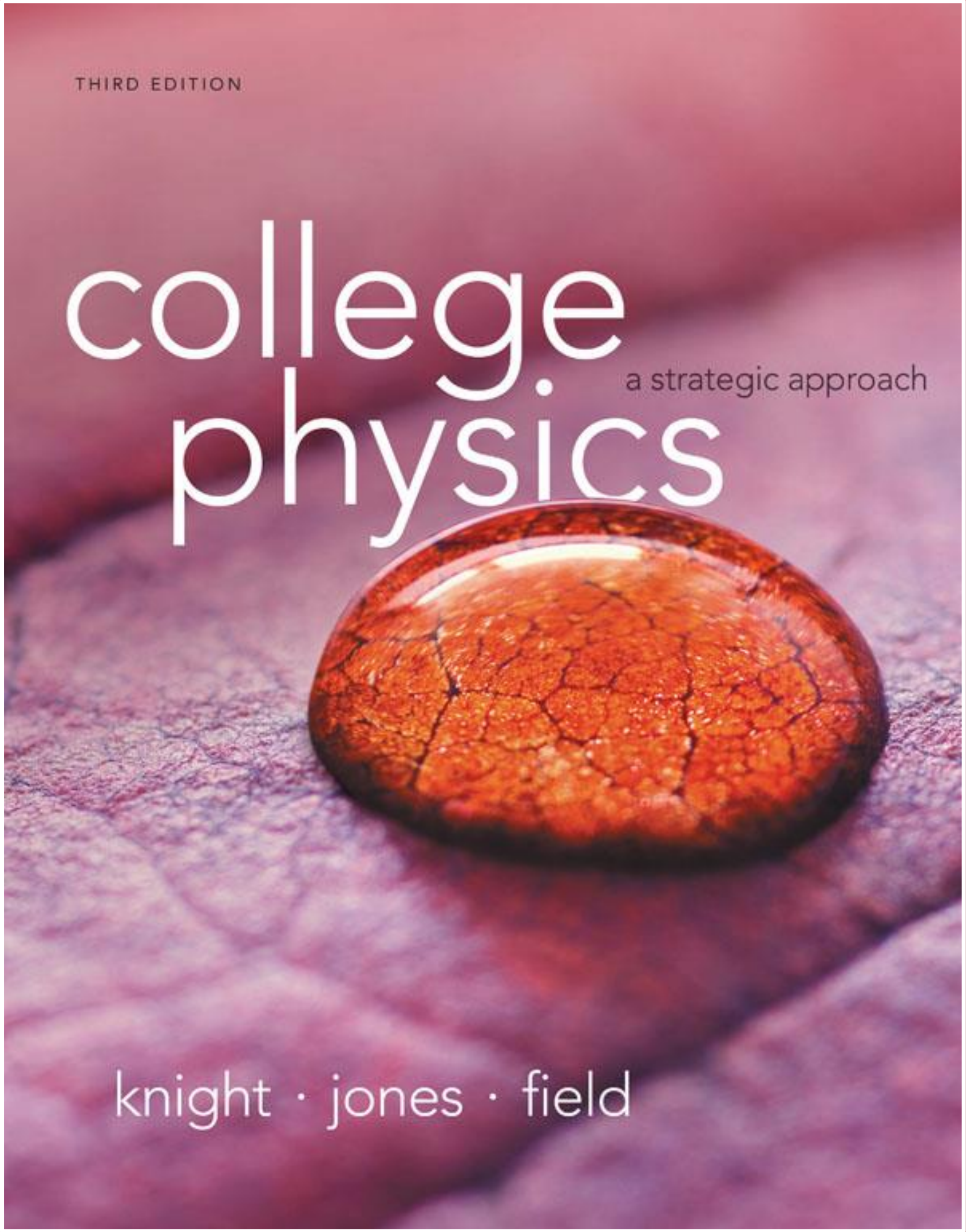


Lecture Presentation

Chapter 19

Optical Instruments

Suggested Videos for Chapter 19

- **Prelecture Videos**
  - *The Camera and the Eye*
  - *Optical Instruments*
  - *Resolution and Dispersion*
- **Class Videos**
  - *Telephoto Lens*
  - *The Eye*
  - *Vision Differences*
  - *Biological Mirrors (Part V Summary)*
- **Video Tutor Solutions**
  - *Optical Instruments*

Suggested Simulations for Chapter 19

- **ActivPhysics**
  - *15.12*
  - *16.8*

- **PhETs**
  - *Geometric Optics*
  - *Color Vision*

Chapter 19 Optical Instruments

Chapter Goal: To understand how common optical instruments work.

Chapter 19 Preview
Looking Ahead: The Human Eye

- Our most important optical instruments are our own eyes, which use a lens to focus light onto the light-sensitive retina.

- You'll learn how near- and farsightedness can be corrected using eyeglasses or contact lenses.

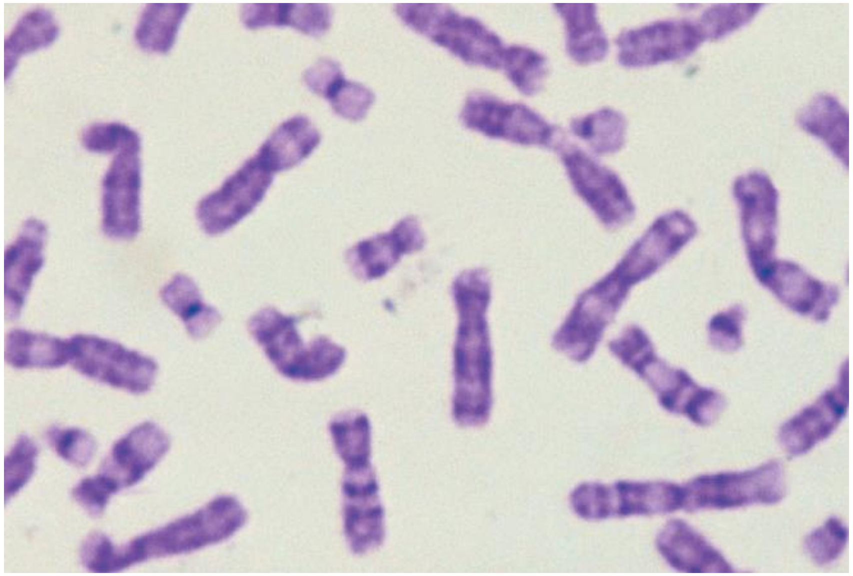
Chapter 19 Preview
Looking Ahead: Optical Instruments

- A converging lens is the simplest magnifier. We'll also study microscopes and telescopes.

- You'll learn how optical instruments can be designed to magnify objects up to a thousand times.

Chapter 19 Preview
Looking Ahead: Optical Resolution

- This magnified image of chromosomes is slightly blurry because of a limit to the microscope's **resolution** due to diffraction.



- You'll learn that a microscope cannot resolve features much smaller than the wavelength of light.

Chapter 19 Preview
Looking Ahead

The Human Eye

Our most important optical instruments are our own eyes, which use a lens to focus light onto the light-sensitive retina.

You'll learn how near- and farsightedness can be corrected using eyeglasses or contact lenses.

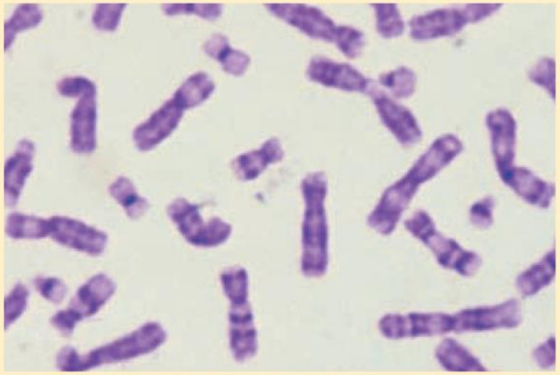
Optical Instruments

A converging lens is the simplest magnifier. We'll also study microscopes and telescopes.

You'll learn how optical instruments can be designed to magnify objects up to a thousand times.

Optical Resolution

This magnified image of chromosomes is slightly blurry because of a limit to the microscope's **resolution** due to diffraction.

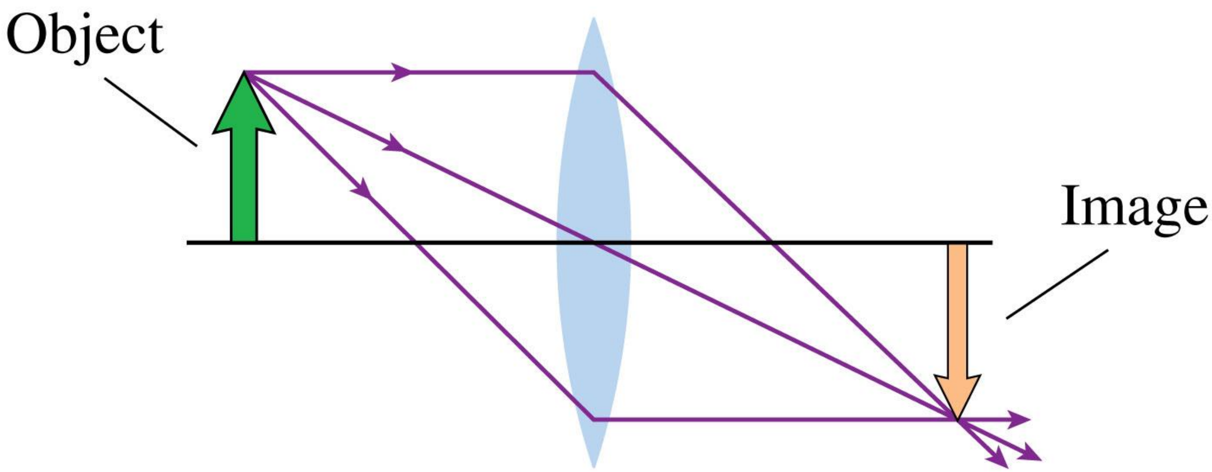


You'll learn that a microscope cannot resolve features much smaller than the wavelength of light.

Text: p. 600

Chapter 19 Preview
Looking Back: Image Formation by Lenses

- In Section 18.5, you learned how a single lens can form a real image of an object. In this chapter, we'll study how *combinations* of two lenses can form highly magnified images, such as those in microscopes and telescopes.
- A real image is one through which light rays actually pass. It's on the opposite side of the lens from the object.



Chapter 19 Preview
Stop to Think

A converging lens creates a real, inverted image. For this to occur, the object must be

A. Closer to the lens than the focal point.
B. Farther from the lens than the focal point.
C. At the focal point.

Reading Question 19.1

The units of refractive power are

A. Watts
B. m^2
C. m^{-1}
D. Joules

Reading Question 19.1

The units of refractive power are

A. Watts
B. m^2
C. m^{-1}
D. Joules

Reading Question 19.2

Accommodation of the eye refers to its ability to

A. Focus on both nearby and distant objects.
B. Move in the eye socket to look in different directions.
C. See on both the brightest days and in the dimmest light.
D. See both in air and while under water.

Reading Question 19.2

Accommodation of the eye refers to its ability to

✔ A. Focus on both nearby and distant objects.
B. Move in the eye socket to look in different directions.
C. See on both the brightest days and in the dimmest light.
D. See both in air and while under water.

Reading Question 19.3

In the way that a magnifier is usually used, the object is placed

A. At the focal point of the lens.
B. At the near point of the eye.
C. At the far point of the eye.
D. In contact with the lens.

Reading Question 19.3

In the way that a magnifier is usually used, the object is placed

✔ A. At the focal point of the lens.
B. At the near point of the eye.
C. At the far point of the eye.
D. In contact with the lens.

Reading Question 19.4

The magnification of a microscope is increased when

A. The focal length of the objective lens is increased.
B. The focal length of the objective lens is decreased.
C. The focal length of the eyepiece is increased.
D. The distance between the objective lens and eyepiece is decreased.

Reading Question 19.4

The magnification of a microscope is increased when

A. The focal length of the objective lens is increased.
✔ B. The focal length of the objective lens is decreased.
C. The focal length of the eyepiece is increased.
D. The distance between the objective lens and eyepiece is decreased.

Reading Question 19.5

The fundamental resolution of an optical instrument is set by

A. The accuracy to which lenses can be polished.
B. The fact that white light is composed of all visible colors.
C. The fact that all types of glass have nearly the same index of refraction.
D. The wave nature of light.

Reading Question 19.5

The fundamental resolution of an optical instrument is set by

A. The accuracy to which lenses can be polished.
B. The fact that white light is composed of all visible colors.
C. The fact that all types of glass have nearly the same index of refraction.
✔ D. The wave nature of light.

Section 19.1 The Camera

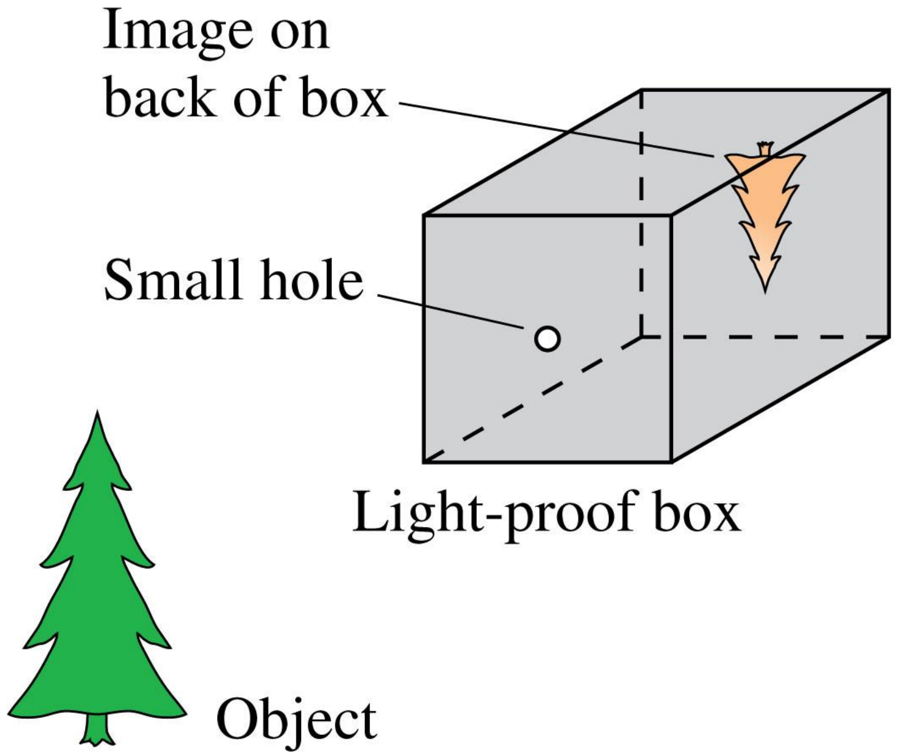
The Camera

- A **camera** is a device that projects a real image onto a plane surface, where the image can be recorded onto film or an electronic detector.

The Camera

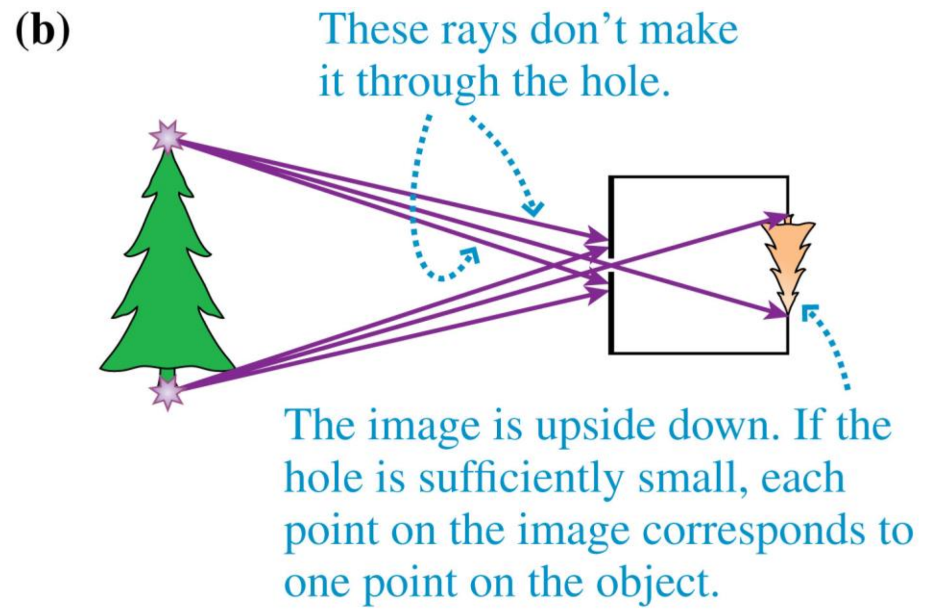
- A **pinhole camera** is a lightproof box with a small hole punched in it.
- If the hole is sufficiently small, it allows only one light ray from each point of an object to enter the box.

(a)



The Camera

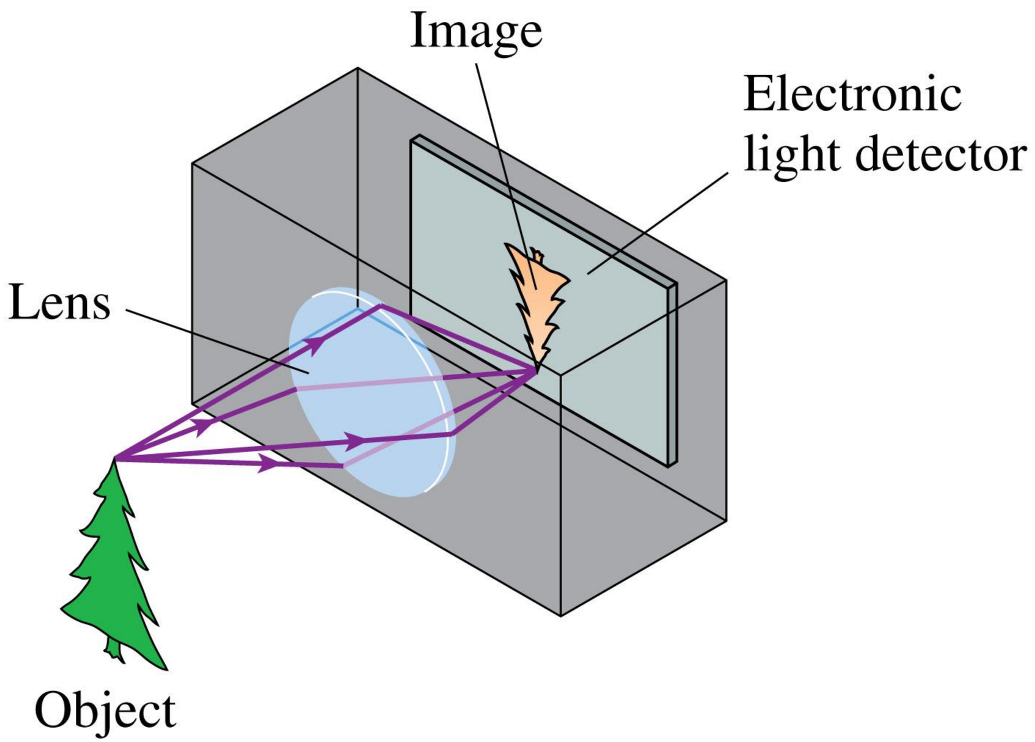
- Each point thus illuminates one small patch on the film inside the box, creating an image.
- Maximum sharpness is achieved by making the hole smaller, which also makes the image dimmer.



- Practical pinhole cameras therefore produce images with some blur or that are otherwise are too dark.

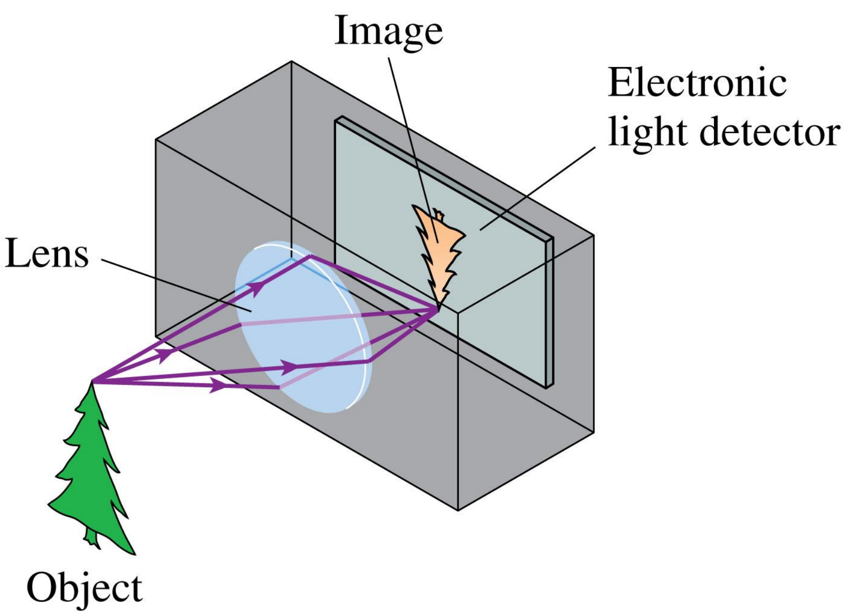
The Camera

- Standard cameras use a converging lens to project a real image onto its electronic detector.
- Lenses can be large, letting in a lot of light and still giving a sharply focused image.



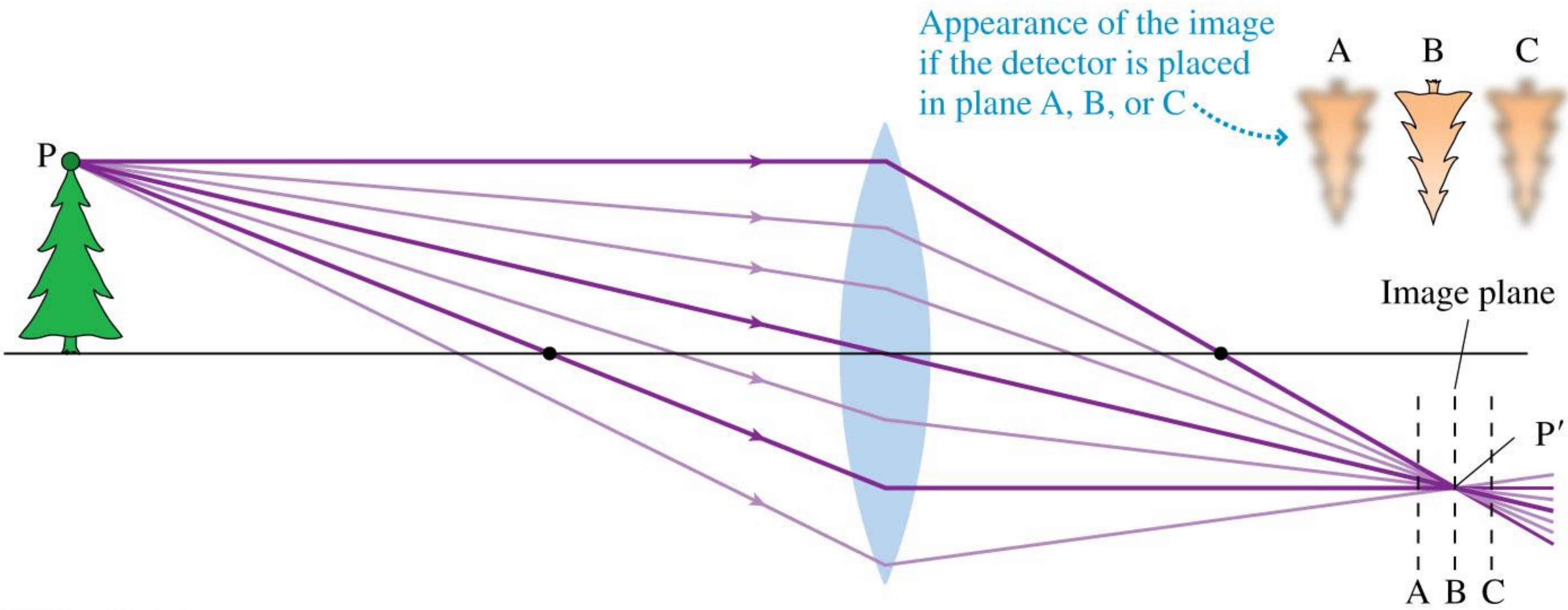
The Camera

- The *shutter* is an opaque barrier briefly moved out of the way to allow light to pass through the lens.
- The *diaphragm* is a set of leaves that can move in from outside the lens to effectively reduce the size of the lens, controlling the amount of light that reaches the detector.



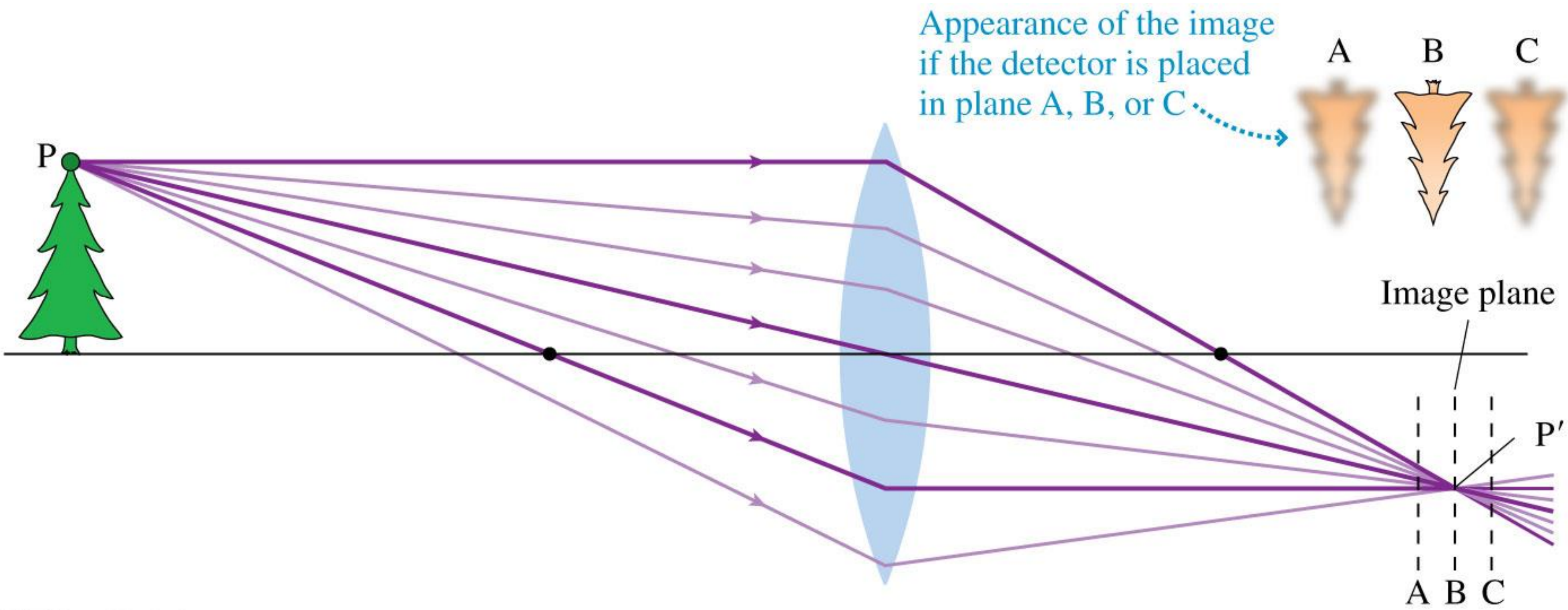
The Camera

- If the electronic detector is located on the image plane, then a sharp image will form on it.



