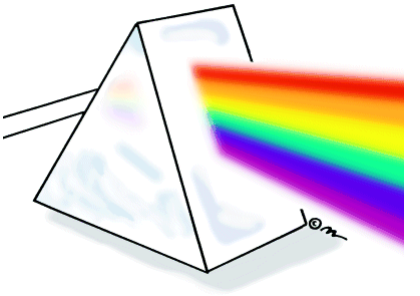
EP118 Optics

TOPIC 8
OPTICAL INSTRUMENTS



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8.1 Introduction

- An optical instrument either
  - processes light waves to enhance an image for viewing, or
  - analyzes light waves (or photons) to determine one of a number of characteristic properties.

- In this chapter, we will see several optical instruments used in Optics and their resolving powers.

8.2 Camera

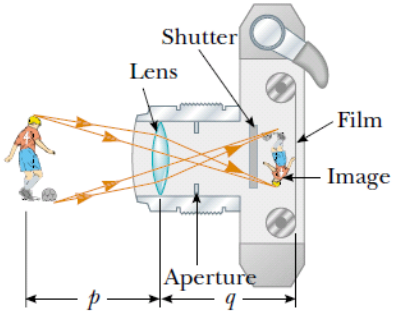
- A camera is a device that records/stores images.
- These images may be still photographs or moving images such as videos or movies.

- Essential features:

Converging lens produces a real image, and a film behind the lens receives the image.

One focuses the camera by varying the distance between lens and film.

Aperture is a hole or an opening through which light travels.



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a large aperture

a small aperture

- The shutter is opened for selected time intervals, called **exposure times**.
- Typical shutter speeds: (1/30)s, (1/60)s, (1/125)s, and (1/250) s.

- The intensity *I* of the light reaching the film is proportional to the area of the lens (or diameter-square D^2 of aperture) and inversely proportional to focal length *f* (*k* is a constant).

$$I = k\frac{D^2}{f^2}$$

- The ratio f/D is called the f-number (*lens speed*) of a lens:

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

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

- If Δt is the exposure time then energy received per unit area will be proportional to: $I\,\Delta t$

EXAMPLE 1

The lens of a certain 35-mm camera has a focal length of 55 mm and a speed (an f-number) of f/1.8. The correct exposure time for this speed under certain conditions is known to be (1/500) s.

(*35 mm is the width of the film strip and f/1.8 means f-number = f/D = 1.8*)

(a) Determine the diameter of the lens.

(b) Calculate the correct exposure time if the f-number is changed to f/4 under the same lighting conditions.

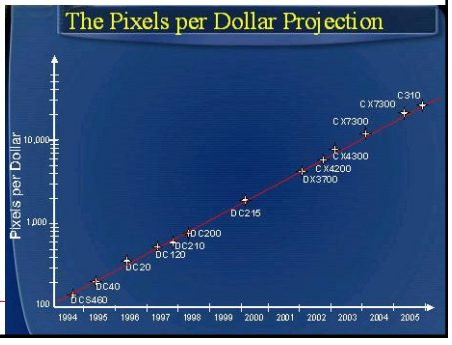
SOLUTION

- Digital cameras are similar to the cameras except that the light does not form an image on photographic film.
- The image in a digital camera is formed on a charge-coupled device (CCD), which digitizes the image, turning it into binary code.
- Digital cameras use a regular grid of pixels to store data. (*Pixel are the smallest unit of picture that can be controlled*).

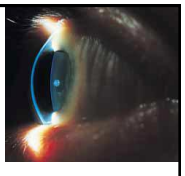
640x480 image --> 307,200 pixels

3872x2592 image --> 10,036,224 pixels, or approximately 10 MegaPixels.

- The digital information is then stored on a memory chip for playback on the screen of the camera, or it can be downloaded to a computer and sent to a friend or relative through the Internet.

