Chapter 23 Ray Optics

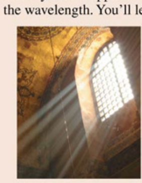
Chapter Goal: To understand and apply the ray model of light.

Slide 23-2

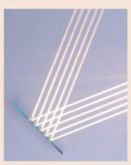
Chapter 23 Preview

The Ray Model of Light

The ray model applies when light interacts with objects that are very large compared to the wavelength. You'll learn that . . .



. . . light rays travel in straight lines unless they are . . .



. . . reflected by a surface or . . .

. . . refracted at a boundary.

Light rays can also be *scattered* or *absorbed* by the medium they travel through.

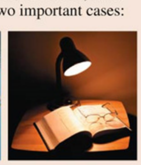
Slide 23-3

Chapter 23 Preview

Reflection

Light rays can bounce, or **reflect,** off a surface. There are two important cases:

Specular reflection, like from a mirror.



Diffuse reflection, like from the page of this book.

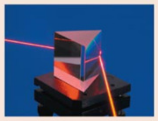
You'll learn to use the *law of reflection.*

Slide 23-4

Chapter 23 Preview

Refraction

When light rays travel from one medium to another, they change directions, or **refract,** at the boundary.



Refraction causes the laser beam to change direction as it goes through the prism.

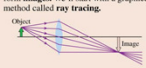
You'll learn to use *Snell's law* to find the angles on both sides.

 Slide 23-5

Chapter 23 Preview

Images Formed by Lenses and Mirrors

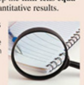
You'll discover how lenses and mirrors form **images.** We'll start with a graphical method called **ray tracing.**



Ray tracing shows how this lens forms a *real image* on the opposite side of the lens from the object.

We'll then develop the **thin-lens equation** for more quantitative results.

A magnifying glass creates a *virtual image* that you see by looking through the lens.



We'll use the same graphical and mathematical techniques to understand how curved mirrors create images.

The passenger-side rearview mirror is curved, allowing you to see a wider field of view.

 Slide 23-6

Chapter 23 Reading Quiz

 Slide 23-7

Reading Question 23.1

What is specular reflection?

A. The image of a specimen.
B. A reflection that separates different colors.
C. Reflection by a flat smooth object.
D. Reflection in which the image is virtual and special.
E. This topic is not covered in Chapter 23.

 Slide 23-8

Reading Question 23.2

What is diffuse reflection?

A. A reflection that separates different colors.
B. Reflection by a surface with tiny irregularities that cause the reflected rays to leave in many random directions.
C. Reflection that increases in size linearly with distance from the mirror.
D. Reflection in which the image is virtual.
E. This topic is not covered in Chapter 23.

 Slide 23-10

Reading Question 23.3

A paraxial ray

A. Moves in a parabolic path.
B. Is a ray that has been reflected from a parabolic mirror.
C. Is a ray that moves nearly parallel to the optical axis.
D. Is a ray that moves exactly parallel to the optical axis.

 Slide 23-12

Reading Question 23.4

A virtual image is

A. The cause of optical illusions.
B. A point from which rays appear to diverge.
C. An image that only seems to exist.
D. The image that is left in space after you remove a viewing screen.

Slide 23-14

Reading Question 23.5

The focal length of a converging lens is

A. The distance at which an image is formed.
B. The distance at which an object must be placed to form an image.
C. The distance at which parallel light rays are focused.
D. The distance from the front surface to the back surface.

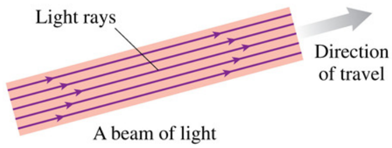
Slide 23-16

Chapter 23 Content, Examples, and QuickCheck Questions

Slide 23-18

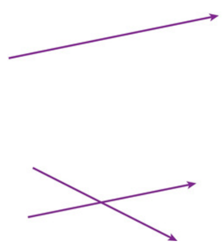
The Ray Model of Light

- Let us define a **light ray** as a line in the direction along which light energy is flowing.
- Any narrow beam of light, such as a laser beam, is actually a bundle of many parallel light rays.
- You can think of a single light ray as the limiting case of a laser beam whose diameter approaches zero.



Slide 23-19

The Ray Model of Light



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

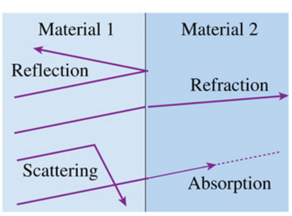
Slide 23-20

The Ray Model of Light

Light interacts with matter in four different ways:

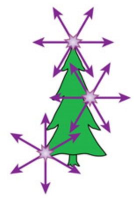
At an interface between two materials, light can be either *reflected* or *refracted.*

Within a material, light can be either *scattered* or *absorbed.*

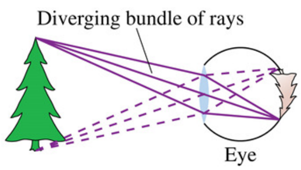


Slide 23-21

The Ray Model of Light

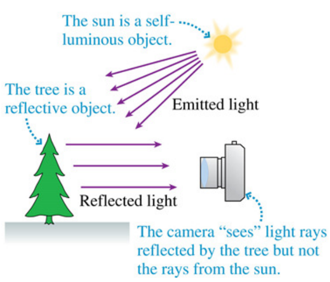


- An **object** is a source of light rays.
- Rays originate from *every* point on the object, and each point sends rays in *all* directions.



- 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.

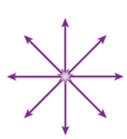
Objects



- Objects can be either self-luminous, such as the sun, flames, and lightbulbs, or reflective.
- Most objects are reflective.