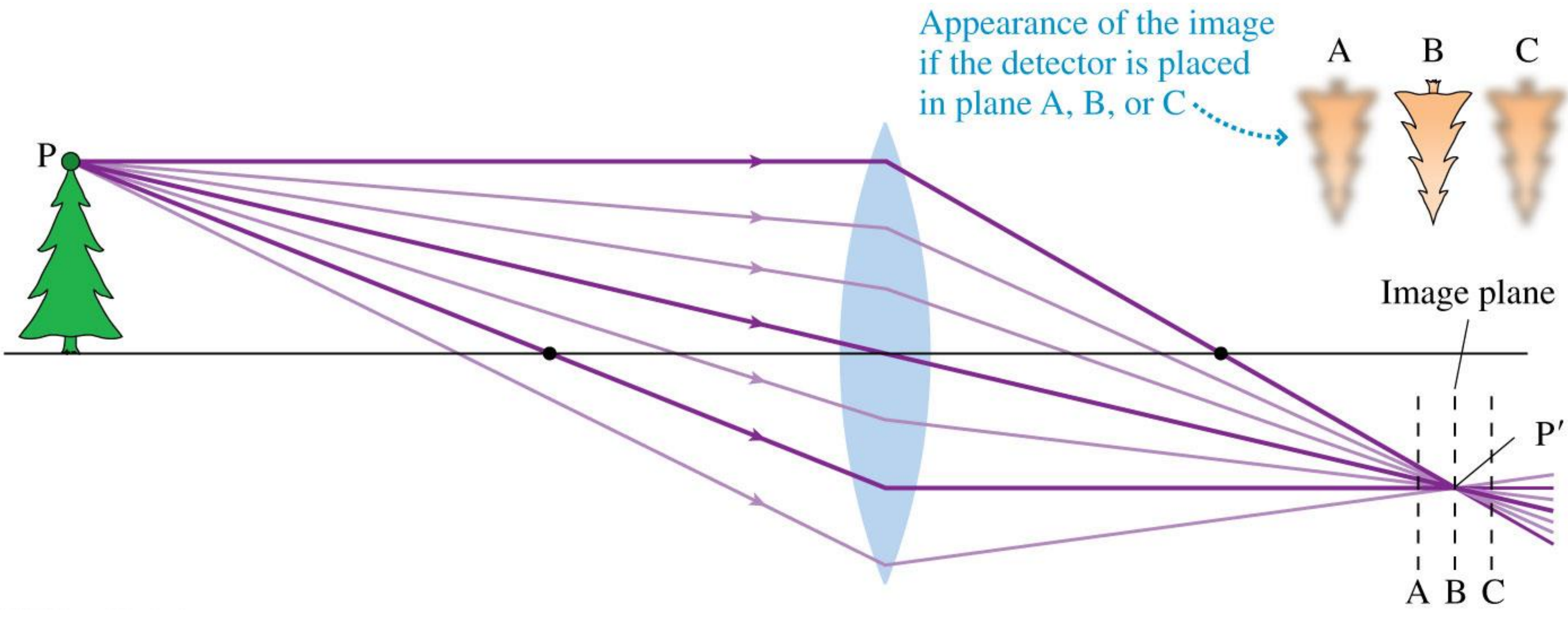
The Camera

- If the electronic detector is located in *front* of the image plane, the rays have not converged and would form a small blurry *circle* instead of a sharp point.



The Camera

- If the detector is located *behind* the image plane, the rays would be diverging and again create a blurry image.



The Camera

- Rather than move the detector, a camera is **focused** by moving the *lens*.

QuickCheck 19.1

Your camera is focused on a distant mountain. Now you want to focus on a nearby flower. You'll need to

A. Move the lens closer to the film.
B. Move the lens farther from the film.
C. You won't need to move the lens at all.

QuickCheck 19.1

Your camera is focused on a distant mountain. Now you want to focus on a nearby flower. You'll need to

A. Move the lens closer to the film.

✔ B. Move the lens farther from the film.

C. You won't need to move the lens at all.

Example 19.1 Focusing a camera

A digital camera whose lens has a focal length of 8.0 mm is used to take a picture of an object 30 cm away. What must be the distance from the lens to the light-sensitive detector in order for the image to be in focus?

PREPARE As shown in Figure 19.3, the image will be in focus when the detector is in the image plane. Thus we need to find the image distance, knowing the object distance $s = 30$ cm and the lens's focal length $f = 8.0$ mm.

Example 19.1 Focusing a camera (cont.)

SOLVE We can rearrange the thin-lens equation, Equation 18.11, to solve for the image distance s':

$$\frac{1}{s'} = \frac{1}{f} - \frac{1}{s} = \frac{1}{0.0080\ \text{m}} - \frac{1}{0.30\ \text{m}} = 122\ \text{m}^{-1}$$

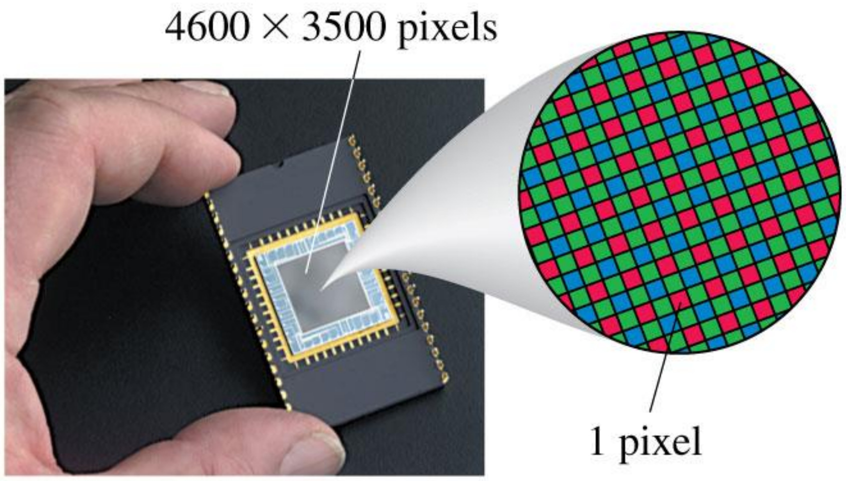
Thus $s' = 1/122\ \text{m}^{-1} = 0.0082\ \text{m} = 8.2\ \text{mm}$. The lens-detector distance has to be 8.2 mm.

Example 19.1 Focusing a camera (cont.)

ASSESS When the object is infinitely far away, the image, by definition, is at the focal length: $s' = f = 8.0$ mm. If the object is brought to 30 cm, the lens has to move forward a distance of only 8.2 mm – 8.0 mm = 0.2 mm to bring the object into focus. In general, camera lenses don't need to move far.

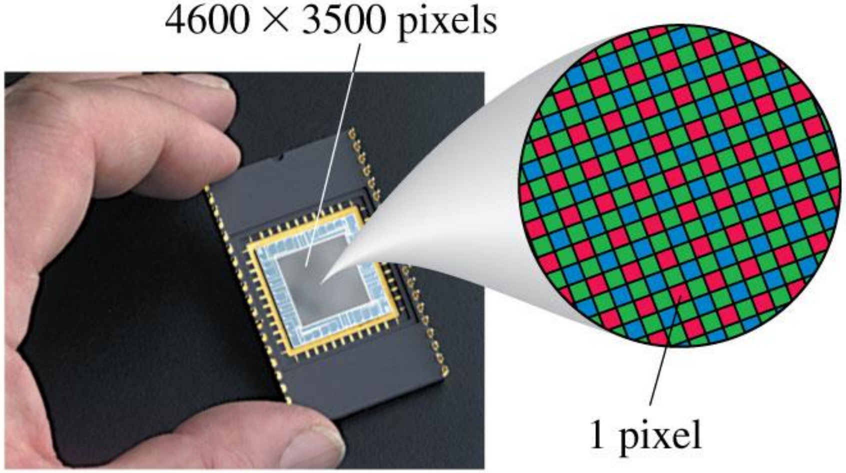
The Camera

- To record the image, digital cameras use a *charge-coupled device* or **CCD**.
- A CCD consists of an array of millions of detectors called *pixels*.
- When light hits a pixel, it generates an electronic charge proportional to the light intensity.



The Camera

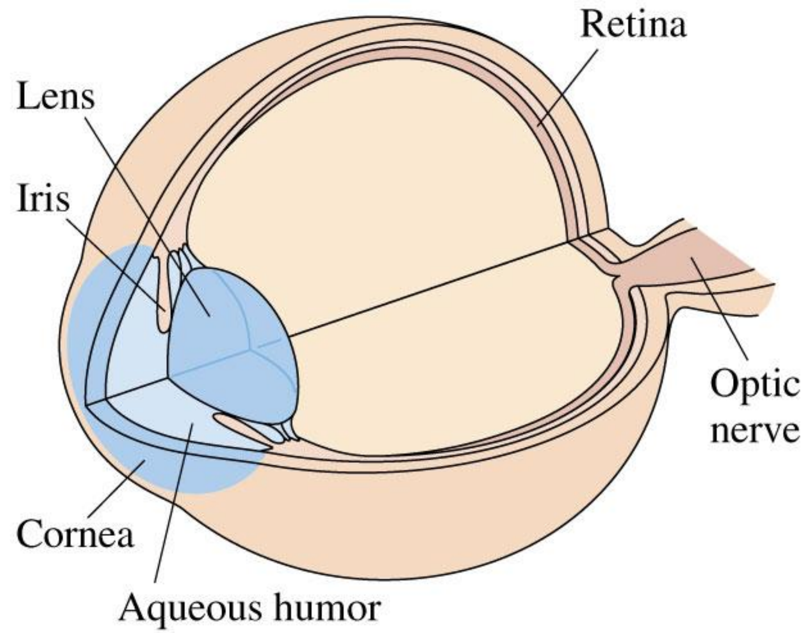
- An image is recorded on the CCD in terms of little packets of charge.
- A CCD "chip" has pixels covered by red, blue, and green filters, which only record the intensity of light with that color.
- Later, the microprocessor interpolates nearby colors to give each pixel an overall true color.



Section 19.2 The Human Eye

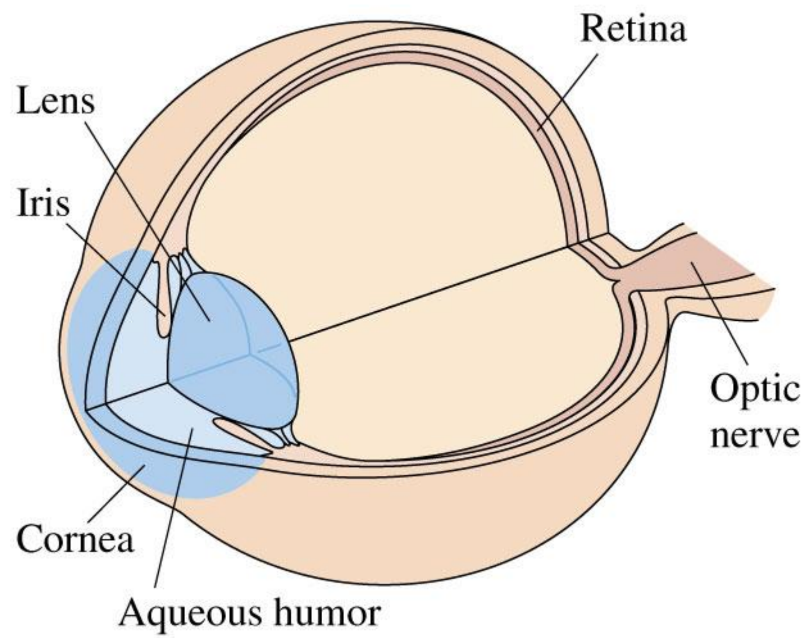
The Human Eye

- Like the camera, the eye has three main functional groups:
  - An optical system to focus incoming light
  - A diaphragm to adjust the amount of light entering the eye
  - A light-sensitive surface to detect the resulting image



The Human Eye

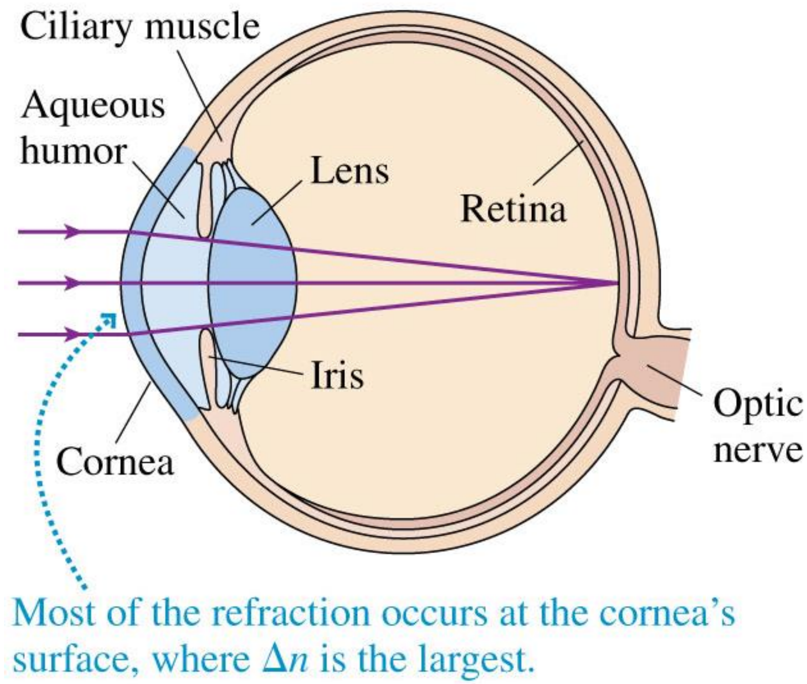
- The *cornea*, the *aqueous humor*, and the *lens* refract incoming light rays to produce an image.
- The *iris* determines how much light enters the eye, like the diaphragm of the camera.



- The *retina* is the light-sensitive surface on which the image is formed, like the CCD of the camera.

Focusing and Accommodation

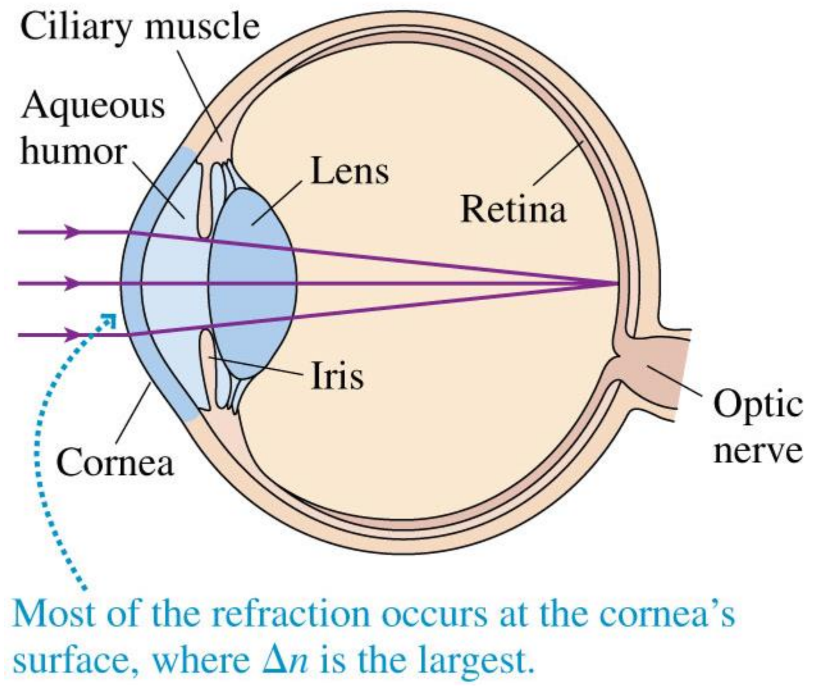
- Light is refracted by, in turn, the cornea, the aqueous humor, and the lens.
- The indices of refraction (*n*) in these parts of the eye differ somewhat, but average around 1.4.



- Most of the eye's refraction happens at the cornea due to its curvature and the large difference in the indices of refraction of air and the cornea.

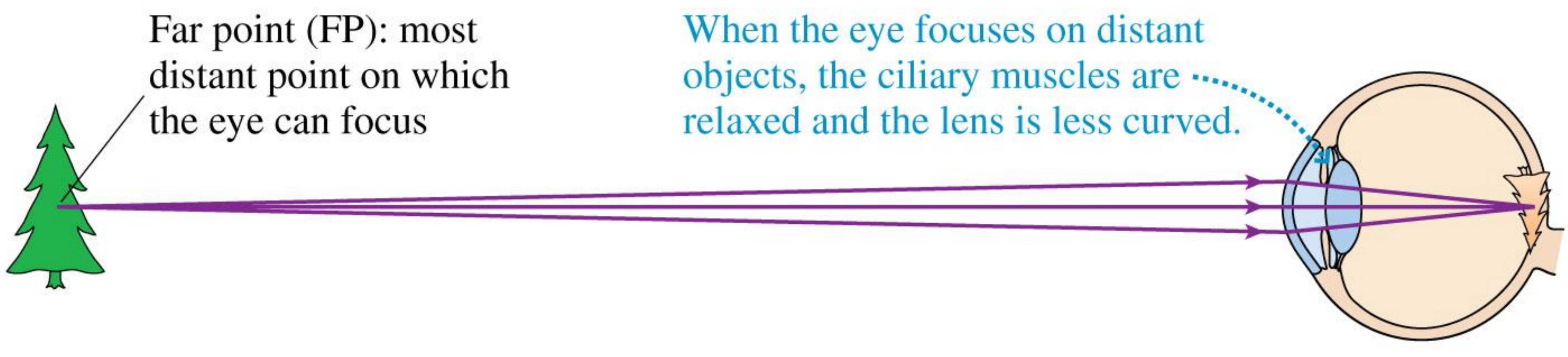
Focusing and Accommodation

- The lens's index of refraction does not differ much from the fluid in which it is embedded.
- When the lens is removed (like for a cataract), the cornea alone provides a marginal level of vision.



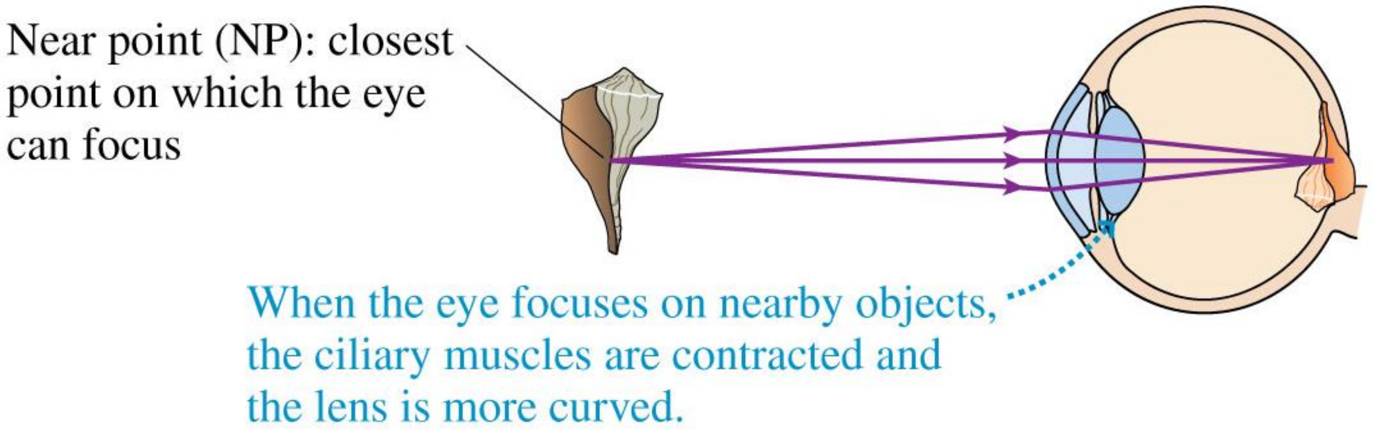
Focusing and Accommodation

- The eye must refocus for distant and near-by objects. It changes the focal length by changing the lens itself.



Focusing and Accommodation

- **Accommodation** is the process of changing the lens shape as the eye focuses at different distances.



Focusing and Accommodation

- The **far point** (FP) is the most distant point on which the relaxed eye can focus. For normal vision, it is infinity.
- The **near point** (NP) is the closest point on which the eye can focus with the ciliary muscles fully contracted. Objects closer than the NP cannot be brought to sharp focus.

QuickCheck 19.2

Jamie's far point is 30 cm from her eye, and her near point is 10 cm from her eye. To correct her vision, Jamie needs glasses that create an image of distant objects that is

A. At her near point.
B. At her far point.
C. At infinity.
D. 25 cm from her eye.

QuickCheck 19.2

Jamie's far point is 30 cm from her eye, and her near point is 10 cm from her eye. To correct her vision, Jamie needs glasses that create an image of distant objects that is

A. At her near point.
✔ B. At her far point.
C. At infinity.
D. 25 cm from her eye.

Vision Defects and Their Correction

- **Presbyopia** is the loss of accommodation, which arises because the lens loses flexibility.
- For children, the NP can be as little as 10 cm, for young adults the average is 25 cm. At age 40–45, the NP moves out and can reach 200 cm by age 60.
- Presbyopia is known as a *refractive error* in the eye.
- Other refractive errors include *hyperopia* and *myopia*.
- All three can be corrected with lenses.

Vision Defects and Their Correction

- Corrective lenses are prescribed by their **refractive power**:

$$P = \frac{1}{f}$$

Refractive power of a lens with focal length f

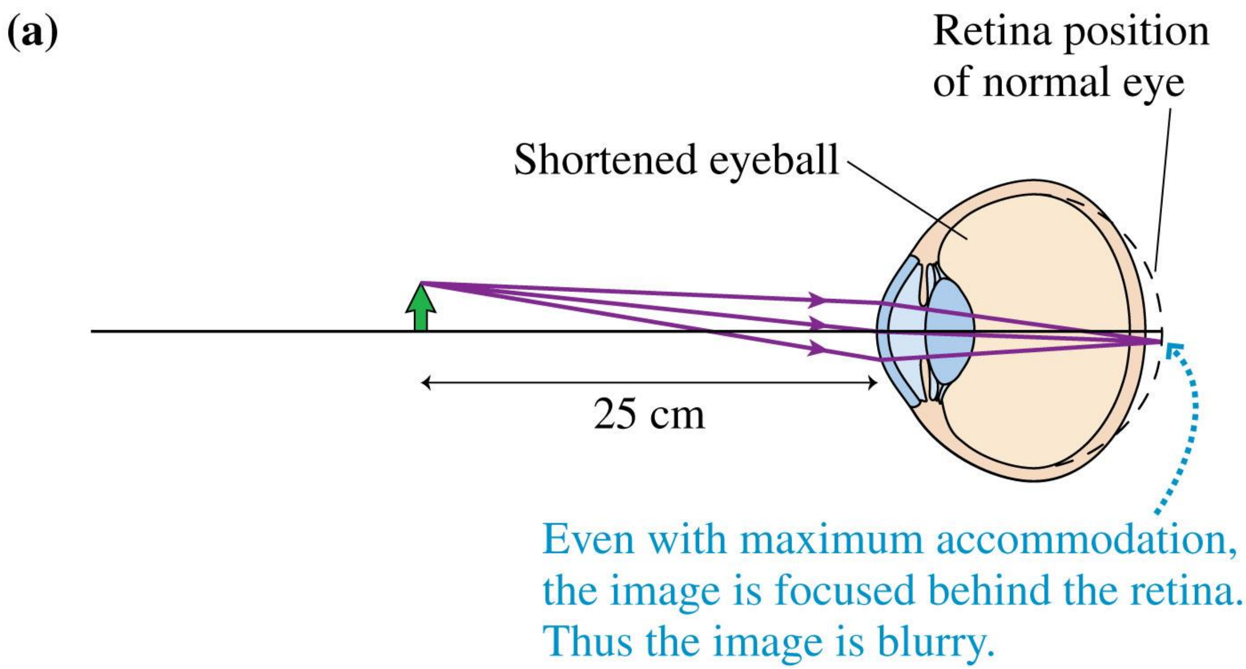
- The SI unit of refractive power is a **diopter** D:

$$1\ \text{D} = 1\ \text{m}^{-1}$$

- A lens with higher refractive power (shorter focal length) causes light rays to refract through a larger angle.