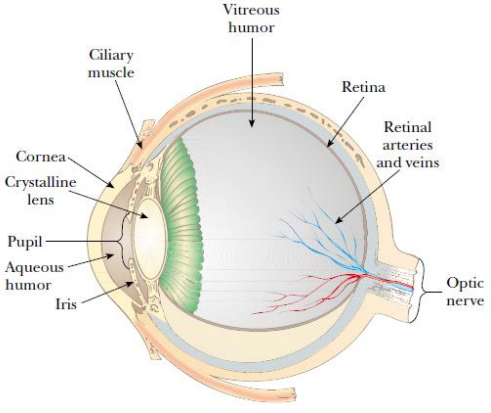


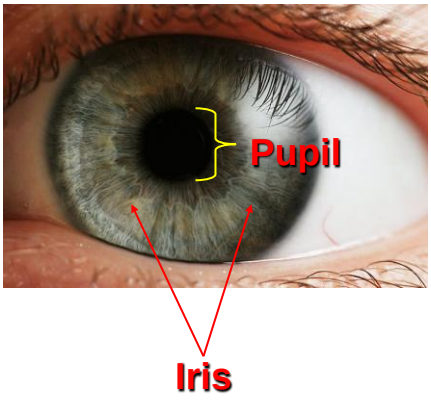
8.3 Eye (Perfect Light Detector)



- A normal eye focuses light and produces a sharp image better than a camera.
- Human eye can detect even a few photons in dark.

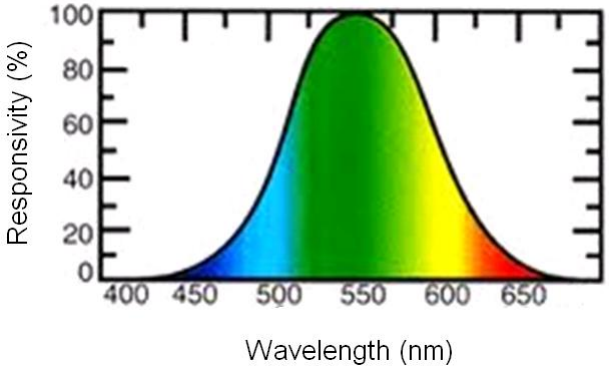
1. Light entering the eye passes through a transparent structure called the cornea.
2. Pupils are opening in the iris.
3. Crystalline lens focuses light onto the back surface of the eye, the retina which consists of millions of sensitive receptors called *rods* and *cones*.
4. The receptors send light impulses via the optic nerve to the brain, where an image is perceived.





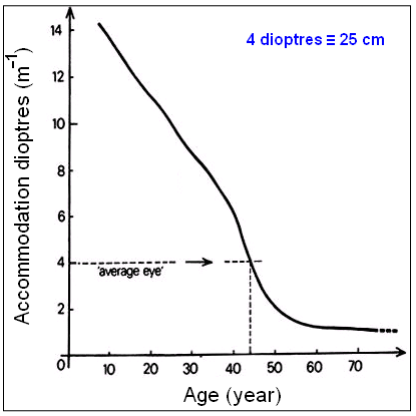
Spectral Response of Eye

The human eye is not equally sensitive to all wavelengths of visible light.



Accomodation

- The eye focuses on an object by varying the shape of the pliable crystalline lens (by ciliary muscle) through an amazing process called **accommodation** (*göz uyumu*).



- The **near point** is the closest distance for which the lens can accommodate to focus light on the retina.

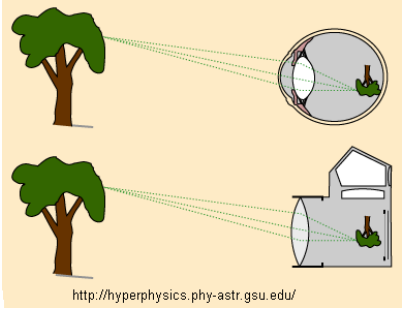
  This distance usually increases with age and has an average value of 25 cm = 0.25 m.

$$P = \frac{1}{0.25\,\mathrm{m}} = 4\,\mathrm{m}^{-1} = 4\,\mathrm{D}$$

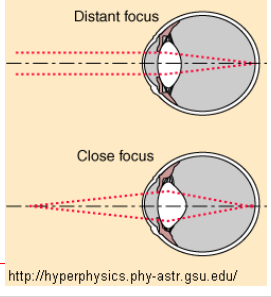
- The **far point** of the eye represents the greatest distance for which the lens of the relaxed eye can focus light on the retina. For normal vision "far point –> ∞"
- *For normal eye, range accommodation is between 25 cm and ∞.*

