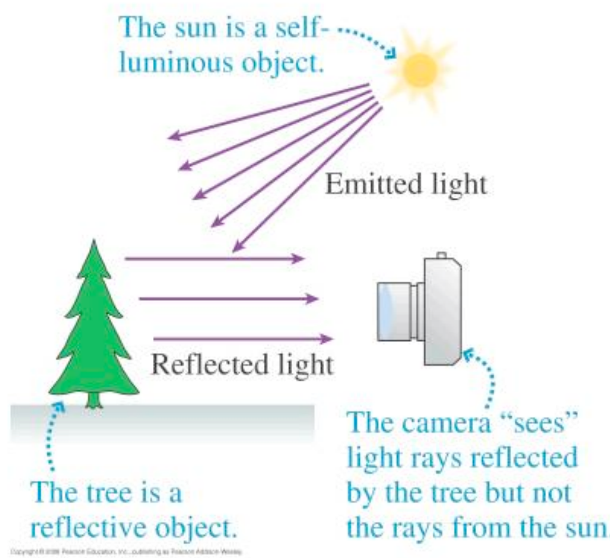
$a < D_c$ diffraction important; use wave theory

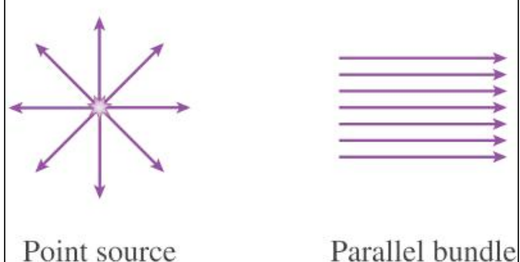
$a > D_c$ diffraction negligible; use ray model

Sound fills space behind opening because $\lambda/\alpha > 1$ easily. For light to do the same a=.001 mm

Ray Optics







Line of sight

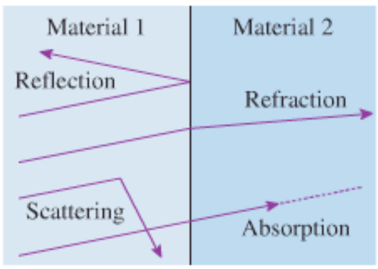
The ray model of light

Light rays travel in straight lines.

Light travels through a transparent material in straight lines called light rays. The speed of light is $v = c/n$, where n is the index of refraction of the material.

Light rays can cross.

Light rays do not interact with each other. Two rays can cross without either being affected in any way.

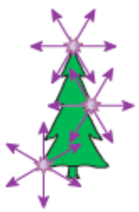


A light ray travels forever unless it interacts with matter.

A light ray continues forever unless it has an interaction with matter that causes the ray to change direction or to be absorbed. Light interacts with matter in four different ways:

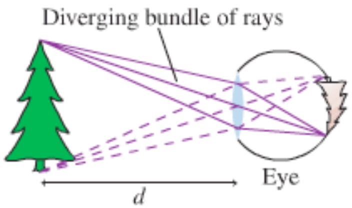
- At an interface between two materials, light can be either *reflected* or *refracted.*
- Within a material, light can be either *scattered* or *absorbed.*

These interactions are discussed later in the chapter.



An object is a source of light rays.

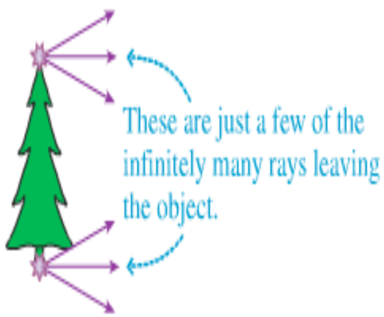
An **object** is a source of light rays. Rays originate from *every* point on the object, and each point sends rays in *all* directions. We make no distinction between self-luminous objects and reflective objects.



The eye sees by focusing a diverging bundle of rays.

The eye "sees" an object when *diverging* bundles of rays from each point on the object enter the pupil and are focused to an image on the retina. (Imaging is discussed later in the chapter.) From the movements the eye's lens has to make to focus the image, your brain "computes" the distance d at which the rays originated, and you perceive the object as being at that point.

FIGURE 23.4 A ray diagram simplifies the situation by showing only a few rays.



Ray Diagrams

Rays originate from *every* point on an object and travel outward in *all* directions, but a diagram trying to show all these rays would be hopelessly messy and confusing. To simplify the picture, we usually use a **ray diagram** showing only a few rays. For example, FIGURE 23.4 is a ray diagram showing only a few rays leaving the top and bottom points of the object and traveling to the right. These rays will be sufficient to show us how the object is imaged by lenses or mirrors.

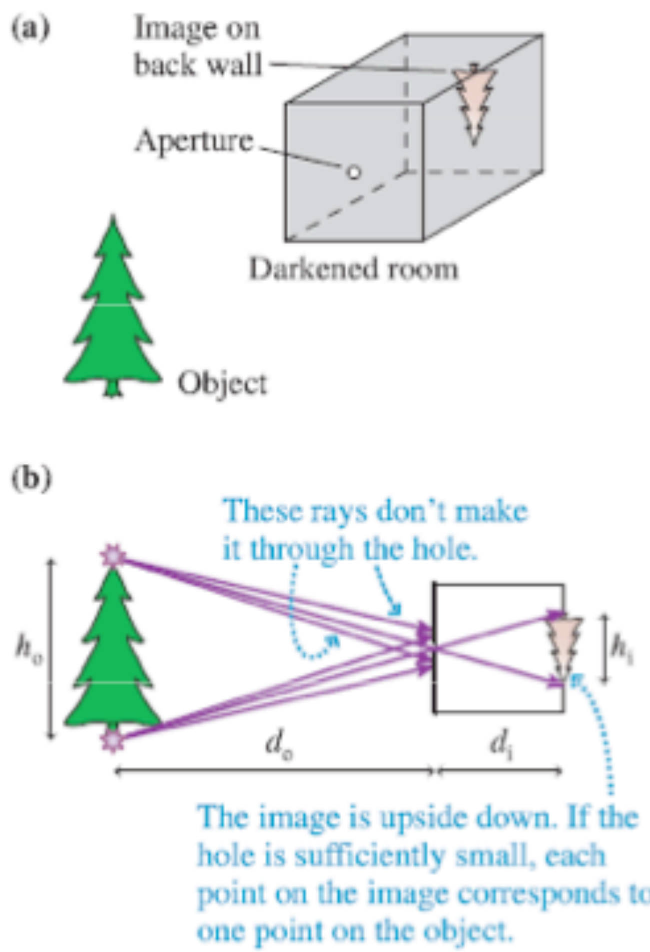
NOTE ▶ Ray diagrams are the basis for a *pictorial representation* that we'll use throughout this chapter. Be careful not think that a ray diagram shows all of the rays. The rays shown on the diagram are just a subset of the infinitely many rays leaving the object. ◀

Ray diagram

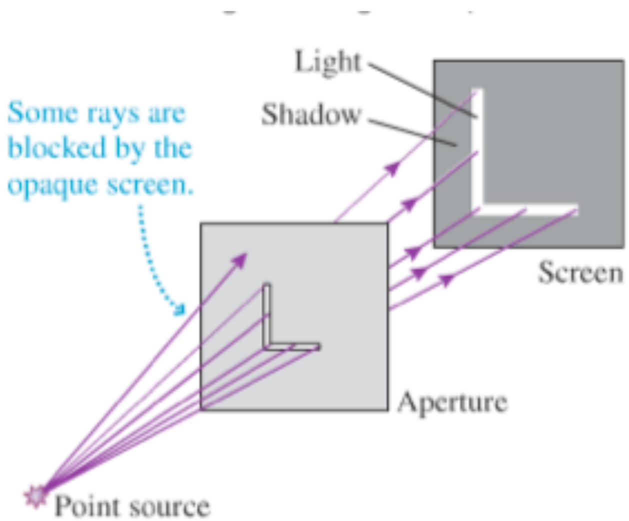
Examples of ray diagrams

Aperture- A hole through which light is transmitted or collected

FIGURE 23.5 A camera obscura.