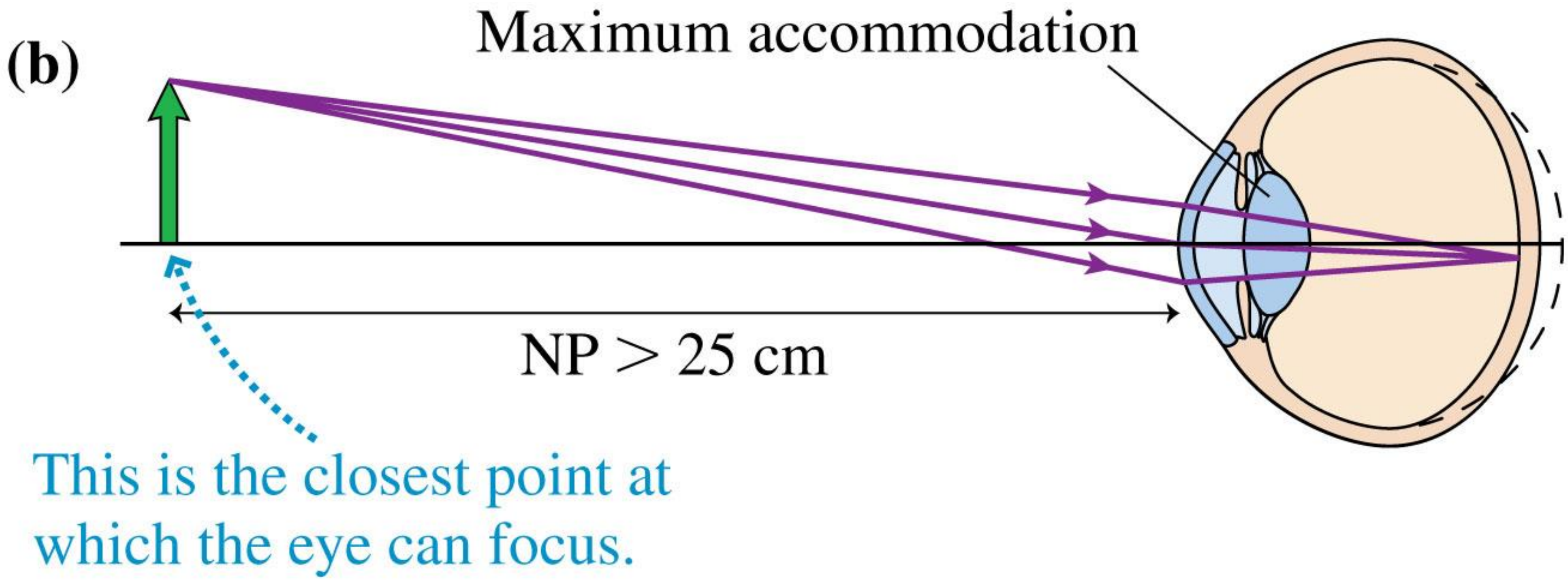
Vision Defects and Their Correction

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



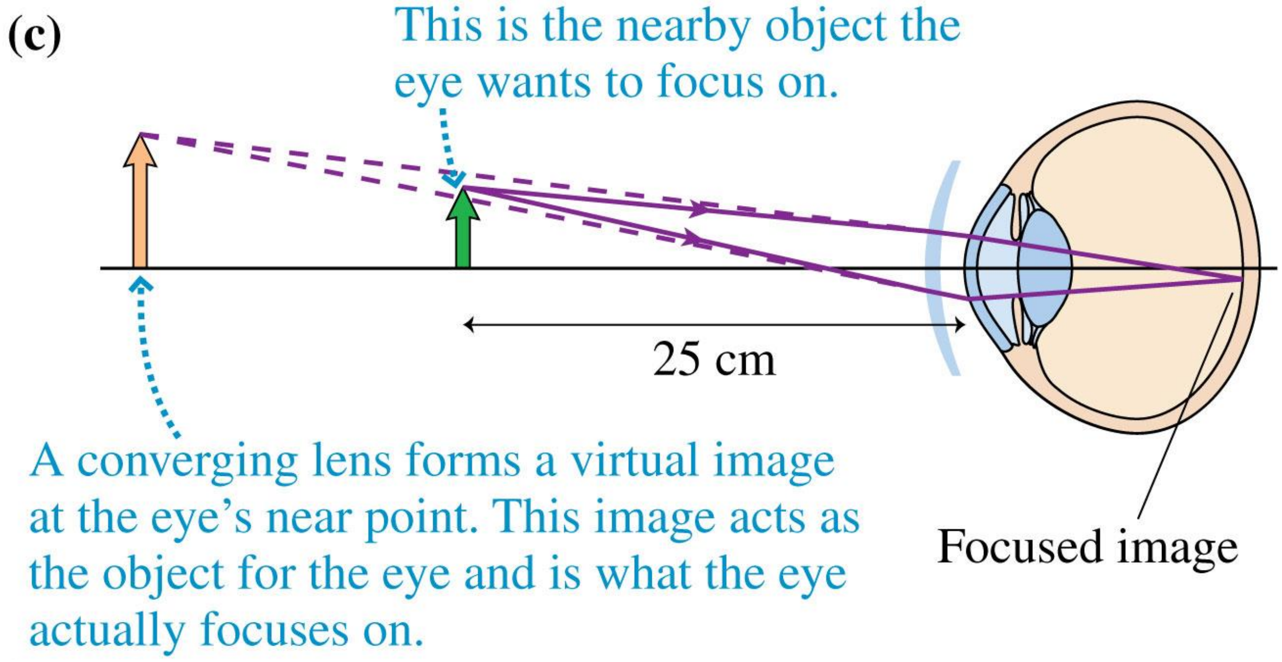
Vision Defects and Their Correction

- With hyperopia, no amount of accommodation can allow the eye to focus on an object 25 cm away. The person can see faraway objects with some accommodation of the eye.

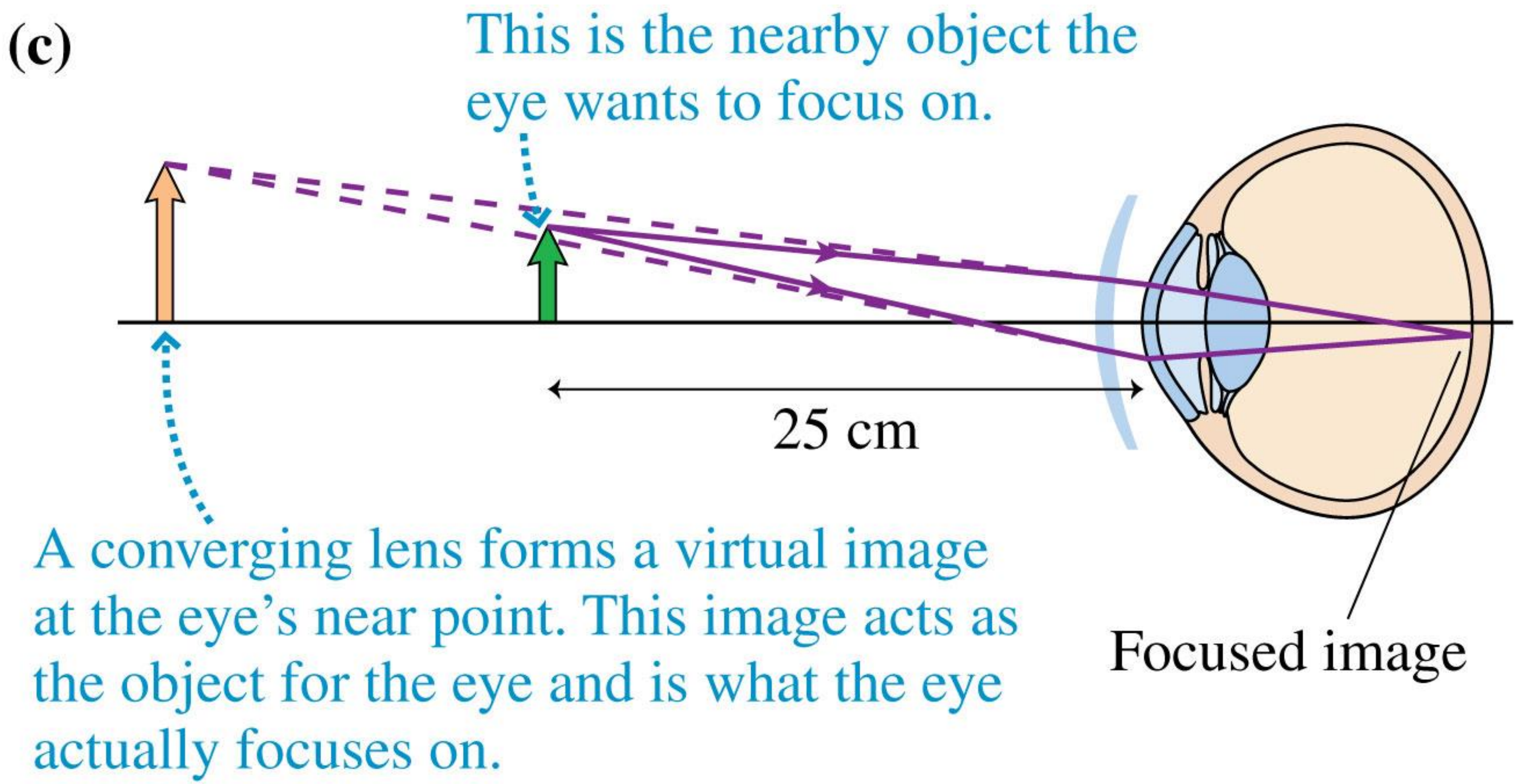


Vision Defects and Their Correction

- For a person with hyperopia, his or her eye needs assistance to focus the rays from a nearby object onto a closer-than-normal retina.
- The assistance is obtained by adding refractive power with a positive (converging) lens.

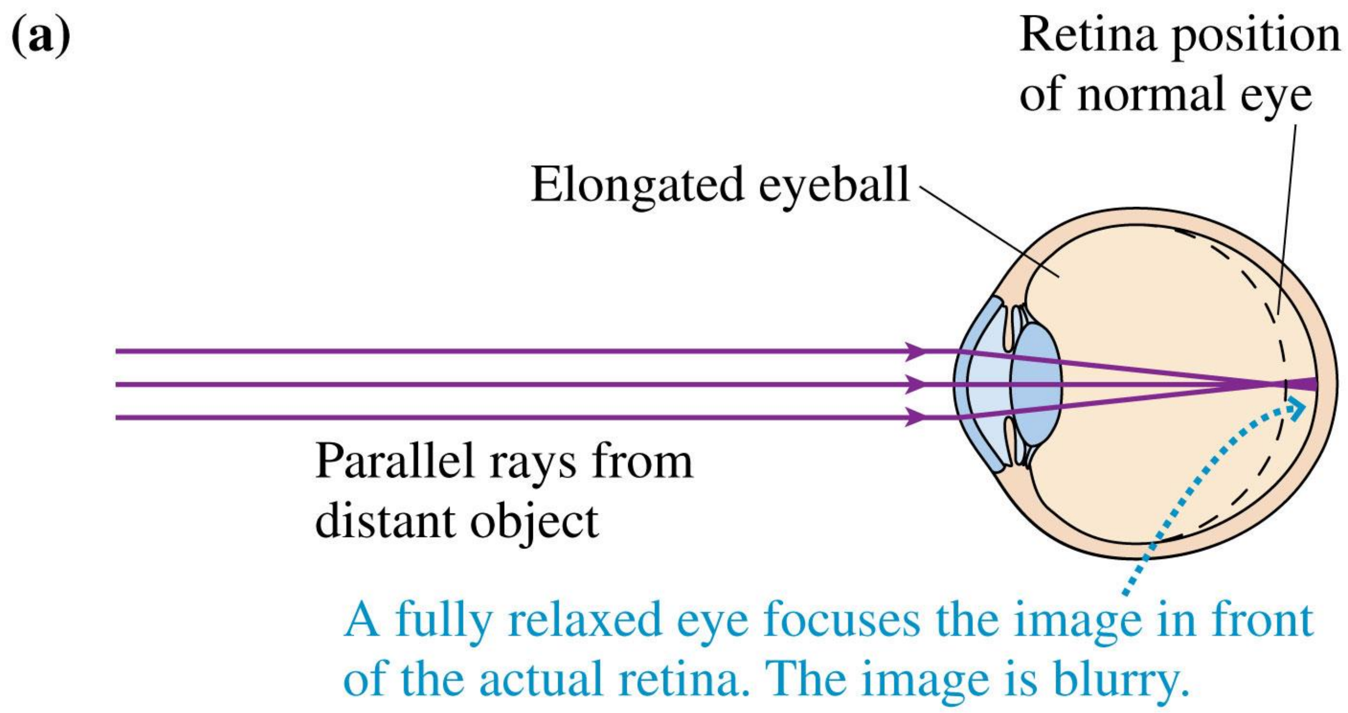


Vision Defects and Their Correction



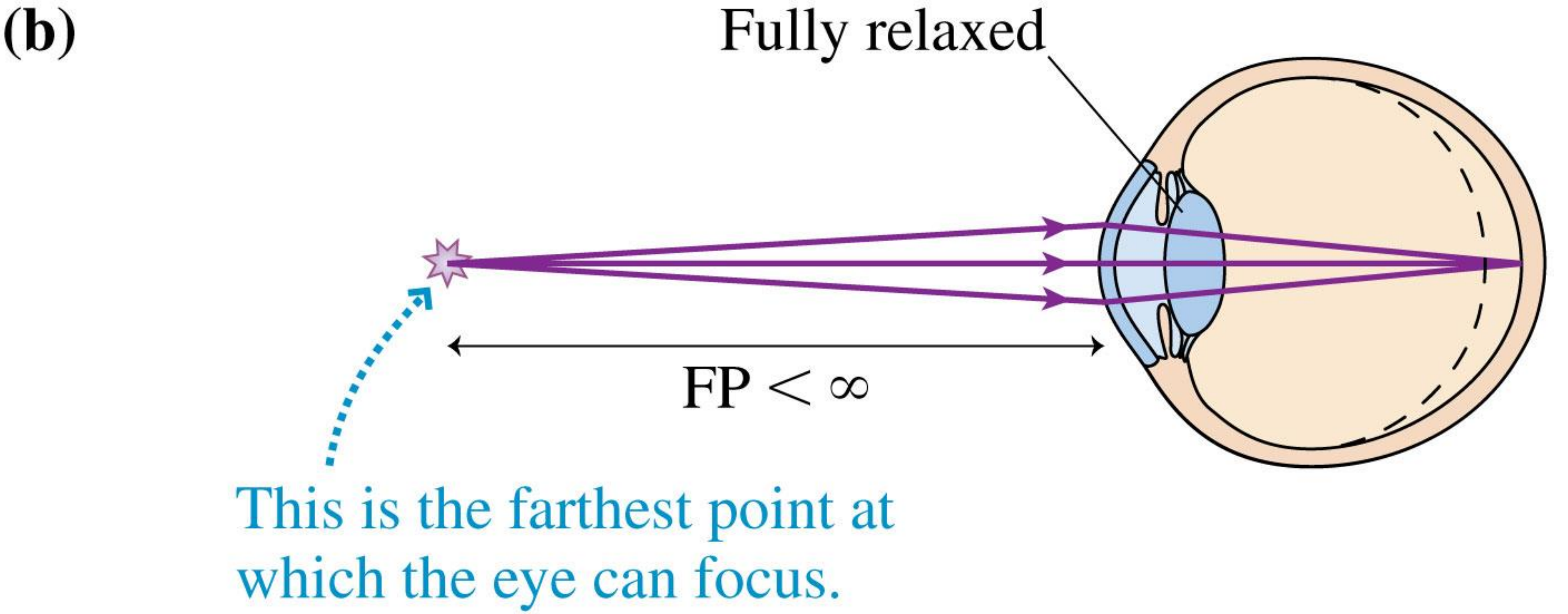
Vision Defects and Their Correction

- *Nearsightedness*, or **myopia**, describes the condition of a person who can clearly see objects nearby when the eye is relaxed (and extremely close objects with accommodation).
- Rays from a distant object come to focus in front of the retina and have begun to diverge by the time they reach the retina.



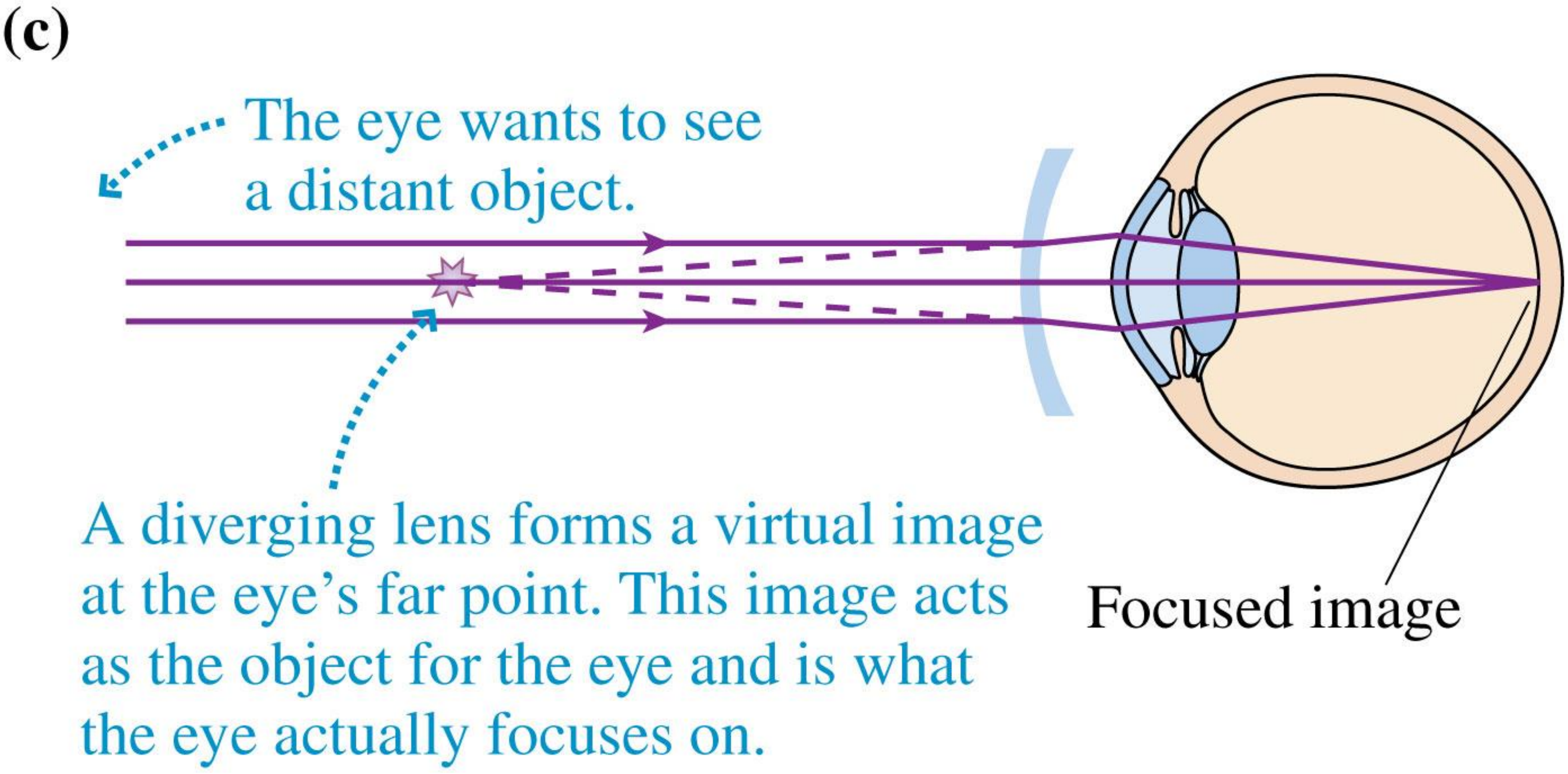
Vision Defects and Their Correction

- Myopia is caused when the eyeball is too long for a fully relaxed eye to focus distant objects onto the retina.



Vision Defects and Their Correction

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



QuickCheck 19.3

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

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

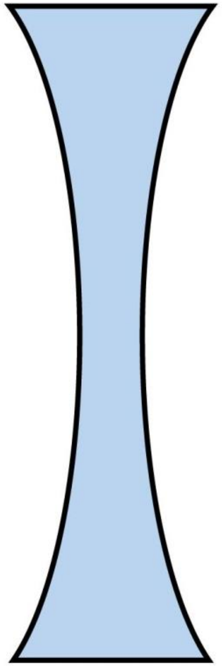
QuickCheck 19.3

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

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

QuickCheck 19.4

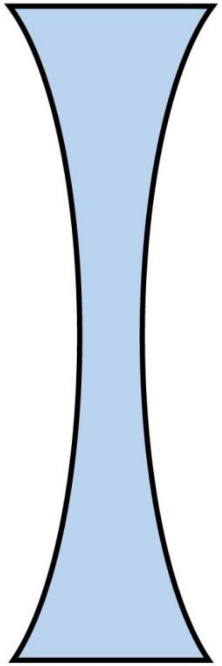
If your vision is improved with lenses that look like the one on the right, then you must have



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

QuickCheck 19.4

If your vision is improved with lenses that look like the one on the right, then you must have



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

Example 19.3 Correcting myopia

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

PREPARE 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.

Example 19.3 Correcting myopia (cont.)

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.

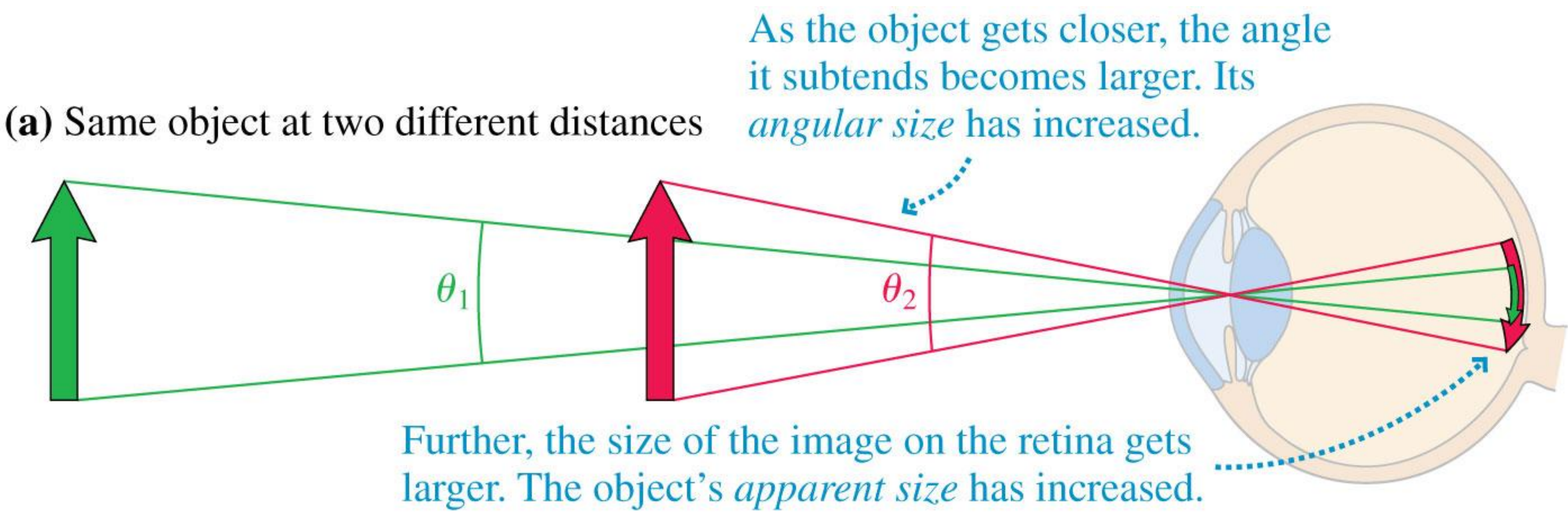
Try It Yourself: Inverted Vision

Just like a camera, the lens of the eye produces an *inverted* image on the retina. The brain is wired to "flip" this inverted image and interpret it as being upright. To show this directly, try this simple experiment. Poke a small hole in a card using a pin and, holding the card a few inches away, look through the hole at a lightbulb. While doing so, move the head of the pin between the hole and your eye; you'll see an *upside-down* pinhead. The hole acts as a point source that casts an *erect* shadow of the pin on your retina. The brain then inverts this erect shadow, making it appear inverted.

Section 19.3 The Magnifier

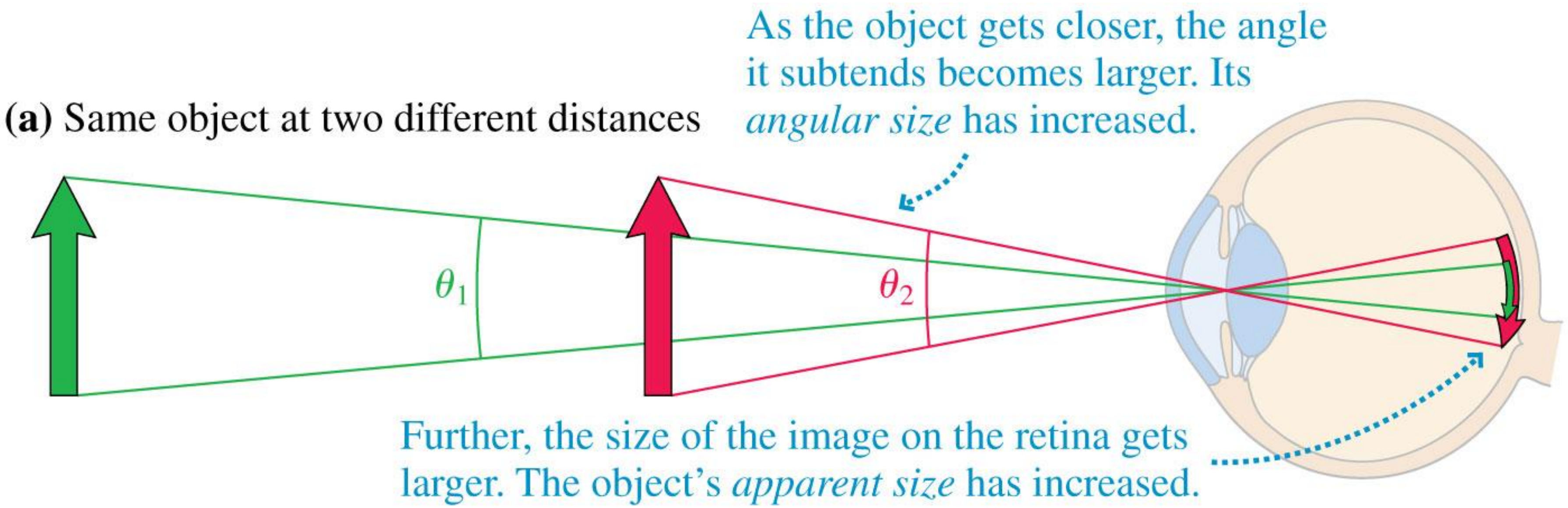
Angular Size and Apparent Size

- Our brains interpret a larger image on the retina as representing a larger-appearing *object*.



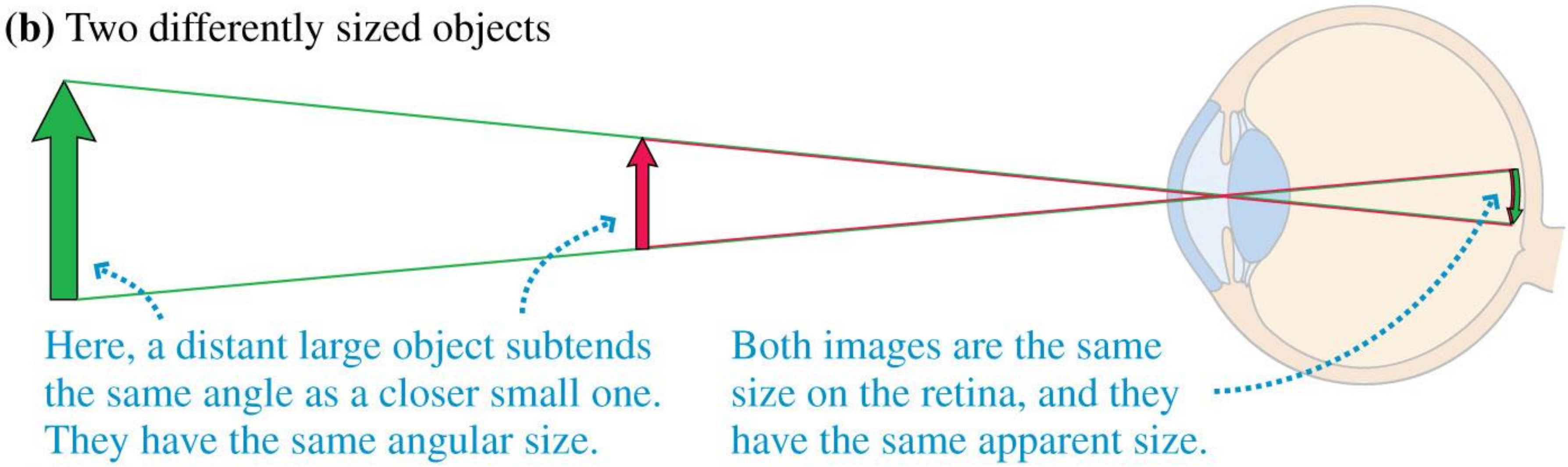
Angular Size and Apparent Size

- The **angular size** is the angle *subtended* by an object (angles θ_1, θ_2).