Objects

- The diverging rays from a **point source** are emitted in all directions.
- Each point on an object is a point source of light rays.
- A **parallel bundle** of rays could be a laser beam, or light from a *distant object.*

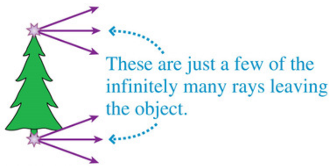


Point source

Parallel bundle

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 messy and confusing.
- To simplify the picture, we use a **ray diagram** showing only a few rays.

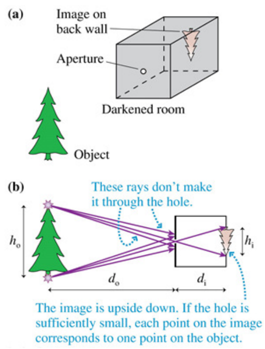


 Slide 23-25

Apertures

- A **camera obscura** is a darkened room with a single, small hole, called an **aperture.**
- The geometry of the rays causes the image to be upside down.
- The object and image heights are related by:

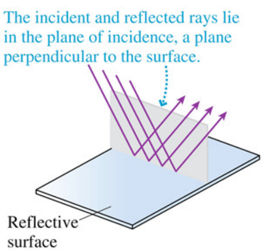
$$\frac{h_i}{h_o} = \frac{d_i}{d_o}$$



 Slide 23-26

Specular Reflection of Light

Reflection from a flat, smooth surface, such as a mirror or a piece of polished metal, is called **specular reflection**.



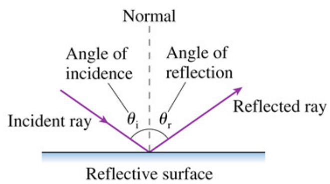
 Slide 23-32

Reflection

The **law of reflection** states that:

1. The incident ray and the reflected ray are in the same plane normal to the surface, and
2. The angle of reflection equals the angle of incidence:

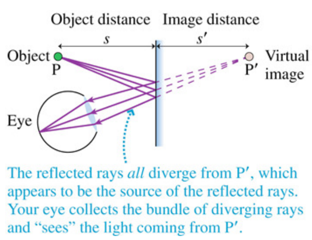
$$\theta_r = \theta_I$$



 Slide 23-33

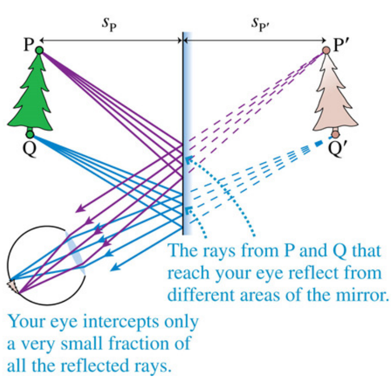
The Plane Mirror

- 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, $s' = s$.



 Slide 23-39

The Plane Mirror



 Slide 23-40

Example 23.2 How High Is the Mirror?

EXAMPLE 23.2 How high is the mirror?

If your height is h, what is the shortest mirror on the wall in which you can see your full image? Where must the top of the mirror be hung?

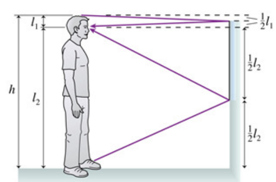
MODEL Use the ray model of light.

Slide 23-43

Example 23.2 How High Is the Mirror?

EXAMPLE 23.2 How high is the mirror?

SOLVE Let the distance from your eyes to the top of your head be l_1 and the distance to your feet be l_2. Your height is $h = l_1 + l_2$. A light ray from the top of your head that reflects from the mirror at $\theta_r = \theta_i$ and enters your eye must, by congruent triangles, strike the mirror a distance $\frac{1}{2}l_1$ above your eyes. Similarly, a ray from your foot to your eye strikes the mirror a distance $\frac{1}{2}l_2$ below your eyes.

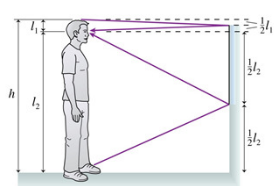


Slide 23-45

Example 23.2 How High Is the Mirror?

EXAMPLE 23.2 How high is the mirror?

The distance between these two points on the mirror is $\frac{1}{2}l_1 + \frac{1}{2}l_2 = \frac{1}{2}h$. A ray from anywhere else on your body will reach your eye if it strikes the mirror between these two points. Pieces of the mirror outside these two points are irrelevant, not because rays don't strike them but because the reflected rays don't reach your eye. Thus the shortest mirror in which you can see your full reflection is $\frac{1}{2}h$. But this will work only if the top of the mirror is hung midway between your eyes and the top of your head.



Slide 23-46

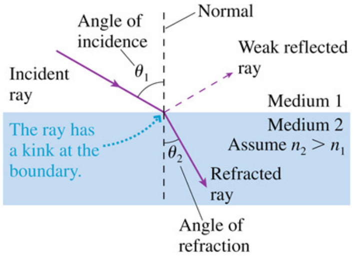
Refraction

Two things happen when a light ray is incident on a smooth boundary between two transparent materials:

1. Part of the light *reflects* from the boundary, obeying the law of reflection.
2. Part of the light continues into the second medium. The transmission of light from one medium to another, but with a change in direction, is called **refraction**.

