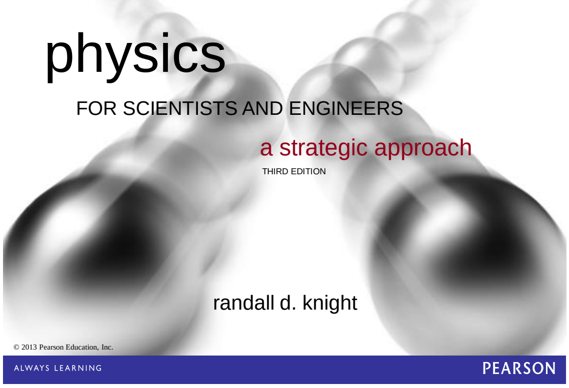
Class 7, Chapter 24 Preclass Notes



physics

FOR SCIENTISTS AND ENGINEERS

a strategic approach

THIRD EDITION

randall d. knight

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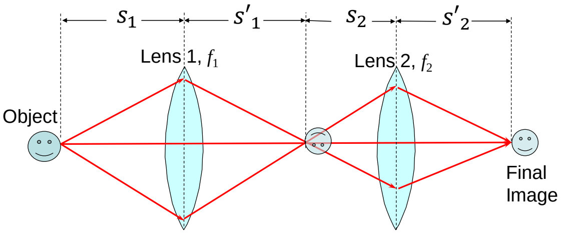
Chapter 24 Optical Instruments

Chapter Goal: To understand some common optical instruments and their limitations.

Lenses in Combination

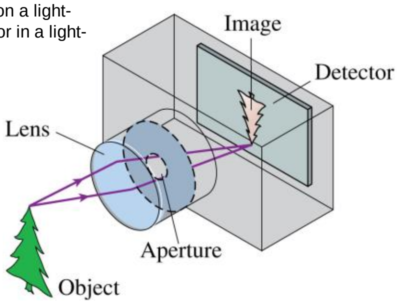
- The analysis of multi-lens systems requires only one new rule: **The image of the first lens acts as the object for the second lens.**



$$\frac{1}{f_1} = \frac{1}{s_1} + \frac{1}{s'_1} \qquad \frac{1}{f_2} = \frac{1}{s_2} + \frac{1}{s'_2}$$

The Camera

- A **camera** "takes a picture" by using a lens to form a real, inverted image on a light-sensitive detector in a light-tight box.



The Camera

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

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

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

Controlling the Exposure

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

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

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

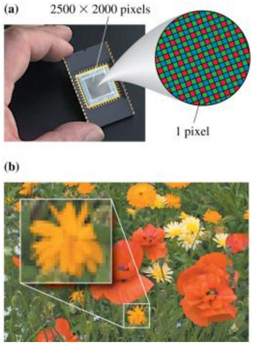
$$I \propto \frac{D^2}{f^2} = \frac{1}{(f\text{-number})^2}$$

Controlling the Exposure

- Focal length and *f*-number information is stamped on a camera lens.
- This lens is labeled $5.8\text{–}23.2\ \text{mm}\ 1{:}2.6\text{–}5.5$.
- The first numbers are the range of focal lengths.
- They span a factor of 4, so this is a $4\times$ zoom lens.
- The second numbers show that the minimum *f*-number ranges from $f/2.6$ (for the $f = 5.8\ \text{mm}$ focal length) to $f/5.5$ (for the $f = 23.2\ \text{mm}$ focal length).