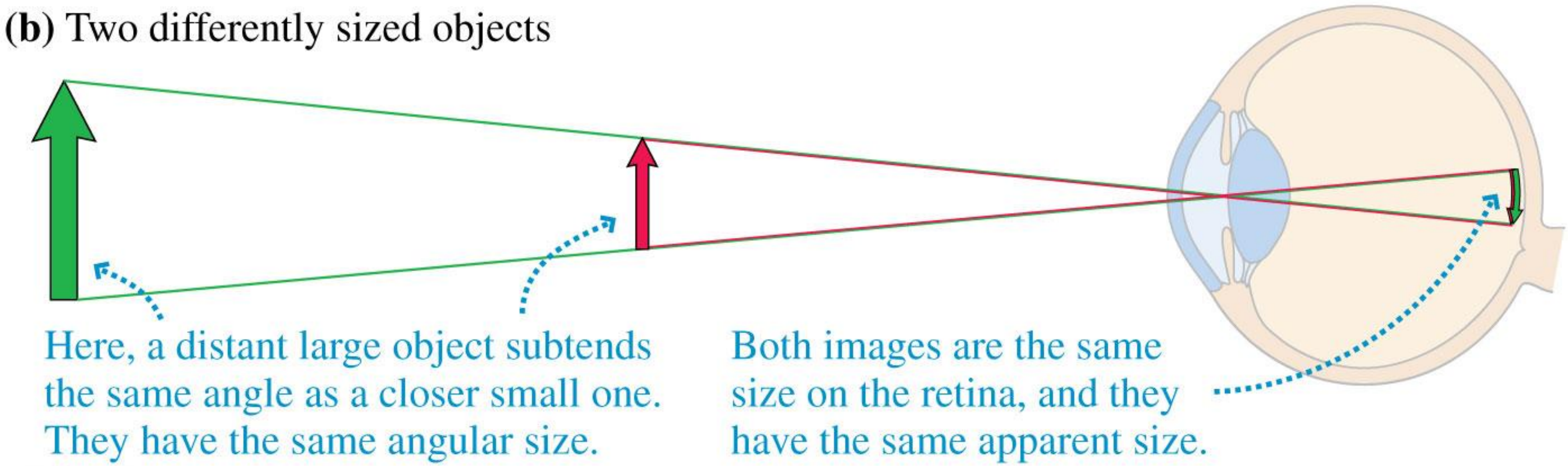
Angular Size and Apparent Size

- **Objects that subtend a larger angle appear larger to the eye.**



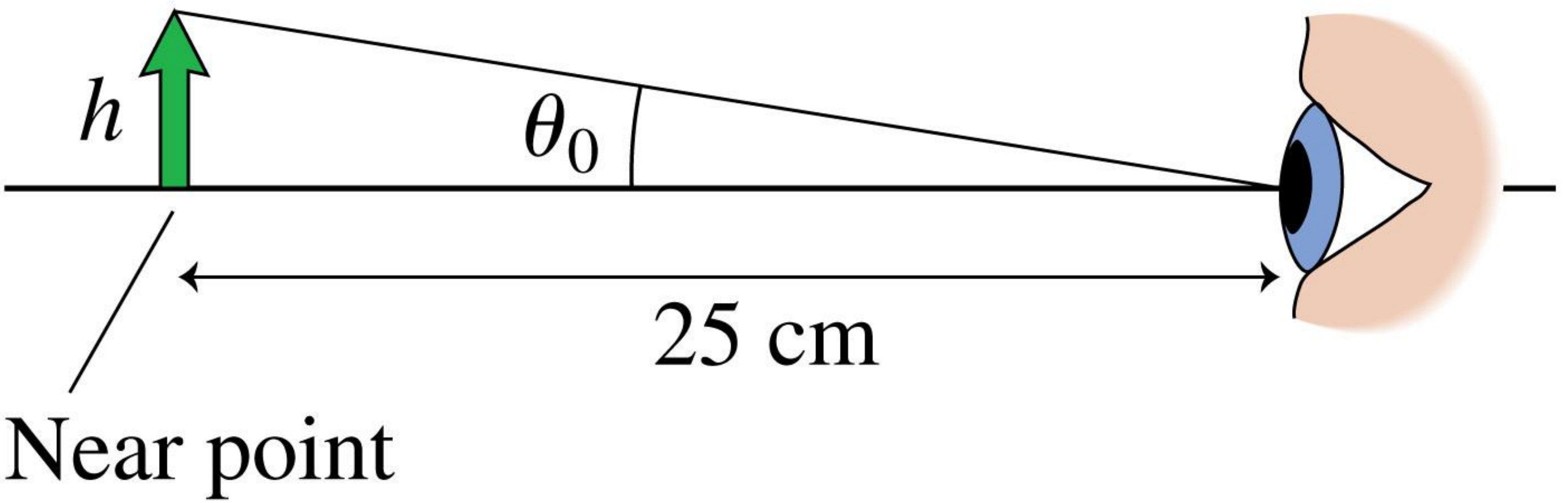
Angular Size and Apparent Size

- From the earth, the sun and the moon have about the same apparent size even though the sun is 400 times larger.



Using a Magnifier

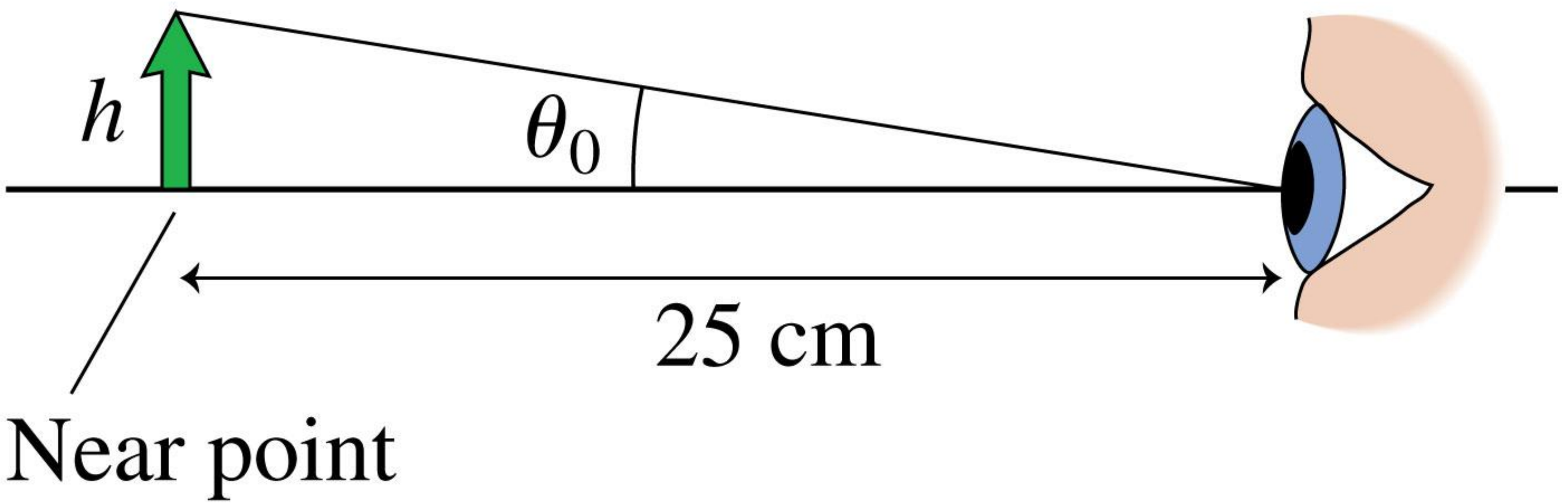
- The eye cannot focus on objects closer than its near point (25 cm).
- Thus, an in-focus object has a maximum angular size θ_0.



Using a Magnifier

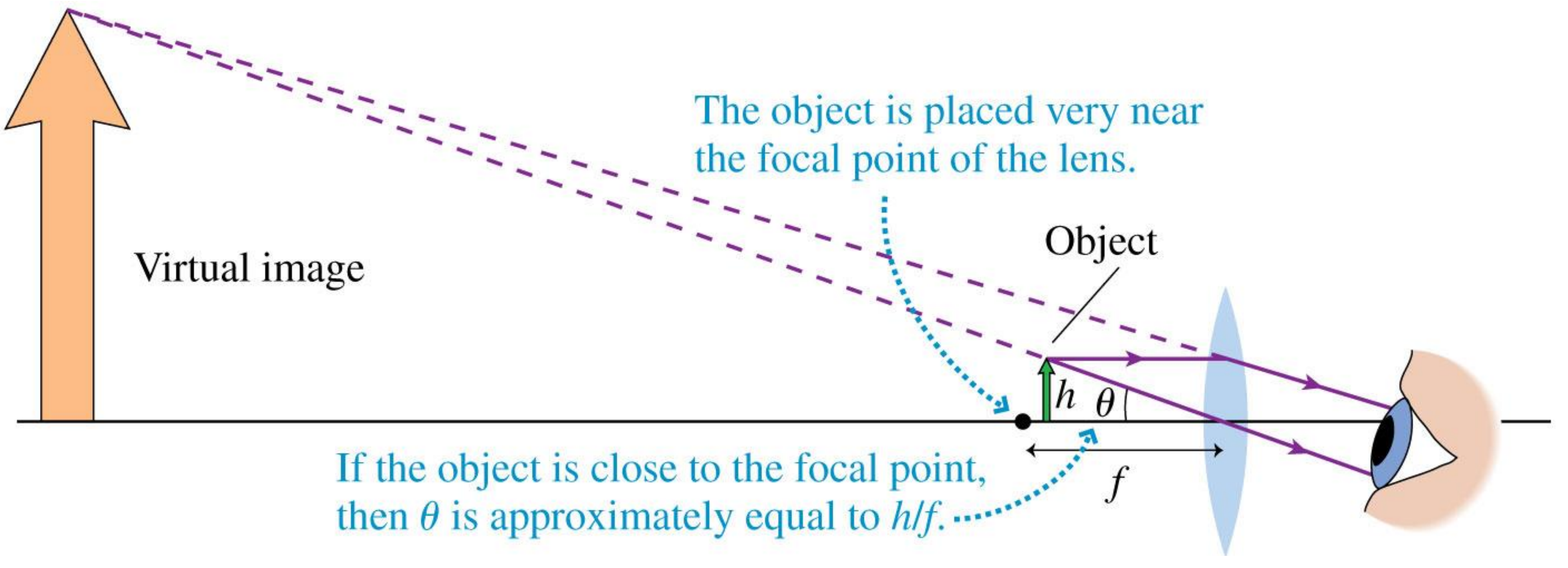
- From the geometry of the image, $\tan \theta_0 = h/25\text{ cm}$.
- Using the small-angle approximation, we find

$$\theta_0 \approx \frac{h}{25\text{ cm}}$$



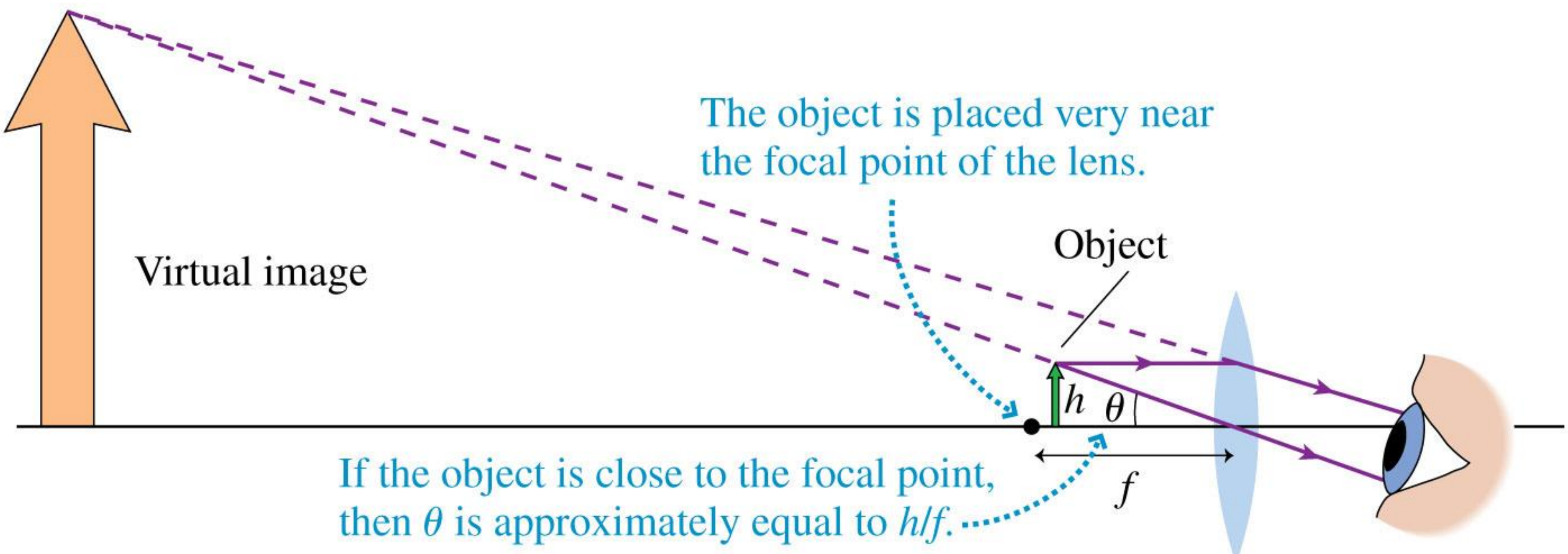
Using a Magnifier

- The magnifier lens is held such that the object is at or just inside the lens's focal point.
- This produces a virtual image far from the lens.



Using a Magnifier

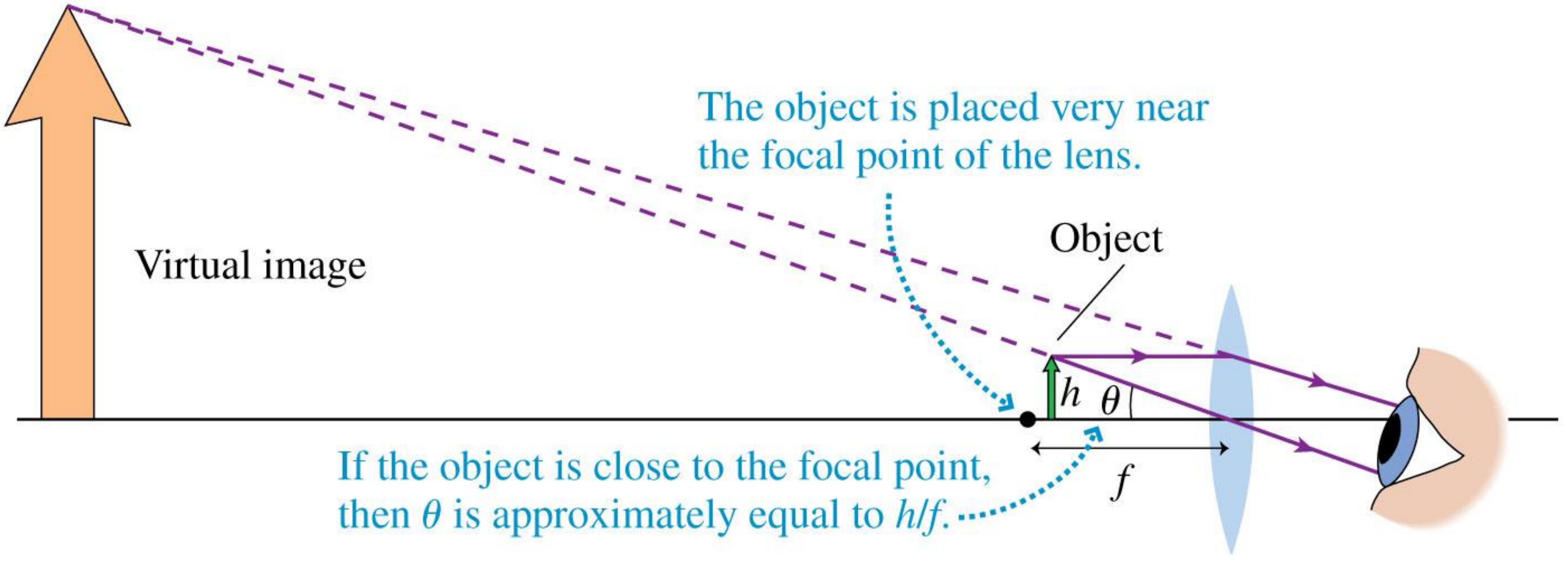
- The location of the virtual image in a magnifier is convenient because your eye muscles are fully relaxed when looking at a distant object. The distant virtual image is what the eye focuses on with a magnifier.



Using a Magnifier

- The angular size of the object, if located at the focal point *f* of the magnifier, is

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



Using a Magnifier

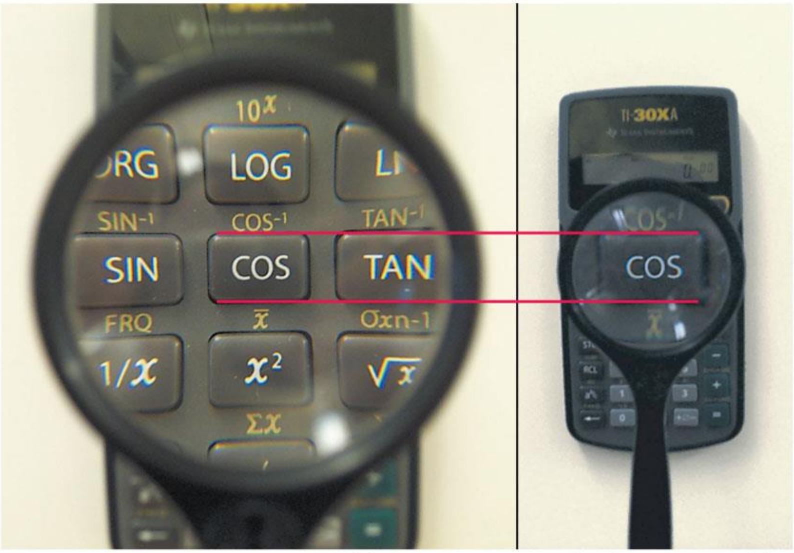
- The angular size of the object when using the magnifier is larger than without the magnifier by a factor of

$$M = \frac{\theta}{\theta_0} = \frac{h/f}{h/25\text{ cm}} = \frac{25\text{ cm}}{f}$$

- *M* is the **angular magnification** of the magnifier.

Conceptual Example 19.4 The angular size of a magnified image

An object is placed right at the focal point of a magnifier. How does the apparent size of the image depend on where the *eye* is placed relative to the lens?



Eye close to magnifier   Eye far from magnifier

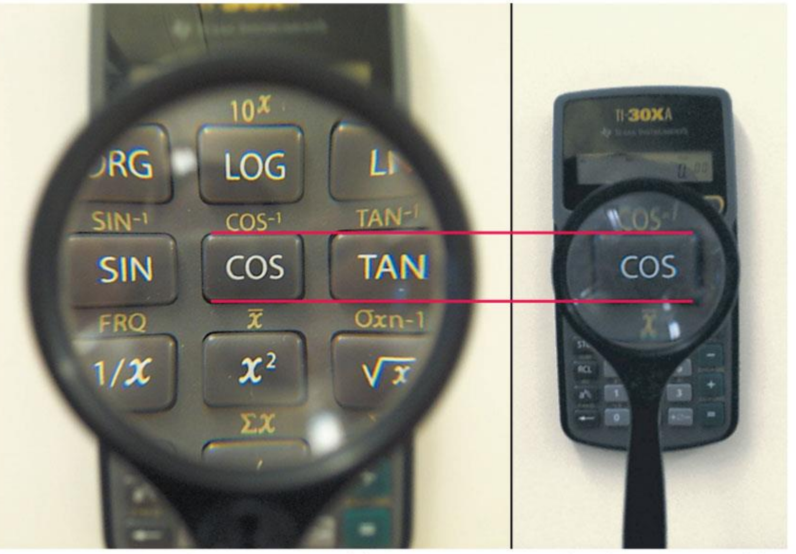
Conceptual Example 19.4 The angular size of a magnified image (cont.)

REASON When the object is precisely at the focal point of the lens, Equation 19.2 holds exactly. The angular size is equal to *h/f independent* of the position of the eye. Thus the object's apparent size is independent of the eye's position as well. FIGURE 19.12 shows a calculator at the focal point of a magnifier. The apparent size of the COS button is the same whether the camera taking the picture is close to or far from the lens.

Eye close to magnifier Eye far from magnifier

Conceptual Example 19.4 The angular size of a magnified image (cont.)

ASSESS When the object is at the magnifier's focus, we've seen that the image is at infinity. The situation is similar to observing any "infinitely" distant object, such as the moon. If you walk closer to or farther from the moon, its apparent size doesn't change at all. The same holds for a virtual *image* at infinity: Its apparent size is independent of the point from which you observe it.



Eye close to magnifier   Eye far from magnifier

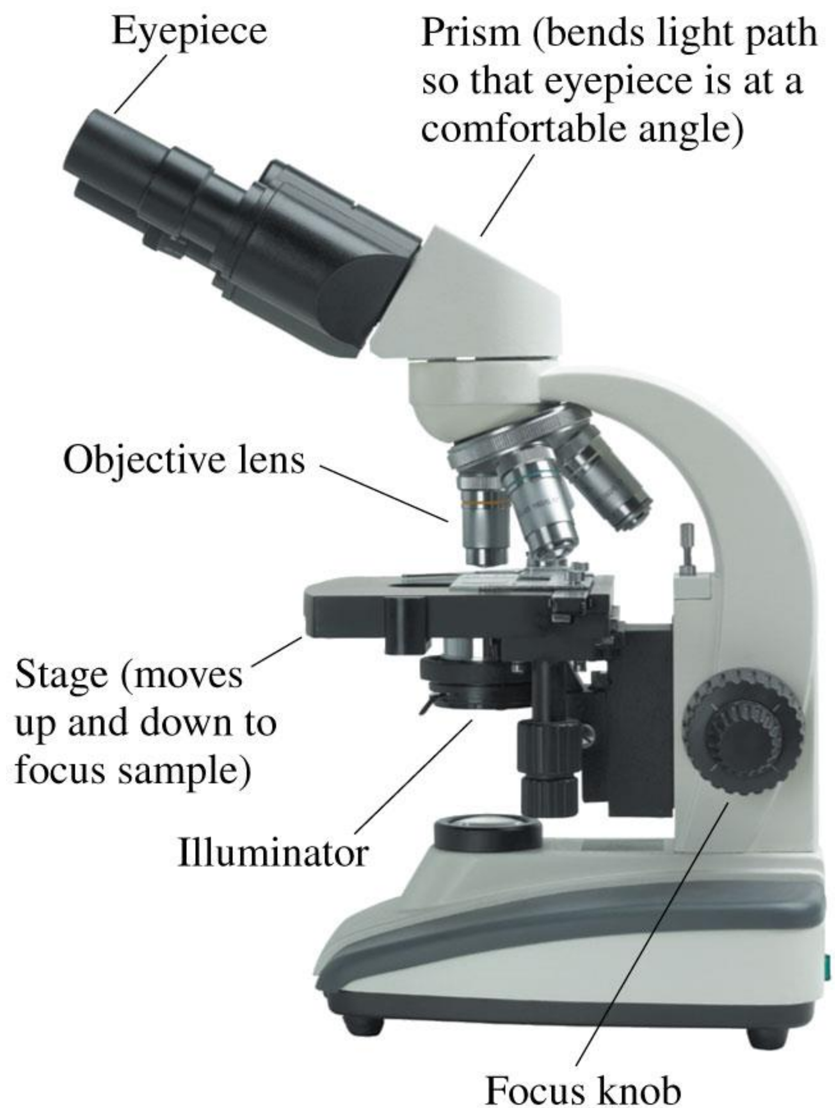
Section 19.4 The Microscope

The Microscope

- A combination of lenses can be used to get higher magnifications than are possible with a simple magnifier.
- **The image of the first lens acts as the object for the second lens.**

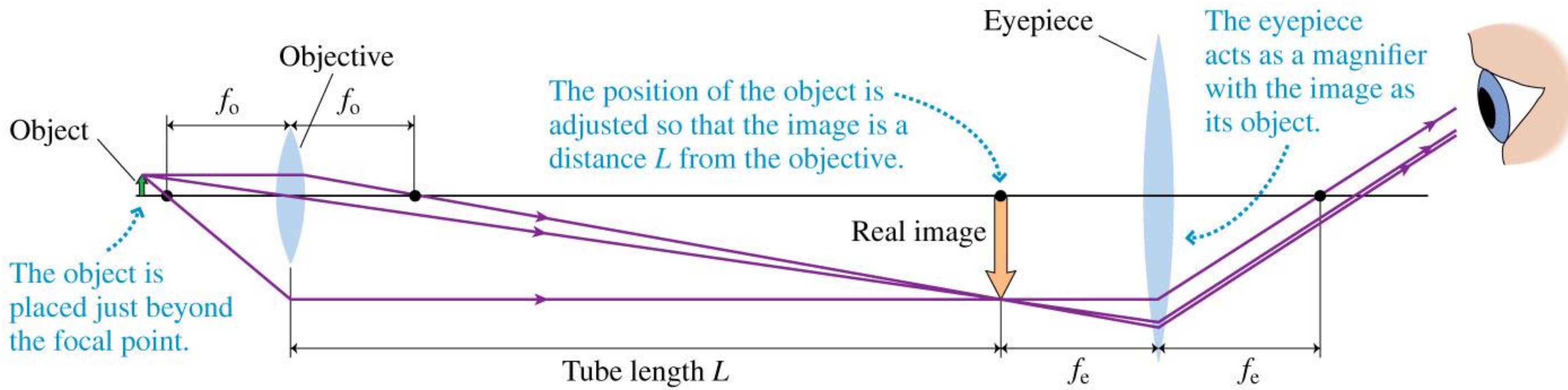
The Microscope

- A microscope attains a magnification of up to 1000 using two lenses in combination.
- The **objective lens** is a converging lens with a relatively short focal length.
- The **eyepiece** is an ordinary magnifier that further enlarges the image created by the objective lens.



