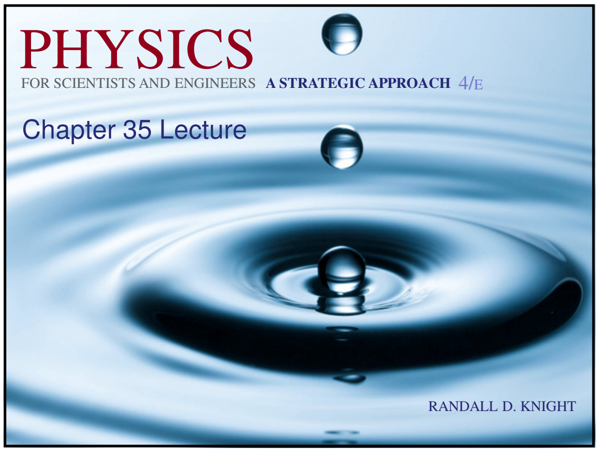

Chapter 35 Optical Instruments

IN THIS CHAPTER, you will learn about some common optical instruments and their limitations.

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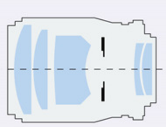
Chapter 35 Preview

What is an optical instrument?

Optical instruments, such as cameras, microscopes, and telescopes, are used to produce images for viewing or detection. Most use several individual lenses in combination to improve performance. You'll learn how to analyze a system with multiple lenses.



« LOOKING BACK Sections 34.5–34.6 Thin lenses

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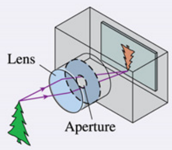
Chapter 35 Preview

How does a camera work?

A camera uses a lens—made of several individual lenses—to project a real image onto a light-sensitive detector. The detector in a digital camera uses millions of tiny pixels.

- You'll learn about focusing and zoom.
- You'll also learn how to calculate a lens's *f*-number, which, along with shutter speed, determines the exposure.



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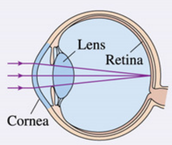
Slide 35-4

Chapter 35 Preview

How does vision work?

The human eye is much like a camera; the cornea and lens together focus a real image onto the retina. You'll learn about two defects of vision—myopia (nearsightedness) and hyperopia (farsightedness)—and how they can be corrected with eyeglasses.



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Chapter 35 Preview

What optical systems are used to magnify things?

Lenses and mirrors can be used to magnify objects both near and far.

- A simple magnifying glass has a low magnification of $2\times$ or $3\times$.
- Microscopes use two sets of lenses to reach magnifications up to $1000\times$.
- Telescopes magnify distant objects.

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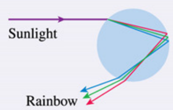
Chapter 35 Preview

Is color important in optics?

Color depends on the wavelength of light.

- The index of refraction is slightly wavelength dependent, so different wavelengths refract at different angles. This is the main reason we have rainbows.
- Many materials absorb or scatter some wavelengths more than others.



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Chapter 35 Preview

What is the resolution of an optical system?

Light passing through a lens undergoes diffraction, just like light passing through a circular hole. Images are not perfect points but are tiny diffraction patterns, and this limits how well two nearby objects can be resolved. You'll learn about Rayleigh's criterion for the resolution of two images.

« LOOKING BACK Section 33.6 Circular diffraction

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Chapter 35 Reading Questions

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Reading Question 35.1

With what unit is *lens power* measured?

A. Biopter
B. Diopter
C. Watt
D. Rayleigh

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Reading Question 35.1

With what unit is *lens power* measured?

A. Biopter
✔**B. Diopter**
C. Watt
D. Rayleigh

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Reading Question 35.2

Accommodation of the eye refers to its ability to

A. Rotate in the eye socket to look in different directions.
B. Focus on both nearby and distant objects.
C. See in both very bright and very dim light.
D. See both in air and while underwater.

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Reading Question 35.2

Accommodation of the eye refers to its ability to

A. Rotate in the eye socket to look in different directions.
✔**B. Focus on both nearby and distant objects.**
C. See in both very bright and very dim light.
D. See both in air and while underwater.

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Reading Question 35.3

The magnification of a simple magnifier is increased if

A. The focal length of the lens is increased.
B. The focal length of the lens is decreased.
C. The diameter of the lens is increased.
D. The diameter of the lens is decreased.

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Reading Question 35.3

The magnification of a simple magnifier is increased if

A. The focal length of the lens is increased.
✔**B. The focal length of the lens is decreased.**
C. The diameter of the lens is increased.
D. The diameter of the lens is decreased.

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Reading Question 35.4

The fundamental resolution of a lens or telescope is determined by

A. The parallax theorem.
B. The numerical aperture of the lens.
C. Rayleigh's criterion.
D. The lens maker's principle.

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Reading Question 35.4

The fundamental resolution of a lens or telescope is determined by

A. The parallax theorem.
B. The numerical aperture of the lens.
✔ **C. Rayleigh's criterion.**
D. The lens maker's principle.

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Chapter 35 Content, Examples, and QuickCheck Questions

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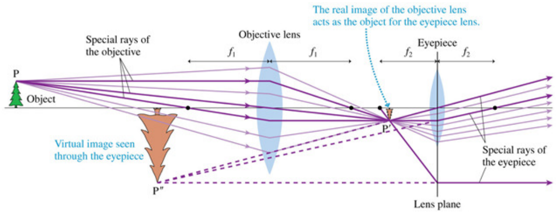
Lenses in Combination

- The analysis of multi-lens systems requires only one new rule: **The image of the first lens acts as the object for the second lens.**
- Below is a ray-tracing diagram of a simple astronomical telescope.