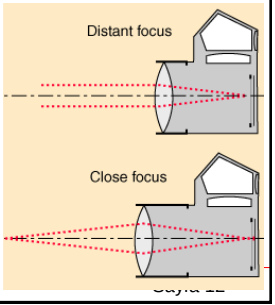
Eye and Camera

Image formation



Accommodation in Eye and Camera





Conditions of Eye

Normal vision | Myopia vision

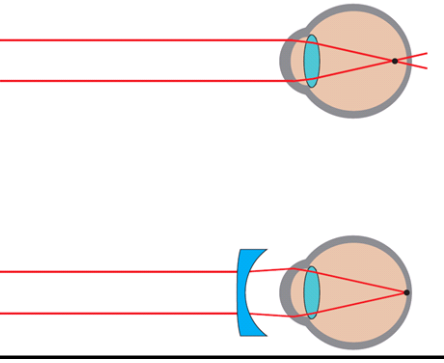
Near-sightedness (or myopia)

- is a vision condition in which close objects are seen clearly, but objects farther away appear blurred.
- Nearsightedness occurs if the eyeball is too long or the cornea, as a result, the light entering the eye isn't focused correctly.
- Nearsightedness is corrected with a diverging lens.
- The far point of a nearsighted person is not infinity (~1 m).

- *The purpose of the lens is to "move" an object from infinity to a distance (x) where it can be seen clearly.*

$$\frac{1}{f} = \frac{1}{\infty} + \frac{1}{x}$$

where f < 0.



EXAMPLE 2

A particular nearsighted person is unable to see objects clearly when they are beyond 2 m away. What should be the focal length and power of the lens ?

SOLUTION

A dioptre, or diopter, is a unit of measurement of the optical power of a lens or curved mirror, which is equal to the reciprocal of the focal length measured in metres (that is, 1/metres).

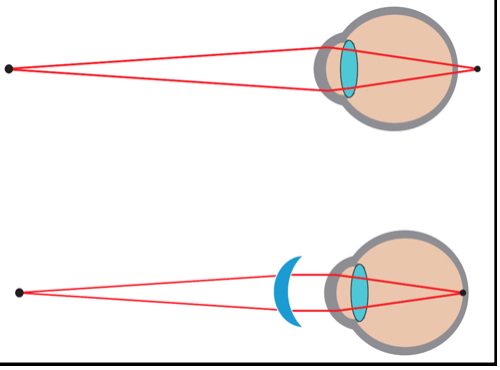
Far-sightedness (or hyperopia)

Normal vision | Hyperopia vision

- is a vision condition in which distant objects are usually seen clearly, but close ones do not come into proper focus.
- Farsightedness occurs if your eyeball is too short or the cornea has too little curvature, so light entering your eye is not focused correctly.
- Farsightedness is corrected with a converging lens.
- The near point of a farsighted person is much farther away from 25 cm.
- *The purpose of the lens is to "move" an object from a distance (x) where it can be seen clearly to near point (25 cm).*

$$\frac{1}{f} = \frac{1}{0.25\,\text{m}} + \frac{1}{x}$$

where f > 0.



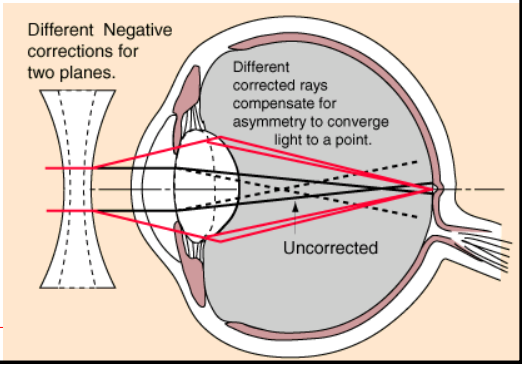
EXAMPLE 3

A particular farsighted person is unable to see objects clearly when they are closer than 1 m. What should be the focal length and power of the lens?

SOLUTION

Astigmatism

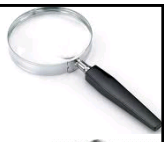
- Astigmatizm is a vision condition that causes blurred vision due either to the irregular shape of the cornea, the clear front cover of the eye, or sometimes the curvature of the lens inside the eye.
- Astigmatism frequently occurs with other vision conditions like nearsightedness (myopia) and farsightedness (hyperopia).
- Astigmatism can be corrected with lenses that have different curvatures in two mutually perpendicular directions.
- Laser surgery is also a possible treatment option for some types of astigmatism.