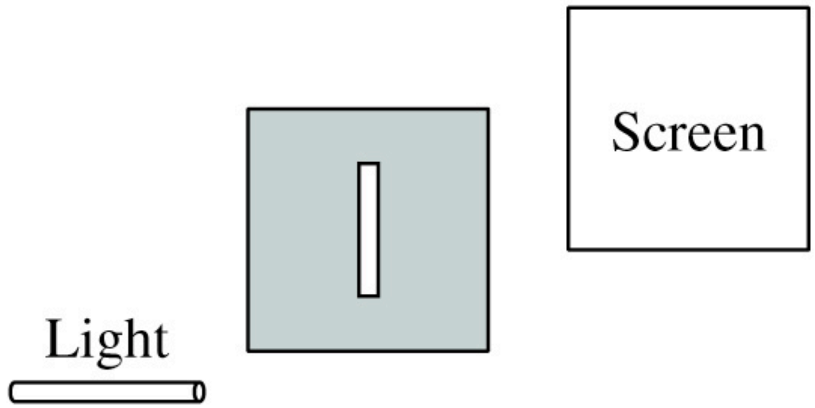


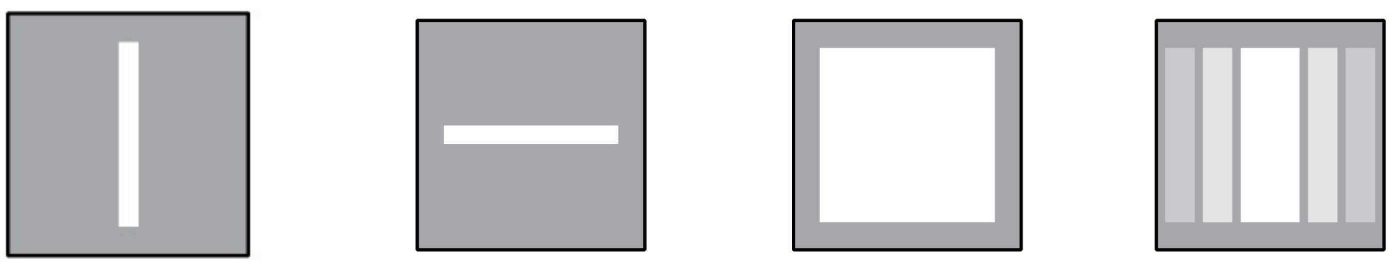
$$h_i / h_o = d_i / d_o$$



Point projection

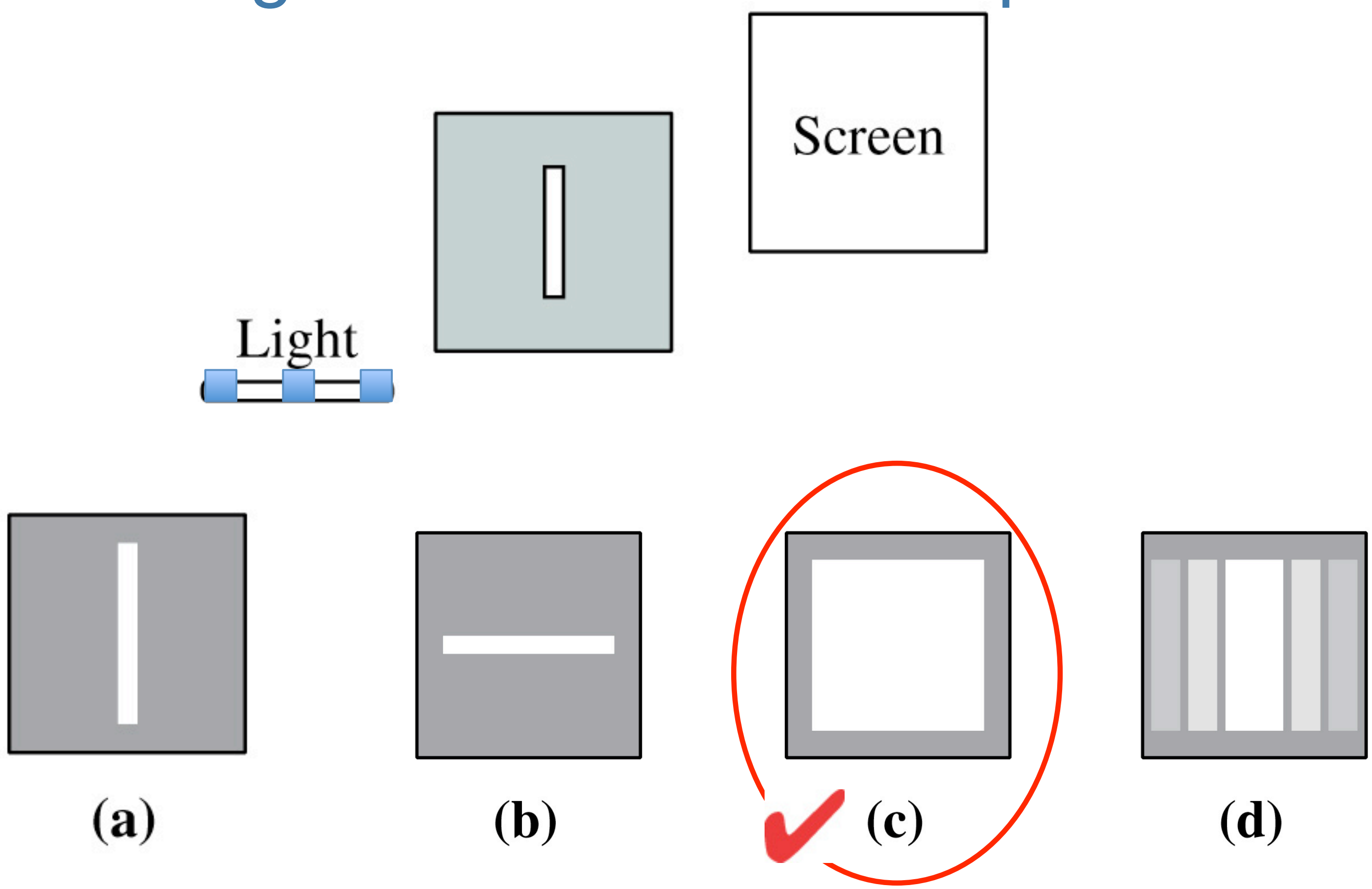
A long, thin light bulb illuminates a vertical aperture. Which pattern of light do you see on a viewing screen behind the aperture?





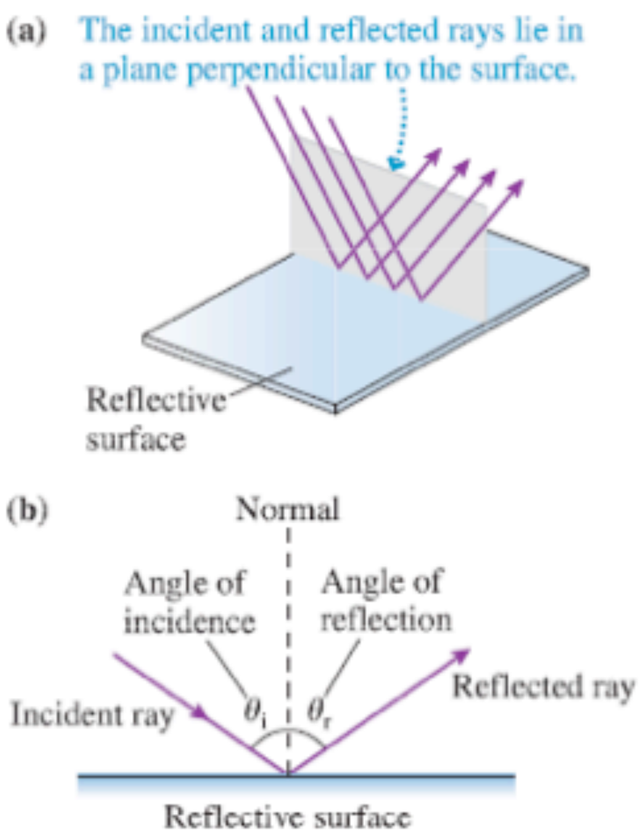
(a) (b) (c) (d)

A long, thin light bulb illuminates a vertical aperture. Which pattern of light do you see on a viewing screen behind the aperture?



Law of reflection (specular)

FIGURE 23.7 Specular reflection of light.

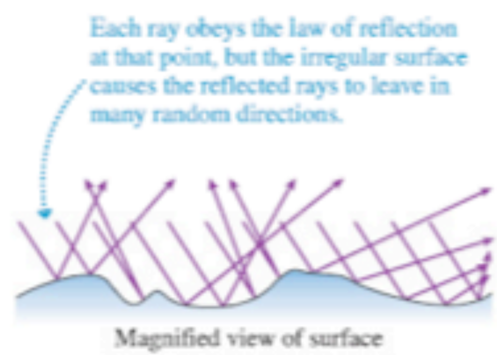


Specular reflection (object smooth and flat over an area large compared to wavelength)

For large flat mirror:
Angle of incidence = angle of reflection

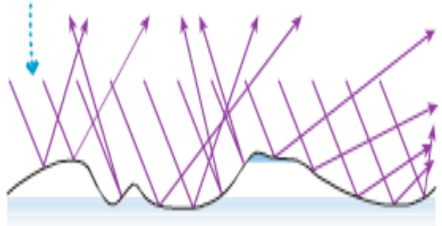
Diffusive reflection (object not smooth, but locally obeys the law of reflection)

FIGURE 23.9 Diffuse reflection from an irregular surface.



Diffuse Reflection

FIGURE 23.9 Diffuse reflection from an irregular surface.

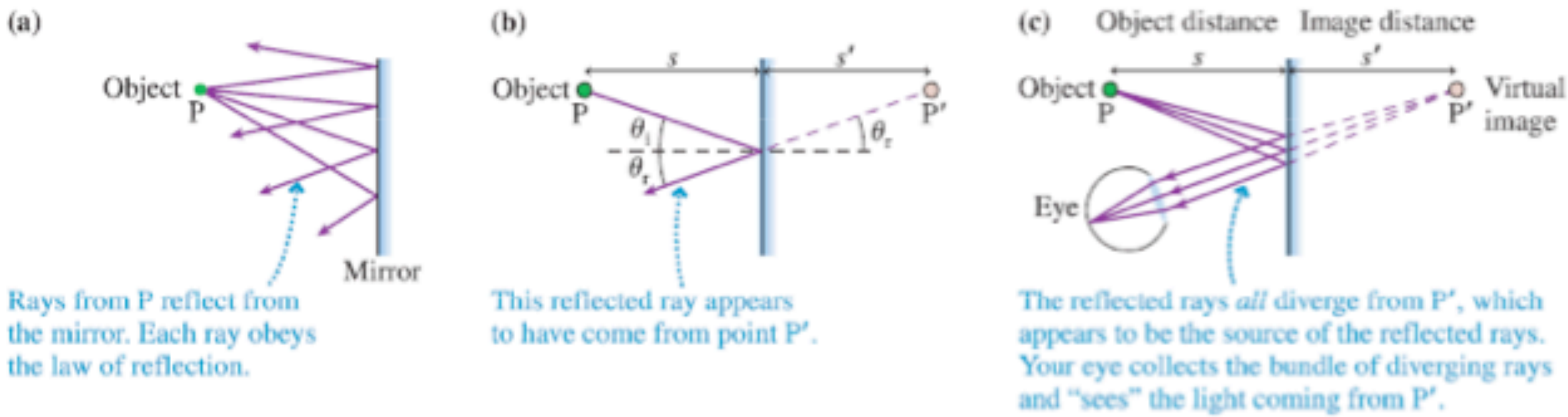


Most objects are seen by virtue of their reflected light. For a "rough" surface, the law of reflection $\theta_r = \theta_i$ is obeyed at each point but the irregularities of the surface cause the reflected rays to leave in many random directions. This situation, shown in FIGURE 23.9, is called **diffuse reflection.** It is how you see this page, the wall, your hand, your friend, and so on. Diffuse reflection is far more prevalent than the mirror-like specular reflection.