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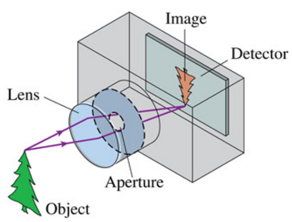
The Camera

- A **camera** "takes a picture" by using a lens to form a real, inverted image on a light-sensitive detector in a light-tight box.
- We can model a combination lens as a single lens with an **effective focal length** (usually called simply "the focal length").
- A *zoom lens* changes the effective focal length by varying the spacing between the converging lens and the diverging lens.



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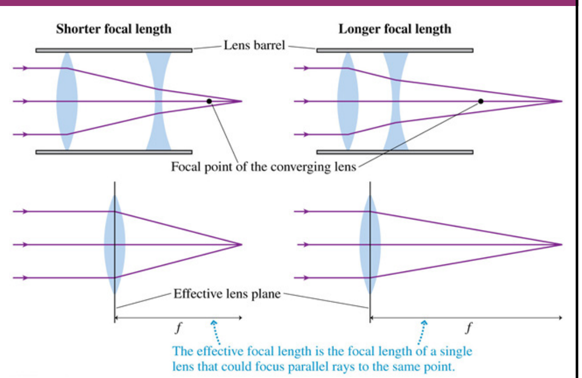
A Simple Camera Lens Is a Combination Lens



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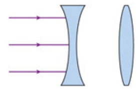
QuickCheck 35.1

The parallel light rays will be focused at a point _______ the second lens than would light focused by the second lens acting alone.



A. closer to
B. the same distance from
C. farther from

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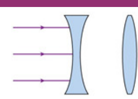
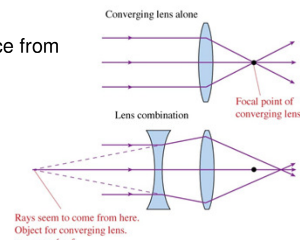
QuickCheck 35.1

The parallel light rays will be focused at a point _______ the second lens than would light focused by the second lens acting alone.



A. closer to
B. the same distance from
✔ **C. farther from**



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Example 35.2 Focusing a Camera

EXAMPLE 35.2 | Focusing a camera

Your digital camera lens, with an effective focal length of 10.0 mm, is focused on a flower 20.0 cm away. You then turn to take a picture of a distant landscape. How far, and in which direction, must the lens move to bring the landscape into focus?

MODEL Model the camera's combination lens as a single thin lens with $f = 10.0$ mm. Image and object distances are measured from the effective lens plane. Assume all the lenses in the combination move together as the camera refocuses.

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Example 35.2 Focusing a Camera

EXAMPLE 35.2 Focusing a camera

SOLVE The flower is at object distance $s = 20.0\text{ cm} = 200\text{ mm}$. When the camera is focused, the image distance between the effective lens plane and the detector is found by solving the thin-lens equation $1/s + 1/s' = 1/f$ to give

$$s' = \left(\frac{1}{f} - \frac{1}{s}\right)^{-1} = \left(\frac{1}{10.0\text{ mm}} - \frac{1}{200\text{ mm}}\right)^{-1} = 10.5\text{ mm}$$

The distant landscape is effectively at object distance $s = \infty$, so its image distance is $s' = f = 10.0\text{ mm}$. To refocus as you shift scenes, the lens must move 0.5 mm closer to the detector.

ASSESS The required motion of the lens is very small, about the diameter of the lead used in a mechanical pencil.

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Zoom Lenses

- When cameras focus on objects that are more than 10 focal lengths away (roughly $s > 20\text{ cm}$ for a typical digital camera), the object is essentially "at infinity" and $s' \approx f$.
- The lateral magnification of the image is

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

- The magnification is much less than 1, because $s >> f$, so the image on the detector is much smaller than the object itself.
- More important, **the size of the image is directly proportional to the focal length of the lens**.

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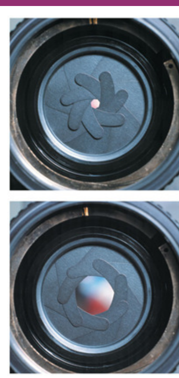
Controlling the Exposure

- The amount of light passing through the lens is controlled by an adjustable **aperture**, shown in the photos.
- The aperture sets the effective diameter D of the lens.
- The light-gathering ability of a lens is specified by its ***f*-number**, defined as

$$f\text{-number} = \frac{f}{D}$$

- The light intensity on the detector is related to the lens's f-number by

$$I \propto \frac{D^2}{f^2} = \frac{1}{(f\text{-number})^2}$$



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QuickCheck 35.2

If the f-number of a camera lens is doubled, say from F4.0 to F8.0, that means the diameter of the lens aperture is

A. Quadrupled (increased by a factor of 4).
B. Doubled (increased by a factor of 2).
C. Halved (decreased by a factor of 2).
D. Quartered (decreased by a factor of 4).

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QuickCheck 35.2

If the f-number of a camera lens is doubled, say from F4.0 to F8.0, that means the diameter of the lens aperture is

A. Quadrupled (increased by a factor of 4).
B. Doubled (increased by a factor of 2).
✔**C. Halved (decreased by a factor of 2).** $f\text{-number} = f/D$
D. Quartered (decreased by a factor of 4).

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Controlling the Exposure

- Focal length and f-number information is stamped on a camera lens.
- This lens is labeled 5.8–23.2 mm 1:2.6–5.5.
- The first numbers are the range of focal lengths.

- They span a factor of 4, so this is a 4 × zoom lens.
- The second numbers show that the minimum f-number ranges from $f/2.6$ (for the $f = 5.8$ mm focal length) to $f/5.5$ (for the $f = 23.2$ mm focal length).