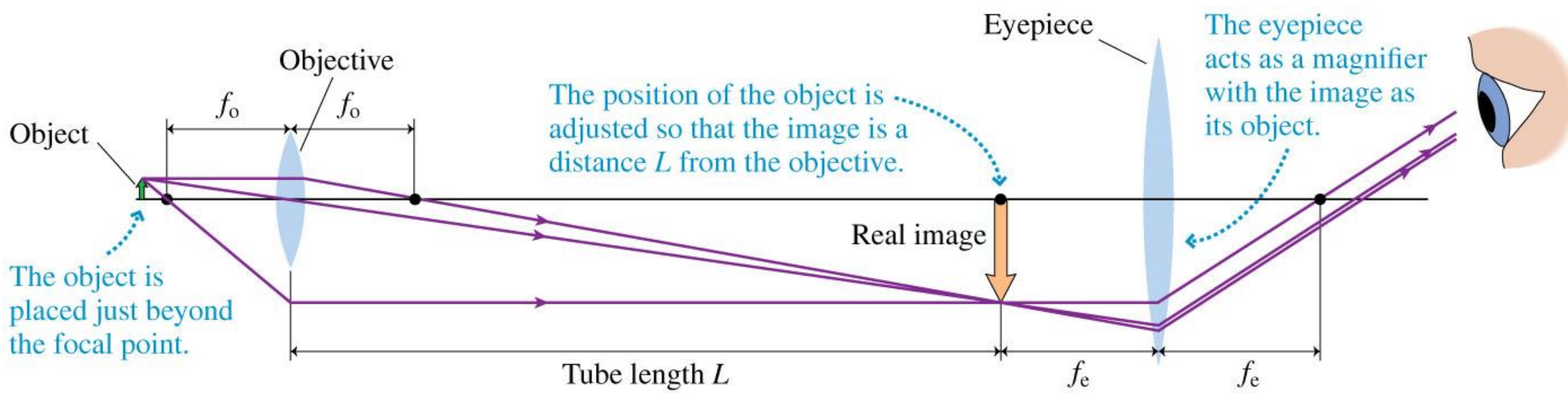
The Microscope

- The **tube length** L is the distance from the objective lens to the real image.



The Microscope

- To focus the microscope, one moves the sample stage up and down (the object left and right, in the figure) until the object distance is correct for placing the image at *L*.



The Microscope

- The magnification of the objective lens is

$$m_o = -\frac{s'}{s} \approx -\frac{L}{f_o}$$

- Together with the objective and eyepiece, the total angular magnification is

$$M = m_o M_e = -\frac{L}{f_o}\frac{25\text{ cm}}{f_e}$$

- The minus sign shows that the image is inverted.
- The magnification of a microscope objective is called its "power".

Example 19.6 Finding the focal length of a microscope objective

A biological microscope objective is labeled “20×.” What is its focal length?

PREPARE The “20×” means that the objective has a magnification m_o of –20. We can use Equation 19.4 with L as 160 mm, which we’ve seen is the standard length for a biological microscope.

Example 19.6 Finding the focal length of a microscope objective (cont.)

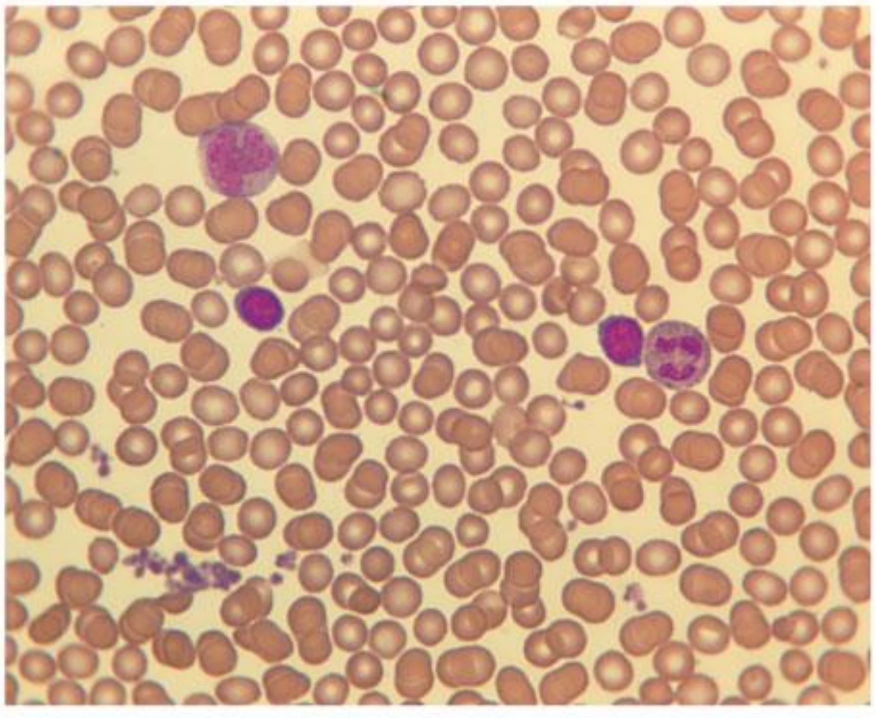
SOLVE From Equation 19.4 we have

$$f_o = -\frac{L}{m_o} = -\frac{160\text{ mm}}{-20} = 8.0\text{ mm}$$

ASSESS This focal length is significantly shorter than the tube length, in agreement with Figure 19.15.

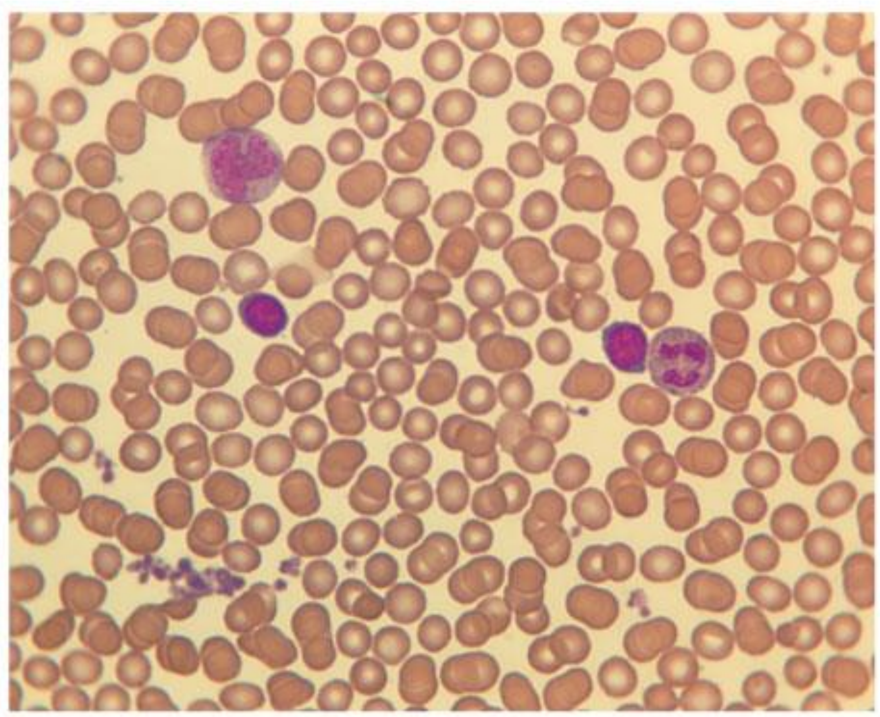
Example 19.7 Viewing blood cells

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?



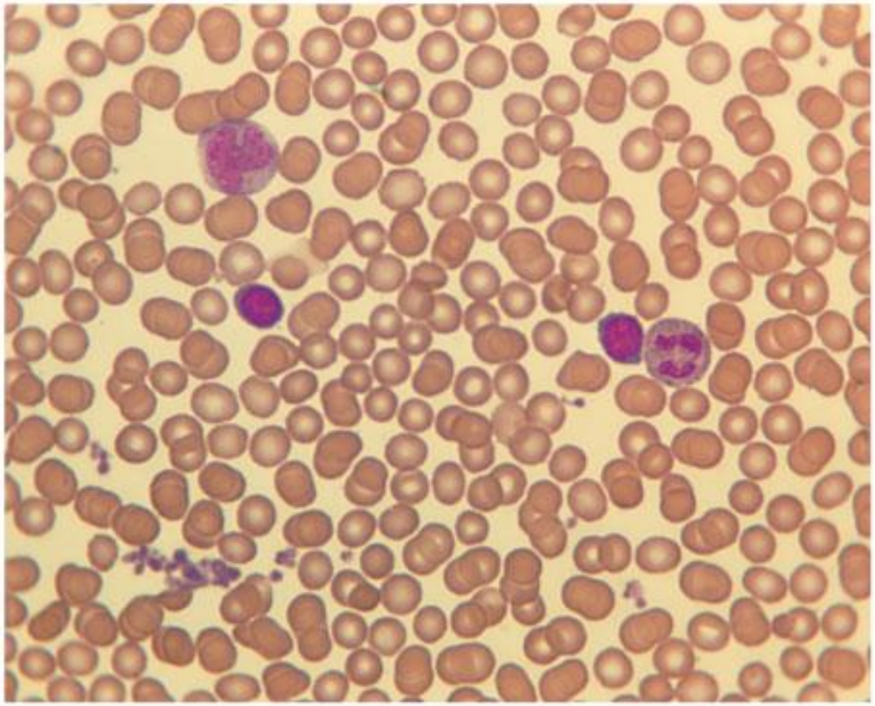
Example 19.7 Viewing blood cells (cont.)

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



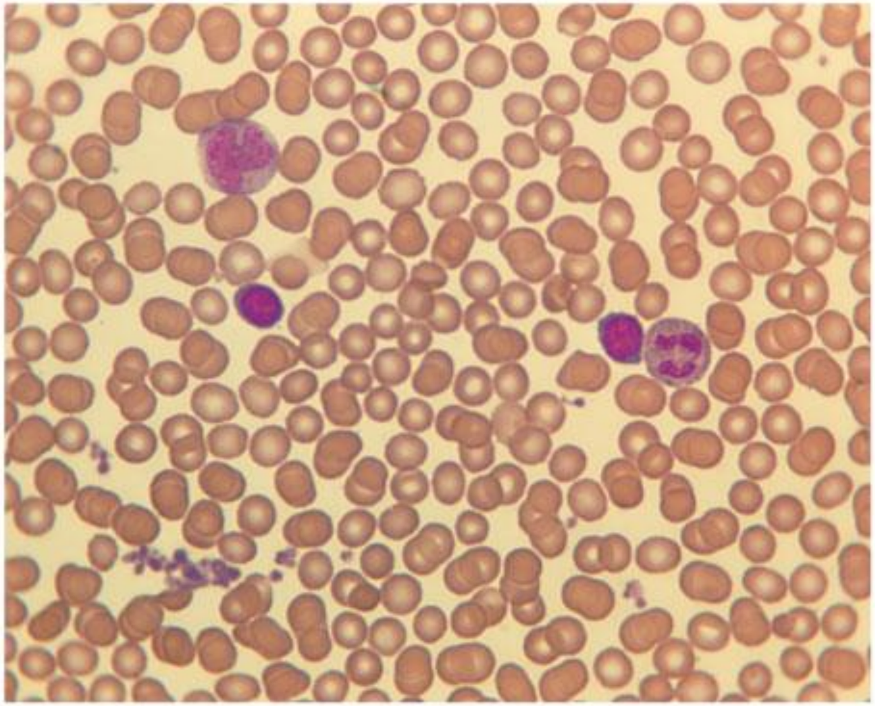
Example 19.7 Viewing blood cells (cont.)

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



Example 19.7 Viewing blood cells (cont.)

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.



Example Problem

A student uses a microscope to view an amoeba. If the objective has a focal length of 1.0 cm, the eyepiece has a focal length of 2.5 cm, and the amoeba is 1.1 cm from the objective, what is the microscope's magnification?

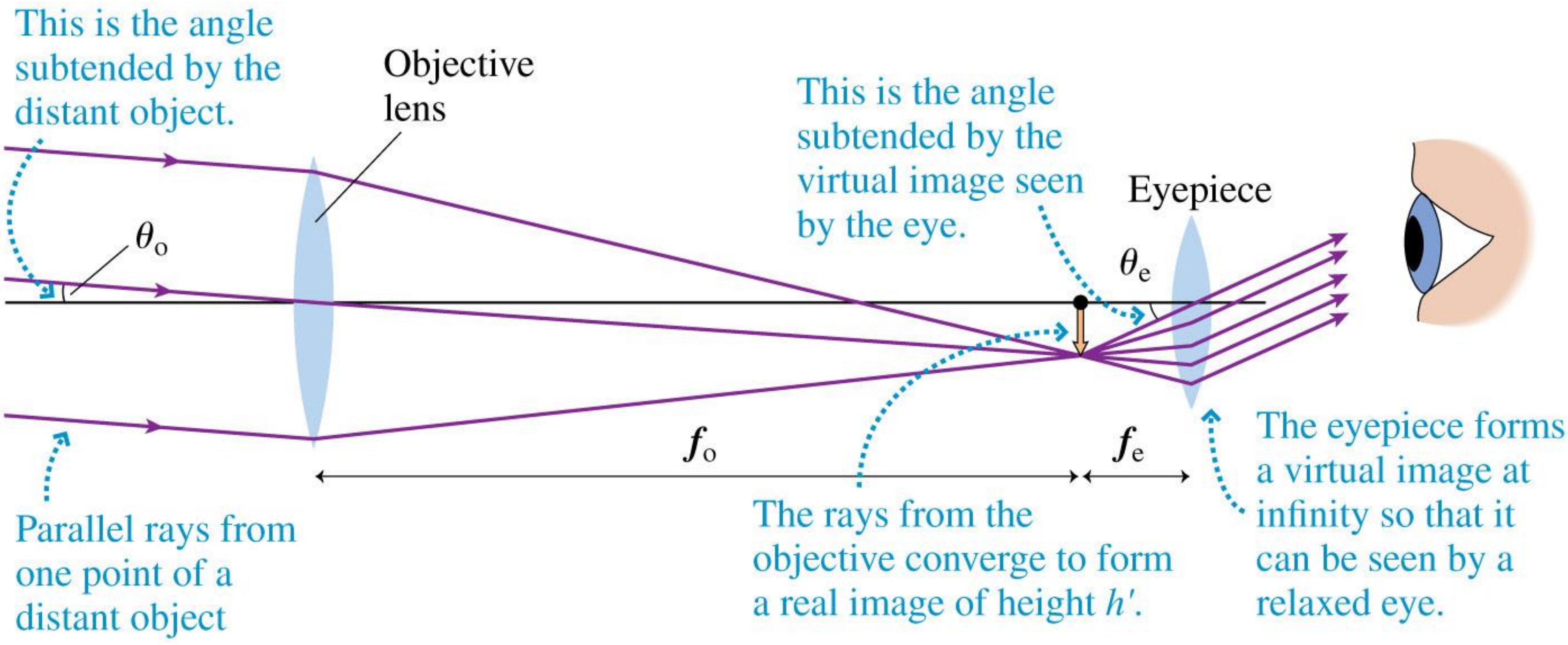
Section 19.5 The Telescope

The Telescope

- A *telescope* is used to magnify distant objects.

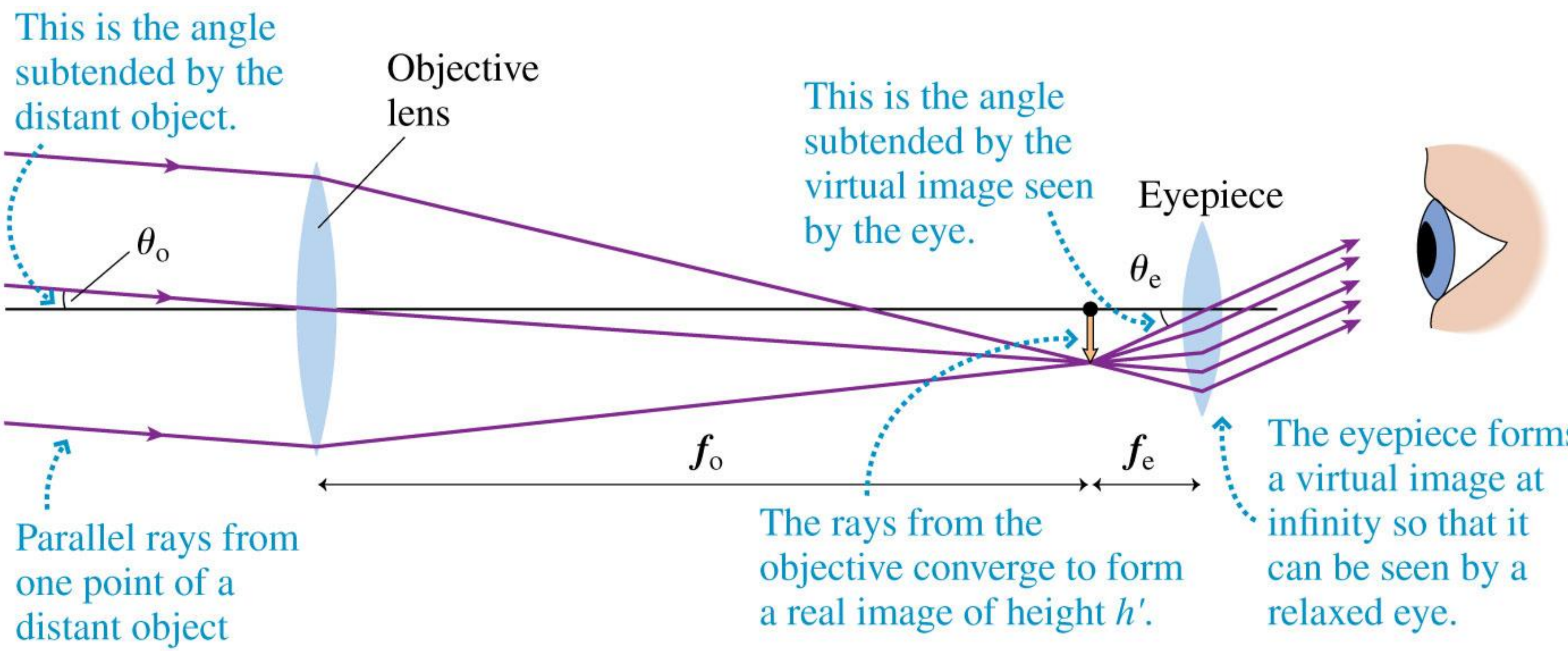
The Telescope

- A telescope has two lenses like a microscope, but the objective has a very long focal length rather than a short one.



The Telescope

- The converging objective takes the rays coming from infinity and forms a real image of the distant object at the lens's focal point. The eyepiece is a simple magnifier.



The Telescope

- The original object subtends the angle θ_o. The image is at a distance f_o and has a height of

$$h' \approx -f_o\theta_o$$

- The image is now the object for the eyepiece which is a magnifier with focal length f_e. The image height h' has an angular size

$$\theta_e = \frac{h'}{f_e} = \frac{-f_o\theta_o}{f_e}$$

The Telescope

- The telescope's angular magnification is the ratio of the angular sizes:

$$M = \frac{\theta_e}{\theta_o} = -\frac{f_o}{f_e}$$

- To get higher magnification, the focal length of the objective should be large and that of the eyepiece small.

QuickCheck 19.5

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.

QuickCheck 19.5

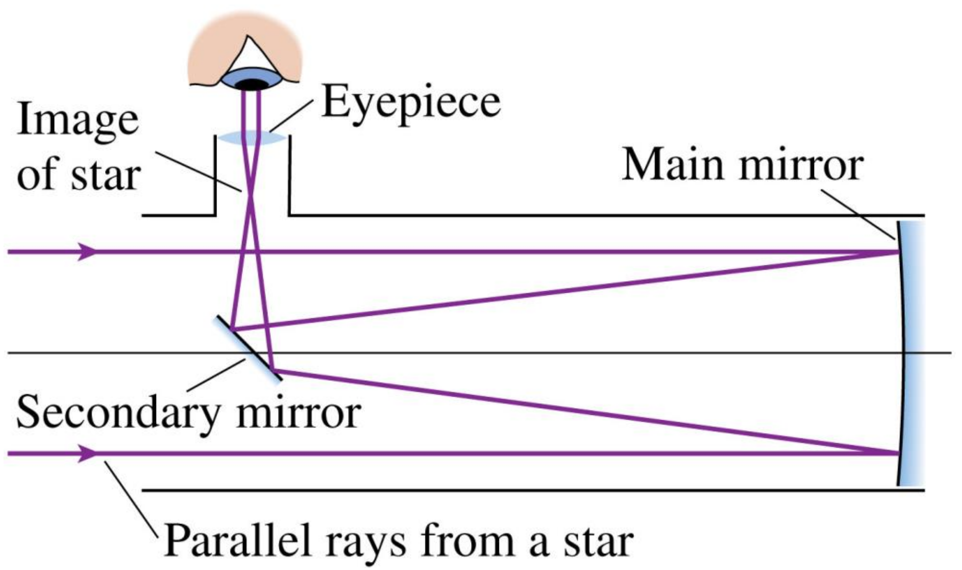
If you increase the diameter of a telescope's objective lens (and, of course, increase the diameter of the tube) with no other changes, then the telescope will have

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.

The Telescope

- A *refracting telescope* uses a lens as its objective.
- A *reflecting telescope* uses a concave mirror instead of a lens. A secondary mirror deflects the image to an eyepiece on the side of the telescope.
- Mirrors are useful because big mirrors can be supported along the back surface, whereas lenses cannot.



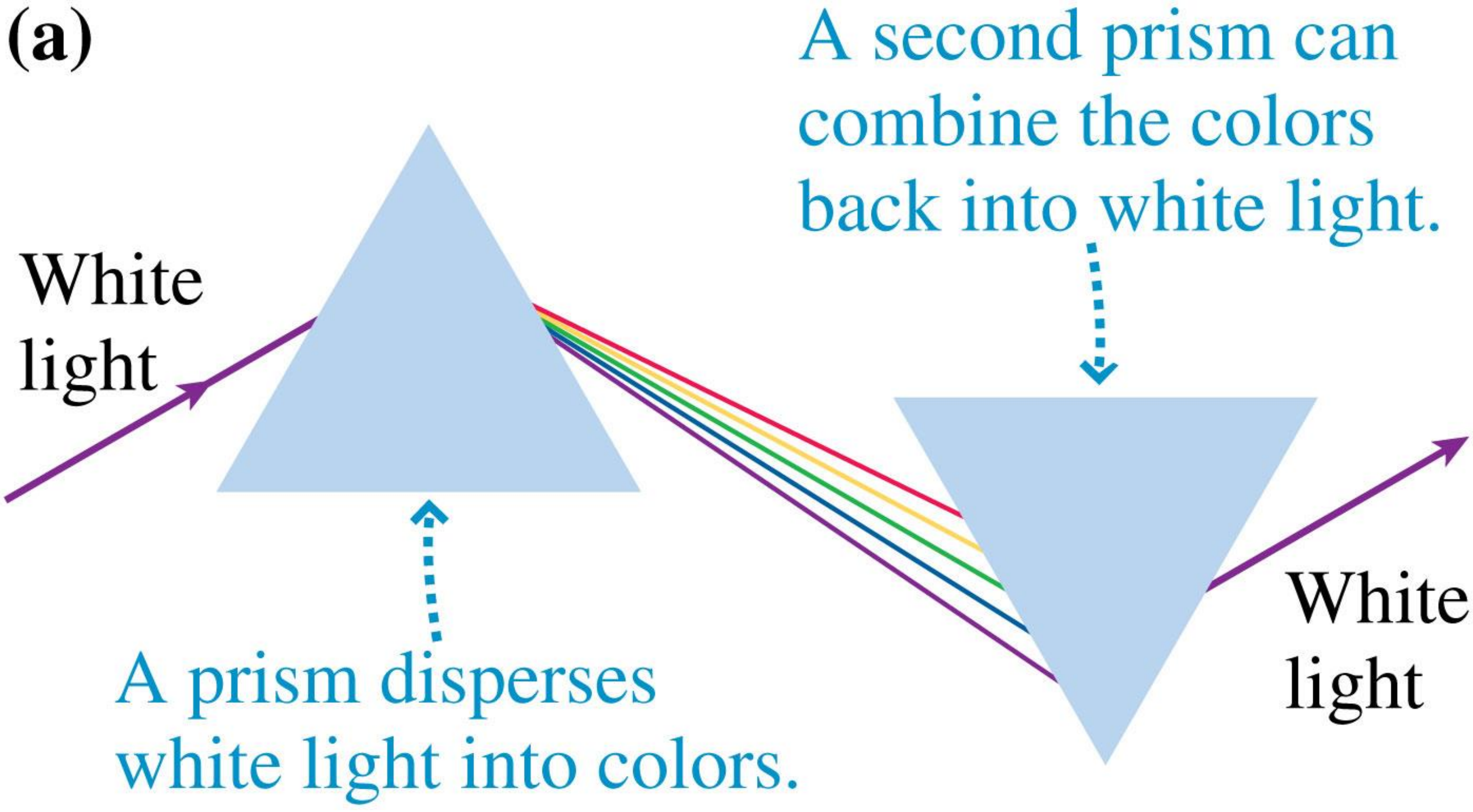
Example Problem

The objective lens and the eyepiece lens of a telescope are 1.0 m apart. The telescope has an angular magnification of 50. Find the focal lengths of the eyepiece and the objective.