By a "rough" surface, we mean a surface that is rough or irregular in comparison to the wavelength of light. Because visible-light wavelengths are $\approx 0.5\ \mu m$, any surface with texture, scratches, or other irregularities larger than $1\ \mu m$ will cause diffuse reflection rather than specular reflection. A piece of paper may feel quite smooth to your hand, but a microscope would show that the surface consists of distinct fibers much larger than $1\ \mu m$. By contrast, the irregularities on a mirror or a piece of polished metal are much smaller than $1\ \mu m$. The law of reflection is equally valid for both specular and diffuse reflection, but the nature of the surface causes the outcomes to be quite different.

Law of reflection

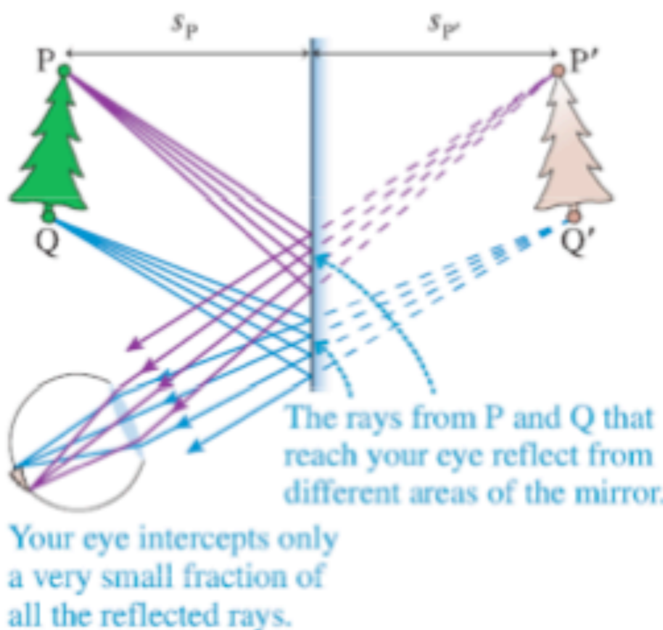
FIGURE 23.10 The light rays reflecting from a plane mirror.



$$s' = s \qquad \text{(plane mirror)}$$

Law of reflection

FIGURE 23.11 Each point on the extended object has a corresponding image point an equal distance on the opposite side of the mirror.



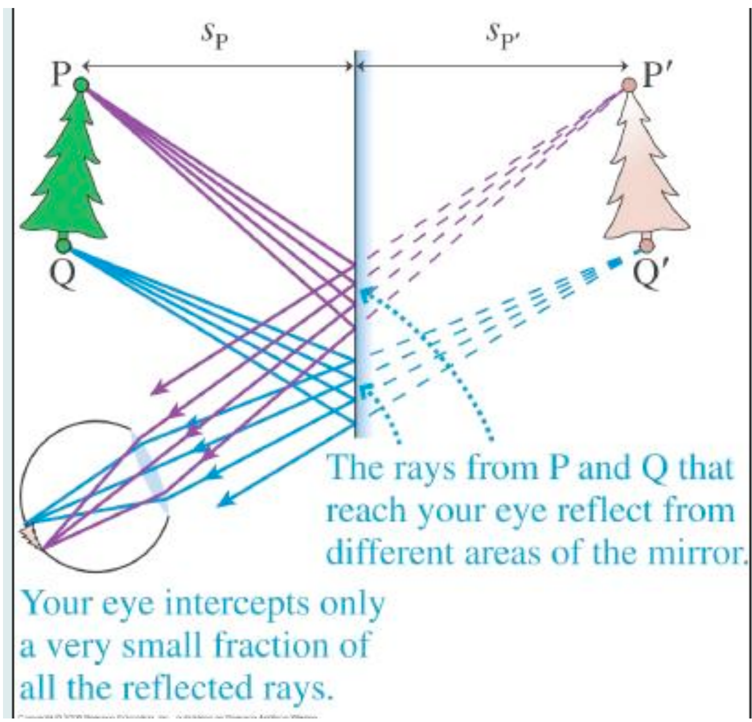
Virtual image – light rays do not physically pass through image.

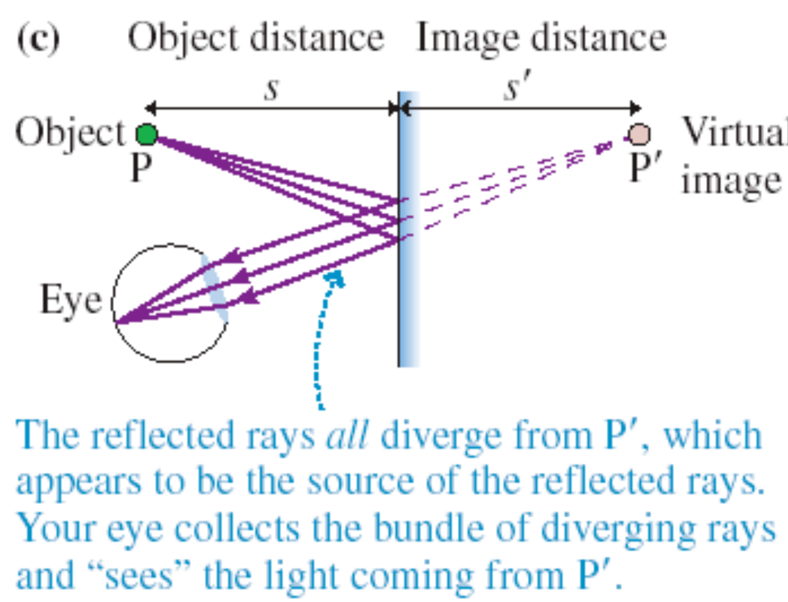
Eye perceives the rays diverging from the image location

1. Rays from each point on the object spread out in all directions and strike *every point* on the mirror. Only a very few of these rays enter your eye, but the other rays are very real and might be seen by other observers.
2. Rays from points P and Q enter your eye after reflecting from *different* areas of the mirror. This is why you can't always see the full image of an object in a very small mirror.

Virtual Image

Consider P, a source of rays which reflect from a mirror. The reflected rays appear to emanate from P', the same distance behind the mirror as P is in front of the mirror. That is, $s' = s$. All rays DIVERGE from the virtual image