Presbyopia (old-age vision)

- Presbyopia is a vision condition in which the crystalline lens of your eye loses its flexibility, which makes it difficult for you to focus on close objects.
- Beginning in middle age, most people lose some of their accommodation ability as the *ciliary muscle* weakens and the lens hardens.
- Unlike farsightedness, which is a mismatch between focusing power and eye length, presbyopia is due to a reduction in accommodation ability.

8.4 Magnifier

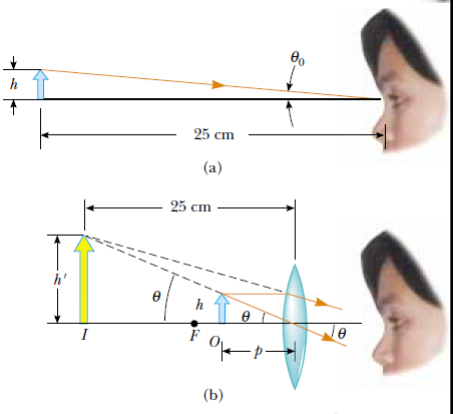


- The magnifier consists of a single converging lens
- Angular magnification (*m*)

$$m = \frac{\theta}{\theta_0}$$

- *m* is a maximum when the image is at the near point (*q* = − 25 cm).
- Object distance (*p*) is:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{-25\,\text{cm}}$$



- Small angle approximations:

$$\left.\begin{aligned}\tan\theta_0 \approx \theta_0 \approx \frac{h}{25}\\ \tan\theta \approx \theta \approx \frac{h}{p}\end{aligned}\right\} \quad m_{\max} = \frac{\theta}{\theta_0} = \frac{h/p}{h/25} = 1 + \frac{25\,\text{cm}}{f}$$

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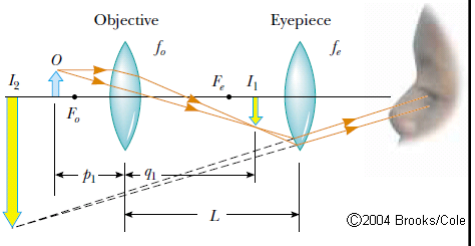
8.5 Microscope

- Greater magnification can be achieved by combining two lenses in a device called a **compound microscope**.

- Objective lens has a very short focal length f_o < 1 cm
- Eyepiece has a focal length f_e of a few centimeters.
- The two lenses are separated by a distance *L*.



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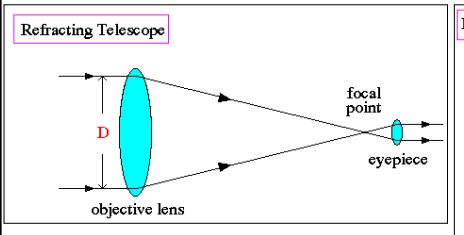
- Total magnification is:

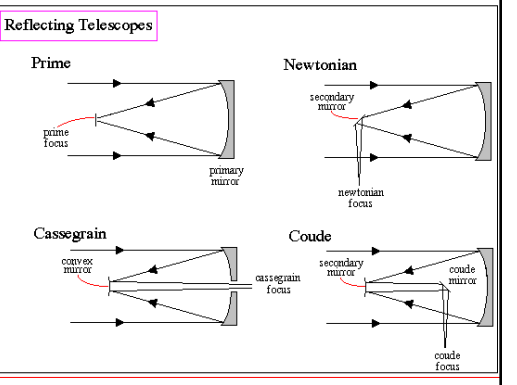
$$m = -\frac{L}{f_o}\left(\frac{25\,\text{cm}}{f_e}\right)$$

The negative sign indicates that the image is inverted.

