Lecture PowerPoints

Chapter 23

Physics: Principles with Applications, 7th edition

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23-1 The Ray Model of Light

Light very often travels in straight lines. We represent light using rays, which are straight lines emanating from an object. This is an idealization, but is very useful for geometric optics.
23-2 Reflection; Image Formation by a Plane Mirror

Law of reflection: the angle of reflection (that the ray makes with the normal to a surface) equals the angle of incidence.
When light reflects from a rough surface, the law of reflection still holds, but the angle of incidence varies. This is called diffuse reflection.
23-2 Reflection; Image Formation by a Plane Mirror

With diffuse reflection, your eye sees reflected light at all angles. With specular reflection (from a mirror), your eye must be in the correct position.
What you see when you look into a plane (flat) mirror is an image, which appears to be behind the mirror.
This is called a virtual image, as the light does not go through it. The distance of the image from the mirror is equal to the distance of the object from the mirror.

Question:
A lighted candle is placed a short distance from a plane mirror, as shown in the figure. At which location will the image of the flame appear to be located?
Examples

Two plane mirrors make an angle of 30° with each other. A light ray enters the system and is reflected once off of each mirror. Through what angle is the ray turned?

• **Answer:** 60°

• A person jogs toward a plane mirror at a speed of 3 m/s. How fast is he approaching his image in the mirror?

• **Answer:** 6 m/s
Spherical mirrors are shaped like sections of a sphere, and may be reflective on either the inside (concave) or outside (convex).
Rays coming from a faraway object are effectively parallel.
Parallel rays striking a spherical mirror do not all converge at exactly the same place if the curvature of the mirror is large; this is called spherical aberration.
If the curvature is small, the focus is much more precise; the focal point is where the rays converge.
23-3 Formation of Images by Spherical Mirrors

Using geometry, we find that the focal length is half the radius of curvature:

\[ f = \frac{r}{2}. \quad (23-1) \]

Spherical aberration can be avoided by using a parabolic reflector; these are more difficult and expensive to make, and so are used only when necessary, such as in research telescopes.

Question: The focal length of a concave mirror has a magnitude of 20 cm. What is its radius of curvature?

- A) 10 cm
- B) 40 cm
- C) 20 cm
23-3 Formation of Images by Spherical Mirrors

We use ray diagrams to determine where an image will be. For mirrors, we use three key rays, all of which begin on the object:

1. A ray parallel to the axis; after reflection it passes through the focal point
2. A ray through the focal point; after reflection it is parallel to the axis
3. A ray perpendicular to the mirror; it reflects back on itself
23-3 Formation of Images by Spherical Mirrors

(a) Ray 1 goes out from O' parallel to the axis and reflects through F.

(b) Ray 2 goes through F and then reflects back parallel to the axis.

(c) Ray 3 is perpendicular to mirror, and so must reflect back on itself and go through C (center of curvature).
The intersection of these three rays gives the position of the image of that point on the object. To get a full image, we can do the same with other points (two points suffice for many purposes).
Geometrically, we can derive an equation that relates the object distance, image distance, and focal length of the mirror:

\[
\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}.
\]  

(23-2)
We can also find the magnification (ratio of image height to object height).

\[ m = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \quad (23-3) \]

The negative sign indicates that the image is inverted. This object is between the center of curvature and the focal point, and its image is larger, inverted, and real.
If an object is inside the focal point, its image will be upright, larger, and virtual.
23-3 Formation of Images by Spherical Mirrors

If an object is outside the center of curvature of a concave mirror, its image will be inverted, smaller, and real.
For a convex mirror, the image is always virtual, upright, and smaller.
Problem Solving: Spherical Mirrors

1. Draw a ray diagram; the image is where the rays intersect.

2. Apply the mirror and magnification equations.

3. Sign conventions: if the object, image, or focal point is on the reflective side of the mirror, its distance is positive, and negative otherwise. Magnification is positive if image is upright, negative otherwise.