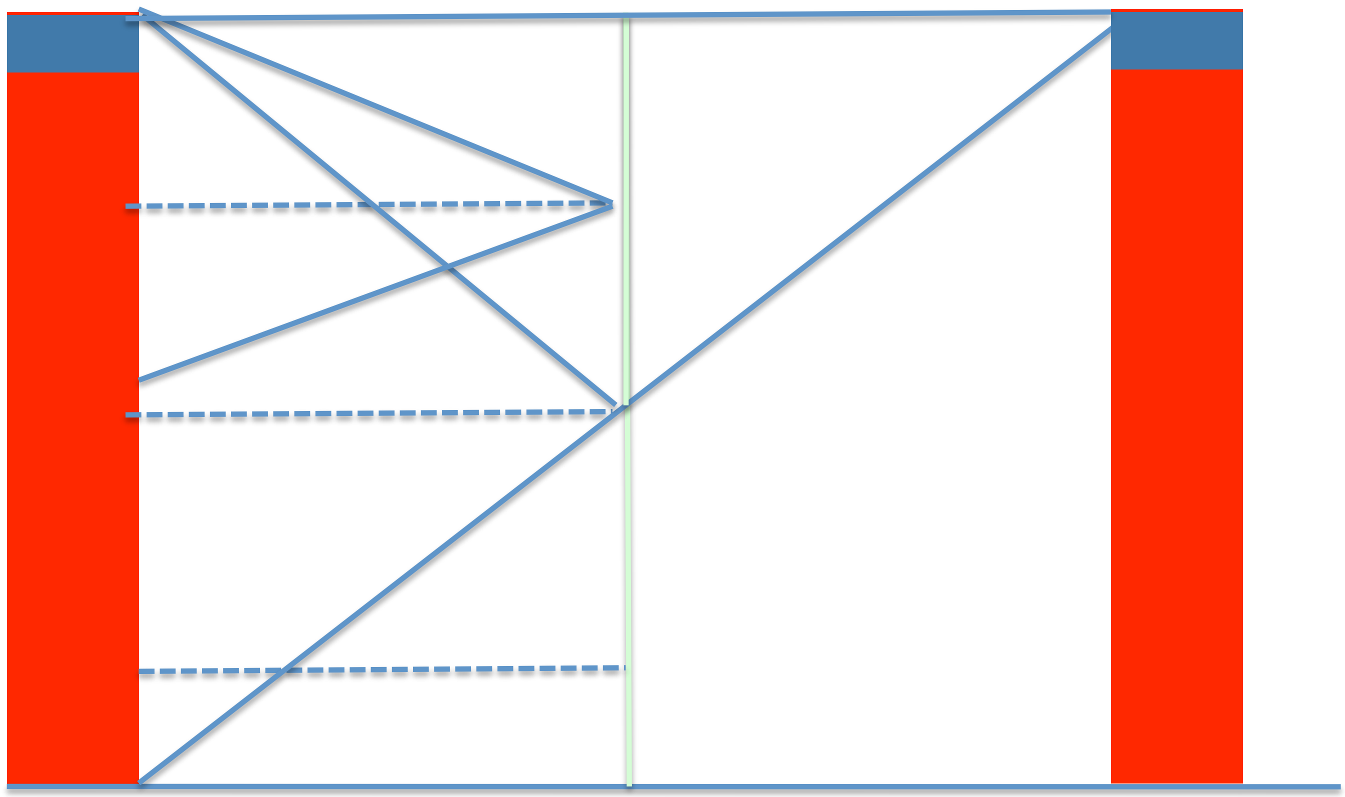
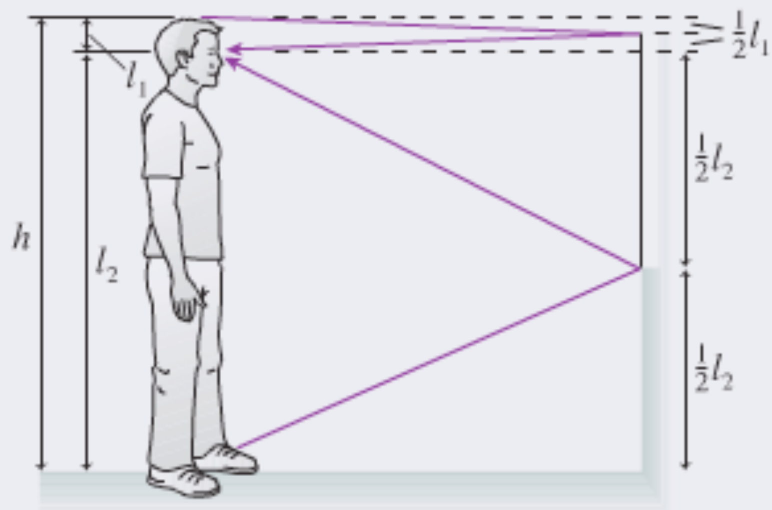
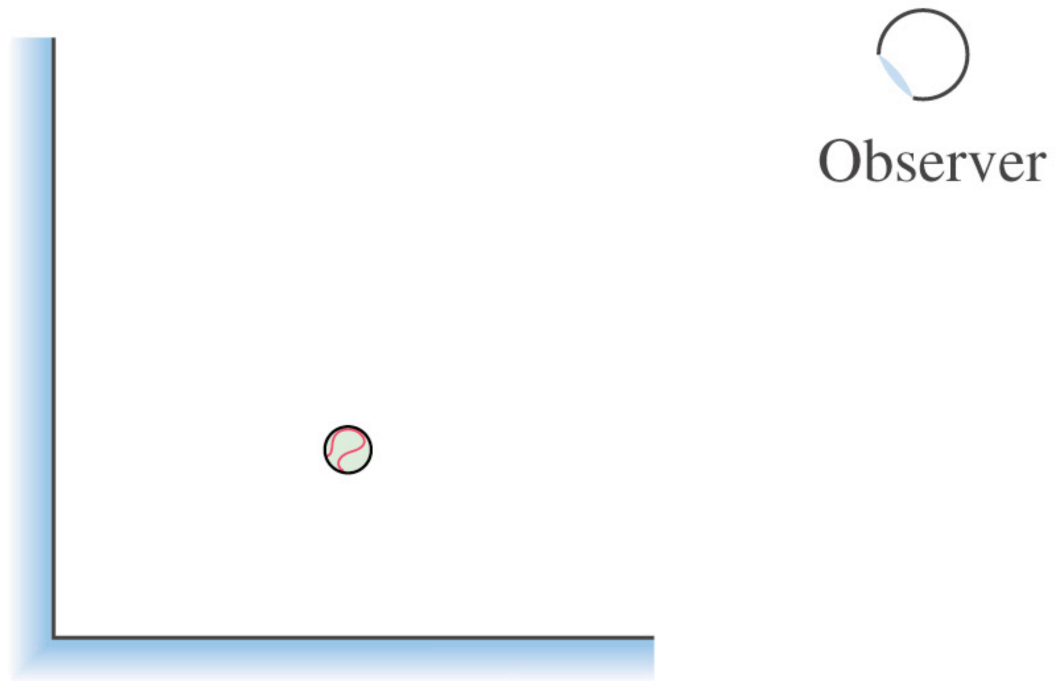


FIGURE 23.12 Pictorial representation of light rays from your head and feet reflecting into your eye.



Two plane mirrors form a right angle. How many images of the ball can you see in the mirrors?

A. 1
B. 2
C. 3
D. 4



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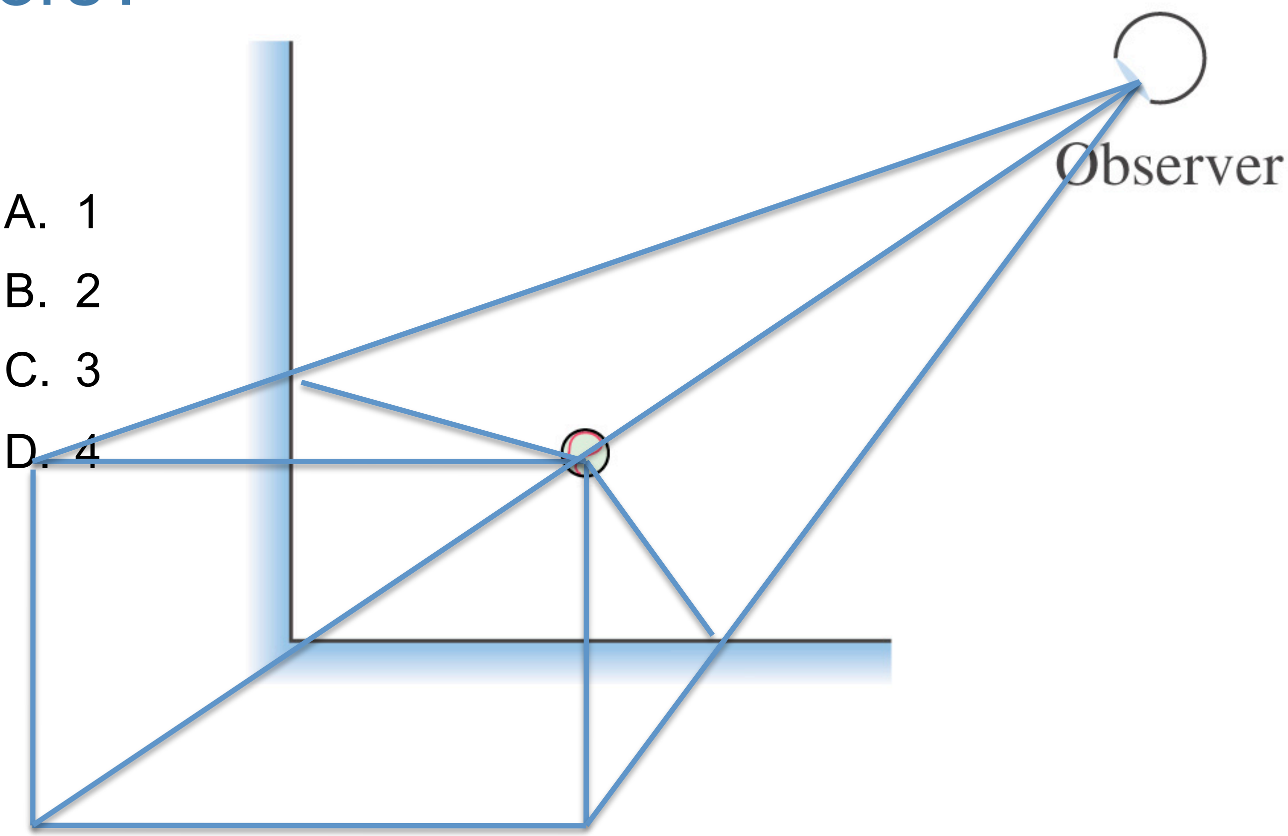
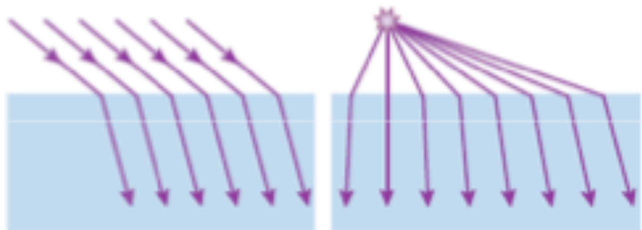
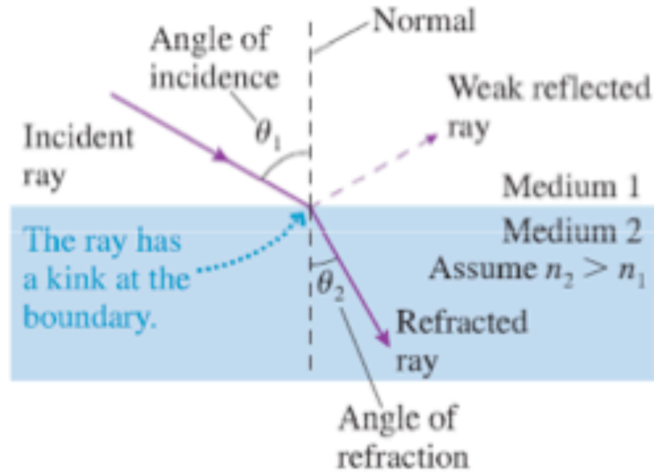


