Chapter 25
Optical Instruments

\[ M = \frac{\theta'}{\theta} \]

where \( \theta \) and \( \theta' \) are shown in Fig. 25–17. We work in terms of the focal length by noting that \( \theta = h/N \) (Fig. 25–17b) and \( \theta' = h/f \) (Fig. 25–17a), where \( h \) is the height of the object and we assume that \( \theta \) is very small so \( \theta \) and \( \theta' \) (in radians) equal their sines and tangents. If the object is placed precisely at the focal point; the image will be at infinity and the object height divided by the eye height gives the magnification. The greater the magnification, the greater the magnification. We see that the shorter the focal length, the greater the magnification because of blurring due to spherical aberration.

\[ M = \frac{h/f}{h/N} = \frac{N}{f} \]
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• Resolution of the Human Eye and Useful Magnification
• Specialty Microscopes and Contrast
• X-Rays and X-Ray Diffraction
• X-Ray Imaging and Computed Tomography (CT Scan)
Basic parts of a camera:

- Lens
- Light-tight box
- Shutter
- Film or electronic sensor
A digital camera uses CCD sensors instead of film. The digitized image is sent to a processor for storage and later retrieval.
Camera adjustments:

• Shutter speed: controls the amount of time light enters the camera. A faster shutter speed makes a sharper picture.

• f-stop: controls the maximum opening of the shutter. This allows the right amount of light to enter to properly expose the film, and must be adjusted for external light conditions.

• Focusing: this adjusts the position of the lens so that the image is positioned on the film.
25-1 Cameras, Film, and Digital

There is a certain range of distances over which objects will be in focus; this is called the depth of field of the lens. Objects closer or farther will be blurred.

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25-2 The Human Eye; Corrective Lenses

The human eye resembles a camera in its basic functioning, with an adjustable lens, the iris, and the retina.
Most of the refraction is done at the surface of the cornea; the lens makes small adjustments to focus at different distances.
Near point: closest distance at which eye can focus clearly. Normal is about 25 cm.

Far point: farthest distance at which object can be seen clearly. Normal is at infinity.

Nearsightedness: far point is too close.

Farsightedness: near point is too far away.
Nearsightedness can be corrected with a diverging lens.
25-2 The Human Eye; Corrective Lenses

And farsightedness with a converging lens.

(c) Farsighted eye

(d) Corrected farsighted eye
Vision is blurry underwater because light rays are bent much less than they would be if entering the eye from air. This can be avoided by wearing goggles.
A magnifying glass (simple magnifier) is a converging lens. It allows us to focus on objects closer than the near point, so that they make a larger, and therefore clearer, image on the retina.
25-3 Magnifying Glass

The power of a magnifying glass is described by its angular magnification:

\[ M = \frac{\theta'}{\theta} \quad (25-1) \]

If the eye is relaxed (\(N\) is the near point distance and \(f\) the focal length):

\[ M = \frac{\theta'}{\theta} = \frac{h/f}{h/N} = \frac{N}{f}. \quad (25-2a) \]

If the eye is focused at the near point:

\[ M = \frac{N}{f} + 1. \quad (25-2b) \]
25-4 Telescopes

A refracting telescope consists of two lenses at opposite ends of a long tube. The objective lens is closest to the object, and the eyepiece is closest to the eye.

The magnification is given by:

$$M = \frac{\theta'}{\theta} = \frac{(h/f_e)}{(h/f_o)} = -\frac{f_o}{f_e} \quad (25-3)$$
25-4 Telescopes

Parallel rays from object at $\infty$

Objective lens

Eyepiece

$\theta$

$\theta'$

$I_2$

$I_1$

$F_o$

$F_e$

$F_e'$

$h$
Astronomical telescopes need to gather as much light as possible, meaning that the objective must be as large as possible. Hence, mirrors are used instead of lenses, as they can be made much larger and with more precision.
A terrestrial telescope, used for viewing objects on Earth, should produce an upright image. Here are two models, a Galilean type and a spyglass:
A compound microscope also has an objective and an eyepiece; it is different from a telescope in that the object is placed very close to the eyepiece.
25-5 Compound Microscope

The magnification is given by:

\[ M = M_e m_o = \left( \frac{N}{f_e} \right) \left( \frac{\ell - f_e}{d_o} \right) \]  \hspace{1cm} (25-6a)

\[ \approx \frac{N\ell}{f_e f_o} . \]  \hspace{1cm} \[ f_o \text{ and } f_e \ll \ell \]  \hspace{1cm} (25-6b)
Spherical aberration: rays far from the lens axis do not focus at the focal point.