4. Check that your solution agrees with the ray diagram.
Example

A stature that is 3.0 cm tall is positioned 24 cm in front of a concave mirror. The magnitude of the radius of curvature of the mirror is 20 cm.
(a) Is the image real or virtual?
(b) How far is the image from the mirror?
(c) Is the image upright or inverted?
(d) How tall is the image?

Answer: (a) real     (b) 17 cm     (c) inverted     (d) 2.1 cm

Formulas to use for (b):
\[ f = \frac{r}{2} \cdot \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}. \]

For (d):
\[ m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}. \]
In general, light slows somewhat when traveling through a medium. The index of refraction of the medium is the ratio of the speed of light in vacuum to the speed of light in the medium:

\[ n = \frac{c}{v} \]  \hspace{1cm} \text{(23-4)}

<table>
<thead>
<tr>
<th>Material</th>
<th>[ n = \frac{c}{v} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>1.0000</td>
</tr>
<tr>
<td>Air (at STP)</td>
<td>1.0003</td>
</tr>
<tr>
<td>Water</td>
<td>1.33</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>1.36</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
</tr>
<tr>
<td>Fused quartz</td>
<td>1.46</td>
</tr>
<tr>
<td>Crown glass</td>
<td>1.52</td>
</tr>
<tr>
<td>Light flint</td>
<td>1.58</td>
</tr>
<tr>
<td>Plastic</td>
<td></td>
</tr>
<tr>
<td>Acrylic, Lucite, CR-39</td>
<td>1.50</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>1.59</td>
</tr>
<tr>
<td>“High-index”</td>
<td>1.6–1.7</td>
</tr>
<tr>
<td>Sodium chloride</td>
<td>1.53</td>
</tr>
<tr>
<td>Diamond</td>
<td>2.42</td>
</tr>
</tbody>
</table>

\[ \lambda = 589 \text{ nm} \]
Light changes direction when crossing a boundary from one medium to another. This is called refraction, and the angle the outgoing ray makes with the normal is called the angle of refraction.
23-5 Refraction: Snell’s Law

Refraction is what makes objects half-submerged in water look odd.

(a) (b) Foot appears to be here
23-5 Refraction: Snell’s Law

The angle of refraction depends on the indices of refraction, and is given by Snell’s law:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2. \]  (23-5)
Example

A ray of light (ray \( a \)) in air strikes a flat piece of glass at an angle of \( \phi_0 = 84^\circ \) with respect to the normal, as shown in the figure. The index of refraction of the glass is 1.5. What is the angle \( \theta \) between the reflected ray (ray \( b \)) and refracted ray (ray \( c \)) rays?

Answer: 54°.

Strategy: First, find the angle of refraction:

\[
n_1 \sin \phi_0 = n_2 \sin \phi \quad \Rightarrow \quad \sin \phi = \frac{n_1}{n_2} \sin \phi_0
\]

\( \phi = 41^\circ \)

\[
\theta = \left( \frac{\pi}{2} - \phi_0 \right) + \left( \frac{\pi}{2} - \phi \right) = 54^\circ
\]
Example

• Light is incident on an equilateral glass prism at a 45° angle to one face. Calculate the angle at which light emerges from the opposite face. Assume that \( n = 1.54 \).

• Solution:
  
  – Find the angle \( \theta_2 \) for the refraction at the first surface.
    
    \[
    n_{\text{air}} \sin \theta_1 = n \sin \theta_2 \implies 1 \cdot \sin 45^\circ = 1.54 \cdot \sin \theta_2
    \]
    
    \( \theta_2 = 27.33^\circ \)

  – Consider the triangle ABC, and find the angle of incidence at the second surface from the triangle formed by the two sides of the prism and the light path.
    
    \[
    (90^\circ - \theta_2) + (90^\circ - \theta_3) + A = 180^\circ \implies \theta_3 = A - \theta_2 = 60^\circ - 27.33^\circ = 32.67^\circ
    \]