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QuickCheck 35.3

A camera gives a proper exposure when set to a shutter speed of 1/250 s at *f*-number F8.0. The photographer wants to change the shutter speed to 1/1000 s to prevent motion blur. To maintain proper exposure, she should also change the *f*-number to

A. F2.0
B. F4.0
C. F8.0
D. F16
E. F32

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QuickCheck 35.3

A camera gives a proper exposure when set to a shutter speed of 1/250 s at *f*-number F8.0. The photographer wants to change the shutter speed to 1/1000 s to prevent motion blur. To maintain proper exposure, she should also change the *f*-number to

A. F2.0
✔**B. F4.0**
C. F8.0
D. F16
E. F32

Light intensity goes up a factor of 2 when the *f*-number decreases by the square root of 2.

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Example 35.3 Capturing the Action

EXAMPLE 35.3 Capturing the action

Before a race, a photographer finds that she can make a perfectly exposed photo of the track while using a shutter speed of 1/250 s and a lens setting of *f*/8.0. To freeze the sprinters as they go past, she plans to use a shutter speed of 1/1000 s. To what *f*-number must she set her lens?

MODEL The exposure depends on $I\Delta t_{shutter}$, and the light intensity depends inversely on the square of the *f*-number.

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Example 35.3 Capturing the Action

EXAMPLE 35.3 Capturing the action

SOLVE Changing the shutter speed from 1/250 s to 1/1000 s will reduce the light reaching the detector by a factor of 4. To compensate, she needs to let 4 times as much light through the lens. Because $I \propto 1/(f\text{-number})^2$, the intensity will increase by a factor of 4 if she *decreases* the *f*-number by a factor of 2. Thus the correct lens setting is *f*/4.0.

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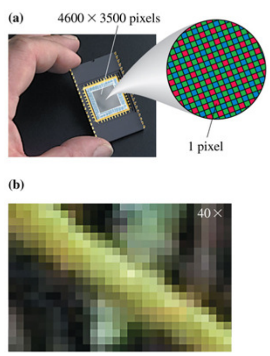
Slide 35-34

The Detector

- Figure (a) shows a CCD "chip."
- To record color information, different pixels are covered by red, green, or blue filters.
- The pixels are so small that the picture looks "smooth" even after some enlargement.
- As you can see in figure (b), sufficient magnification reveals the individual pixels.



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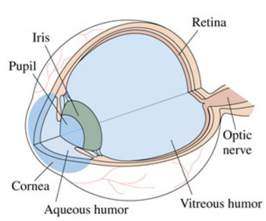
Slide 35-35

Vision

- The human eye is roughly spherical, about 2.4 cm in diameter.
- The transparent **cornea** and the *lens* are the eye's refractive elements.
- The eye is filled with a clear, jellylike fluid called the *aqueous humor* and the *vitreous humor*.



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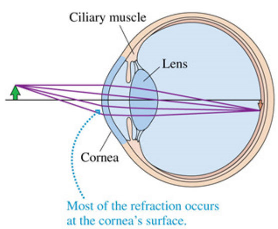
Slide 35-36

Vision

- The indices of refraction of the aqueous and vitreous humors are 1.34, only slightly different from water.
- The lens has an average index of 1.44.
- The **pupil**, a variable-diameter aperture in the **iris**, automatically opens and closes to control the light intensity.
- The *f*-number varies from roughly *f*/3 to *f*/16, very similar to a camera!



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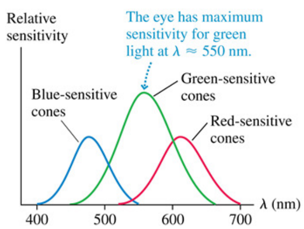
Color Vision

- The eye's detector, the retina, contains light-sensitive cells called cones.
- The figure shows the wavelength responses of the three types of cones in a human eye.



- The relative response of the different cones is interpreted by your brain as light of a particular color.
- Other animals, with slightly different retinal cells, can see ultraviolet or infrared wavelengths that we cannot see.

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Focusing and Accommodation

- The eye focuses by changing the focal length of the lens by using the *ciliary muscles* to change the curvature of the lens surface.
- Tensing the ciliary muscles causes **accommodation**, which decreases the lens's radius of curvature and thus decreases its focal length.

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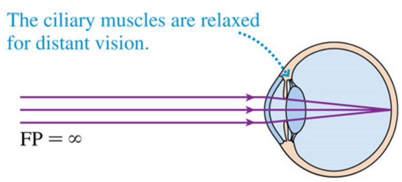
Focusing and Accommodation

- The farthest distance at which a relaxed eye can focus is called the eye's **far point** (FP).
- The far point of a normal eye is infinity; that is, the eye can focus on objects extremely far away.



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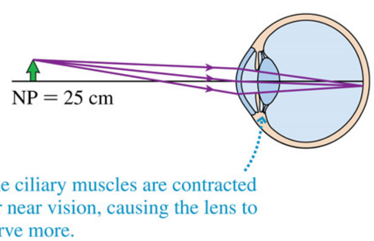
Focusing and Accommodation

- The closest distance at which an eye can focus, using maximum accommodation, is the eye's **near point** (NP).



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Corrective Lenses

- Corrective lenses are prescribed not by their focal length but by their power.
- The power of a lens is the inverse of its focal length:

$$\text{Power of a lens} = P = \frac{1}{f}$$

- The SI unit of lens power is the diopter, abbreviated D, defined as $1\ \text{D} = 1\ \text{m}^{-1}$.
- Thus a lens with $f = 50\ \text{cm} = 0.50\ \text{m}$ has power $P = 2.0\ \text{D}$.

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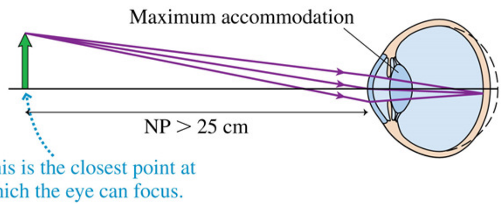
Hyperopia

- A person who is *farsighted* can see faraway objects (but even then must use some accommodation rather than a relaxed eye), but his near point is larger than 25 cm, often much larger, so he cannot focus on nearby objects.