 Slide 23-48

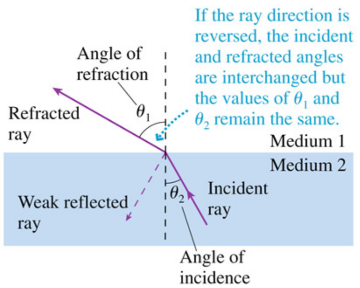
Refraction



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

 Slide 23-49

Refraction



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

 Slide 23-50

Indices of Refraction

TABLE 23.1 Indices of refraction

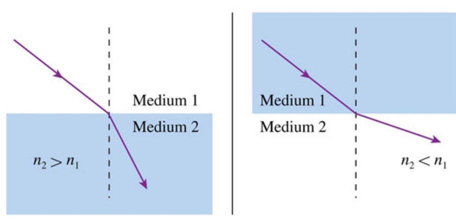
Medium	n
Vacuum	1.00 exactly
Air (actual)	1.0003
Air (accepted)	1.00
Water	1.33
Ethyl alcohol	1.36
Oil	1.46
Glass (typical)	1.50
Polystyrene plastic	1.59
Cubic zirconia	2.18
Diamond	2.41
Silicon (infrared)	3.50

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

Slide 23-51

Refraction

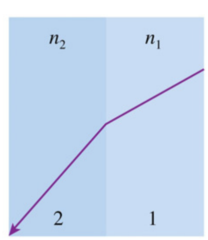
- When a ray is transmitted into a material with a higher index of refraction, it bends *toward* the normal.
- When a ray is transmitted into a material with a lower index of refraction, it bends *away from* the normal.



Slide 23-52

QuickCheck 23.4

A laser beam passing from medium 1 to medium 2 is refracted as shown. Which is true?

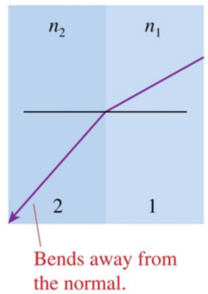


A. $n_1 < n_2$.
B. $n_1 > n_2$.
C. There's not enough information to compare n_1 and n_2.

Slide 23-53

QuickCheck 23.4

A laser beam passing from medium 1 to medium 2 is refracted as shown. Which is true?



A. $n_1 < n_2$.

✔ **B. $n_1 > n_2$.**

C. There's not enough information to compare n_1 and n_2.

Tactics: Analyzing Refraction

TACTICS BOX 23.1 Analyzing refraction

1. **Draw a ray diagram.** Represent the light beam with one ray.
2. **Draw a line normal to the boundary.** Do this at each point where the ray intersects a boundary.
3. **Show the ray bending in the correct direction.** The angle is larger on the side with the smaller index of refraction. This is the qualitative application of Snell's law.
4. **Label angles of incidence and refraction.** Measure all angles from the normal.
5. **Use Snell's law.** Calculate the unknown angle or unknown index of refraction.

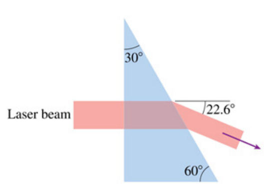
Exercises 11–15

Example 23.4 Measuring the Index of Refraction

EXAMPLE 23.4 Measuring the index of refraction

The figure below shows a laser beam deflected by a 30°-60°-90° prism. What is the prism's index of refraction?

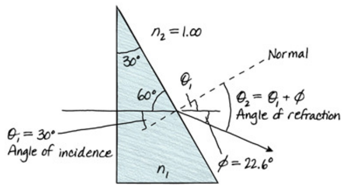
MODEL Represent the laser beam with a single ray and use the ray model of light.



Example 23.4 Measuring the Index of Refraction

EXAMPLE 23.4 Measuring the index of refraction

VISUALIZE The figure below uses the steps of Tactics Box 23.1 to draw a ray diagram. The ray is incident perpendicular to the front face of the prism ($\theta_{incident} = 0°$), thus it is transmitted through the first boundary without deflection. At the second boundary it is especially important to *draw the normal to the surface* at the point of incidence and to *measure angles from the normal.*



θ_1 and θ_2 are measured from the normal.

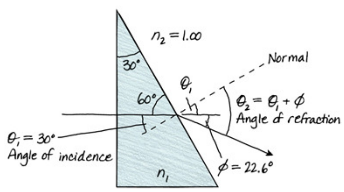
Slide 23-57

Example 23.4 Measuring the Index of Refraction

EXAMPLE 23.4 Measuring the index of refraction

SOLVE From the geometry of the triangle you can find that the laser's angle of incidence on the hypotenuse of the prism is $\theta_1 = 30°$, the same as the apex angle of the prism. The ray exits the prism at angle θ_2 such that the deflection is $\phi = \theta_2 - \theta_1 = 22.6°$. Thus $\theta_2 = 52.6°$. Knowing both angles and $n_2 = 1.00$ for air, we can use Snell's law to find n_1:

$$n_1 = \frac{n_2 \sin\theta_2}{\sin\theta_1} = \frac{1.00 \sin 52.6°}{\sin 30°} = 1.59$$



θ_1 and θ_2 are measured from the normal.

Slide 23-58

Example 23.4 Measuring the Index of Refraction

$n_1 = 1.59$

ASSESS Referring to the indices of refraction in Table 23.1, we see that the prism is made of plastic.

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

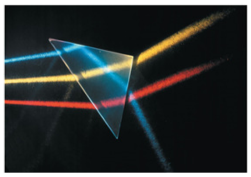
Slide 23-59

Total Internal Reflection

- When a ray crosses a boundary into a material with a lower index of refraction, it bends *away* from the normal.
- As the angle θ_1 increases, the refraction angle θ_2 approaches 90°, and the fraction of the light energy transmitted decreases while the fraction reflected increases.
- The critical angle of incidence occurs when $\theta_2 = 90°$:

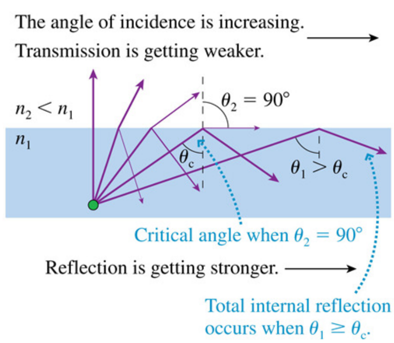
$$\theta_c = \sin^{-1} \frac{n_2}{n_1}$$

- The refracted light vanishes at the critical angle and the reflection becomes 100% for any angle $\theta_1 > \theta_c$.