  – Use refraction at the second surface to find \( \theta_4 \):
    
    \[
    n \sin \theta_3 = n_{\text{air}} \sin \theta_4 \implies 1.54 \cdot \sin 32.67^\circ = 1 \cdot \sin \theta_4
    \]
    
    \( \theta_4 = 56.2^\circ \)
23-6 Total Internal Reflection; Fiber Optics

If light passes into a medium with a smaller index of refraction, the angle of refraction is larger. There is an angle of incidence for which the angle of refraction will be 90°; this is called the critical angle:

\[
\sin \theta_C = \frac{n_2}{n_1} \sin 90° = \frac{n_2}{n_1}. \quad (23-6)
\]
If the angle of incidence is larger than this, no transmission occurs. This is called total internal reflection.
23-6 Total Internal Reflection; Fiber Optics

Binoculars often use total internal reflection; this gives true 100% reflection, which even the best mirror cannot do.

For glass, $n=1.5$, $\theta_c=41.8^\circ$. Therefore $45^\circ$ prism will reflect all light internally:
Total internal reflection is also the principle behind fiber optics. Light will be transmitted along the fiber even if it is not straight. An image can be formed using multiple small fibers. Applications: Fiber-optic cables in communications and medicine. They can support over 100 separate wavelengths, each modulated to carry more than 10 gigabits of information per second.
Example

• Light enters a substance from air at 30.0° to the normal. It continues within the substance at 23.0° to the normal. What is the critical angle for this substance when it is surrounded by air?
• Answer: 51.4°
• Solution: Use formula

$$\sin \theta_c = \frac{n_{\text{air}}}{n_{\text{subs.}}}$$

To find the index of refraction of substance, use Snell’s law

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

\[
\frac{n_{\text{subs.}}}{n_{\text{air}}} = \frac{\sin \theta_1}{\sin \theta_2} = \frac{\sin(30\degree)}{\sin(23\degree)} = 1.279
\]

Now, our first medium is this substance, and we need to find a critical angle for a ray that moves from substance to air:

$$\sin \theta_c = \frac{n_{\text{air}}}{n_{\text{subs.}}} = \frac{1}{1.279} \Rightarrow \theta_c = 51.4\degree$$
Thin lenses are those whose thickness is small compared to their radius of curvature. They may be either converging (a) or diverging (b).

Two faces can be concave, convex or plane.

Converging lenses are thicker in the center than at the edges. Diverging lenses are thinner in the center than at the edges.
Lenses are made of glass or transparent plastic with index of refraction greater that of air.

Consider parallel rays that enters the lens. According to Snell’s law, each ray will experience a refraction.

Parallel rays are brought to a focus by a converging lens (one that is thicker in the center than it is at the edge).

Distance from the focal point $F$ to the center of the lens is called the **focal length**, $f$.
23-7 Thin Lenses; Ray Tracing

A diverging lens (thicker at the edge than in the center) make parallel light diverge; the focal point is that point where the diverging rays would converge if projected back.

Parallel rays at an angle are focused on the focal plane.
23-7 Thin Lenses; Ray Tracing

The power of a lens is the inverse of its focal length.

\[ P = \frac{1}{f}. \]  \hspace{1cm} (23-7)

Focal length \( f \) is the same on both sides of the lens.

Lens power is measured in diopters, D.

\[ 1 \text{ D} = 1 \text{ m}^{-1} \]
Ray tracing for thin lenses is similar to that for mirrors. We have three key rays:

1. This ray comes in parallel to the axis and exits through the focal point.
2. This ray comes in through the focal point and exits parallel to the axis.
3. This ray goes through the center of the lens and is undeflected.
23-7 Thin Lenses; Ray Tracing

(a) Ray 1 leaves one point on object going parallel to the axis, then refracts through focal point behind the lens.