Section 19.6 Color and Dispersion

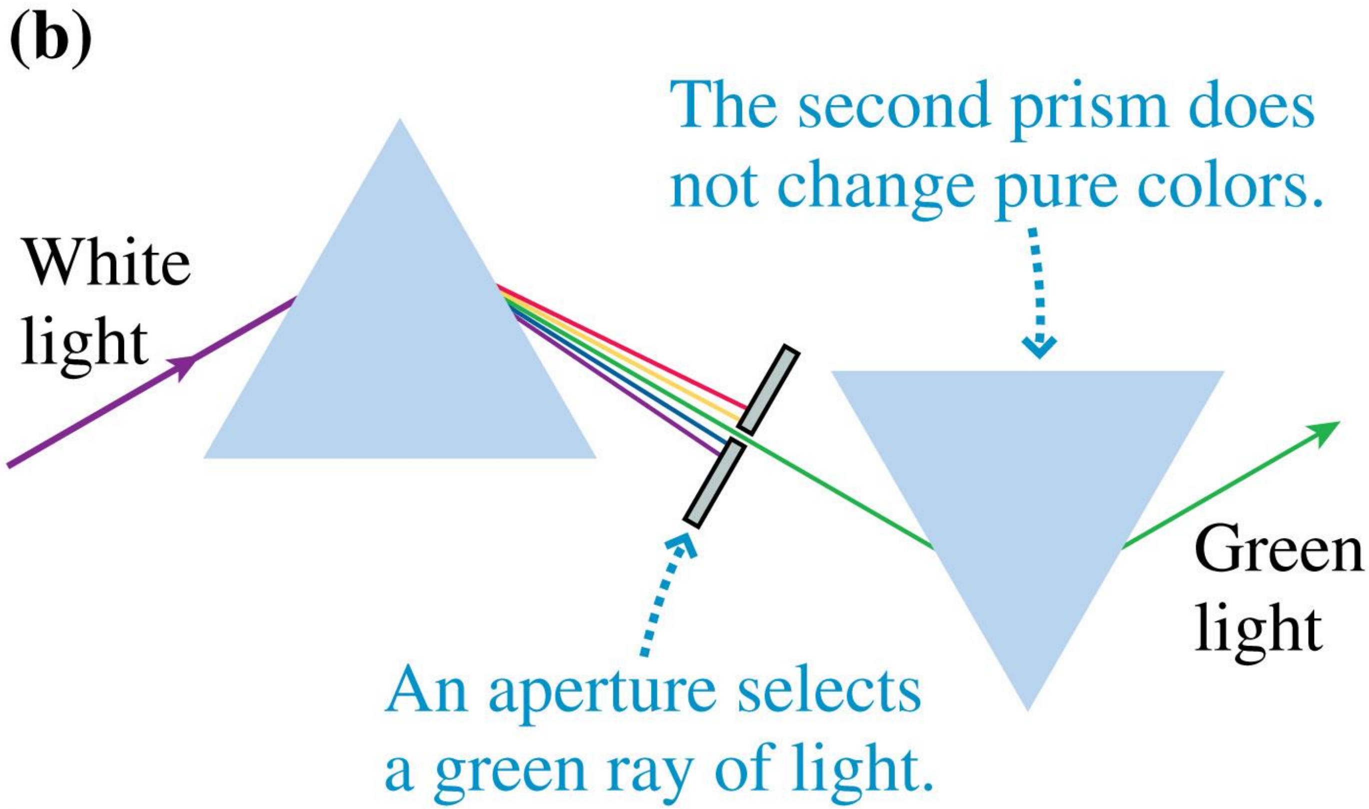
Color

- A prism *disperses* light. Newton used prisms to study color.



Color

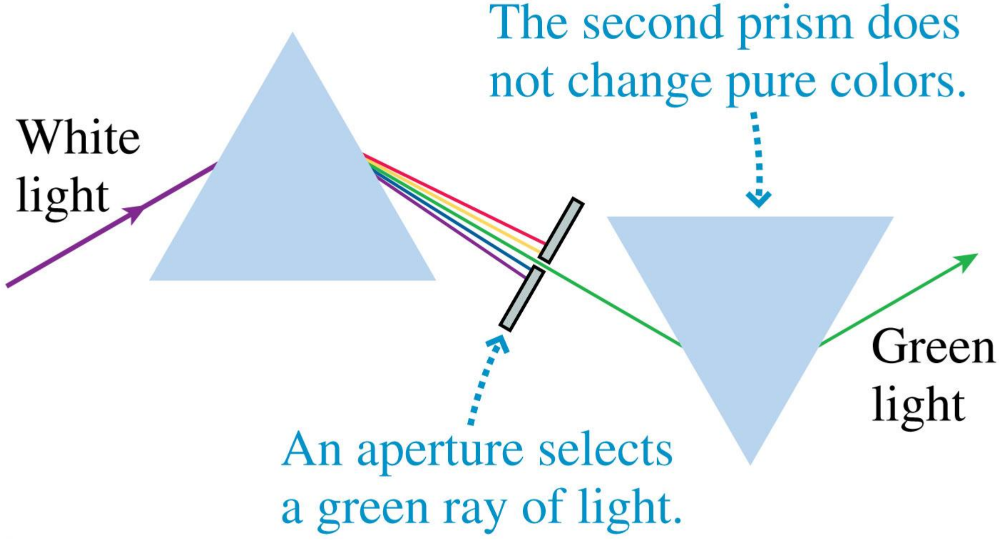
- The emerging light from a second prism is white only if *all* the rays are allowed to move between the two prisms.



Color

- Newton blocked all the rays of light from the first prism except for those of one color. Only that color was seen through the second prism and it was unchanged.
- Newton recognized that this meant the color is associated with light itself; the prism was not altering the properties of light.

(b)



Color

- Experiments show:
  1. What we perceive as white light is a mixture of all colors. White light can be dispersed into its various colors and, equally important, mixing all the colors produces white light.
  2. The index of refraction of a transparent material differs slightly for different colors of light. Glass has a slightly higher index of refraction for violet light than for green light or red light. Consequently, different colors of light refract at slightly different angles.

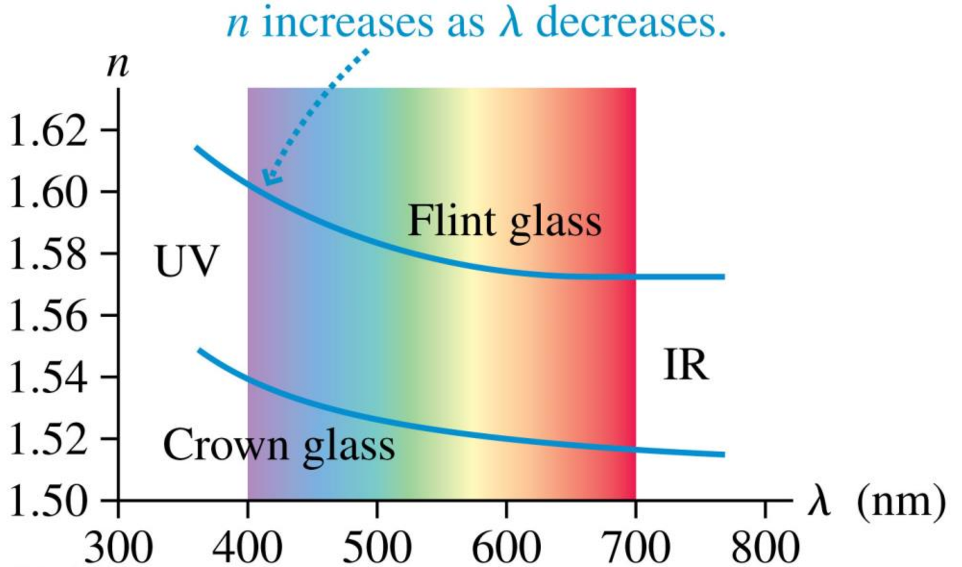
Dispersion

TABLE 19.1 A brief summary of the visible spectrum of light

Color	Approximate wavelength
Deepest red	700 nm
Red	650 nm
Yellow	600 nm
Green	550 nm
Blue	450 nm
Deepest violet	400 nm

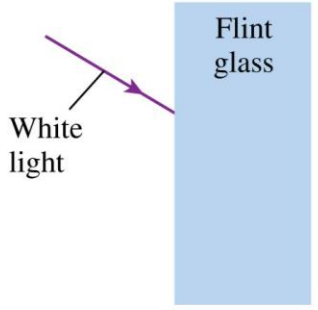
Dispersion

- **Dispersion** is the slight variation of the index of refraction with wavelength.
- This figure shows the *dispersion curves* of two common glasses.
- ***n* is higher when the wavelength is *shorter*.**
- Therefore, violet light refracts more than red light.



QuickCheck 19.6

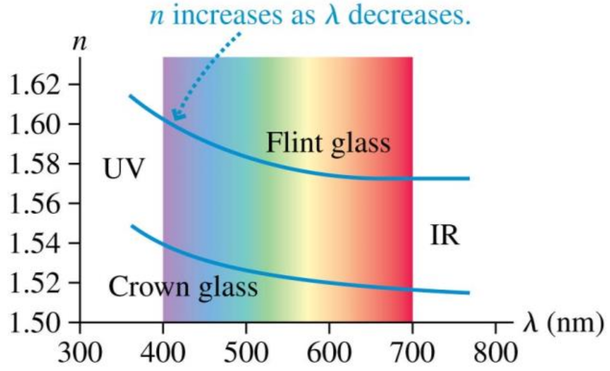
A narrow beam of white light is incident at an angle on a piece of flint glass. As the light refracts into the glass,



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 light were already traveling in the same direction.



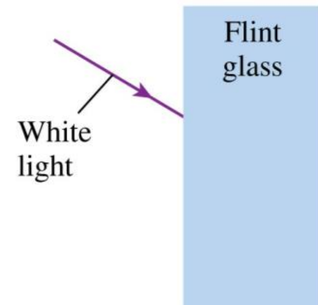
QuickCheck 19.6

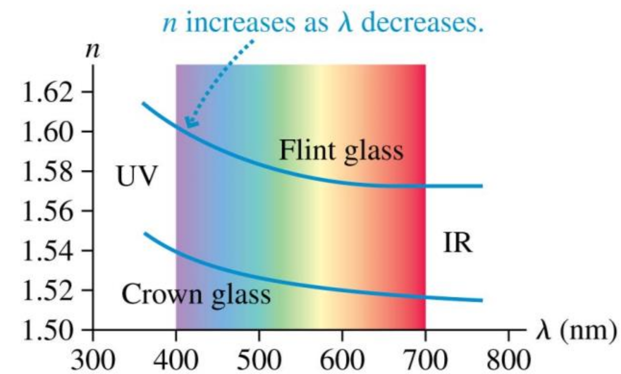
A narrow beam of white light is incident at an angle on a piece of flint glass. As the light refracts into the glass,

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 light were already traveling in the same direction.





Example 19.8 Dispersing light with a prism

Example 18.4 in Chapter 18 found that a ray incident on a 30° prism is deflected by 22.6° if the prism's index of refraction is 1.59. Suppose this is the index of refraction of deep violet light, and that deep red light has an index of refraction of 1.54.

a. What is the deflection angle for deep red light?

b. If a beam of white light is dispersed by this prism, how wide is the rainbow spectrum on a screen 2.0 m away?

PREPARE Figure 18.18 in Example 18.4 showed the geometry. A ray is incident on the hypotenuse of the prism at $\theta_1 = 30°$.

Example 19.8 Dispersing light with a prism (cont.)

SOLVE

a. If $n_1 = 1.54$ for deep red light, the refraction angle is

$$\theta_2 = \sin^{-1}\left(\frac{n_1 \sin\theta_1}{n_2}\right) = \sin^{-1}\left(\frac{1.54 \sin 30°}{1.00}\right) = 50.35°$$

Example 18.4 showed that the deflection angle is $\phi = \theta_2 - \theta_1$, so deep red light is deflected by $\phi_{\text{red}} = 20.35°$. This angle is slightly smaller than the deflection angle for violet light, $\phi_{\text{violet}} = 22.60°$.

Example 19.8 Dispersing light with a prism (cont.)

b. The entire spectrum is spread between $\phi_{\text{red}} = 20.35°$ and $\phi_{\text{violet}} = 22.60°$. The angular spread is

$$\delta = \phi_{\text{violet}} - \phi_{\text{red}} = 2.25° = 0.0393 \text{ rad}$$

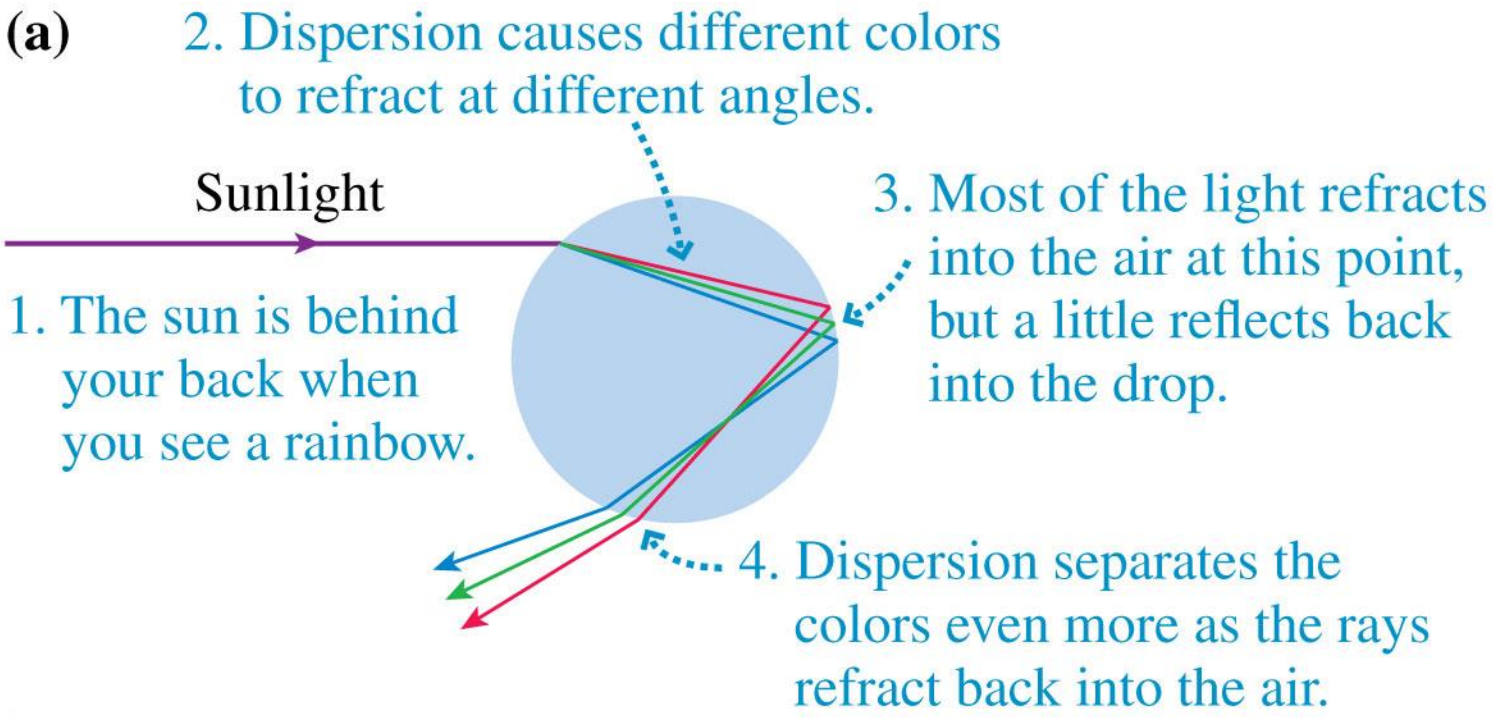
At distance r, the spectrum spans an arc length

$$s = r\delta = (2.0 \text{ m})(0.0393 \text{ rad}) = 0.0785 \text{ m} = 7.9 \text{ cm}$$

Example 19.8 Dispersing light with a prism (cont.)

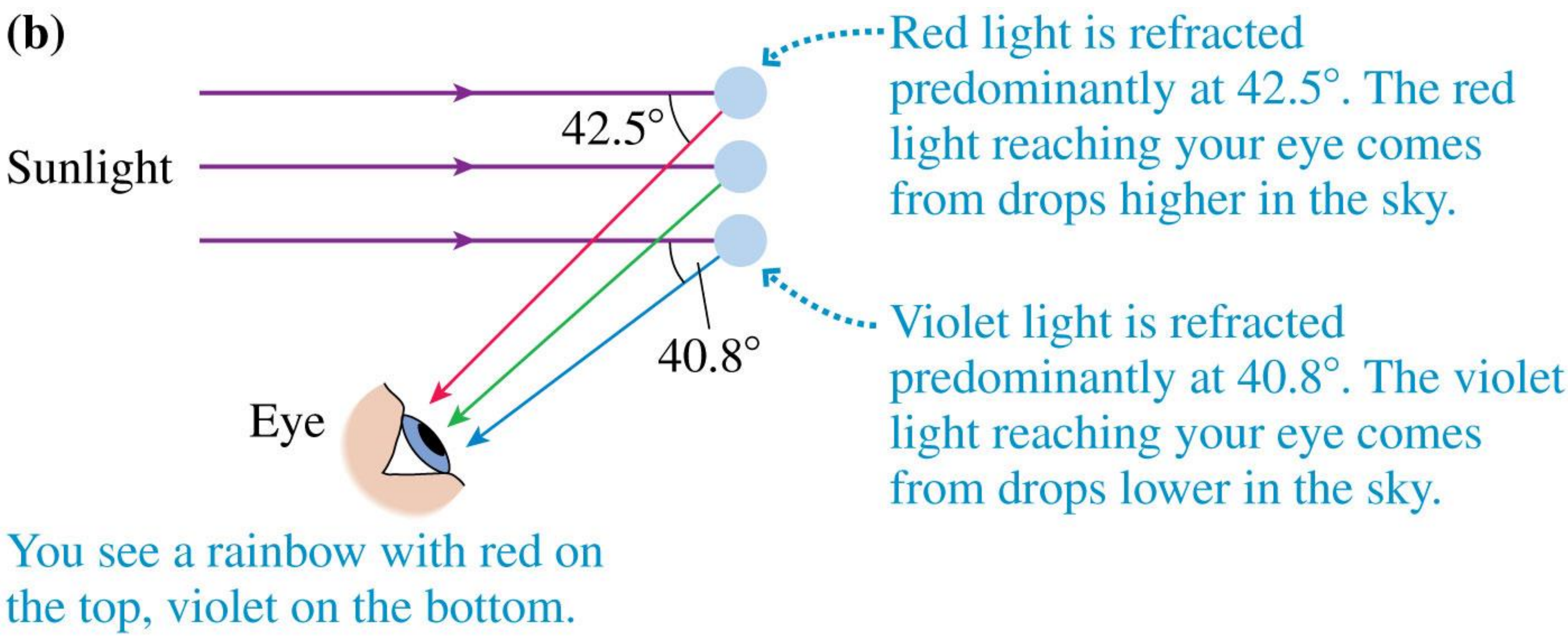
ASSESS Notice that we needed three significant figures for ϕ_{red} and ϕ_{violet} in order to determine δ, the *difference* between the two angles, to two significant figures. The angle is so small that there's no appreciable difference between arc length and a straight line. The spectrum will be 7.9 cm wide at a distance of 2.0 m.

Rainbows



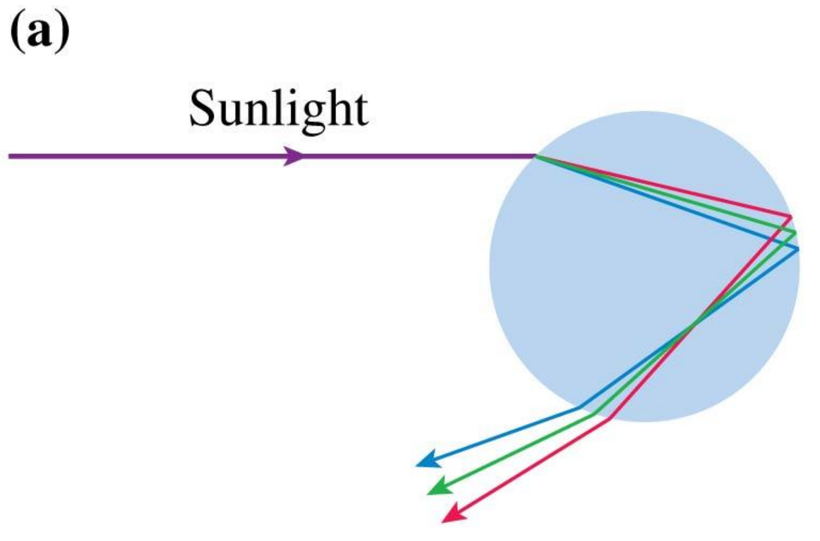
(a)
2. Dispersion causes different colors to refract at different angles.
Sunlight
3. Most of the light refracts into the air at this point, but a little reflects back into the drop.
1. The sun is behind your back when you see a rainbow.
4. Dispersion separates the colors even more as the rays refract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

Rainbows


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

Rainbows

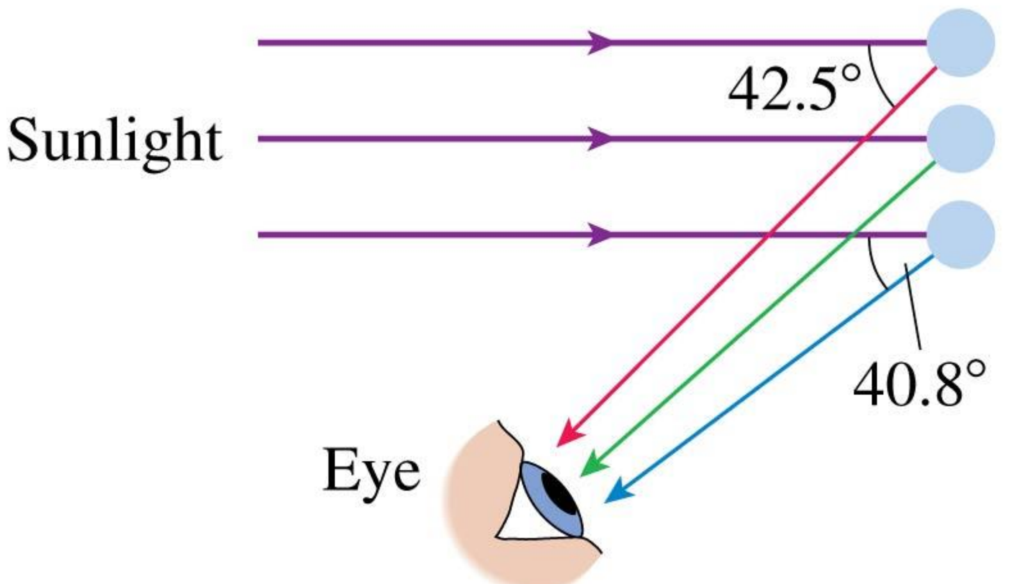
- The dispersion from one raindrop may lead you to think that the top edge of a rainbow is violet, but it is not.
- The rays leaving the drop spread out and do not all reach your eye.
- A ray of red light that does reach your eye comes from a drop *higher* in the sky than a ray of violet light.



Rainbows

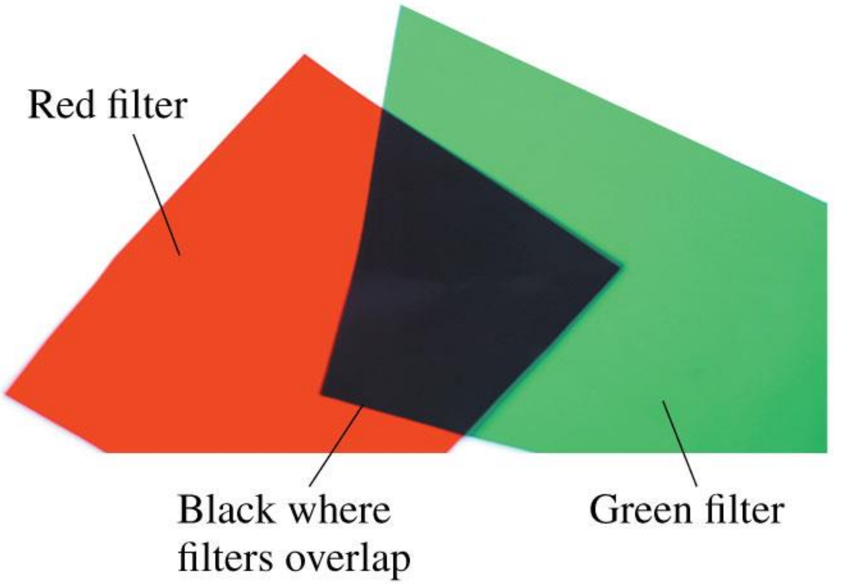
- You see a rainbow refract towards your eye from different raindrops, not the same raindrop.
- You have to look higher in the sky to see the red light, and so red is always the top edge of a rainbow.

(b)



Colored Filters and Colored Objects

- Green glass is green because it *removes* any light that is not green.
- Colored glass *absorbs* all wavelengths except those of one color, which is transmitted through the glass without hindrance.



- Colored glass or plastic is a *filter* that removes all wavelengths except a chosen few.

Conceptual Example 19.9 Filtering light

White light passes through a green filter and is observed on a screen. Describe how the screen will look if a second green filter is placed between the first filter and the screen. Describe how the screen will look if a red filter is placed between the green filter and the screen.

Conceptual Example 19.9 Filtering light (cont.)

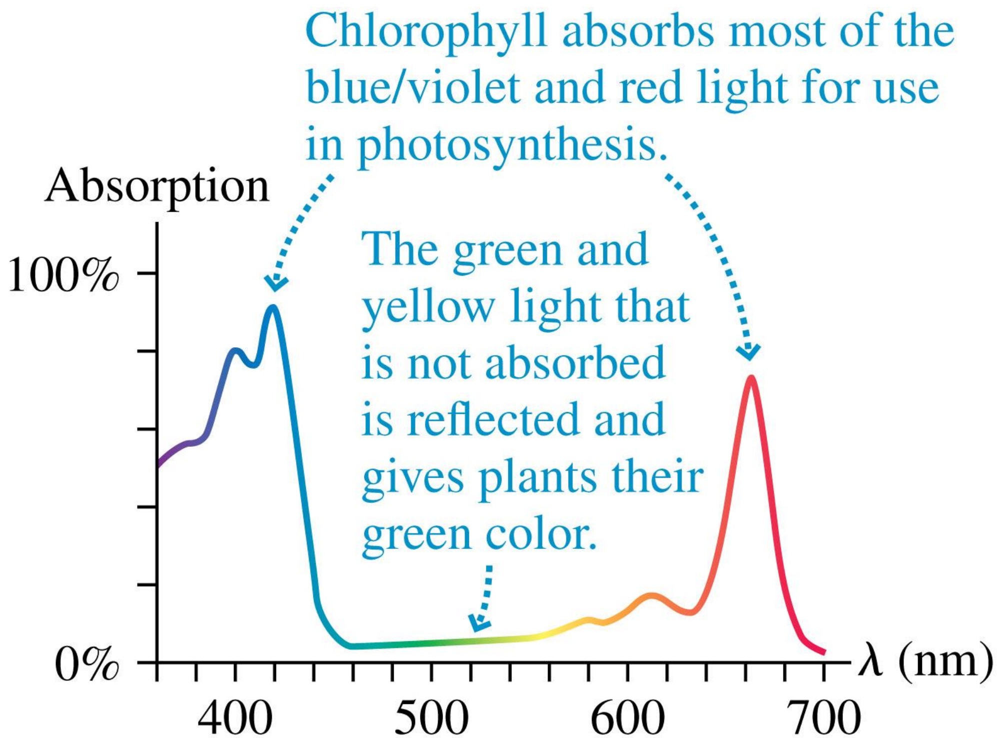
REASON The first filter removes all light except for wavelengths near 550 nm that we perceive as green light. A second green filter doesn't have anything to do. The nongreen wavelengths have already been removed, and the green light emerging from the first filter will pass through the second filter without difficulty. The screen will continue to be green and its intensity will not change. A red filter, by contrast, absorbs all wavelengths except those near 650 nm. The red filter will absorb the green light, and *no* light will reach the screen. The screen will be dark.