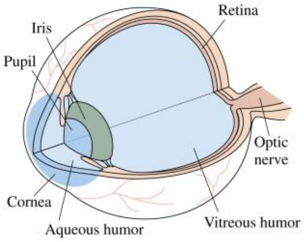
The Detector

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



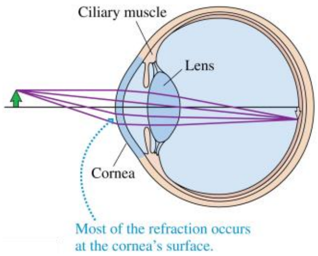
Vision

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



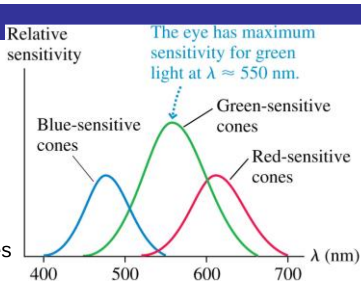
Vision

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



Most of the refraction occurs at the cornea's surface.

Color Vision

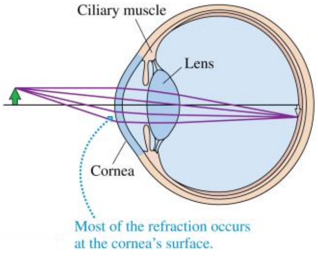


The eye has maximum sensitivity for green light at $\lambda \approx 550$ nm.

- The eye's detector, the retina, contains light-sensitive cells called cones.
- The figure shows the wavelength responses of the three types of cones in a human eye.
- The relative response of the different cones is interpreted by your brain as light of a particular color.
- Other animals, with slightly different retinal cells, can see ultraviolet or infrared wavelengths that we cannot see.

Focusing and Accommodation

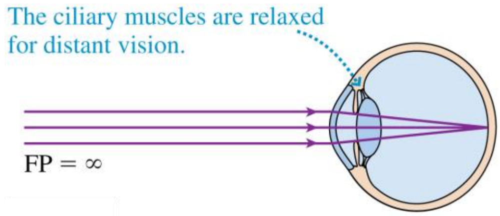
- The eye focuses by changing the focal length of the lens by using the *ciliary muscles* to change the curvature of the lens surface.
- Tensing the ciliary muscles causes **accommodation,** which decreases the lens's radius of curvature and thus decreases its focal length.



Most of the refraction occurs at the cornea's surface.

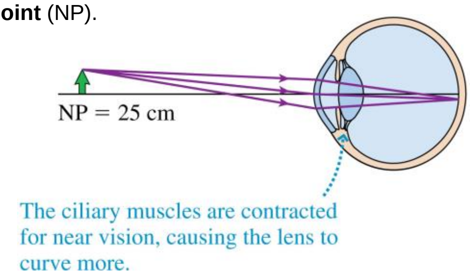
Focusing and Accommodation

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


The ciliary muscles are relaxed for distant vision.

Focusing and Accommodation

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



The ciliary muscles are contracted for near vision, causing the lens to curve more.

Corrective Lenses

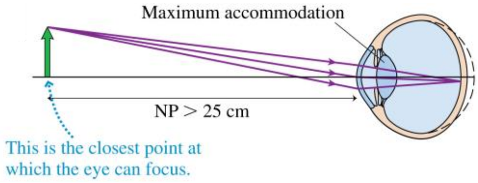
- Corrective lenses are prescribed not by their focal length but by their power.
- The power of a lens is the inverse of its focal length:

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

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

Hyperopia

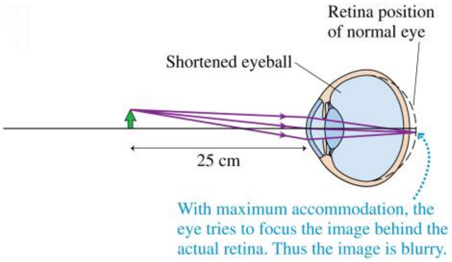
A person who is *farsighted* can see faraway objects (but even then must use some accommodation rather than a relaxed eye), but his near point is larger than $25\ \mathrm{cm}$, often much larger, so he cannot focus on nearby objects.



This is the closest point at which the eye can focus.