 Slide 23-60

Total Internal Reflection



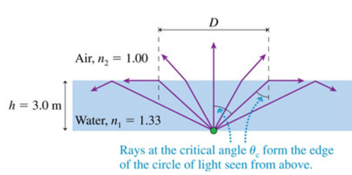
 Slide 23-61

Example 23.5 Total Internal Reflection

EXAMPLE 23.5 Total internal reflection

A lightbulb is set in the bottom of a 3.0-m-deep swimming pool. What is the diameter of the circle of light seen on the water's surface from above?

MODEL Represent the lightbulb as a point source and use the ray model of light.

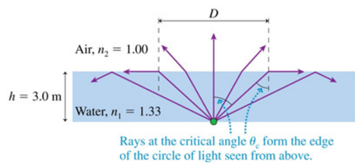


 Slide 23-64

Example 23.5 Total Internal Reflection

EXAMPLE 23.5 Total internal reflection

VISUALIZE The figure below is a pictorial representation of the light rays. The lightbulb emits rays at all angles, but only some of the rays refract into the air where they can be seen from above. Rays striking the surface at greater than the critical angle undergo TIR and remain within the water. The diameter of the circle of light is the distance between the two points at which rays strike the surface at the critical angle.

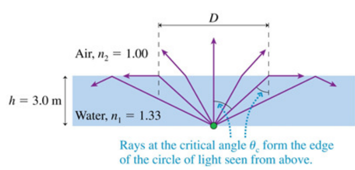


Example 23.5 Total Internal Reflection

EXAMPLE 23.5 Total internal reflection

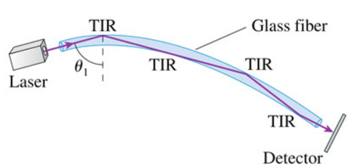
SOLVE From trigonometry, the circle diameter is $D = 2h\tan\theta_c$, where h is the depth of the water. The critical angle for a water-air boundary is $\theta_c = \sin^{-1}(1.00/1.33) = 48.7°$. Thus

$$D = 2(3.0\text{ m})\tan 48.7° = 6.8\text{ m}$$



Fiber Optics

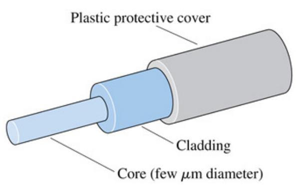
- The most important modern application of **total internal reflection** (TIR) is optical fibers.
- Light rays enter the glass fiber, then impinge on the inside wall of the glass at an angle above the critical angle, so they undergo TIR and remain inside the glass.
- The light continues to “bounce” its way down the tube as if it were inside a pipe.



Fiber Optics

- In a practical optical fiber, a small-diameter glass core is surrounded by a layer of glass cladding.
- The glasses used for the core and the cladding have:

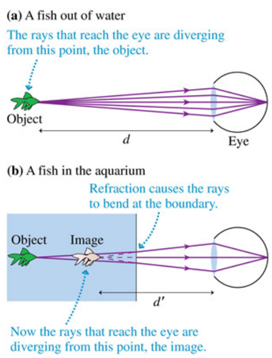
$$n_{\text{core}} > n_{\text{cladding}}$$



 Slide 23-68

Image Formation by Refraction

If you see a fish that appears to be swimming close to the front window of the aquarium, but then look through the side of the aquarium, you'll find that the fish is actually farther from the window than you thought.



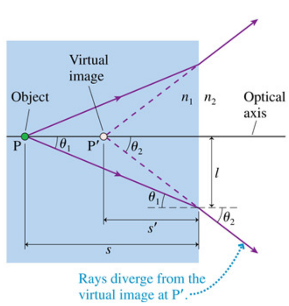
 Slide 23-69

Image Formation by Refraction

- Rays emerge from a material with $n_1 > n_2$.
- Consider only **paraxial rays**, for which θ_1 and θ_2 are quite small.
- In this case:

$$s' = \frac{n_2}{n_1}s$$

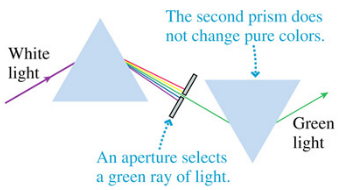
where s is the **object distance** and s' is the **image distance.**



 Slide 23-70

Color and Dispersion

- A prism *disperses* white light into various colors.
- When a particular color of light enters a prism, its color does not change.



 Slide 23-76

Color

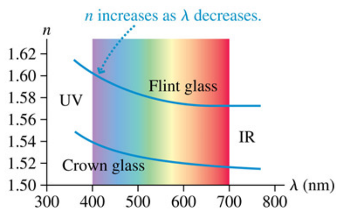
- Different colors are associated with light of different wavelengths.
- The longest wavelengths are perceived as red light and the shortest as violet light.
- What we perceive as white light is a mixture of all colors.

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

 Slide 23-77

Dispersion

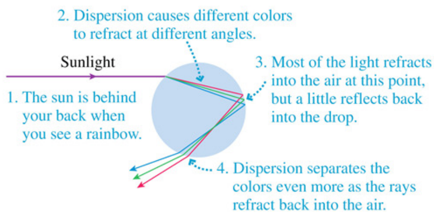
- The slight variation of index of refraction with wavelength is known as **dispersion.**
- Shown is the dispersion curves of two common glasses.
- Notice that ***n* is *larger* when the wavelength is *shorter***, thus violet light refracts more than red light.