Colored Filters and Colored Objects

- Opaque objects appear colored by virtue of *pigments* that absorb light from some wavelengths but *reflect* light of other wavelengths.

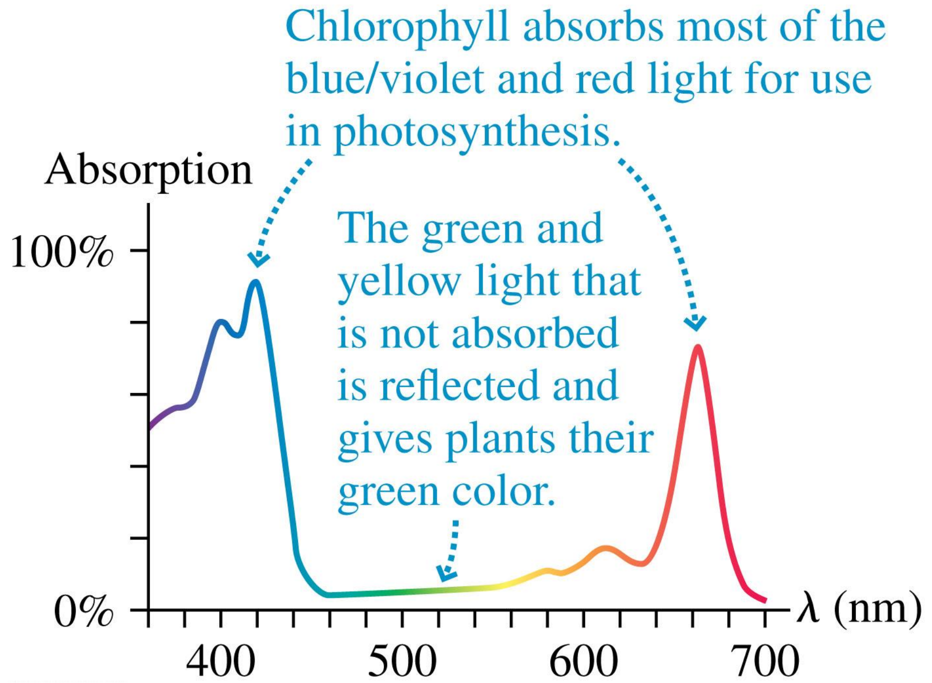
Colored Filters and Colored Objects

- This is the absorption curve of *chlorophyll*.
- The chemical reactions of photosynthesis use red light and blue/violet light; thus chlorophyll has evolved to absorb those colors from sunlight.



Colored Filters and Colored Objects

- Green and yellow light are not absorbed, but instead *reflected*, giving the object a greenish-yellow color.
- 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.



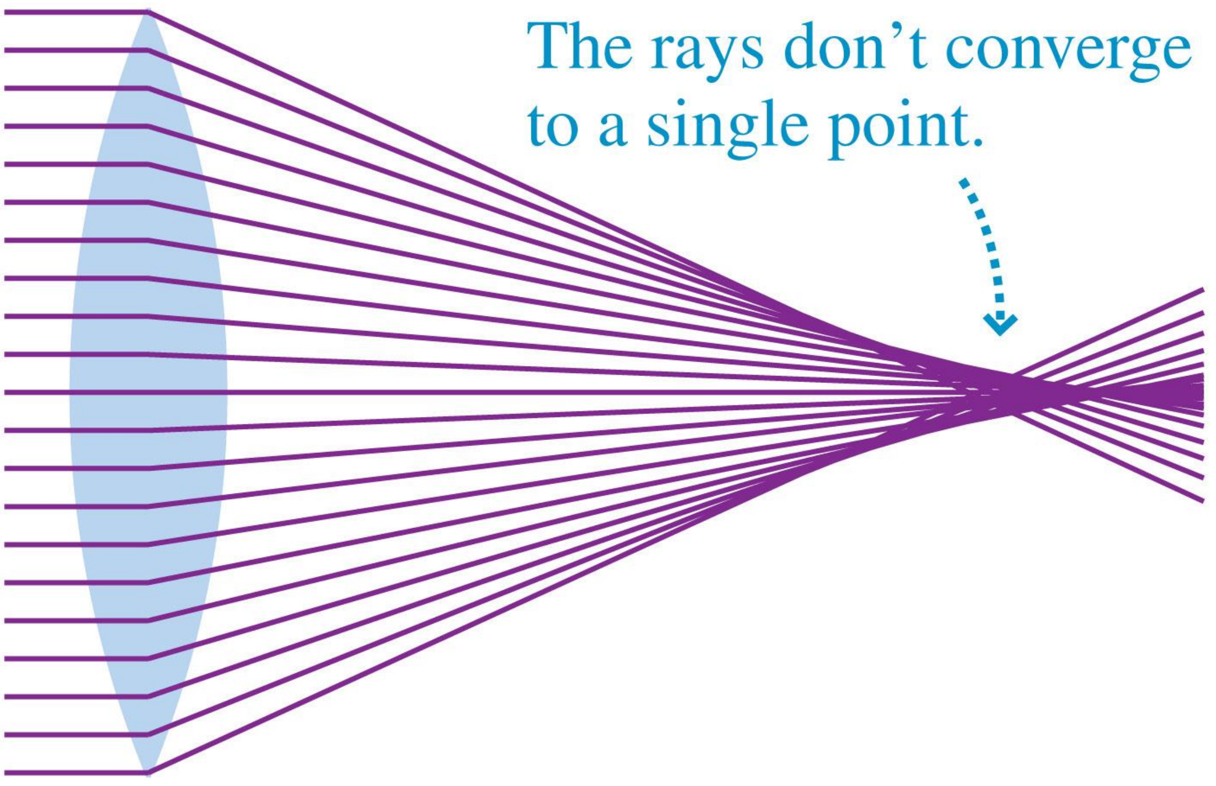
Section 19.7 Resolution of Optical Instruments

Resolution of Optical Instruments

- All real optical instruments are limited in the details they can observe.
- **Aberrations** are an example of a practical limit, caused by imperfections in the lens.
- Even a perfect lens has a fundamental limit set by the diffraction of light.
- An optical system's **resolution** is its ability to make out the fine details of an object.

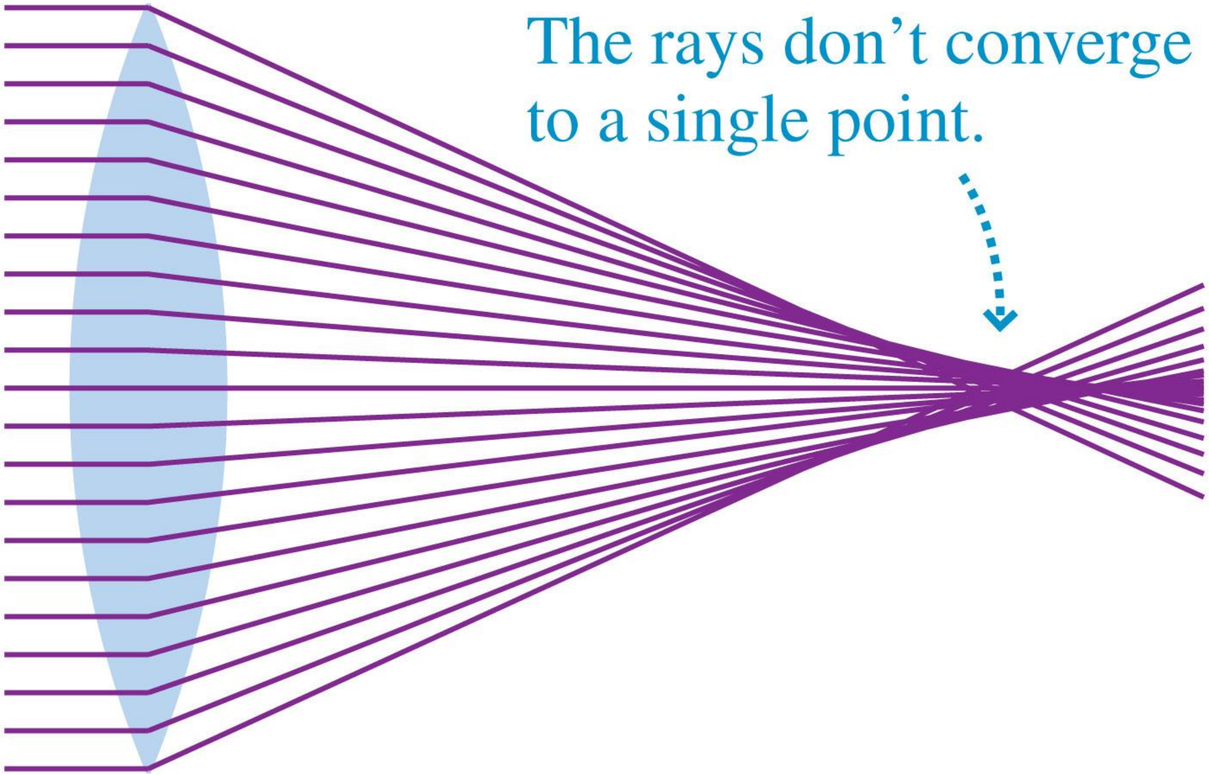
Aberrations

- For a real lens with spherical surfaces, the rays that pass near the lens's center come to a focus a bit farther from the lens than those that pass near its edge.



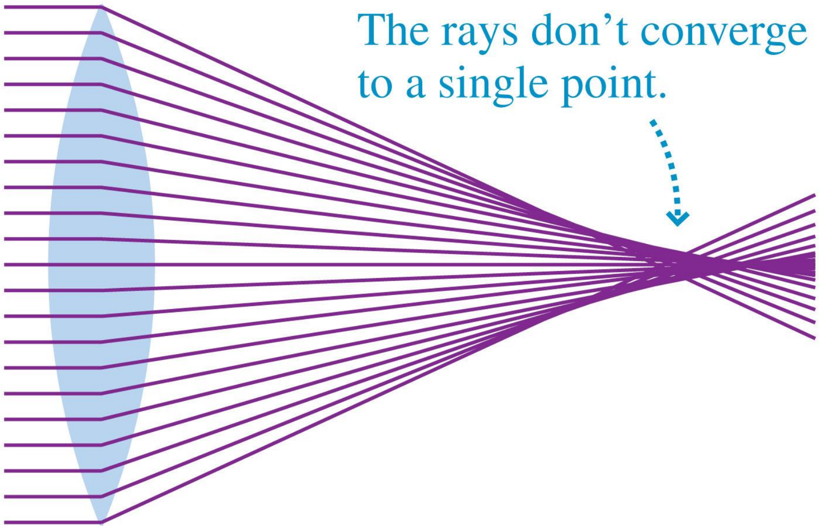
Aberrations

- For a real lens, there is no single focal point; even at the best focus the image is a bit blurred.
- The inability for a real lens to focus perfectly is called **spherical aberration**.



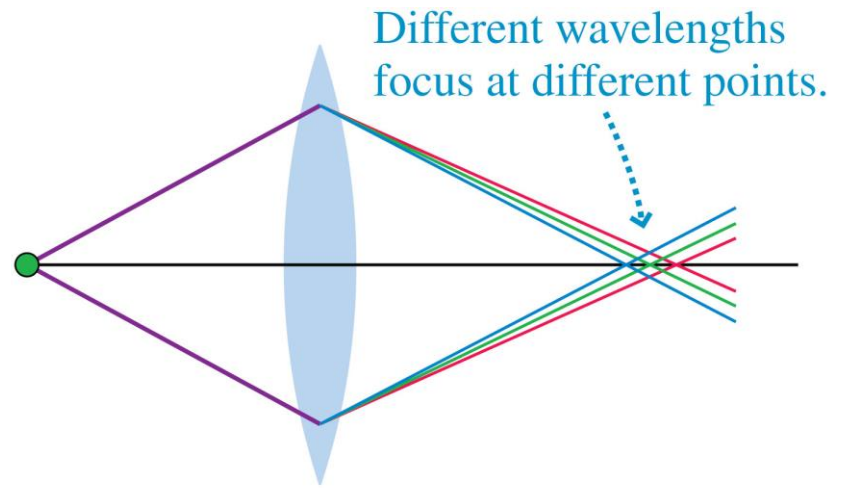
Aberrations

- The outer rays are most responsible for poor focus.
- The effects of spherical aberration can be minimized by using a diaphragm to pass only rays near the optical axis. This is at the expense of light-gathering ability.
- At night, the iris of the eye is wide open, so vision is poor but more sensitive.



Aberrations

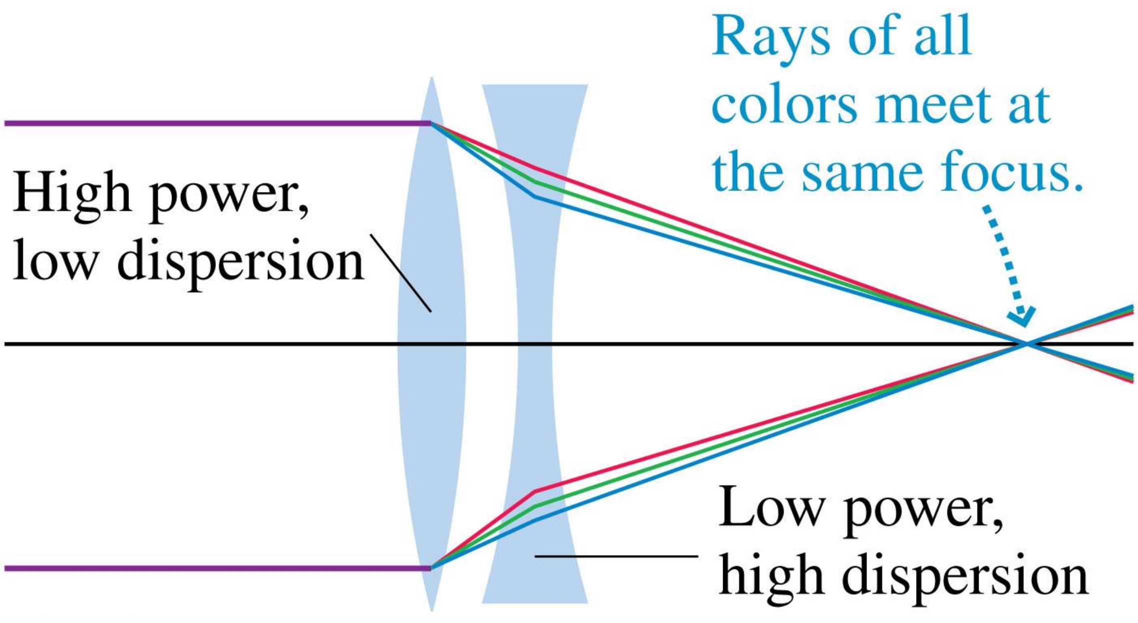
- **Chromatic aberration** is due to dispersion in a glass.
- The index of refraction for violet light is higher than that for red light, so a lens's focal length is slightly shorter.



- Different colors focus at slightly different distances from the lens.
- If red is sharply focused, then violet is not well focused.

Correcting Aberrations

- An **achromatic doublet** is the use of two lenses in combination to greatly reduce chromatic aberration.
- A converging lens is paired with a weaker diverging lens.
- The weaker diverging lens has a greater dispersion and can therefore bring the colors dispersed by the first lens back together into white light.

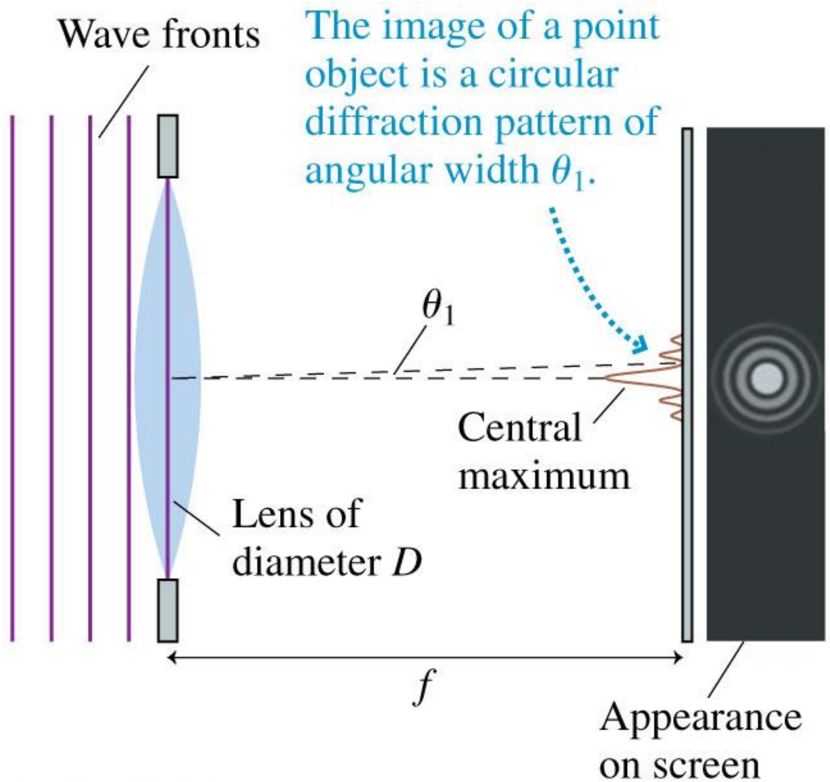


Correcting Aberrations

- Achromatic doublets also minimize spherical aberration.
- The base principle of achromatic doublets is used for the objectives of microscopes.

Resolution and the Wave Nature of Light

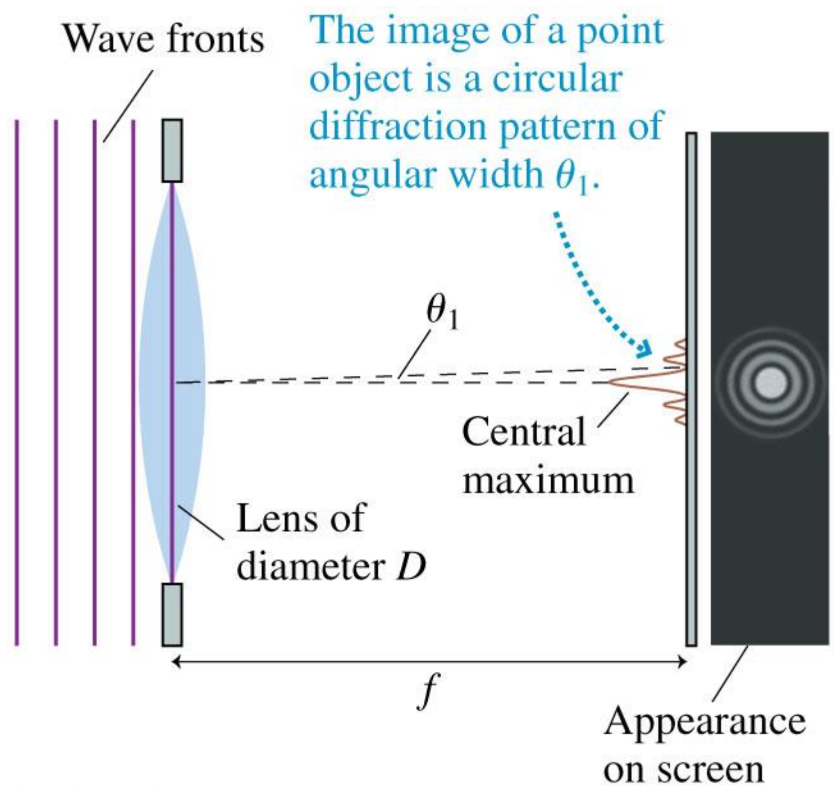
- Only waves passing *through* a lens can be focused, so the lens acts like a circular aperture of diameter *D* in an opaque barrier.
- The lens focuses *and diffracts* light waves.



Resolution and the Wave Nature of Light

- Light from a distant point source focuses not to a perfect point but instead to a small circular diffraction pattern.
- The angle θ_1 of the outer edge of the central maximum is

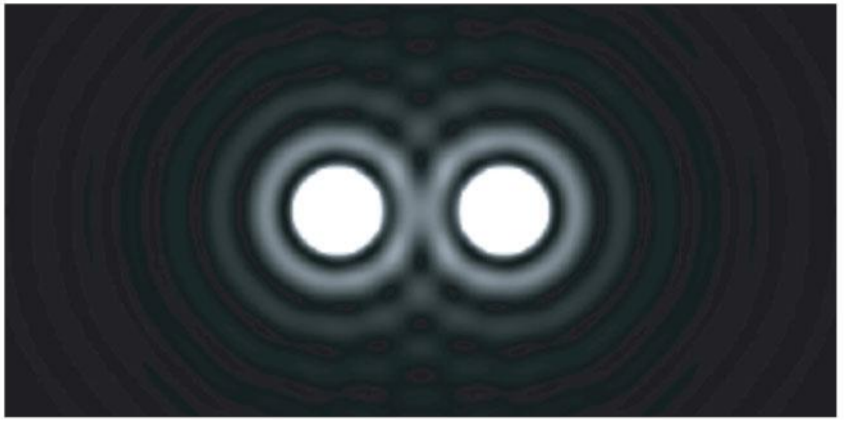
$$\theta_1 = \frac{1.22\lambda}{D}$$



Resolution and the Wave Nature of Light

- In a telescope, two stars separated by only a small angle in the sky appear as two diffraction images.
- Because they are clearly two separated stars, we say they are *resolved*.

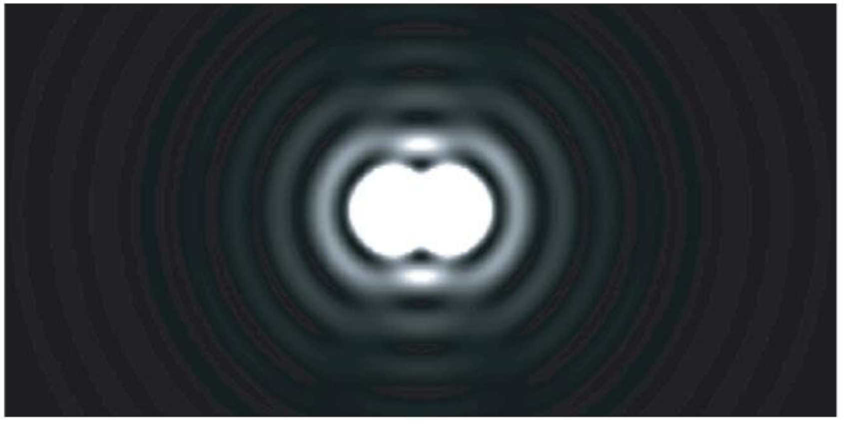
(a) Stars resolved



Resolution and the Wave Nature of Light

- When the diffraction patterns of the stars overlap, it becomes difficult to see them as two independent stars: They are barely resolved.

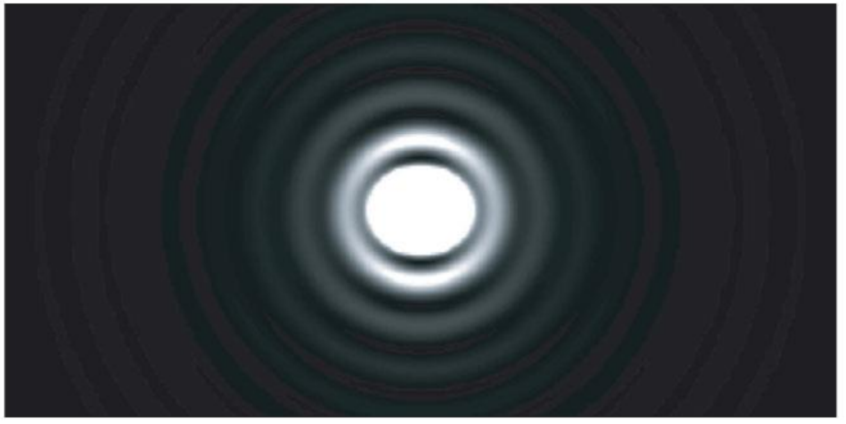
(b) Stars just resolved



Resolution and the Wave Nature of Light

- The two very nearby stars in this figure are so close together than we cannot resolve them at all.

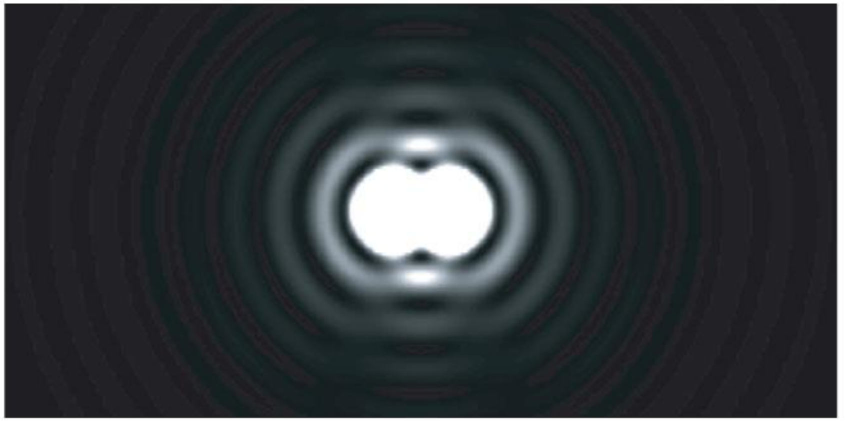
(c) Stars not resolved



Resolution and the Wave Nature of Light

- **Rayleigh's criterion** is a rule to determine how close two diffraction patterns can be before they can no longer be resolved.
- When two stars are just resolved, *the central maximum of the diffraction pattern of one star lies on top of the first dark fringe of the diffraction pattern of the other star.*

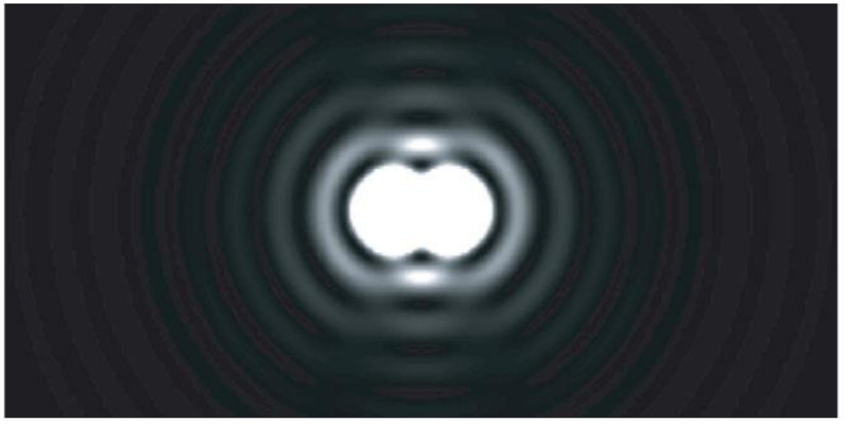
(b) Stars just resolved



Resolution and the Wave Nature of Light

- The angle between the central maximum and the first dark fringe is θ_1, so the centers of the two stars are separated by angle $\theta_1 = 1.22\ \lambda/D$.