A. 1
B. 2
C. 3
D. 4

Refraction



Refraction of a parallel beam of light and of rays from a point source



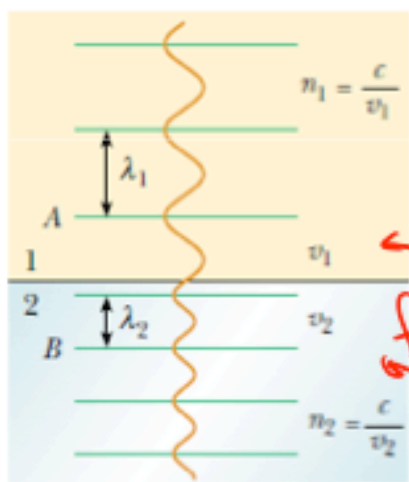


Figure 35.14 As a wave moves from medium 1 to medium 2, its wavelength changes but its frequency remains constant.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \text{(Snell's law of refraction)}$$

$$n = \frac{c}{v_{\text{medium}}}$$

$$v_{\text{medium}} = c/n$$

f the same (Recall Fresnel Coef. "t")

$\lambda f = v = \frac{c}{n}$ + $\lambda_0 f = c \Rightarrow \lambda = \frac{\lambda_0}{n}$

FIGURE 23.15 Refraction of light rays.

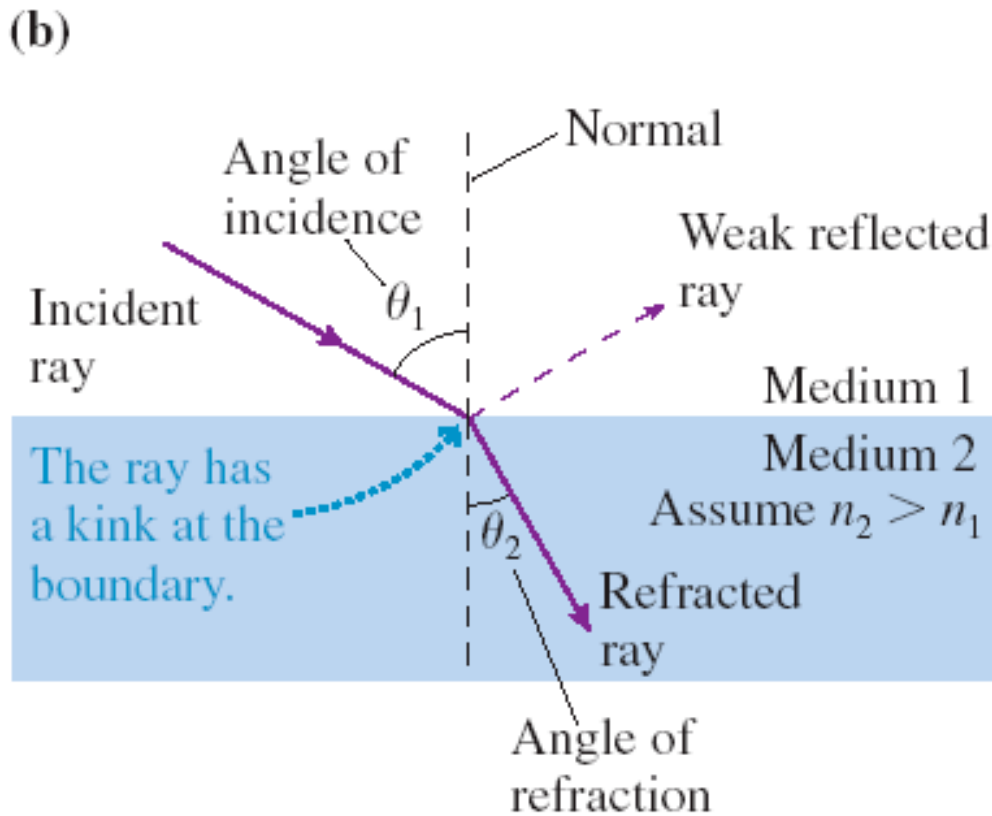
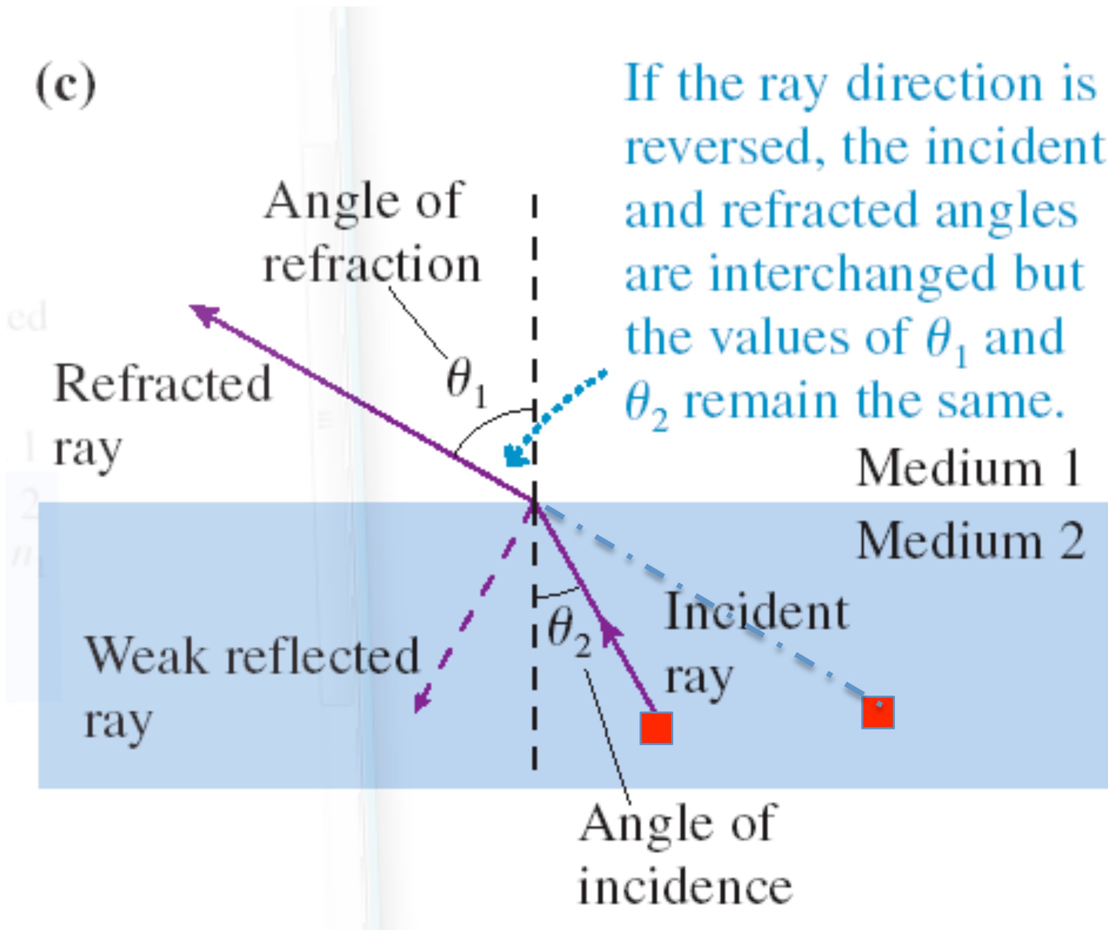


FIGURE 23.15 Refraction of light rays.



Refraction

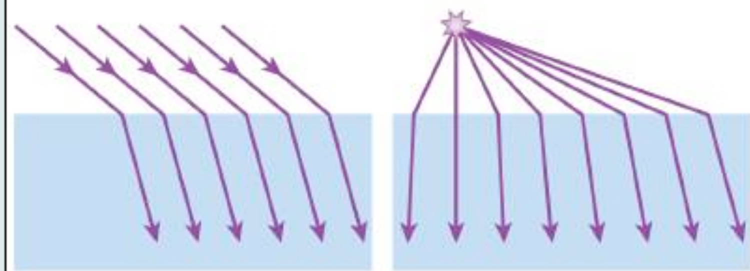
Snell's law states that if a ray refracts between medium 1 and medium 2, having indices of refraction n_1 an n_2, the ray angles θ_1 and θ_2 in the two media are related by

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \text{(Snell's law of refraction)}$$

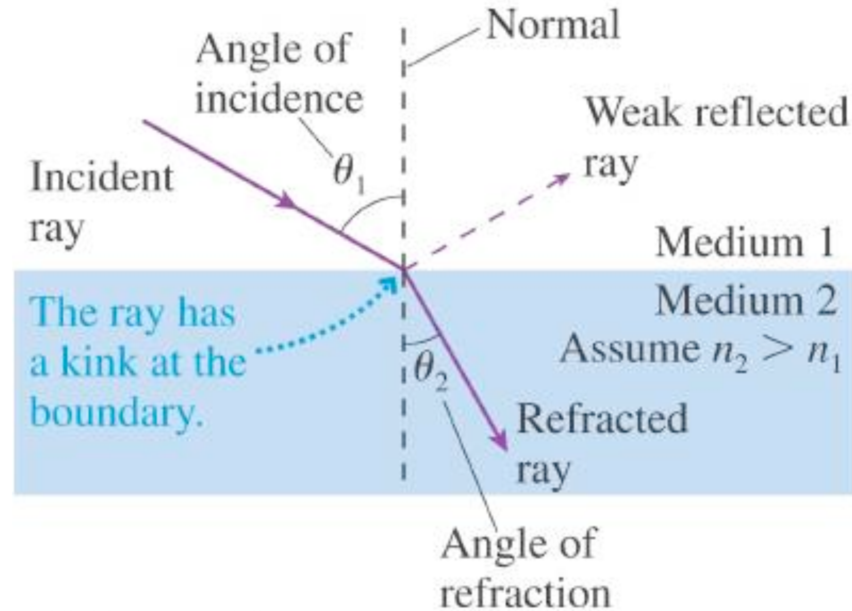
Notice that Snell's law does not mention which is the incident angle and which is the refracted angle.