 Slide 23-78

Rainbows

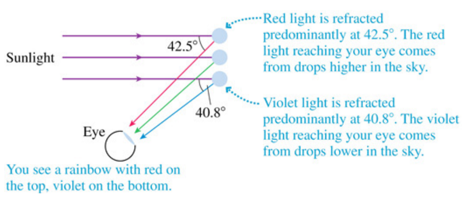
- One of the most interesting sources of color in nature is the rainbow.
- The basic cause of the rainbow is a combination of refraction, reflection, and dispersion.



 Slide 23-79

Rainbows

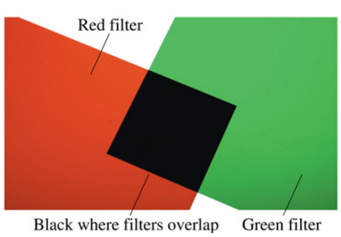
- A ray of red light reaching your eye comes from a drop *higher* in the sky than a ray of violet light.
- You have to look higher in the sky to see the red light than to see the violet light.



 Slide 23-80

Colored Filters and Colored Objects

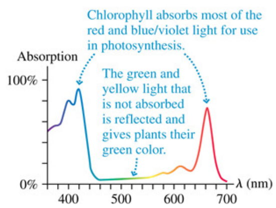
- Green glass is green because it absorbs any light that is "not green."
- If a green filter and a red filter are overlapped, no light gets through.
- The green filter transmits only green light, which is then absorbed by the red filter because it is "not red."



 Slide 23-83

Colored Filters and Colored Objects

- The figure below shows the absorption curve of *chlorophyll*, which is essential for photosynthesis in green plants.
- The chemical reactions of photosynthesis absorb red light and blue/violet light from sunlight and puts it to use.
- When you look at the green leaves on a tree, you're seeing the light that was reflected because it *wasn't* needed for photosynthesis.

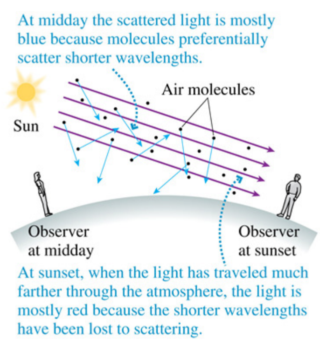


 Slide 23-84

Light Scattering: Blue Skies and Red Sunsets

- Light can scatter from small particles that are suspended in a medium.
- **Rayleigh scattering** from atoms and molecules depends inversely on the fourth power of the wavelength:

$$I_{\text{scattered}} \propto \lambda^4$$



 Slide 23-85

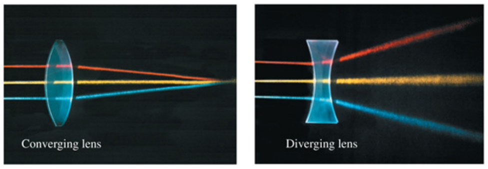
Light Scattering: Blue Skies and Red Sunsets

Sunsets are red because all the blue light has scattered as the sunlight passes through the atmosphere.

 Slide 23-86

Lenses

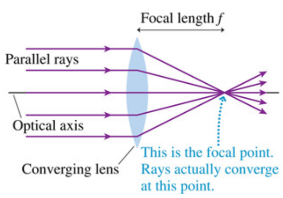
- The photos below show parallel light rays entering two different lenses.
- The left lens, called a **converging lens**, causes the rays to refract *toward* the optical axis.
- The right lens, called a **diverging lens**, refracts parallel rays *away from* the optical axis.



 Slide 23-87

Converging Lenses

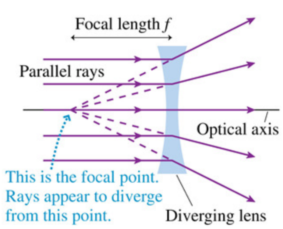
- A **converging lens** is thicker in the center than at the edges.
- The focal length *f* is the distance from the lens at which rays parallel to the optical axis converge.
- The focal length is a property *of the lens*, independent of how the lens is used.



 Slide 23-88

Diverging Lenses

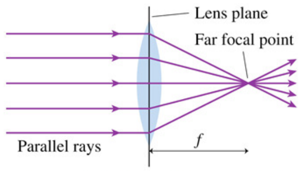
- A **diverging lens** is thicker at the edges than in the center.
- The focal length *f* is the distance from the lens at which rays parallel to the optical axis appear to diverge.
- The focal length is a property *of the lens*, independent of how the lens is used.



 Slide 23-89

Thin Lenses: Ray Tracing

- Three situations form the basis for ray tracing through a thin **converging lens.**
- Situation 1:
  A ray initially parallel to the optic axis will go through the far focal point after passing through the lens.

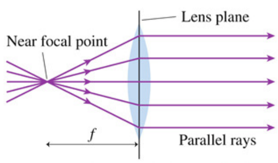


Any ray initially parallel to the optical axis will refract through the focal point on the far side of the lens.

Slide 23-92

Thin Lenses: Ray Tracing

- Three situations form the basis for ray tracing through a thin **converging lens.**
- Situation 2:
  A ray through the near focal point of a thin lens becomes parallel to the optic axis after passing through the lens.

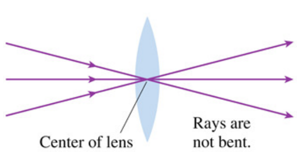


Any ray passing through the near focal point emerges from the lens parallel to the optical axis.