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QuickCheck 35.4

If the near point of your eye is at 75 cm, you are

A. Nearsighted.
B. Farsighted.
C. Sharp-sighted.

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Slide 35-44

QuickCheck 35.4

If the near point of your eye is at 75 cm, you are

A. Nearsighted.
✔**B. Farsighted.**
C. Sharp-sighted.

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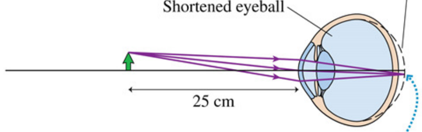
Slide 35-45

Hyperopia

- The cause of farsightedness—called **hyperopia**—is an eyeball that is too short for the refractive power of the cornea and lens.



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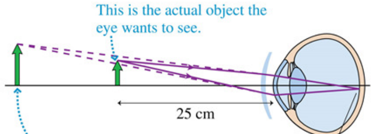
Hyperopia

- With hyperopia, the eye needs assistance to focus the rays from a near object onto the closer-than-normal retina.
- This assistance is obtained by adding refractive power with the positive (i.e., converging) lens.



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Example 35.4 Correcting Hyperopia

EXAMPLE 35.4 **Correcting hyperopia**

Sanjay has hyperopia. The near point of his left eye is 150 cm. What prescription lens will restore normal vision?

MODEL Normal vision will allow Sanjay to focus on an object 25 cm away. In measuring distances, we'll ignore the small space between the lens and his eye.

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Example 35.4 Correcting Hyperopia

EXAMPLE 35.4 **Correcting hyperopia**

SOLVE Because Sanjay can see objects at 150 cm, using maximum accommodation, we want a lens that creates a virtual image at position $s' = -150$ cm (negative because it's a virtual image) of an object held at $s = 25$ cm. From the thin-lens equation,

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'} = \frac{1}{0.25\text{ m}} + \frac{1}{-1.50\text{ m}} = 3.3\text{ m}^{-1}$$

$1/f$ is the lens power, and m^{-1} are diopters. Thus the prescription is for a lens with power $P = 3.3$ D.

ASSESS Hyperopia is always corrected with a converging lens.

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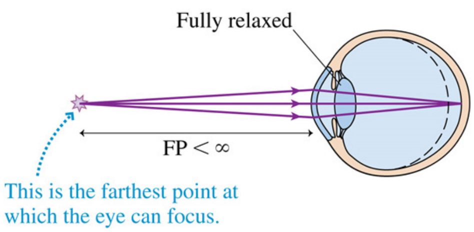
Myopia

- A person who is *nearsighted* can clearly see nearby objects when the eye is relaxed (and extremely close objects by using accommodation), but no amount of relaxation allows her to see distant objects.



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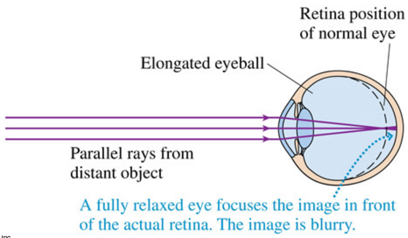
Myopia

- Nearsightedness—called **myopia**—is caused by an eyeball that is too long.
- Rays from a distant object come to a focus in front of the retina and have begun to diverge by the time they reach the retina.



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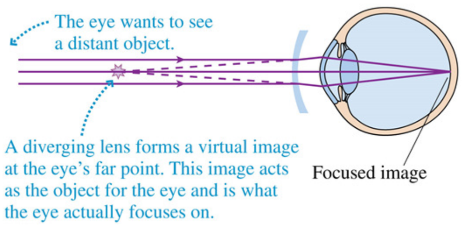
Myopia

- To correct myopia, we needed a diverging lens to slightly defocus the rays and move the image point back to the retina.



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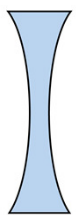
QuickCheck 35.5

If your vision is improved with lenses that look like this:



then you must have

A. Presbyopia.
B. Hyperopia.
C. Transopia.
D. Myopia.

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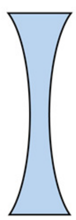
Slide 35-53

QuickCheck 35.5

If your vision is improved with lenses that look like this:



then you must have

A. Presbyopia.
B. Hyperopia.
C. Transopia.
✔**D. Myopia.**

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Slide 35-54

Example 35.5 Correcting Myopia

EXAMPLE 35.5 **Correcting myopia**

Martina has myopia. The far point of her left eye is 200 cm. What prescription lens will restore normal vision?

MODEL Normal vision will allow Martina to focus on a very distant object. In measuring distances, we'll ignore the small space between the lens and her eye.

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Slide 35-55

Example 35.5 Correcting Myopia

EXAMPLE 35.5 **Correcting myopia**

SOLVE Because Martina can see objects at 200 cm with a fully relaxed eye, we want a lens that will create a virtual image at position $s' = -200$ cm (negative because it's a virtual image) of a distant object at $s = \infty$ cm. From the thin-lens equation,

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'} = \frac{1}{\infty\,\text{m}} + \frac{1}{-2.0\,\text{m}} = -0.5\,\text{m}^{-1}$$

Thus the prescription is for a lens with power $P = -0.5$ D.

ASSESS Myopia is always corrected with a diverging lens.

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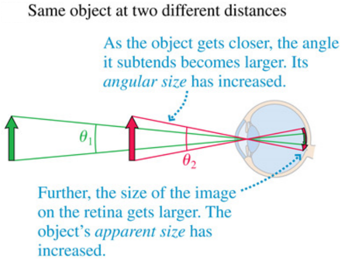
Slide 35-56

Optical Systems That Magnify

- The easiest way to magnify an object requires no extra optics at all: Simply get closer!
- Closer objects look larger because they subtend a larger angle θ, called the **angular size** of the object.