(b) Stars just resolved



Resolution and the Wave Nature of Light

- Rayleigh's criterion says:

  Two objects are resolvable if they are separated by an angle θ that is greater than $\theta_1 = 1.22\,\lambda/D$. If their angular separation is less than θ_1, then they are not resolvable. If their separation is equal to θ_1, then they are just barely resolvable.

- For telescopes, the angle $\theta_1 = 1.22\,\lambda/D$ is called the *angular resolution* of the telescope.
- The angular resolution depends on the lens diameter and the wavelength; magnification is not a factor.

QuickCheck 19.7

Two distant stars are only marginally resolved when viewed through a telescope having a 10× 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.

QuickCheck 19.7

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C. View the stars using infrared wavelengths.
✔ D. View the stars using ultraviolet wavelengths.

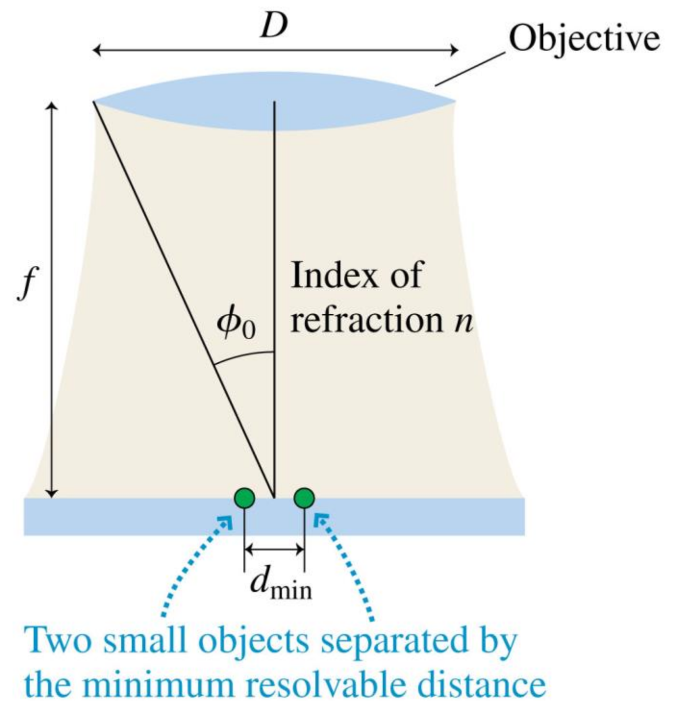
The Resolution of a Microscope

- A microscope differs from a telescope in that it magnifies objects that are very close to the lens.
- The wave nature of light still sets a limit on the ultimate resolution of a microscope.

The Resolution of a Microscope

- Rayleigh's criterion finds the smallest resolvable separation between two objects in a microscope is

$$d_{\min} = \frac{0.61\lambda}{n \sin\phi_0}$$



- ϕ_0 is the angular size of the objective lens and n is the index of refraction of the medium between the objective lens and the specimen observed.

The Resolution of a Microscope

- The quantity $n \sin\phi_0$ is called the **numerical aperture** NA of the objective when immersed in a fluid of index *n*.
- The **resolving power** RP is the minimum resolvable distance of the microscope:

The resolving power . . .

Wavelength of light in vacuum

$$\text{RP} = d_{\min} = \frac{0.61\lambda_0}{\text{NA}}$$

. . . is the smallest resolvable separation between two objects.

Numerical aperture of objective lens

- The lower the resolving power, the *better* the objective is at seeing small details.

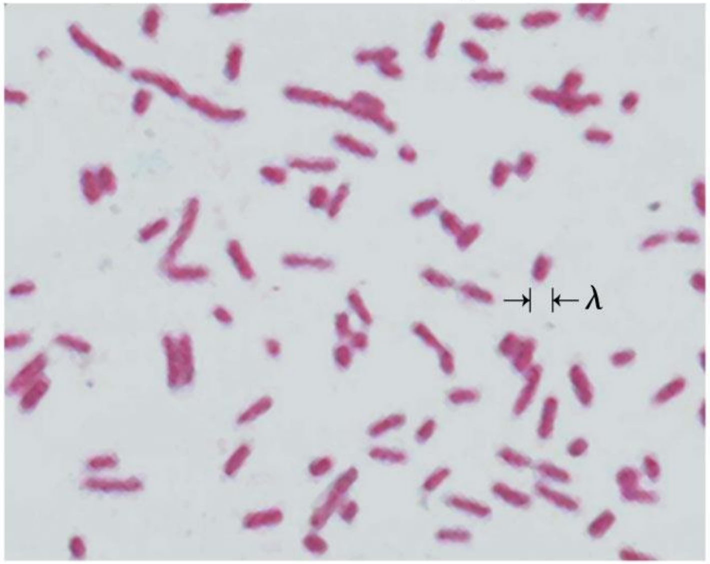
The Resolution of a Microscope

- The **minimum resolving power of a microscope, and thus the size of the smallest detail observable, is about half the wavelength of light.**
- This is a *fundamental limit* set by the wave nature of light.

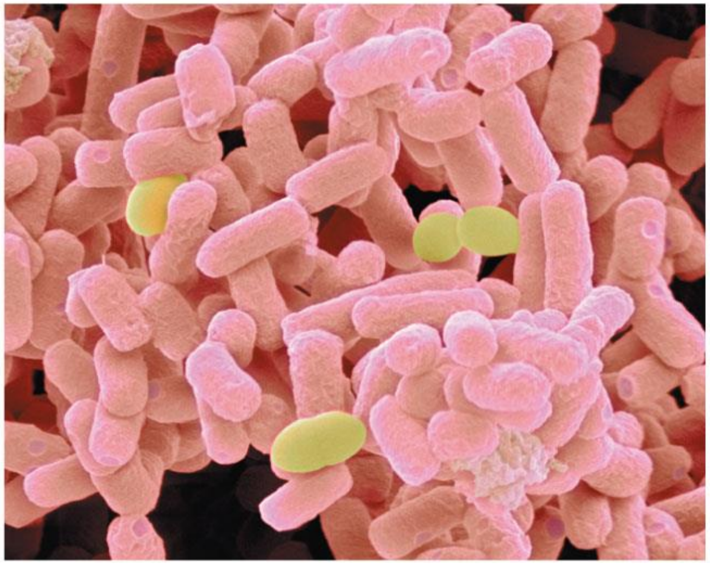
The Resolution of a Microscope

- The micrograph of the bacillus *E. coli* is about equal to the wavelength of light at 500 nm, and the smallest resolved features are about half this.
- An **electron microscope** micrograph of *E. coli* shows a wealth of detail unobservable in the optical picture.

Optical microscope



Electron microscope



Example 19.10 Finding the resolving power of a microscope

A microscope objective lens has a diameter of 6.8 mm and a focal length of 4.0 mm. For a sample viewed in air, what is the resolving power of this objective in red light? In blue light?

PREPARE We can use Equation 19.9 to find the resolving power. We'll need the numerical aperture of the objective, given as NA = $n \sin \phi_0$.

Example 19.10 Finding the resolving power of a microscope (cont.)

SOLVE From the geometry of Figure 19.27,

$$\tan\phi_0 = \frac{D/2}{f} = \frac{3.4\text{ mm}}{4.0\text{ mm}} = 0.85$$

from which $\phi_0 = \tan^{-1} 0.85 = 40.4°$ and $\sin\phi_0 = \sin 40.4° = 0.65$. Hence the numerical aperture is (since $n = 1$ in air)

$$\text{NA} = n\sin\phi_0 = 1 \times 0.65 = 0.65$$

Example 19.10 Finding the resolving power of a microscope (cont.)

Then, from Equation 19.9, the resolving power is

$$\text{RP} = \frac{0.61\lambda_0}{0.65} = 0.94\lambda_0$$

Wavelengths of different colors of light were listed in Table 19.1. For red light, with λ_0 = 650 nm, RP = 610 nm, while blue light, with λ_0 = 450 nm, has RP = 420 nm.

Example 19.10 Finding the resolving power of a microscope (cont.)

ASSESS We see that shorter-wavelength light yields a higher resolution (lower RP). Unfortunately, wavelengths much shorter than 400 nm are invisible, and glass lenses are opaque to light of very short wavelength.

Example Problem

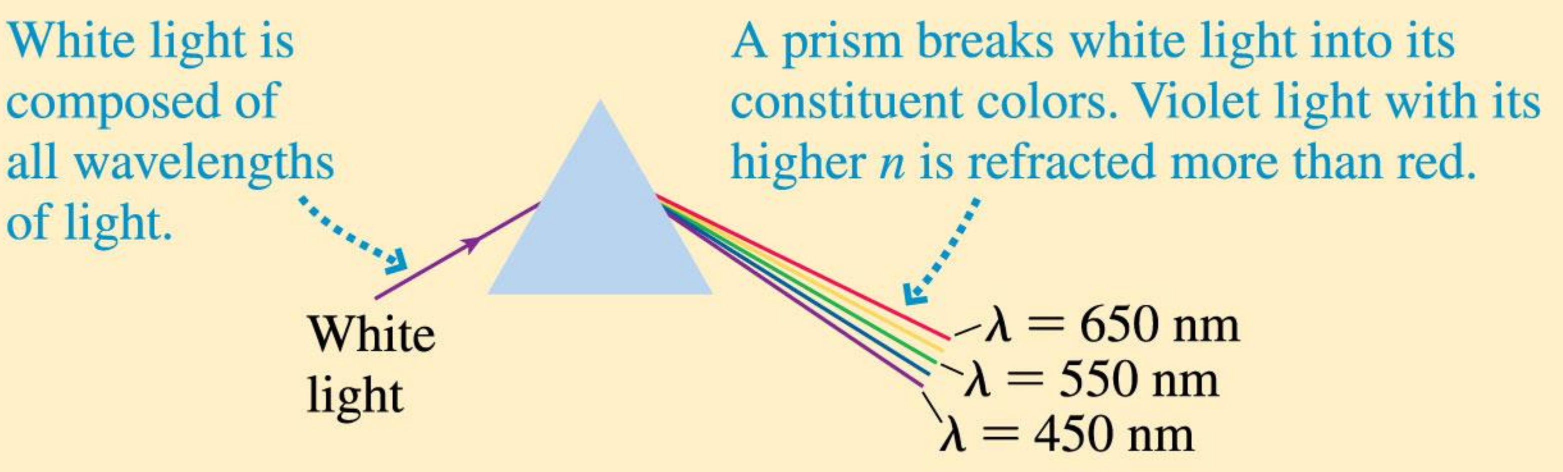
The objective of a microscope has magnifying power of 20×, a numerical aperture of 0.4, a working distance (WD) of 4 mm ($\sim f$) . For a wavelength of light of 450 nm, what is the resolving power of this objective? What is the diameter of its lens?

Summary: Important Concepts

Color and dispersion

The eye perceives light of different wavelengths as having different colors.

Dispersion is the dependence of the index of refraction n of a transparent medium on the wavelength of light: Long wave-lengths have the lowest n, short wavelengths the highest n.

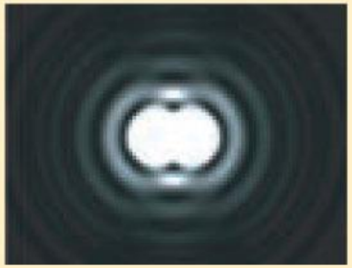


Text: p. 620

Summary: Important Concepts

Resolution of optical instruments

The **resolution** of a telescope or microscope is limited by imperfections, or **aberrations,** in the optical elements, and by the more fundamental limits imposed by diffraction.



For a *microscope*, the minimum resolvable distance between two objects is

$$d_{\text{min}} = \frac{0.61\lambda}{\text{NA}}$$

For a *telescope*, the minimum resolvable angular separation between two objects is

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

Text: p. 620

Summary: Important Concepts

Lenses in combination

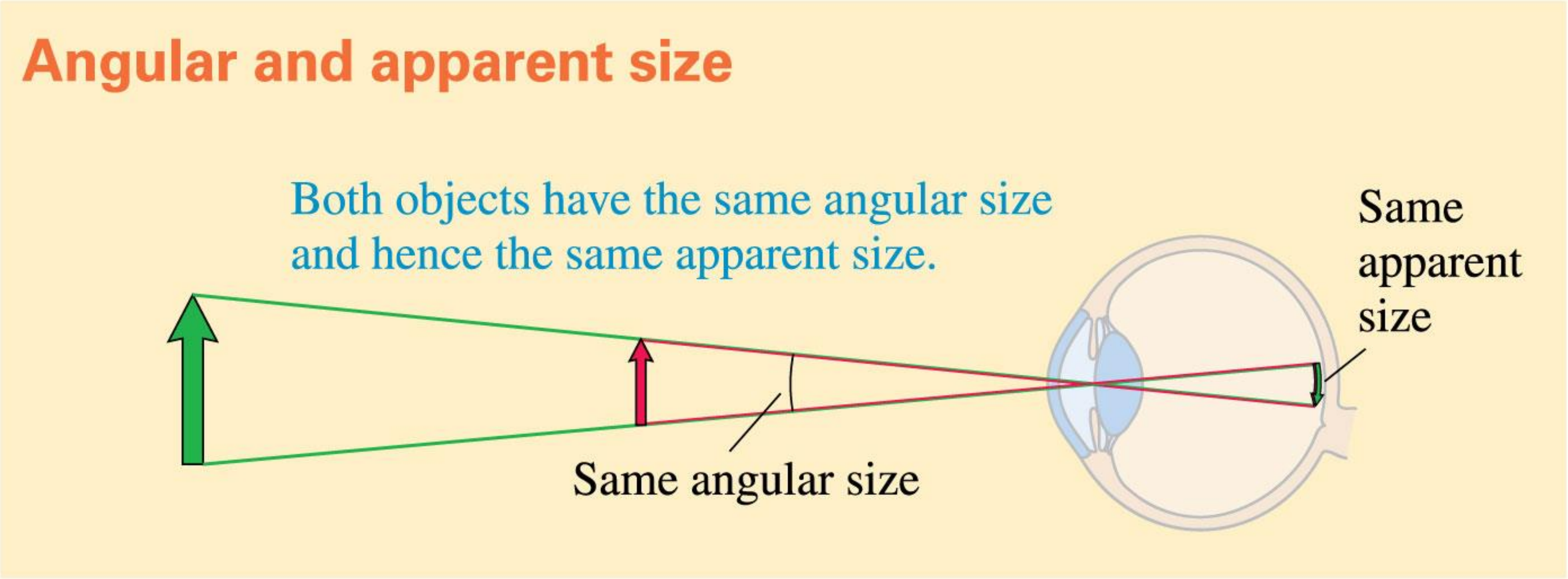
When two lenses are used in combination, the image from the first lens serves as the object for the second.

The **refractive power** P of a lens is the inverse of its focal length: $P = 1/f$. Refractive power is measured in diopters:

$$1\text{ D} = 1\text{ m}^{-1}$$

Text: p. 620

Summary: Important Concepts

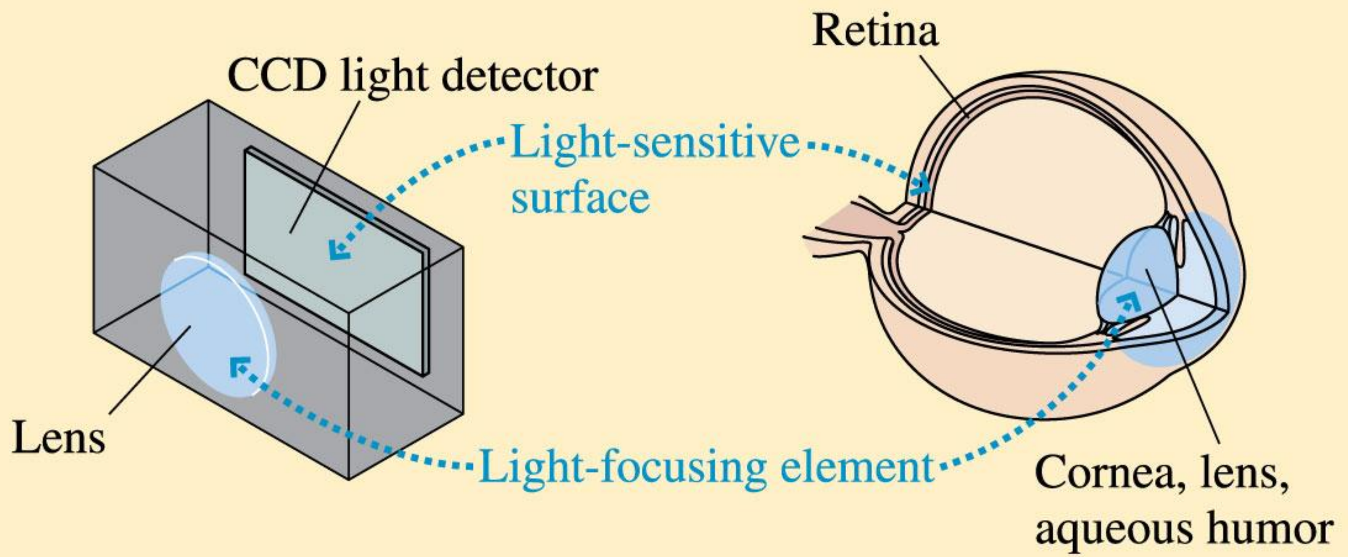


Text: p. 620

Summary: Applications

The camera and the eye

Both the camera and the eye work by focusing an image on a light-sensitive surface.



The camera focuses by changing the lens-detector distance, while the eye focuses by changing the focal length of its lens.

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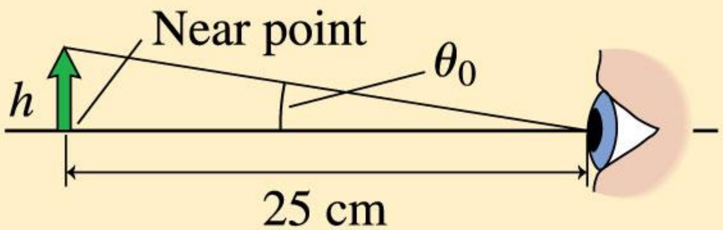
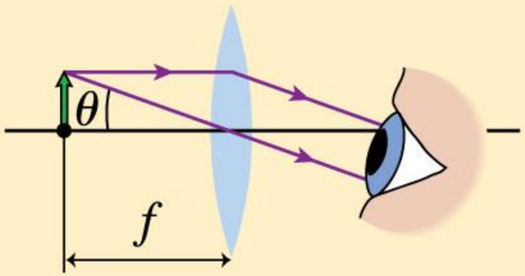
Summary: Applications

The magnifier

Without a lens, an object cannot be viewed closer than the eye's near point of ≈ 25 cm. Its angular size θ_0 is $h/25$ cm.



If the object is now placed at the focal point of a converging lens, its angular size is increased to $\theta = h/f$.

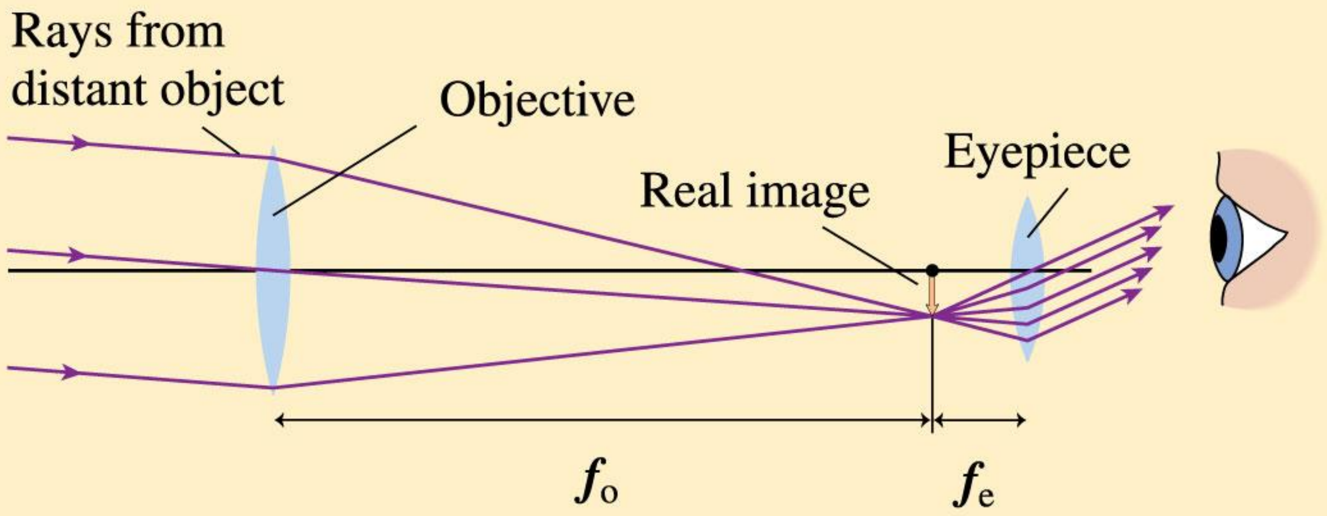


The angular magnification is $M = \theta/\theta_0 = 25 \text{ cm}/f$.

Text: p. 620

Summary: Applications

The telescope magnifies distant objects. The objective lens creates a real image of the distant object. This real image is then magnified by the eyepiece lens, which acts as a simple magnifier. The angular magnification is $M = -f_o/f_e$.

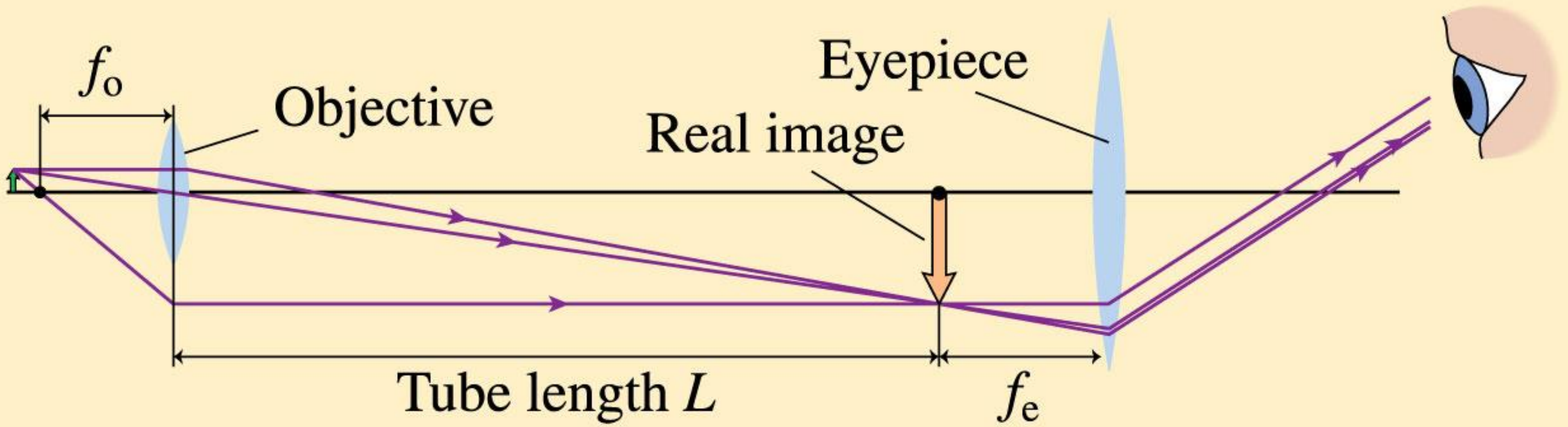


Text: p. 620

Summary: Applications

The microscope magnifies a small, nearby object. The objective lens creates a real image of the object. This real image is then further magnified by the eyepiece lens, which acts as a simple magnifier. The angular magnification is

$$M = -\frac{L \times 25\text{ cm}}{f_o f_e}$$



Text: p. 620

Summary

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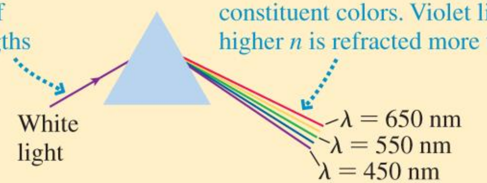

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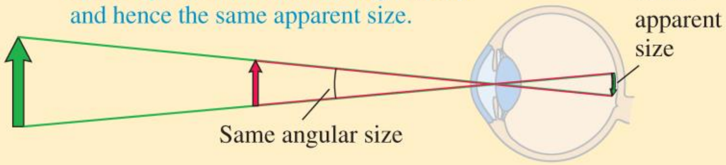
Angular and apparent size



Text: p. 620

Summary

APPLICATIONS

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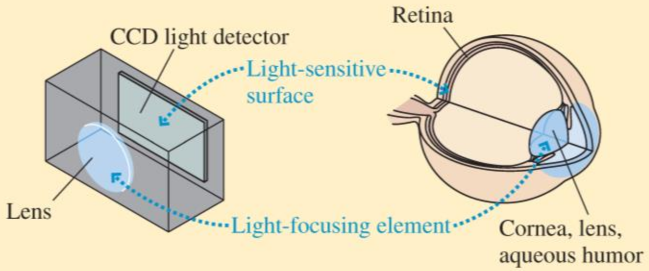

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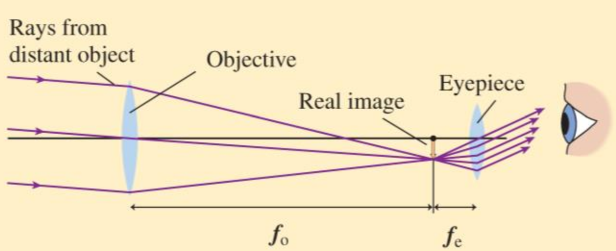
The telescope magnifies distant objects. The objective lens creates a real image of the distant object. This real image is then magnified by the eyepiece lens, which acts as a simple magnifier. The angular magnification is $M = -f_o/f_e$.



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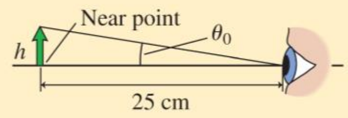

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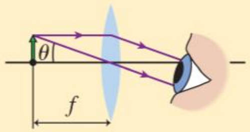

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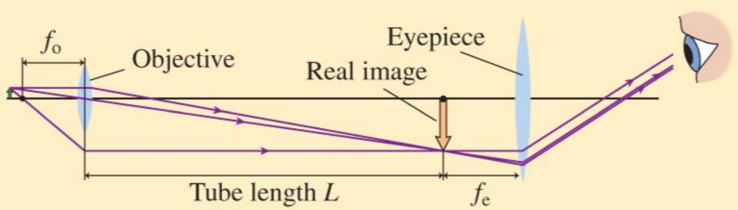
$$M = -\frac{L \times 25\text{ cm}}{f_o f_e}$$



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