Slide 23-93

Thin Lenses: Ray Tracing

- Three situations form the basis for ray tracing through a thin **converging lens.**
- Situation 3:
  A ray through the center of a thin lens is neither bent nor displaced but travels in a straight line.

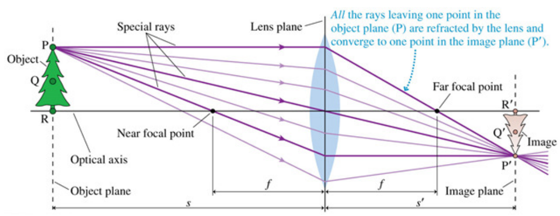


Any ray directed at the center of the lens passes through in a straight line.

Slide 23-94

Thin Lenses: Ray Tracing

Rays from an object point P are refracted by the lens and converge to a real image at point P′.

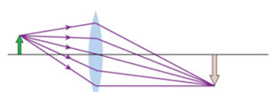


$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \quad \text{(thin-lens equation)}$$

 Slide 23-95

QuickCheck 23.12

A lens creates an image as shown. In this situation, the object distance s is

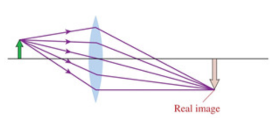


A. Larger than the focal length f.
B. Equal to the focal length f.
C. Smaller than focal length f.

 Slide 23-105

QuickCheck 23.12

A lens creates an image as shown. In this situation, the object distance s is



✔ **A. Larger than the focal length f.**
B. Equal to the focal length f.
C. Smaller than focal length f.

 Slide 23-106

Lateral Magnification

- The image can be either larger or smaller than the object, depending on the location and focal length of the lens.
- The **lateral magnification** m is defined as:

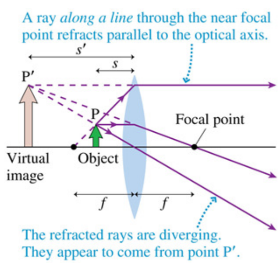
$$m = -\frac{s'}{s}$$

- A positive value of m indicates that the image is upright relative to the object.
- A negative value of m indicates that the image is inverted relative to the object.
- The absolute value of m gives the size ratio of the image and object: $h'/h = |m|$.

 Slide 23-109

Virtual Images

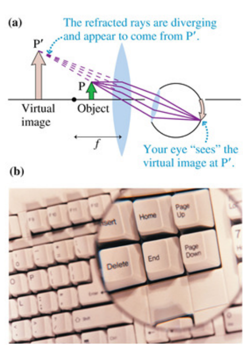
- Consider a converging lens for which the object is *inside* the focal point, at distance $s < f$.
- You can see all three rays appear to diverge from point P′.
- Point P′ is an upright, **virtual image** of the object point P.



 Slide 23-110

Virtual Images

- You can "see" a virtual image by looking through the lens.
- This is exactly what you do with a magnifying glass, microscope or binoculars.



 Slide 23-111

Example 23.9 Magnifying a Flower

EXAMPLE 23.9 Magnifying a flower

To see a flower better, a naturalist holds a 6.0-cm-focal-length magnifying glass 4.0 cm from the flower. What is the magnification?

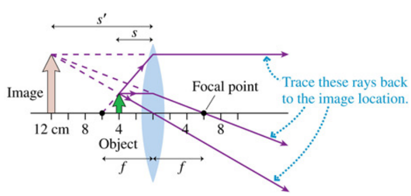
MODEL The flower is in the object plane. Use ray tracing to locate the image.

Slide 23-112

Example 23.9 Magnifying a Flower

EXAMPLE 23.9 Magnifying a flower

VISUALIZE The figure below shows the ray-tracing diagram. The three special rays diverge from the lens, but we can use a straightedge to extend the rays backward to the point from which they diverge. This point, the image point, is seen to be 12 cm to the left of the lens.



Slide 23-113

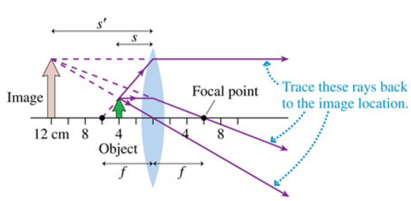
Example 23.9 Magnifying a Flower

EXAMPLE 23.9 Magnifying a flower

Because this is a virtual image, the image distance is $s' = -12$ cm. Thus the magnification is

$$m = -\frac{s'}{s} = -\frac{-12 \text{ cm}}{4.0 \text{ cm}} = 3.0$$

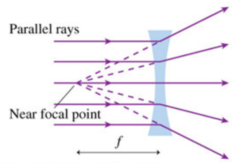
The image is three times as large as the object and, because m is positive, upright.



Slide 23-114

Thin Lenses: Ray Tracing

- Three situations form the basis for ray tracing through a thin **diverging lens.**
- Situation 1:
  A ray initially parallel to the optic axis will appear to diverge from the near focal point after passing through the lens.

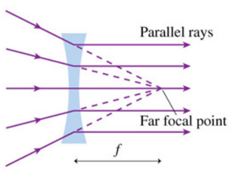


Any ray initially parallel to the optical axis diverges along a line through the near focal point.

 Slide 23-115

Thin Lenses: Ray Tracing

- Three situations form the basis for ray tracing through a thin **diverging lens.**
- Situation 2:
  A ray directed along a line toward the far focal point becomes parallel to the optic axis after passing through the lens.

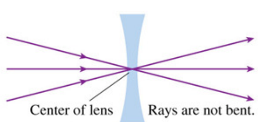


Any ray directed along a line toward the far focal point emerges from the lens parallel to the optical axis.