Same object at two different distances



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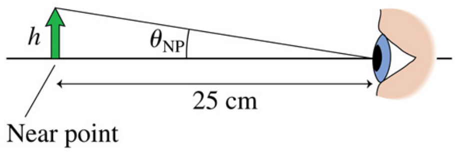
Slide 35-57

Optical Systems That Magnify

- You can’t keep increasing an object’s angular size because you can’t focus on the object if it’s closer than your near point, which is ≈ 25 cm.
- The maximum angular size viewable by your unaided eye is

$$\theta_{NP} = \frac{h}{25\text{ cm}}$$



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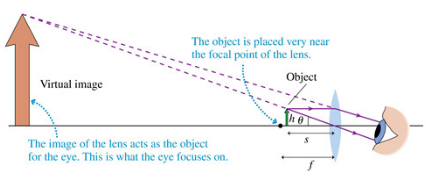
Slide 35-58

The Magnifier

- Suppose we view an object of height h through a single converging lens.
- If the object’s distance from the lens is less than the lens’s focal length, we’ll see an enlarged, upright image.
- Used in this way, the lens is called a **magnifier**.



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Slide 35-59

The Magnifier

- When using a magnifier, your eye sees a virtual image subtending an angle $\theta = h/s$.
- If we place the image at a distance $s' \approx \infty$ the object distance is $s \approx f$, so

$$\theta = \frac{h}{s} \approx \frac{h}{f}$$

- Angular magnification is the ratio of the apparent size of the object when using a magnifying lens rather than simply holding the object at your near point:

$$M = \theta/\theta_{NP}$$

- Combining these equations, we find the angular magnification of a magnifying glass is

$$M = \frac{25\text{ cm}}{f}$$

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Slide 35-60

QuickCheck 35.6

If you view a bug with magnifying lens having a 12.5 cm focal length, then

A. The lateral magnification is 2, the angular magnification is 2.
B. The lateral magnification is ∞, the angular magnification is 2.
C. The lateral magnification is 2, the angular magnification is ∞.
D. The lateral magnification is ∞, the angular magnification is ∞.

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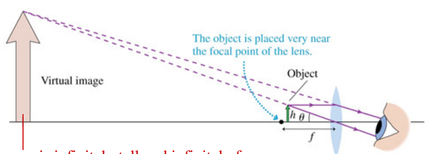
Slide 35-61

QuickCheck 35.6

If you view a bug with magnifying lens having a 12.5 cm focal length, then

A. The lateral magnification is 2, the angular magnification is 2.
✔**B. The lateral magnification is ∞, the angular magnification is 2.**
C. The lateral magnification is 2, the angular magnification is ∞.
D. The lateral magnification is ∞, the angular magnification is ∞.



Ideally, the image is infinitely tall and infinitely far away, making the lateral magnification ∞. But the image still subtends a finite angle, so the angular magnification is not ∞.

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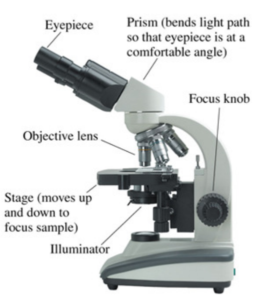
Slide 35-62

The Microscope



- A microscope, whose major parts are shown in the figure, can attain a magnification of up to $1000\times$ by a *two-step* magnification process.
- A specimen to be observed is placed on the *stage* of the microscope, directly beneath the **objective**, a converging lens with a relatively short focal length.
- The objective creates a magnified real image that is further enlarged by the **eyepiece**.

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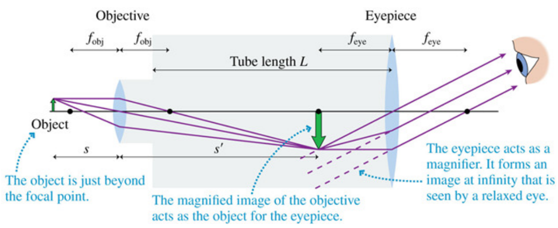
Slide 35-63

The Microscope



- This is a simple two-lens model of a microscope.
- The object is placed just outside the focal point of the objective, which creates a highly magnified real image with lateral magnification $m = -s'/s$.

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The Microscope

- The lateral magnification of the objective is

$$m_{obj} = -\frac{s'}{s} \approx -\frac{L}{f_{obj}}$$

- Together, the objective and eyepiece produce a total angular magnification:

$$M = m_{obj}M_{eye} = -\frac{L}{f_{obj}}\frac{25\text{ cm}}{f_{eye}}$$

- The minus sign shows that the image seen in a microscope is inverted.
- Most biological microscopes are standardized with a tube length $L = 160$ mm.

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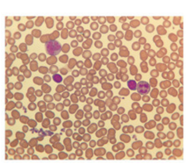
Example 35.6 Viewing Blood Cells

EXAMPLE 35.6 | **Viewing blood cells**

A pathologist inspects a sample of 7-μm-diameter human blood cells under a microscope. She selects a 40× objective and a 10× eyepiece. What size object, viewed from 25 cm, has the same apparent size as a blood cell seen through the microscope?



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Example 35.6 Viewing Blood Cells

EXAMPLE 35.6 Viewing blood cells

MODEL Angular magnification compares the magnified angular size to the angular size seen at the near-point distance of 25 cm.

SOLVE The microscope's angular magnification is $M = -(40) \times (10) = -400$. The magnified cells will have the same apparent size as an object $400 \times 7\ \mu\text{m} \approx 3$ mm in diameter seen from a distance of 25 cm.

ASSESS 3 mm is about the size of a capital O in this textbook, so a blood cell seen through the microscope will have about the same apparent size as an O seen from a comfortable reading distance.