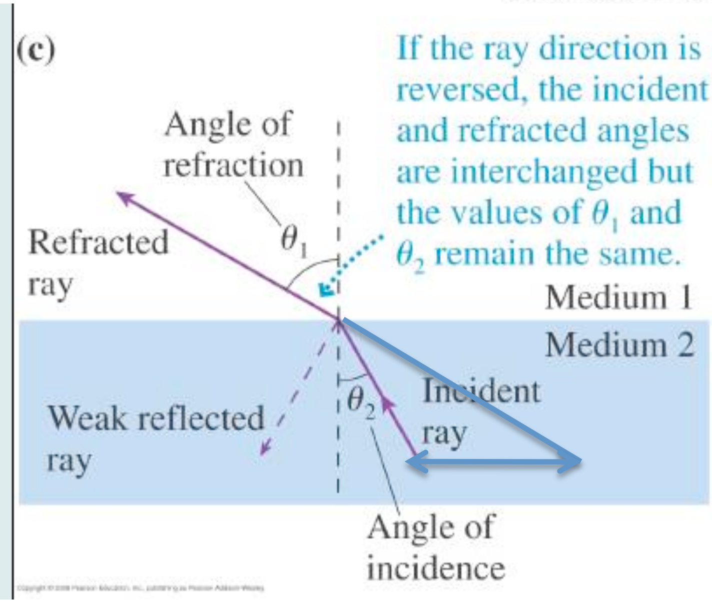
TABLE 23.1 Indices of refraction

Medium	*n*
Vacuum	1.00 exactly
Air (actual)	1.0003
Air (accepted)	1.00
Water	1.33
Ethyl alcohol	1.36
Oil	1.46
Glass (typical)	1.50
Polystyrene plastic	1.59
Cubic zirconia	2.18
Diamond	2.41
Silicon (infrared)	3.50



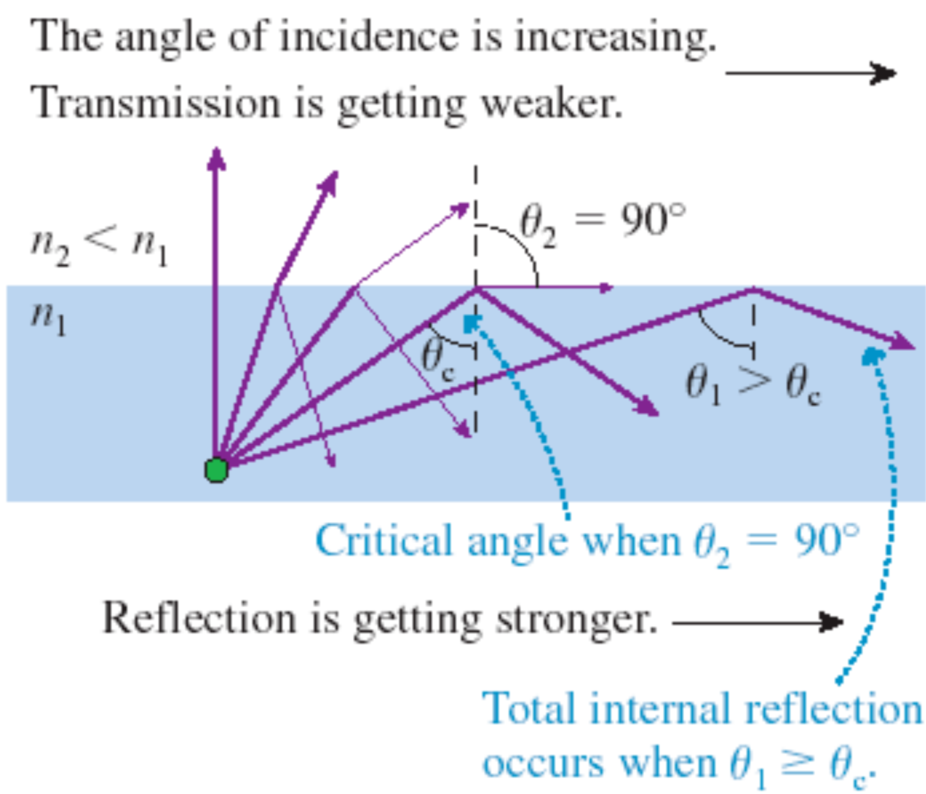
Refraction of a parallel beam of light and of rays from a point source





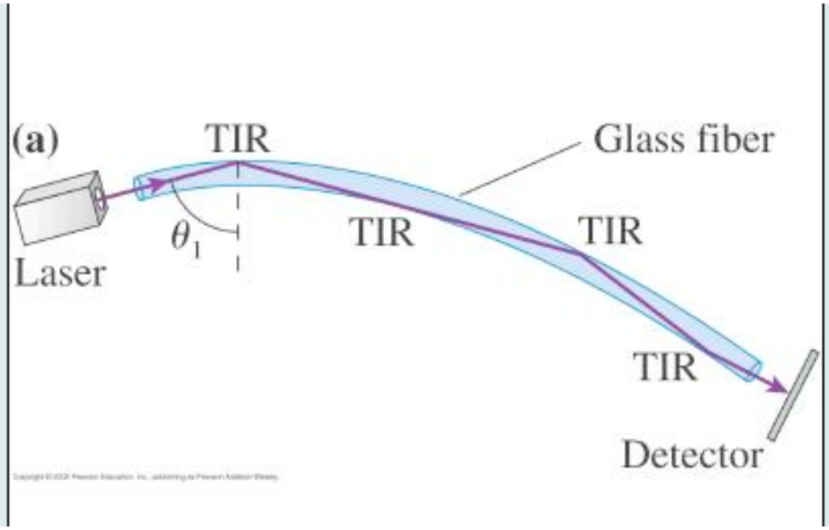
Total Internal Reflection

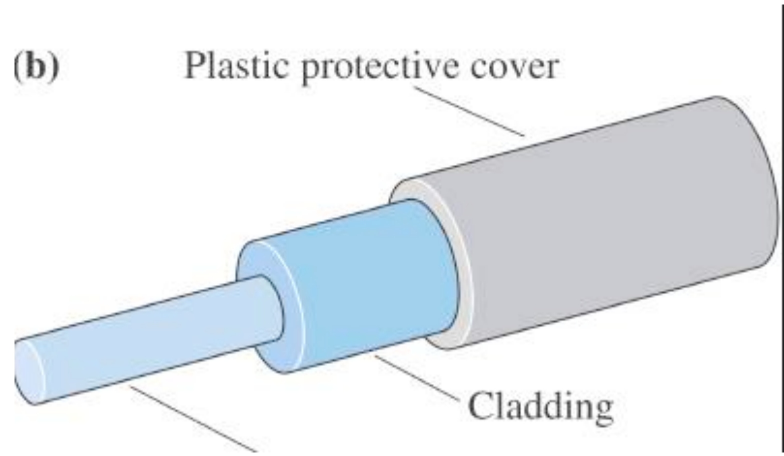
FIGURE 23.22 Refraction and reflection of rays as the angle of incidence increases.



$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \text{(Snell's law of refraction)}$$


(a)
TIR
Glass fiber
θ_1
Laser
TIR
TIR
TIR
Detector


(b)
Plastic protective cover
Cladding

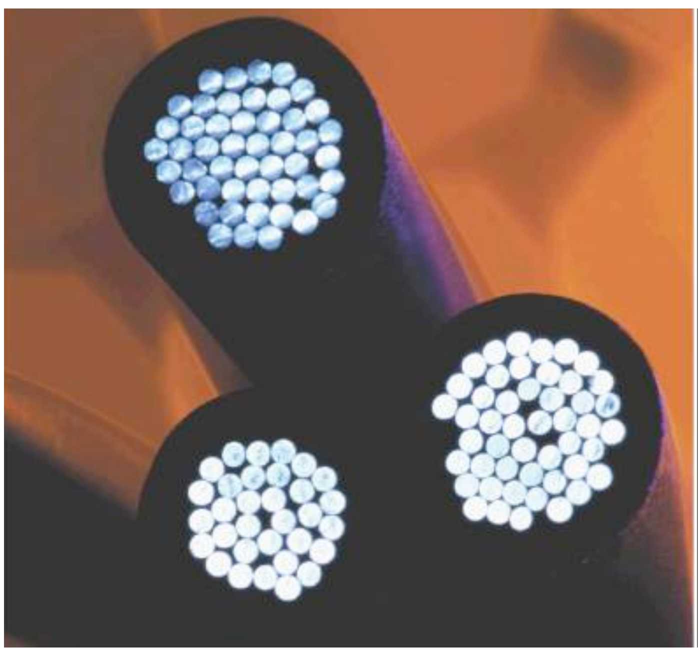
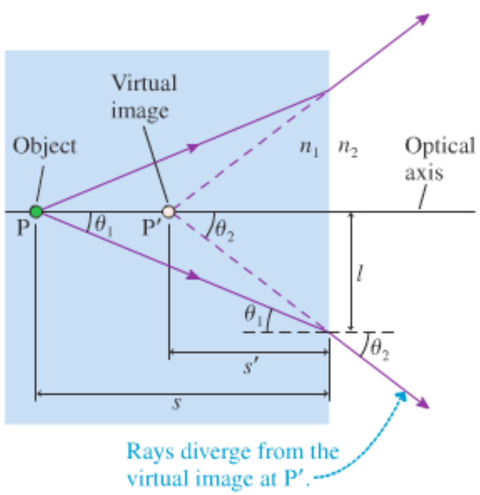


Image by Refraction

FIGURE 23.27 Finding the virtual image P′ of an object at P. We've assumed $n_1 > n_2$.