Hyperopia

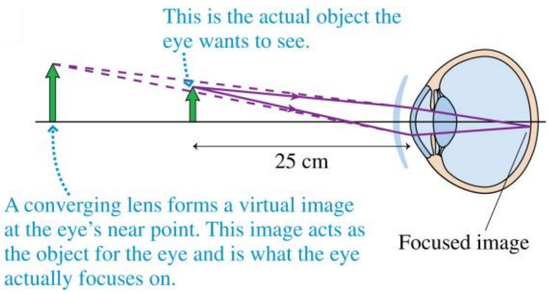
The cause of farsightedness — called **hyperopia** — is an eyeball that is too short for the refractive power of the cornea and lens.



With maximum accommodation, the eye tries to focus the image behind the actual retina. Thus the image is blurry.

Hyperopia

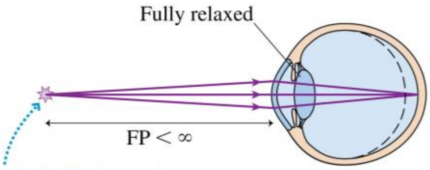
- To correct hyperopia, add a lens with **positive** refractive power (i.e., converging).


This is the actual object the eye wants to see.

A converging lens forms a virtual image at the eye’s near point. This image acts as the object for the eye and is what the eye actually focuses on.

Myopia

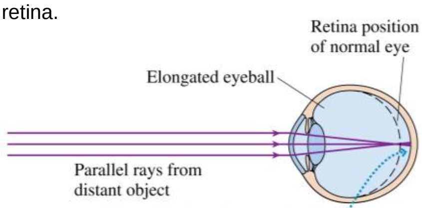
A person who is *nearsighted* can clearly see nearby objects when the eye is relaxed (and extremely close objects by using accommodation), but no amount of relaxation allows her to see distant objects.



This is the farthest point at which the eye can focus.

Myopia

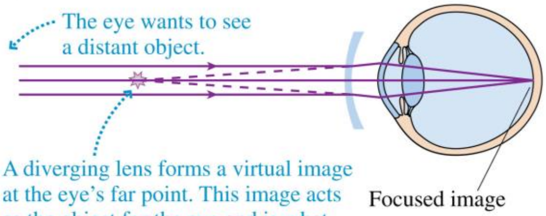
- Nearsightedness—called **myopia**—is caused by an eyeball that is too long.
- Rays from a distant object come to a focus in front of the retina and have begun to diverge by the time they reach the retina.



A fully relaxed eye focuses the image in front of the actual retina. The image is blurry.

Myopia

- To correct myopia, add a lens with **negative** refractive power (i.e., diverging).



The eye wants to see a distant object.

A diverging lens forms a virtual image at the eye's far point. This image acts as the object for the eye and is what the eye actually focuses on.

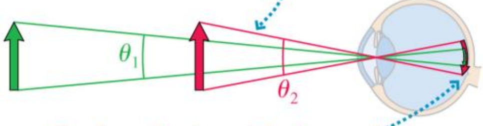
Optical Systems That Magnify

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

[images from a video by GhostchaserNM at http://youtu.be/RKjujP0F9sU]

Optical Systems That Magnify

As the object gets closer, the angle it subtends becomes larger. Its *angular size* has increased.

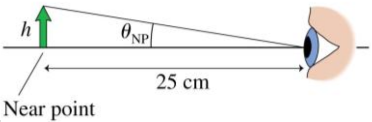


Further, the size of the image on the retina gets larger. The object's *apparent size* has increased.