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The Telescope

- A simple telescope contains a large-diameter objective lens that collects parallel rays from a distant object and forms a real, inverted image at distance $s' = f_{obj}$.
- The focal length of a telescope objective is very nearly the length of the telescope tube.
- The eyepiece functions as a simple magnifier.
- The viewer observes an inverted image.
- The angular magnification of a telescope is

$$M = \frac{\theta_{eye}}{\theta_{obj}} = -\frac{f_{obj}}{f_{eye}}$$

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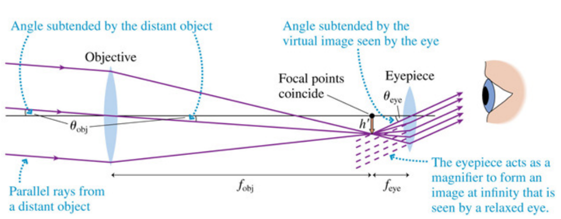
A Refracting Telescope



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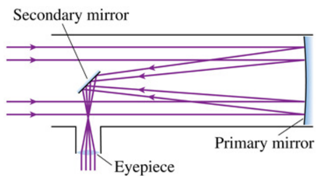
Telescopes

- Large light-gathering power requires a large-diameter objective lens, but large lenses are not practical; they begin to sag under their own weight.
- Thus **refracting telescopes**, with two lenses, are relatively small.
- Serious astronomy is done with a **reflecting telescope**, such as the one shown in the figure.



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QuickCheck 35.7

If you increase the diameter of a telescope's objective lens (and, of course, increase the diameter of the tube) with no other changes, then the telescope will have

A. A larger magnification; more light-collecting power.
B. The same magnification; more light-collecting power.
C. A smaller magnification; more light-collecting power.
D. A larger magnification; the same light-collecting power.
E. A smaller magnification; the same light-collecting power.

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QuickCheck 35.7

If you increase the diameter of a telescope's objective lens (and, of course, increase the diameter of the tube) with no other changes, then the telescope will have

A. A larger magnification; more light-collecting power.
✔**B. The same magnification; more light-collecting power.**
C. A smaller magnification; more light-collecting power.
D. A larger magnification; the same light-collecting power.
E. A smaller magnification; the same light-collecting power.

Magnification depends only on the lens's focal length, which didn't change, not on its diameter.

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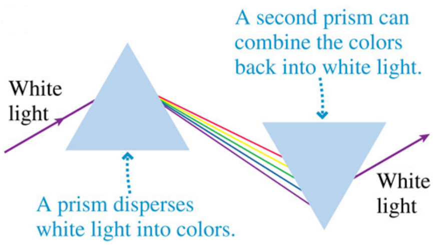
Color and Dispersion

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



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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.

TABLE 35.1 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

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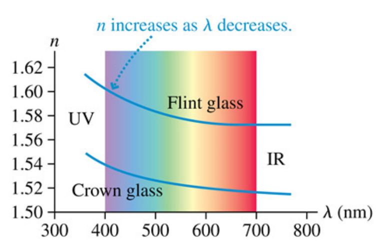
Dispersion

- 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.



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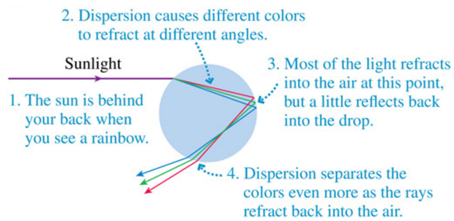
Rainbows

- 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.



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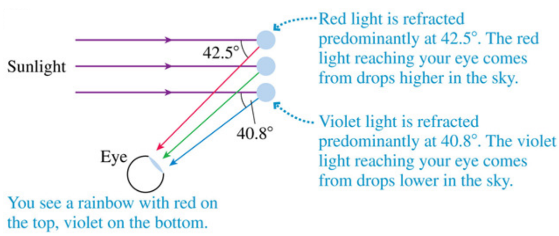
Rainbows

- 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.



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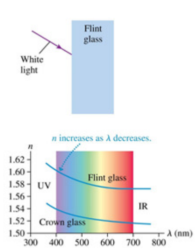
QuickCheck 35.8

A narrow beam of white light is incident at an angle on a piece of flint glass. As the light refracts into the glass,

A. It forms a slightly diverging cone with red rays on top, violet rays on the bottom.
B. It forms a slightly diverging cone with violet rays on top, red rays on the bottom.
C. It remains a narrow beam of white light because all the colors of white were already traveling in the same direction.



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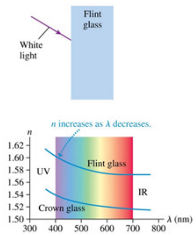
QuickCheck 35.8

A narrow beam of white light is incident at an angle on a piece of flint glass. As the light refracts into the glass,

✔ **A. It forms a slightly diverging cone with red rays on top, violet rays on the bottom.**

B. It forms a slightly diverging cone with violet rays on top, red rays on the bottom.

C. It remains a narrow beam of white light because all the colors of white were already traveling in the same direction.



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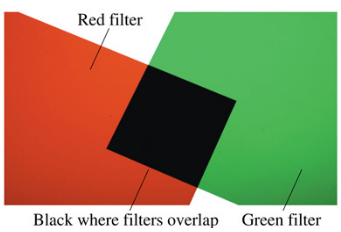
Colored Filters and Colored Objects

- 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."



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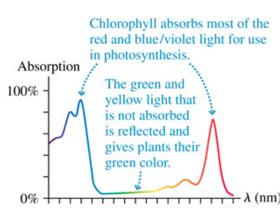
Colored Filters and Colored Objects

- 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.