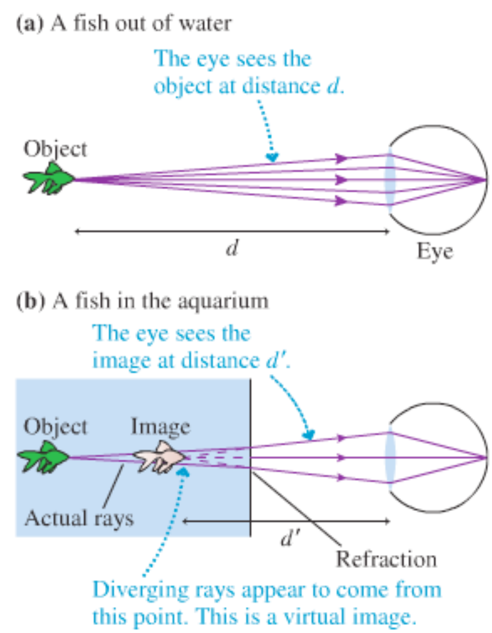


$$l = s\tan\theta_1 = s'\tan\theta_2$$

$$s' = \frac{\tan\theta_1}{\tan\theta_2}s \approx \frac{\sin\theta_1}{\sin\theta_2}s = \frac{\eta_2}{\eta_1}s$$

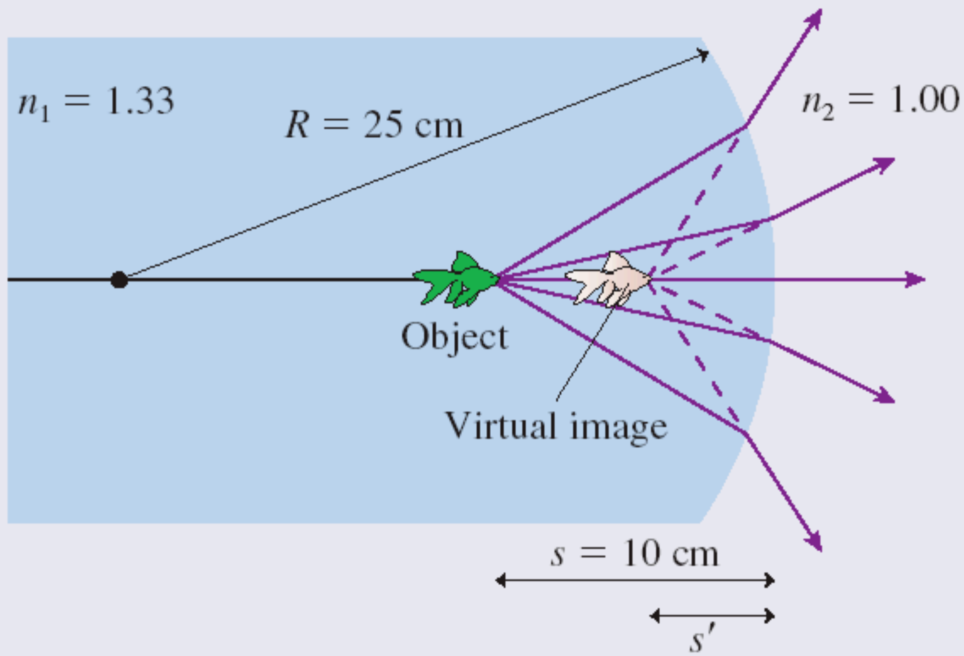
$$for\,\theta_1, \theta_2 << 1$$

FIGURE 23.26 Refraction of the light rays causes a fish in the aquarium to be seen at distance d'.

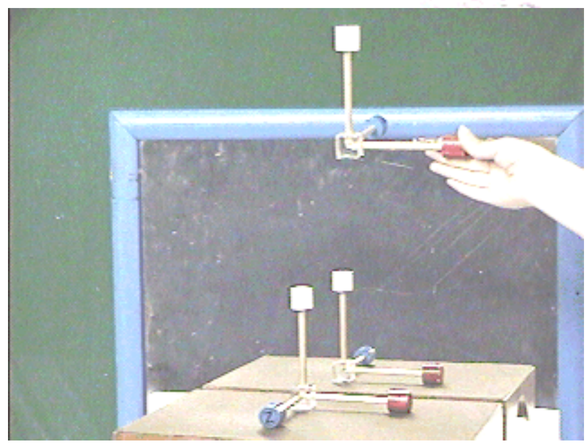


EXAMPLE 23.13 A goldfish in a bowl

FIGURE 23.46 The curved surface of a fish bowl produces a virtual image of the fish.



Does Mirror Reverses Left and Right?



Color

Different colors are associated with light of different wavelengths. The longest wavelengths are perceived as red light and the shortest as violet light. Table 23.2 is a brief summary of the *visible spectrum* of light.

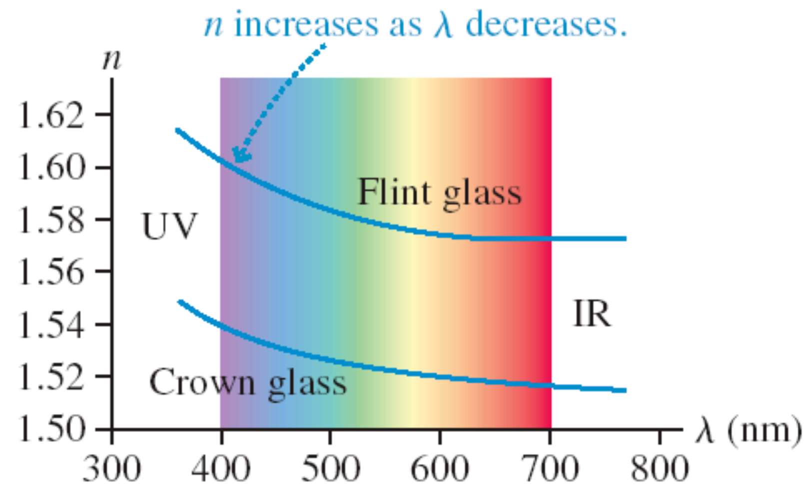
TABLE 23.2 A brief summary of the visible spectrum of light

Color	Approximate wavelength
Deepest red	700 nm
Red	650 nm
Green	550 nm
Blue	450 nm
Deepest violet	400 nm