8.6 Telescope

- Telescopes are designed to aid in viewing distant objects, such as the planets in our Solar System.
- There are two different types:
  - **refracting telescopes** *uses a combination of lenses*
  - **reflecting telescopes** *uses a curved mirror and a lens*

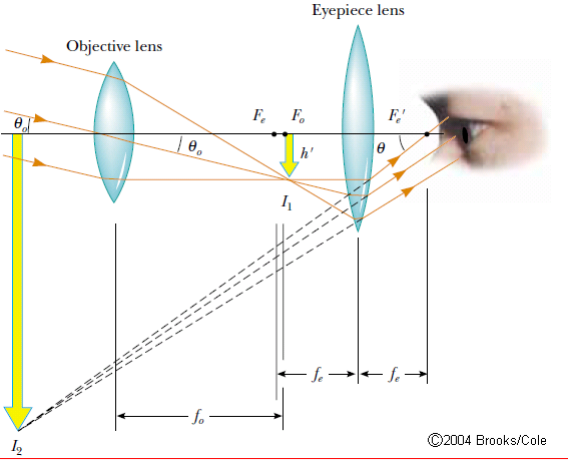




- Angular magnification (for small angles)

$$m \approx \frac{\theta}{\theta_0} = -\frac{f_o}{f_e}$$

- *The negative sign indicates that the image is inverted.*



- The largest *reflecting* telescopes in the world are at the Keck Observatory on Mauna Kea, Hawaii at an elevation of 4,145 meters.
- Two telescopes with diameters of 10 m, each containing 36 hexagonally shaped, computer-controlled mirrors that work together to form a large reflecting surface.

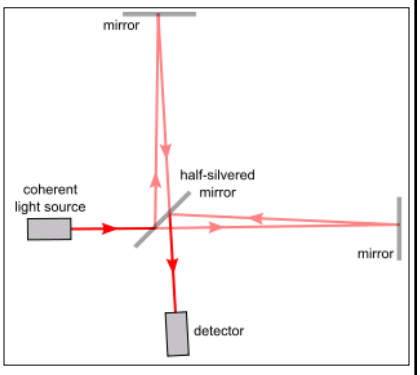
EXAMPLE 4

The largest *refracting* telescope in the world (*Yerkes Observatory*) has a 1.0-m diameter objective lens of focal length 20.0 m. Assume it is used with an eyepiece of focal length 1.5 cm. Determine the magnification of the Sun as seen through this telescope.

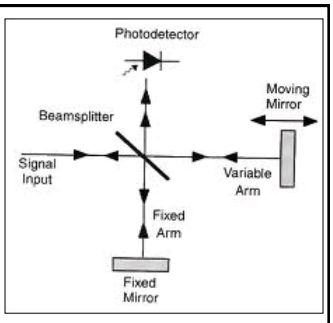
SOLUTION

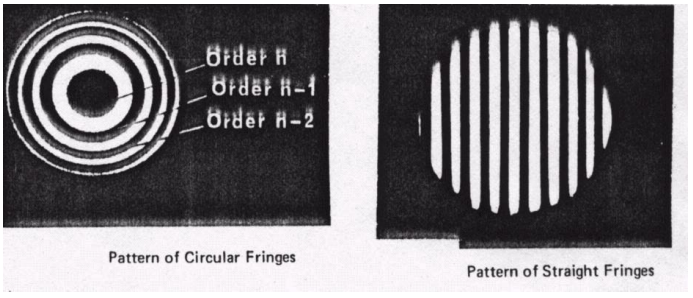
8.7 Interferometer

- An instrument used to interfere waves is called an **interferometer**.
- Interferometry is a technique used in the fields of
  - astronomy
  - fiber optics
  - oceanography
  - seismology
  - nuclear and particle physics
  - remote sensing and etc…
- Interferometers divide a beam of light into two or more parts which travel different paths and recombine to form interference (constructive or destructive) fringes.



- Using the Michelson Interferometer (*see lab sheets*), a small displacement transmitted to the movable mirror can be readily measured by counting the number of fringes.



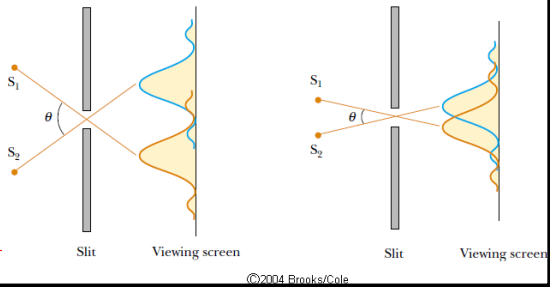


8.8 Optical Resolution

- Optical resolution describes the ability of an imaging system to resolve detail in the object that is being imaged.
- To distinguish between closely spaced objects is limited because of the wave nature of light.