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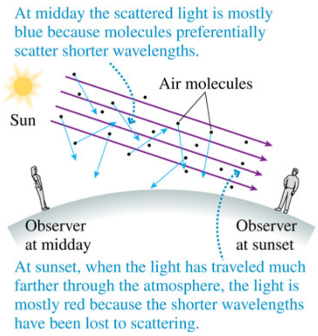
Light Scattering: Blue Skies and Red Sunsets

- 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:

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



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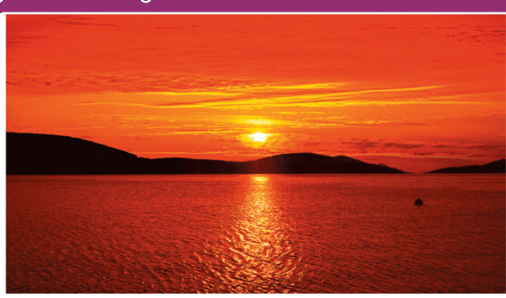
Light Scattering: Blue Skies and Red Sunsets



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

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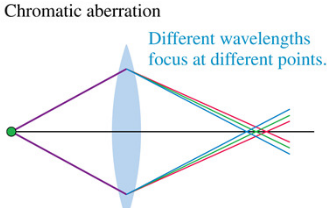
Chromatic Aberration

- Any actual glass lens has dispersion, that is, its index of refraction varies slightly with wavelength.
- Consequently, different colors of light come to a focus at slightly different distances from the lens.
- This is called **chromatic aberration**.

Chromatic aberration



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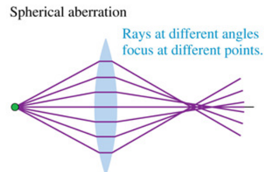
Spherical Aberration

- Our analysis of thin lenses was based on paraxial rays traveling nearly parallel to the optical axis.
- Rays incident on the outer edges of a spherical surface are not focused at exactly the same point as rays incident near the center.
- This imaging error, shown below, is called **spherical aberration**.



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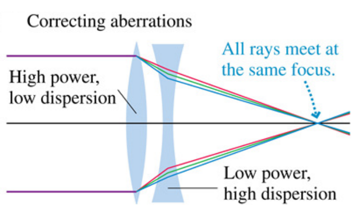
Correcting Aberrations

- A *combination lens* uses lenses of different materials and focal lengths in order to partly correct for chromatic and spherical aberration.
- Most optical instruments use combination lenses rather than single lenses.



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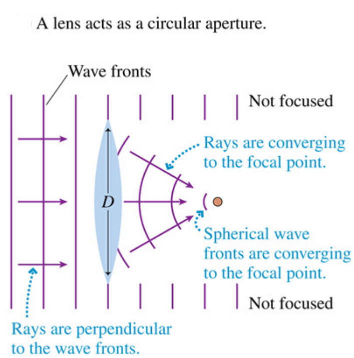
Slide 35-86

Circular Lens Diffraction

- A lens acts as a circular aperture of diameter D.
- Consequently, the lens focuses and *diffracts* the light wave.



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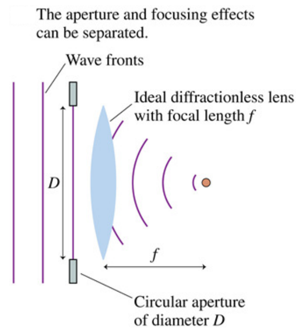
Circular Lens Diffraction

- A lens can be modeled as an aperture followed by an ideal lens.
- You learned in Chapter 33 that a circular aperture produces a diffraction pattern with a bright central maximum surrounded by dimmer fringes.



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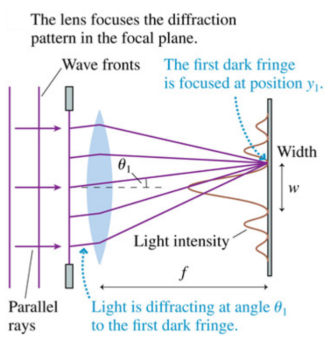
Circular Lens Diffraction

- A converging lens brings the diffraction pattern to a focus in the image plane.
- As a result, a perfect lens focuses parallel light rays not to a perfect point of light, but to a small, circular diffraction pattern.



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Circular Lens Diffraction

- The minimum spot size to which a lens can focus light of wavelength λ is

$$w_{min} \approx 2f\theta_1 = \frac{2.44\lambda f}{D} \qquad \text{(minimum spot size)}$$

  where D is the diameter of the circular aperture of the lens, and f is the focal length.
- In order to resolve two points, their angular separation must be greater than λ_{min}, where

$$\theta_{min} = \frac{1.22\lambda}{D} \qquad \text{(angular resolution of a lens)}$$

  is called the **angular resolution** of the lens.

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QuickCheck 35.9

To focus light to the smallest possible spot, you should choose a lens with

A. The largest focal length and the largest diameter.
B. The largest focal length and the smallest diameter.
C. The smallest focal length and the largest diameter.
D. The smallest focal length and the smallest diameter.

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Slide 35-91

QuickCheck 35.9

To focus light to the smallest possible spot, you should choose a lens with

A. The largest focal length and the largest diameter.
B. The largest focal length and the smallest diameter.
✔**C. The smallest focal length and the largest diameter.**
D. The smallest focal length and the smallest diameter.

$$w_{\text{min}} = \frac{2.44\lambda f}{D}$$

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Slide 35-92

Example 35.8 Seeing Stars

EXAMPLE 35.8 Seeing stars

A 12-cm-diameter telescope lens has a focal length of 1.0 m. What is the diameter of the image of a star in the focal plane if the lens is diffraction limited *and* if the earth's atmosphere is not a limitation?

MODEL Stars are so far away that they appear as points in space. An ideal diffractionless lens would focus their light to arbitrarily small points. Diffraction prevents this. Model the telescope lens as a 12-cm-diameter aperture in front of an ideal lens with a 1.0 m focal length.

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Example 35.8 Seeing Stars

EXAMPLE 35.8 Seeing stars

SOLVE The minimum spot size in the focal plane of this lens is

$$w = \frac{2.44\lambda f}{D}$$

where D is the lens diameter. What is λ? Because stars emit white light, the *longest* wavelengths spread the most and determine the size of the image that is seen. If we use $\lambda = 700$ nm as the approximate upper limit of visible wavelengths, we find $w = 1.4 \times 10^{-5}$ m $= 14\ \mu$m.