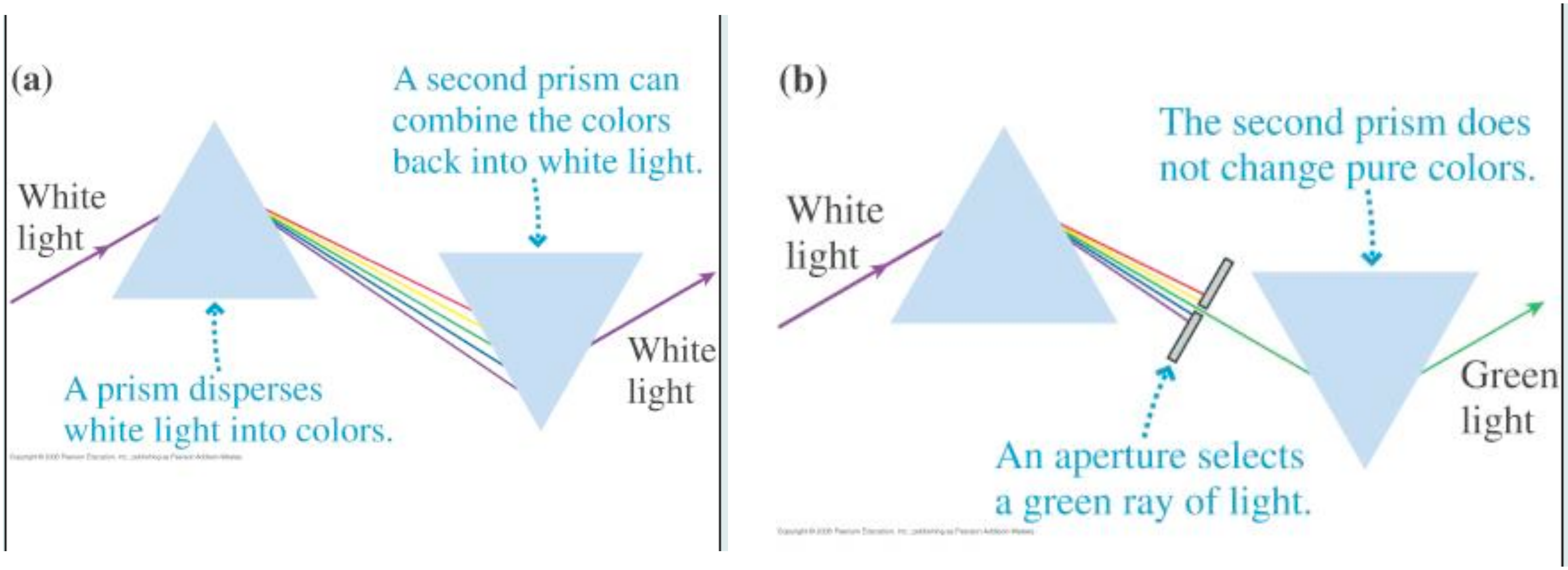
Dispersion

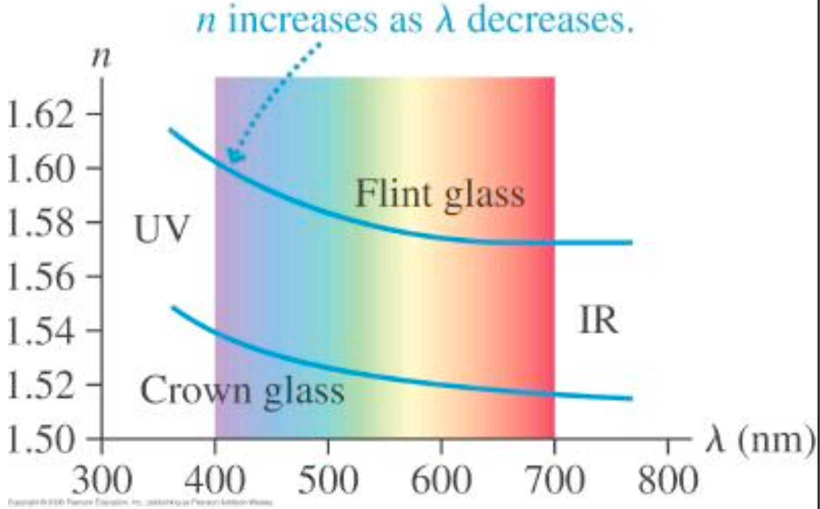
The slight variation of index of refraction with wavelength is known as dispersion. Shown is the dispersion curves of two common glasses. Notice that *n* is larger when the wavelength is shorter, thus violet light refracts more than red light.

FIGURE 23.29 Dispersion curves show how the index of refraction varies with wavelength.



1





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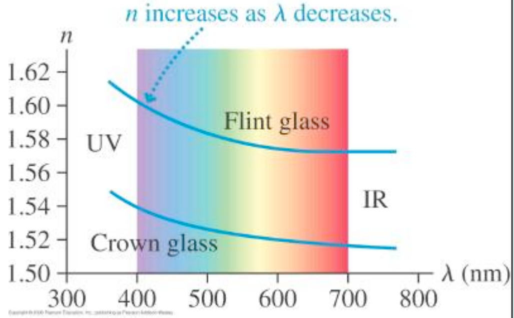
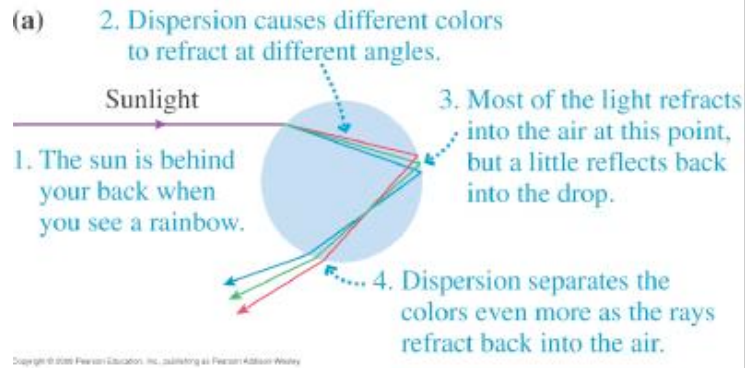
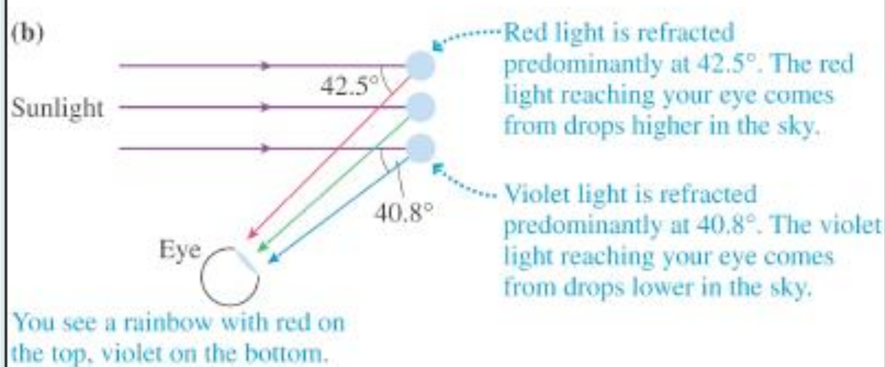
RAINBOW



n increases as λ decreases.
n
1.62
1.60
1.58
1.56
1.54
1.52
1.50
UV
Flint glass
IR
Crown glass
300
400
500
600
700
800
λ (nm)

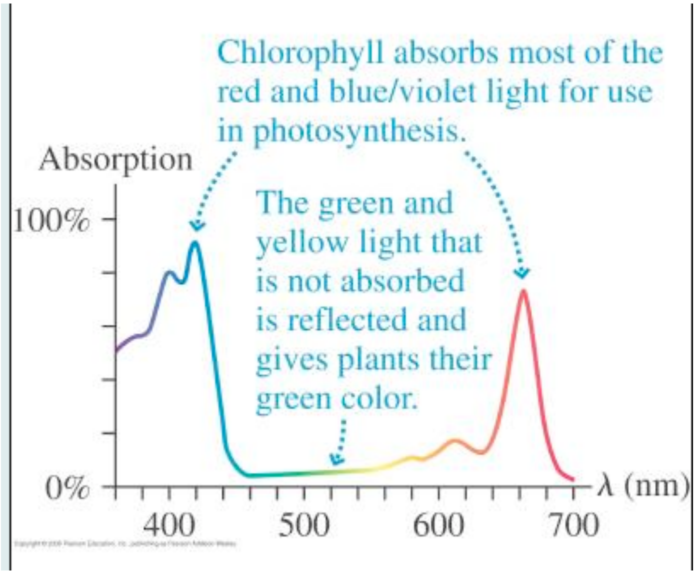


(a)
2. Dispersion causes different colors to refract at different angles.
Sunlight
3. Most of the light refracts into the air at this point, but a little reflects back into the drop.
1. The sun is behind your back when you see a rainbow.
4. Dispersion separates the colors even more as the rays refract back into the air.

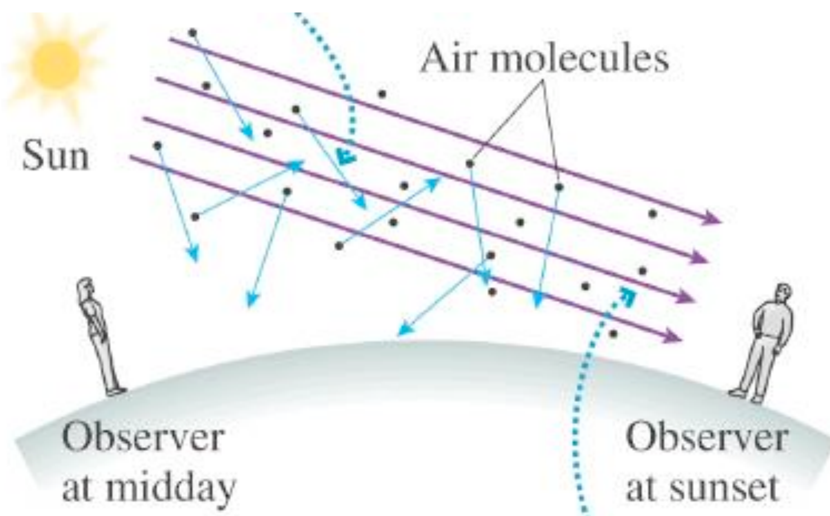


(b)
Sunlight
42.5°
40.8°
Eye
Red light is refracted predominantly at 42.5°. The red light reaching your eye comes from drops higher in the sky.
Violet light is refracted predominantly at 40.8°. The violet light reaching your eye comes from drops lower in the sky.
You see a rainbow with red on the top, violet on the bottom.

Why are plants green?

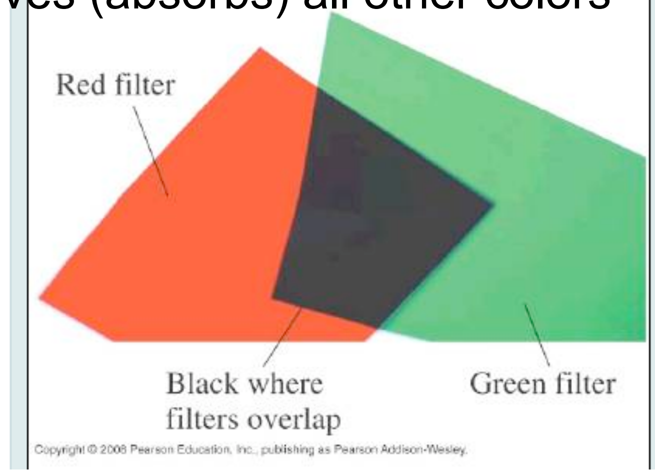


Why are sunsets red –Why is the sky blue



$I_{sc} \sim (1/\lambda)^4$
Raleigh scattering
Blue scatters 16 times more than red

Green glass green because it removes (absorbs) all other colors



What is a lens?

Device that provides a capability to create bright and well focused images. How?

Use Refraction to create images out of divergent light rays

- Focal point
- Focal length
  - Property of lens no matter how it is used
  - Distance from lens that paraxial rays converge
  - Reversibility