 Slide 23-116

Thin Lenses: Ray Tracing

- Three situations form the basis for ray tracing through a thin **diverging lens.**
- Situation 3:
  A ray through the center of a thin lens is neither bent nor displaced but travels in a straight line.

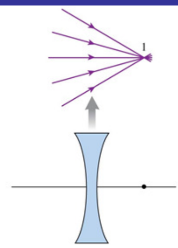


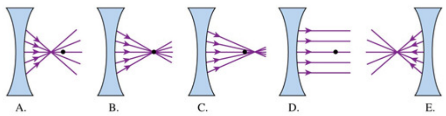
Any ray directed at the center of the lens passes through in a straight line.

 Slide 23-117

QuickCheck 23.14

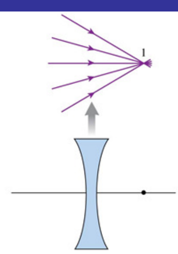
Light rays are converging to point 1. The lens is inserted into the rays with its focal point at point 1. Which picture shows the rays leaving the lens?

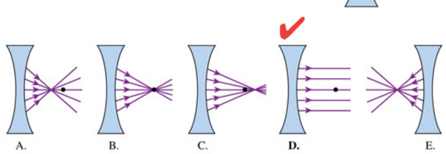




QuickCheck 23.14

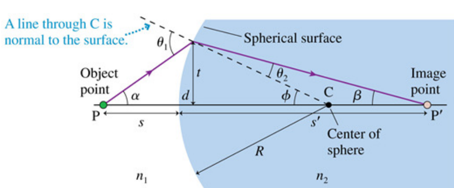
Light rays are converging to point 1. The lens is inserted into the rays with its focal point at point 1. Which picture shows the rays leaving the lens?





Thin Lenses: Refraction Theory

- Consider a spherical boundary between two transparent media with indices of refraction n_1 and n_2.
- The sphere has radius of curvature R and is centered at point C.



Thin Lenses: Refraction Theory

If an object is located at distance s from a spherical refracting surface, an image will be formed at distance s' given by:

$$\frac{n_1}{s} + \frac{n_2}{s'} = \frac{n_2 - n_1}{R}$$

TABLE 23.3 Sign convention for refracting surfaces

	Positive	Negative
R	Convex toward the object	Concave toward the object
s'	Real image, opposite side from object	Virtual image, same side as object

Example 23.12 A Goldfish in a Bowl

EXAMPLE 23.12 A goldfish in a bowl

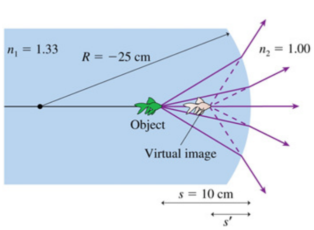
A goldfish lives in a spherical fish bowl 50 cm in diameter. If the fish is 10 cm from the near edge of the bowl, where does the fish appear when viewed from the outside?

MODEL Model the fish as a point source and consider the paraxial rays that refract from the water into the air. The thin glass wall has little effect and will be ignored.

Example 23.12 A Goldfish in a Bowl

EXAMPLE 23.12 A goldfish in a bowl

VISUALIZE The figure below shows the rays refracting *away* from the normal as they move from the water into the air. We expect to find a virtual image at a distance less than 10 cm.



Example 23.12 A Goldfish in a Bowl

EXAMPLE 23.12 A goldfish in a bowl

SOLVE The object is in the water, so $n_1 = 1.33$ and $n_2 = 1.00$. The inner surface is concave (you can remember "concave" because it's like looking into a cave), so $R = -25$ cm. The object distance is $s = 10$ cm. Thus Equation 23.21 is

$$\frac{1.33}{10\text{ cm}} + \frac{1.00}{s'} = \frac{1.00 - 1.33}{-25\text{ cm}} = \frac{0.33}{25\text{ cm}}$$

Solving for the image distance s' gives

$$\frac{1.00}{s'} = \frac{0.33}{25\text{ cm}} - \frac{1.33}{10\text{ cm}} = -0.12\text{ cm}^{-1}$$

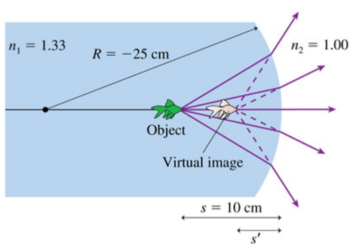
$$s' = \frac{1.00}{-0.12\text{ cm}^{-1}} = -8.3\text{ cm}$$

Example 23.12 A Goldfish in a Bowl

EXAMPLE 23.12 A goldfish in a bowl

ASSESS The image is virtual, located to the left of the boundary. A person looking into the bowl will see a fish that appears to be 8.3 cm from the edge of the bowl.

$s' = -8.3$ cm



Lenses

In an actual lens, rays refract *twice*, at spherical surfaces having radii of curvature R_1 and R_2.

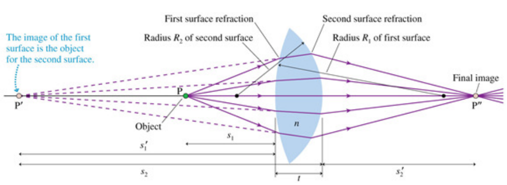


TABLE 23.4 Sign convention for thin lenses

	Positive	Negative
R_1, R_2	Convex toward the object	Concave toward the object
f	Converging lens, thicker in center	Diverging lens, thinner in center
s'	Real image, opposite side from object	Virtual image, same side as object

The Thin Lens Equation

The object distance s is related to the image distance s' by:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \quad \text{(thin-lens equation)}$$

where f is the focal length of the lens, which can be found from:

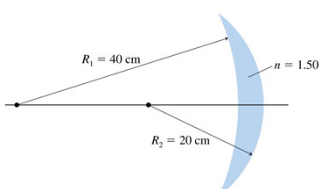
$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \quad \text{(lens maker's equation)}$$

where R_1 is the radius of curvature of the first surface, and R_2 is the radius of curvature of the second surface, and the material surrounding the lens has $n = 1$.