(b) Ray 2 passes through $F'$ in front of the lens; therefore it is parallel to the axis behind the lens.

(c) Ray 3 passes straight through the center of the lens (assumed very thin).
For a diverging lens, we can use the same three rays; the image is upright and virtual.
23-8 The Thin Lens Equation

Consider AFB and FII':

\[
\frac{h_i}{h_o} = \frac{d_i - f}{d_o}
\]

Consider OAO’ and IAI’:

\[
\frac{h_i}{h_o} = \frac{d_i}{d_o}
\]

\[
\Rightarrow \quad \frac{1}{f} - \frac{1}{d_o} = \frac{1}{d_i}
\]
23-8 The Thin Lens Equation

The thin lens equation is the same as the mirror equation:

\[
\frac{1}{f} - \frac{1}{d_i} = \frac{1}{d_o}
\]

or

\[
\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}.
\]
The sign conventions are slightly different:

1. The focal length is positive for converging lenses and negative for diverging.

2. The object distance is positive when the object is on the same side as the light entering the lens (not an issue except in compound systems); otherwise it is negative.

3. The image distance is positive if the image is on the opposite side from the light entering the lens; otherwise it is negative.

4. The height of the image is positive if the image is upright and negative otherwise.
The magnification formula is also the same as that for a mirror:

\[ m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}. \]  \hspace{1cm} (23-9)

The power of a lens is positive if it is converging and negative if it is diverging.

A converging lens referred to as a positive lens, and a diverging lens as a negative lens.
23-8 The Thin Lens Equation

Problem Solving: Thin Lenses

1. Draw a ray diagram. The image is located where the key rays intersect.
2. Solve for unknowns.
3. Follow the sign conventions.
4. Check that your answers are consistent with the ray diagram.
Examples

• A coin is 12 cm in front of a converging lens with focal length of magnitude 4.0 cm. Where is the image?
Answer: 6 cm behind the lens. \[ \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \Rightarrow \frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o} \]

• A certain slide projector has a lens of focal length 15.0 cm. This lens forms an image measuring 100 cm × 100 cm on the screen when a slide whose dimensions are 50.0 mm × 50.0 mm is being magnified. How far from the lens should the screen be placed?
Answer: 3.15 m \[ m = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \]
In lens combinations, the image formed by the first lens becomes the object for the second lens (this is where object distances may be negative).
23-10 Lensmaker’s Equation

This useful equation relates the radii of curvature of the two lens surfaces, and the index of refraction, to the focal length. This useful equation relates the radii of curvature of the two lens surfaces, and the index of refraction, to the focal length.

\[
\frac{1}{f} = (n - 1) \left( \frac{1}{R_1} + \frac{1}{R_2} \right)
\]

(23-10)
Summary of Chapter 23

• Light paths are called rays
• Index of refraction: \( n = \frac{c}{v} \).
• Angle of reflection equals angle of incidence
• Plane mirror: image is virtual, upright, and the same size as the object
• Spherical mirror can be concave or convex
• Focal length of the mirror: \( f = \frac{r}{2} \).
Summary of Chapter 23

- Mirror equation: \( \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \).

- Magnification: \( m = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \).

- Real image: light passes through it

- Virtual image: light does not pass through
Summary of Chapter 23

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

- Total internal reflection occurs when angle of incidence is greater than critical angle:

\[ \sin \theta_C = \frac{n_2}{n_1} \sin 90^\circ = \frac{n_2}{n_1}. \]

- A converging lens focuses incoming parallel rays to a point
Summary of Chapter 23

- A diverging lens spreads incoming rays so that they appear to come from a point.

- Power of a lens:
  \[ P = \frac{1}{f}. \]

- Thin lens equation:
  \[ \frac{1}{f} - \frac{1}{d_i} = \frac{1}{d_o} \]
  or
  \[ \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}. \]

- Magnification:
  \[ m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}. \]