- Consider two non-coherent point sources S1 and S2 (e.g. two stars). Each produce its own diffraction pattern.
  - If θ is large two distinct bright spots would be observed on the screen.
  - If θ is small each source is imaged as a bright central region.

- If the two sources are far enough apart to keep their central maxima from overlapping, their images can be distinguished and are said to be **resolved**.



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Rayleigh's Criterion

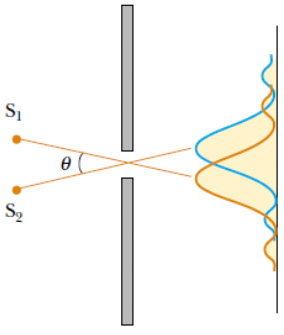
When the central maximum of one image falls on the first minimum of another image, the images are said to be just resolved.

- Minimum angular separation

$$\sin\theta_{\min} = \frac{\lambda}{a}$$

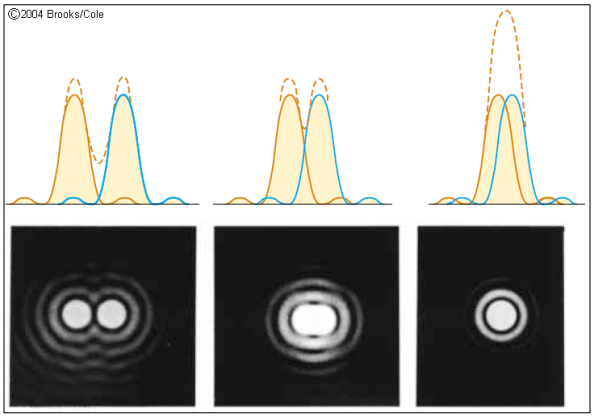
- Small angle approximation

$$\theta_{\min} \approx \frac{\lambda}{a}$$



- if the images are to be resolved , the angle subtended by the two sources at the slit must be greater than λ/a.

- Many optical systems use circular apertures rather than slits



- The limiting angle of resolution of the circular aperture is

$$\theta_{\min} \approx 1.22\frac{\lambda}{D}$$

D is the diameter of the aperture (e.g. lens).

Sayfa 29

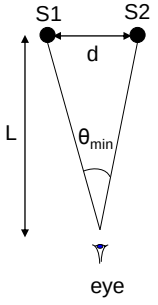
EXAMPLE 5

What is the limiting angle of resolution of the human eye for λ=500 nm and pupil diameter 2 mm?

SOLUTION

$$\theta_{\min} = 1.22\frac{\lambda}{D} = 1.22\frac{500\times10^{-9}}{2\times10^{-3}} = 3\times10^{-4}\ \text{rad}$$

We can use this result to determine the minimum separation distance d between two point sources that the eye can distinguish if they are a distance L from the observer



$$\sin\theta_{\min} \approx \theta_{\min} = \frac{d}{L}$$

$$d \approx L\theta_{\min} = (25\,\text{cm})(3\times10^{-4}\ \text{rad}) = 8\times10^{-3}\ \text{cm}$$

This is approximately equal to the thickness of a human hair.

Sayfa 30

EXAMPLE 6

Light of wavelength 555 nm is used to view an object under a microscope. The aperture of the objective has a diameter of D = 1.5 cm.

(a) What is the limiting angle of resolution?

(b) If it were possible to use visible light of any wavelength, what would be the maximum limit of resolution for this microscope?

SOLUTION

EXAMPLE 7

The Keck telescope at Mauna Kea, Hawaii, has an effective diameter of 10 m. What is its limiting angle of resolution for 555-nm light?

SOLUTION

That is, Any two stars that subtend an angle greater than or equal to this value are resolved (if atmospheric conditions are ideal).

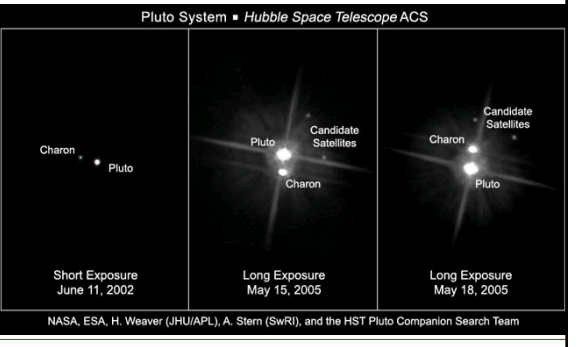
The Keck telescope can never reach its diffraction limit because the limiting angle of resolution is always set by atmospheric blurring at optical wavelengths.