Optical Systems That Magnify

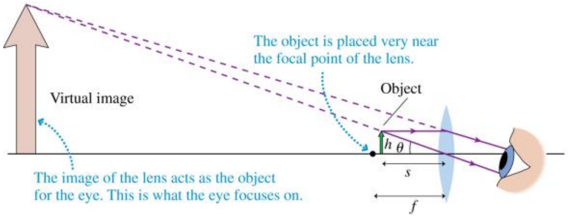
- You can't keep increasing an object's angular size because you can't focus on the object if it's closer than your near point, which is ≈ 25 cm.
- The maximum angular size viewable by your unaided eye is:

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



The Magnifier

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



The Magnifier

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

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

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

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

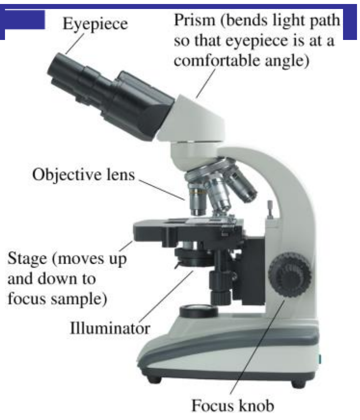
- Combining these equations, we find the angular magnification of a magnifying glass is:

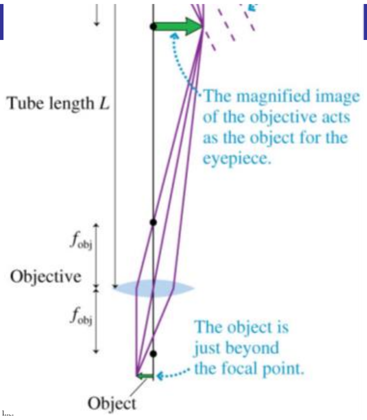
$$M = \frac{25\text{ cm}}{f}$$

The Microscope

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

The Microscope





The Microscope

- The lateral magnification of the objective is:

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

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

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

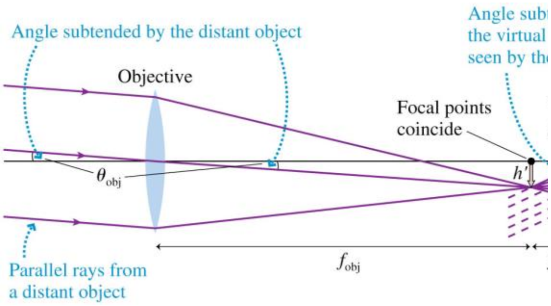
- The minus sign shows that the image seen in a microscope is inverted.
- Most biological microscopes are standardized with a tube length $L = 160$ mm.

The Telescope

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

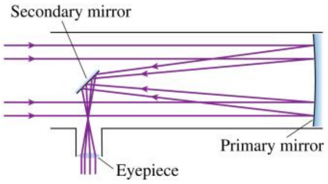
$$M = \frac{\theta_{eye}}{\theta_{obj}} = -\frac{f_{obj}}{f_{eye}}$$

A Refracting Telescope



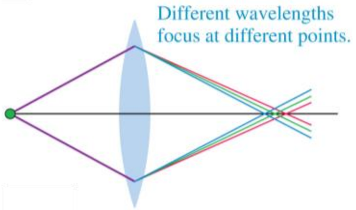
Telescopes

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



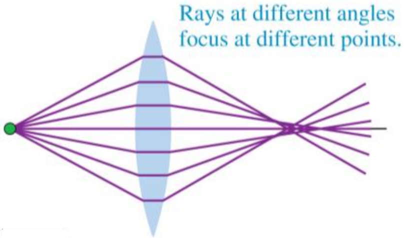
Chromatic Aberration

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



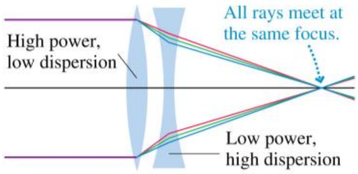
Spherical Aberration

- Our analysis of thin lenses was based on paraxial rays traveling nearly parallel to the optical axis.
- Rays incident on the outer edges of a spherical surface are not focused at exactly the same point as rays incident near the center.



Correcting Aberrations

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



Circular Lens Diffraction

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

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

where D is the diameter of the circular aperture of the lens, and f is the focal length.

- In order to resolve two points, their angular separation must be greater than λ_{min}, where

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

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