ASSESS This is certainly small, and it would appear as a point to your unaided eye. Nonetheless, the spot size would be easily noticed if it were recorded on film and enlarged. Turbulence and temperature effects in the atmosphere, the causes of the "twinkling" of stars, prevent ground-based telescopes from being this good, but space-based telescopes really are diffraction limited.

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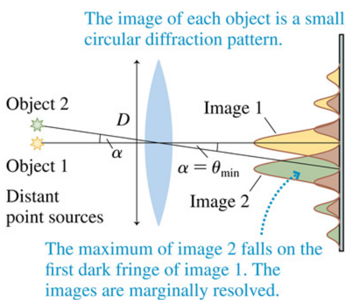
The Resolution of Optical Instruments

- The figure shows two distant point sources being imaged by a lens of diameter D.
- **Rayleigh's criterion** determines how close together two diffraction patterns can be before you can no longer distinguish them.



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Rayleigh's Criterion

- The angular separation between two distant point sources of light is α.
- Rayleigh's criterion states that the two objects are **resolvable** if $\alpha > \theta_{min}$, where

$$\theta_{min} = \frac{1.22\lambda}{D} \quad \text{(angular resolution of a lens)}$$

- Resolved point sources:

Resolved

$\alpha > \theta_{min}$

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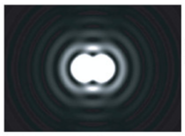
Rayleigh's Criterion

- The angular separation between two distant point sources of light is α.
- Rayleigh's criterion states that the two objects are **marginally resolvable** if $\alpha = \theta_{min}$, where

$$\theta_{\min} = \frac{1.22\lambda}{D} \quad \text{(angular resolution of a lens)}$$

- The central maximum of one image falls exactly on top of the first dark fringe of the other image.
- Marginally resolved point sources:



Marginally resolved

$\alpha = \theta_{\min}$

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Rayleigh's Criterion

- The angular separation between two distant point sources of light is α.
- Rayleigh's criterion states that the two objects are **not resolvable** if $\alpha < \theta_{min}$, because their diffraction patterns are too overlapped:

$$\theta_{\min} = \frac{1.22\lambda}{D} \quad \text{(angular resolution of a lens)}$$

- Unresolved point sources:

Not resolved

$\alpha < \theta_{\min}$

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QuickCheck 35.10

Two distant stars are only marginally resolved when viewed through a telescope having a $10\times$ eyepiece and a filter that passes only light with a wavelength near 500 nm. One way to better resolve the stars would be to

A. Use an eyepiece with a larger magnification.

B. Use an eyepiece with a smaller magnification.

C. View the stars using infrared wavelengths.

D. View the stars using ultraviolet wavelengths.

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Slide 35-99

QuickCheck 35.10

Two distant stars are only marginally resolved when viewed through a telescope having a $10\times$ eyepiece and a filter that passes only light with a wavelength near 500 nm. One way to better resolve the stars would be to

A. Use an eyepiece with a larger magnification.

B. Use an eyepiece with a smaller magnification.

C. View the stars using infrared wavelengths.

✔**D. View the stars using ultraviolet wavelengths.**

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Chapter 35 Summary Slides

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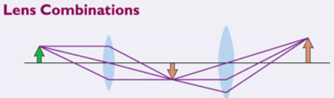
Important Concepts

Lens Combinations



The image of the first lens acts as the object for the second lens.

Lens **power:** $P = \frac{1}{f}$ diopters, $1\text{ D} = 1\text{ m}^{-1}$

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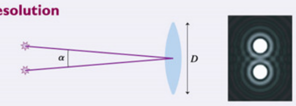
Important Concepts

Resolution



The **angular resolution** of a lens of diameter D is

$$\theta_{min} = 1.22\lambda/D$$

Rayleigh's criterion states that two objects separated by an angle α are marginally resolvable if $\alpha = \theta_{min}$.

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Applications

Cameras

Form a real, inverted image on a detector. The lens's ***f*-number** is

$$f\text{-number} = \frac{f}{D}$$

The light intensity on the detector is

$$I \propto \frac{1}{(f\text{-number})^2}$$

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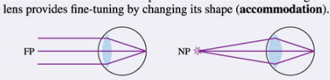
Applications

Vision

Refraction at the cornea is responsible for most of the focusing. The lens provides fine-tuning by changing its shape (**accommodation**).



In normal vision, the eye can focus from a far point (FP) at ∞ (relaxed eye) to a near point (NP) at $\approx$ 25 cm (maximum accommodation).

- **Hyperopia** (farsightedness) is corrected with a converging lens.
- **Myopia** (nearsightedness) is corrected with a diverging lens.

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Applications

Magnifiers

For relaxed-eye viewing, the angular magnification is

$$M = \frac{25\text{ cm}}{f}$$

For microscopes and telescopes, angular magnification, not lateral magnification, is the important characteristic. The eyepiece acts as a magnifier to view the image formed by the objective lens.

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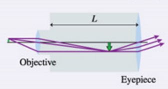
Applications

Microscopes

The object is very close to the focal point of the objective.

The total angular magnification is $M \approx -\frac{L}{f_{obj}}\frac{25\text{ cm}}{f_{eye}}$.



The best possible spatial resolution of a microscope, limited by diffraction, is about one wavelength of light.

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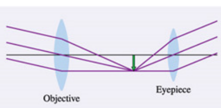
Applications

Telescopes

The object is very far from the objective.



The total angular magnification is $M = -\frac{f_{obj}}{f_{eye}}$.

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Applications

Focusing and spatial resolution

The minimum spot size to which a lens of focal length f and diameter D can focus light is limited by diffraction to

$$w_{min} = \frac{2.44\lambda f}{D}$$

With the best lenses that can be manufactured, $w_{min} \approx \lambda$.

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