The effects of atmospheric blurring

Telescopic images of Pluto and its moon Charon

From an Earth-based telescope Atmospheric blurring (turbulence) results in Charon appearing only as a subtle bump on the edge of Pluto.

From Hubble Space Telescope (HST), photos of Pluto and Charon, are clearly resolved.



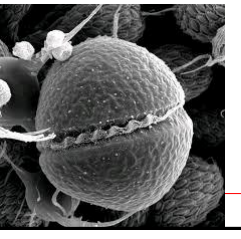
8.9 Electron Microscope

- An electron microscope uses a particle **beam of electrons** to illuminate the specimen and produce a magnified image.
- Electron microscopes have a greater resolving power than a light-powered optical microscope, because electrons have wavelengths about 100,000 times shorter than visible light (photons),

  Resolution
  - Elecron microscope: better than 0.2 nm
  - Light microscope : limited by diffraction to about 200 nm

Head of fly

Dinoflagellate (tek hücreli)



8.10 Exercises

1. A camera can be modeled as a simple converging lens that focuses an image on the film, acting as the screen. A camera is initially focused on a distant object. To focus the image of an object close to the camera, the lens must be
(a) moved away from the film (b) left where it is (c) moved toward the film.

2. The *f*-number of a camera is the focal length of the lens divided by its aperture (or diameter). How can the *f*–number of the lens be changed? How does changing this number affect the required exposure time?

3. What is the role of CCD in a digital camera?

4. A camera is being used with a correct exposure at *f*/4 and a shutter speed of (1/16) s. In order to photograph a rapidly moving subject, the shutter speed is changed to (1/128) s. Find the new *f*-number setting needed to maintain satisfactory exposure.

5. What is eye?
(a) sensory organ mediating the sense of sight
(b) A structure that detects light and converts it into neural responses that the brain interprets
(c) A structure whose anatomy is designed to focus light rays so that an image is formed on the back of the retina
(d) All of the above

6. A nearsighted person cannot see objects clearly beyond 50 cm (her far point). If she has no astigmatism and contact lenses are prescribed for her, what power and type of lens are required to correct her vision?

7. A farsighted person cannot see objects clearly closer than 50 cm (her near point). If she has no astigmatism and contact lenses are prescribed for her, what power and type of lens are required to correct her vision?

8. Consider the phenomenon of accommodation. Under what condition do the ciliary muscles have to do the most work?
(a)When shortening the focal length of the cornea-lens system to view far off objects
(b) When lengthening the focal length of the cornea-lens system to view far off objects
(c) When shortening the focal length of the cornea-lens system to view objects that are near.
(d) When lengthening the focal length of the cornea-lens system to view objects that are near.

9. How does an optometrist correct for hyperopia?
(a) Equips the eye with a diverging lens to shorten the focal length of the cornea-lens system
(b) Equips the eye with a diverging lens to lengthen the focal length of the cornea-lens system
(c) Equips the eye with a converging lens to shorten the focal length of the cornea-lens system
(d) Equips the eye with a converging lens to lengthen the focal length of the cornea-lens system

11. (a) What is the maximum magnification that is possible with a diverging lens having a focal length of 5 cm? (b) To obtain maximum magnification, where should the object be placed?

12. The distance between eyepiece and objective lens in a certain compound microscope is 25.0 cm. The focal length of the eyepiece is 2.5 cm, and that of the objective is 0.4 cm. What is the overall magnification of the microscope?

13. In EXAPMLE 6, suppose that water (n = 1.33) fills the space between the object and the objective. Calculate the resolving power when 555-nm light is used.

14. Suppose you are observing a binary star with a telescope and are having difficulty resolving the two stars. You decide to use a colored filter to maximize the resolution. (A filter of a given color transmits only that color of light.) What color filter should you choose? (a) blue (b) green (c) yellow (d) red.

15. The distance between the Moon and the Earth 384,000 km. Moon is viewed through a telescope whose mirror has a diameter of 50.0 cm. (a) If the wavelength of the light is 590 nm, what is the angular resolution of the telescope? (b) What is the smallest distance that can be resolved between two points on Moon?

8.11 References

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