Solutions: compound-lens systems; use only central part of lens.
Distortion: caused by variation in magnification with distance from the lens. Barrel and pincushion distortion:
Chromatic aberration: light of different wavelengths has different indices of refraction and focuses at different points.
25-6 Aberrations of Lenses and Mirrors

Solution: Achromatic doublet, made of lenses of two different materials
Resolution is the distance at which a lens can barely distinguish two separate objects.

Resolution is limited by aberrations and by diffraction. Aberrations can be minimized, but diffraction is unavoidable; it is due to the size of the lens compared to the wavelength of the light.
For a circular aperture of diameter $D$, the central maximum has an angular width:

$$\theta = \frac{1.22\lambda}{D}$$
The Rayleigh criterion states that two images are just resolvable when the center of one peak is over the first minimum of the other.
25-8 Resolution of Telescopes and Microscopes; the $\lambda$ Limit

Since the resolution is directly proportional to the wavelength and inversely proportional to the diameter, radio telescopes are built to be very large.
25-8 Resolution of Telescopes and Microscopes; the $\lambda$ Limit

For microscopes, assuming the object is at the focal point, the resolving power is given by:

$$RP = s = f\theta = \frac{1.22\lambda f}{D} \quad (25-8)$$

Typically, the focal length of a microscope lens is half its diameter, which shows that it is not possible to resolve details smaller than the wavelength being used.

$$RP \approx \frac{\lambda}{2} \quad (25-9)$$
25-9 Resolution of the Human Eye and Useful Magnification

The human eye can resolve objects that are about 1 cm apart at a distance of 20 m, or 0.1 mm apart at the near point.

This limits the useful magnification of a light microscope to about $500 \times - 1000 \times$. 
In addition to sufficient resolving power, a microscope must be able to distinguish the object from its background.
25-10 Specialty Microscopes and Contrast

One way to do this is by using an interference microscope, which can detect objects by the change in wavelength as the light passes through them.
The wavelengths of X-rays are very short. Diffraction experiments are impossible to do with conventional diffraction gratings.

Crystals have spacing between their layers that is ideal for diffracting X-rays:
X-ray diffraction is now used to study the internal structure of crystals; this is how the helical structure of DNA was determined.
A conventional X-ray is essentially a shadow; there are no lenses involved.
Computed tomography uses a narrow beam of X-rays, and takes measurements at many different angles. The measurements are sent to a computer, which combines them into a detailed image.
A fan-beam CT scanner is similar to the one on the previous slide, but uses multiple beams and detectors to complete the scan more quickly.
Images can be color-coded to enhance areas of increased X-ray absorption; this improves the image considerably. The size of the pixels is determined by the size of the detectors.
Summary of Chapter 25

• Camera lens forms image by letting light through a shutter; can be adjusted for different light levels using f-stop and focused by moving lens

• Human eye forms image by letting light through pupil; adjusts to different light levels using iris and focuses by changing thickness of lens

• Nearsighted vision is corrected by diverging lens, farsighted by converging
Summary of Chapter 25

- Simple magnifier: object at focal point
- Angular modification:
  \[ M = \frac{\theta'}{\theta} = \frac{h/f}{h/N} = \frac{N}{f}. \]
- Astronomical telescope: objective and eyepiece; object infinitely far away
- Magnification:
  \[ M = \frac{\theta'}{\theta} = \frac{(h/f_e)}{(h/f_o)} = -\frac{f_o}{f_e}. \]
Summary of Chapter 25

• Spherical aberration: rays far from axis do not go through focal point

• Chromatic aberration: different wavelengths have different focal points

• Resolution of optical devices is limited by diffraction