Example 23.13 Focal Length of a Meniscus Lens

EXAMPLE 23.13 Focal length of a meniscus lens

What is the focal length of the glass *meniscus lens* shown in the figure below? Is this a converging or diverging lens?



Example 23.13 Focal Length of a Meniscus Lens

EXAMPLE 23.13 Focal length of a meniscus lens

SOLVE If the object is on the left, then the first surface has $R_1 = -40$ cm (concave toward the object) and the second surface has $R_2 = -20$ cm (also concave toward the object). The index of refraction of glass is $n = 1.50$, so the lens maker's equation is

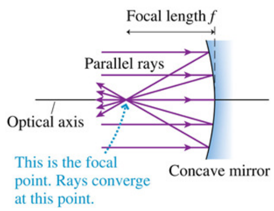
$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = (1.50 - 1)\left(\frac{1}{-40\text{ cm}} - \frac{1}{-20\text{ cm}}\right)$$

$$= 0.0125\text{ cm}^{-1}$$

Inverting this expression gives $f = 80$ cm. This is a converging lens, as seen both from the positive value of f and from the fact that the lens is thicker in the center.

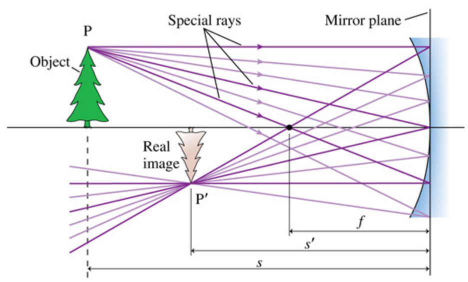
Image Formation with Concave Spherical Mirrors

- The figure shows a **concave mirror**, a mirror in which the edges curve *toward* the light source.
- Rays parallel to the optical axis reflect and pass through the focal point of the mirror.



Slide 23-139

A Real Image Formed by a Concave Mirror

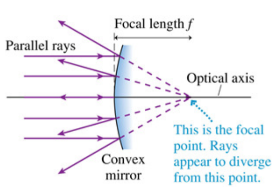


$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \quad \text{(mirror equation)}$$

Slide 23-140

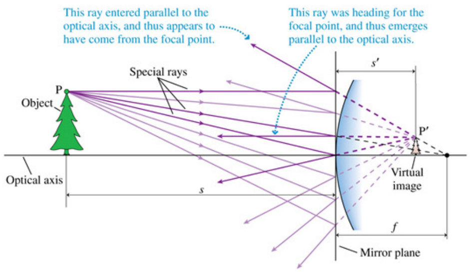
Image Formation with Convex Spherical Mirrors

- The figure shows parallel light rays approaching a mirror in which the edges curve *away from* the light source.
- This is called a **convex mirror.**
- The reflected rays appear to come from a point behind the mirror.



Slide 23-141

A Real Image Formed by a Convex Mirror



$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \qquad \text{(mirror equation)}$$

 Slide 23-142

Image Formation with Spherical Mirrors

A city skyline is reflected in this polished sphere.

 Slide 23-143

The Mirror Equation

For a spherical mirror with negligible thickness, the object and image distances are related by:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \qquad \text{(mirror equation)}$$

where the focal length f is related to the mirror's radius of curvature by:

$$f = \frac{R}{2}$$

TABLE 23.5 Sign convention for spherical mirrors

	Positive	Negative
R, f	Concave toward the object	Convex toward the object
s'	Real image, same side as object	Virtual image, opposite side from object

 Slide 23-146

Chapter 23 Summary Slides

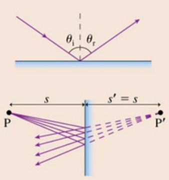
General Principles

Reflection

Law of reflection: $\theta_r = \theta_i$

Reflection can be **specular** (mirror-like) or **diffuse** (from rough surfaces).

Plane mirrors: A virtual image is formed at P' with $s' = s$.



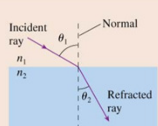
General Principles

Refraction

Snell's law of refraction:

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

Index of refraction is $n = c/v$. The ray is closer to the normal on the side with the larger index of refraction.



If $n_2 < n_1$, **total internal reflection** (TIR) occurs when the angle of incidence $\theta_1 \geq \theta_c = \sin^{-1}(n_2/n_1)$.

Important Concepts

The ray model of light

Light travels along straight lines, called **light rays,** at speed $v = c/n$.

A light ray continues forever unless an interaction with matter causes it to reflect, refract, scatter, or be absorbed.

Light rays come from **objects.** Each point on the object sends rays in all directions.

The eye sees an object (or an image) when diverging rays are collected by the pupil and focused on the retina.

- Ray optics is valid when lenses, mirrors, and apertures are larger than ≈ 1 mm.

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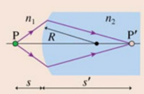
Important Concepts

Image formation



If rays diverge from P and interact with a lens or mirror so that the refracted rays *converge* at P′, then P′ is a real image of P.

If rays diverge from P and interact with a lens or mirror so that the refracted/reflected rays *diverge* from P′ and appear to come from P′, then P′ is a virtual image of P.

Spherical surface: Object and image distances are related by

$$\frac{n_1}{s} + \frac{n_2}{s'} = \frac{n_2 - n_1}{R}$$

Plane surface: $R \rightarrow \infty$, so $|s'/s| = n_2/n_1$.

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