$w = 2L \frac{\lambda}{a}$
Most common situation, e.g. loudspeakers – diaphragm and exit cone

**Figure 22.15** The diffraction of light by a circular opening.

\[
\theta_1 = \frac{1.22\lambda}{D} \quad \text{Radians}
\]

\[
w = 2y_1 = 2L \tan \theta_1 \approx \frac{2.44\lambda L}{D}
\]
Radians

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.

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

$$
w = 2y_1 = 2L \tan \theta_1 \approx \frac{2.44\lambda L}{D}
$$
Wave vs. Ray Model

\[ \theta = \sin^{-1}\left(\frac{\lambda}{a}\right) \]

2.44 \( \frac{\lambda L}{D} = D \)

\( D_c = \sqrt{2.44 \lambda L} \)

\( a < D_c \) 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

A beam of light

Direction of travel

Light rays

The sun is a self-luminous object.

Emitted light

The camera “sees” light rays reflected by the tree but not the rays from the sun.

Reflected light

The tree is a reflective object.

Point source

Parallel bundle

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 \( v = \frac{c}{n} \), 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.
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. ◀
Aperture - A hole through which light is transmitted or collected.

Point projection

$\frac{h_i}{h_o} = \frac{d_i}{d_o}$
A long, thin light bulb illuminates a vertical aperture. Which pattern of light do you see on a viewing screen behind the aperture?

![Diagram](image)

(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)

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)
Diffuse Reflection

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.

(a) Rays from $P$ reflect from the mirror. Each ray obeys the law of reflection.

(b) This reflected ray appears to have come from point $P'$.\[ s' = s \quad \text{(plane mirror)} \]
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
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
Refraction

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

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]  
(Snell’s law of refraction)

\[ n = \frac{c}{v_{\text{medium}}} \]

\[ v_{\text{medium}} = \frac{c}{n} \]

\[ \lambda_f = v = \frac{c}{n} \]

\[ \lambda_f = c \Rightarrow \lambda = \frac{\lambda_0}{n} \]
FIGURE 23.15 Refraction of light rays.

(b)

The ray has a kink at the boundary.

Angle of incidence $\theta_1$

Normal

Weak reflected ray

Medium 1

Assume $n_2 > n_1$

Medium 2

Reflected ray

Angle of refraction $\theta_2$
FIGURE 23.15  Refraction of light rays.

If the ray direction is reversed, the incident and refracted angles are interchanged but the values of $\theta_1$ and $\theta_2$ remain the same.
Refraction

Snell’s law states that if a ray refracts between medium 1 and medium 2, having indices of refraction $n_1$ and $n_2$, the ray angles $\theta_1$ and $\theta_2$ in the two media are related by

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

Notice that Snell’s law does not mention which is the incident angle and which is the refracted angle.
<table>
<thead>
<tr>
<th>Medium</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>1.00 exactly</td>
</tr>
<tr>
<td>Air (actual)</td>
<td>1.0003</td>
</tr>
<tr>
<td>Air (accepted)</td>
<td>1.00</td>
</tr>
<tr>
<td>Water</td>
<td>1.33</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>1.36</td>
</tr>
<tr>
<td>Oil</td>
<td>1.46</td>
</tr>
<tr>
<td>Glass (typical)</td>
<td>1.50</td>
</tr>
<tr>
<td>Polystyrene plastic</td>
<td>1.59</td>
</tr>
<tr>
<td>Cubic zirconia</td>
<td>2.18</td>
</tr>
<tr>
<td>Diamond</td>
<td>2.41</td>
</tr>
<tr>
<td>Silicon (infrared)</td>
<td>3.50</td>
</tr>
</tbody>
</table>
Refraction of a parallel beam of light and of rays from a point source.

The ray has a kink at the boundary.

If the ray direction is reversed, the incident and refracted angles are interchanged but the values of $\theta_1$ and $\theta_2$ remain the same.
Total Internal Reflection

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

The angle of incidence is increasing.
Transmission is getting weaker.

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

\( n_1 \sin \theta_1 = n_2 \sin \theta_2 \)  \( \text{(Snell’s law of refraction)} \)
Image by Refraction

\[ l = s \tan \theta_1 = s' \tan \theta_2 \]

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

\[ f \text{ or } \theta_1, \theta_2 \ll 1 \]
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.

- $n_1 = 1.33$
- $R = 25 \text{ cm}$
- $n_2 = 1.00$
- $s = 10 \text{ cm}$
- $s'$
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>
<thead>
<tr>
<th>Color</th>
<th>Approximate wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deepest red</td>
<td>700 nm</td>
</tr>
<tr>
<td>Red</td>
<td>650 nm</td>
</tr>
<tr>
<td>Green</td>
<td>550 nm</td>
</tr>
<tr>
<td>Blue</td>
<td>450 nm</td>
</tr>
<tr>
<td>Deepest violet</td>
<td>400 nm</td>
</tr>
</tbody>
</table>
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.
A prism disperses white light into colors.

A second prism can combine the colors back into white light.

The second prism does not change pure colors.

An aperture selects a green ray of light.

\[ n \text{ increases as } \lambda \text{ decreases.} \]

<table>
<thead>
<tr>
<th>Color</th>
<th>Approximate wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deepest red</td>
<td>700 nm</td>
</tr>
<tr>
<td>Red</td>
<td>650 nm</td>
</tr>
<tr>
<td>Green</td>
<td>550 nm</td>
</tr>
<tr>
<td>Blue</td>
<td>450 nm</td>
</tr>
<tr>
<td>Deepest violet</td>
<td>400 nm</td>
</tr>
</tbody>
</table>
RAINBOW

2. Dispersion causes different colors to refract at different angles.

3. Most of the light refracts into the air at this point, but a little reflects back into the drop.

4. Dispersion separates the colors even more as the rays refract back into the air.

You see a rainbow with red on the top, violet on the bottom.

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.
Why are plants green?

Chlorophyll absorbs most of the red and blue/violet light for use in photosynthesis. The green and yellow light that is not absorbed is reflected and gives plants their green color.

Why are sunsets red – Why is the sky blue

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

\[ I_{sc} \sim (1/\lambda)^4 \]

Raleigh scattering
Blue scatters 16 times more than red
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