Chapter 3 Optical Instrumentation

3-1 Stops, Pupils, and Windows

3-4 The Camera

3-5 Simple Magnifiers and *Eyepieces*

3-6 Microscopes

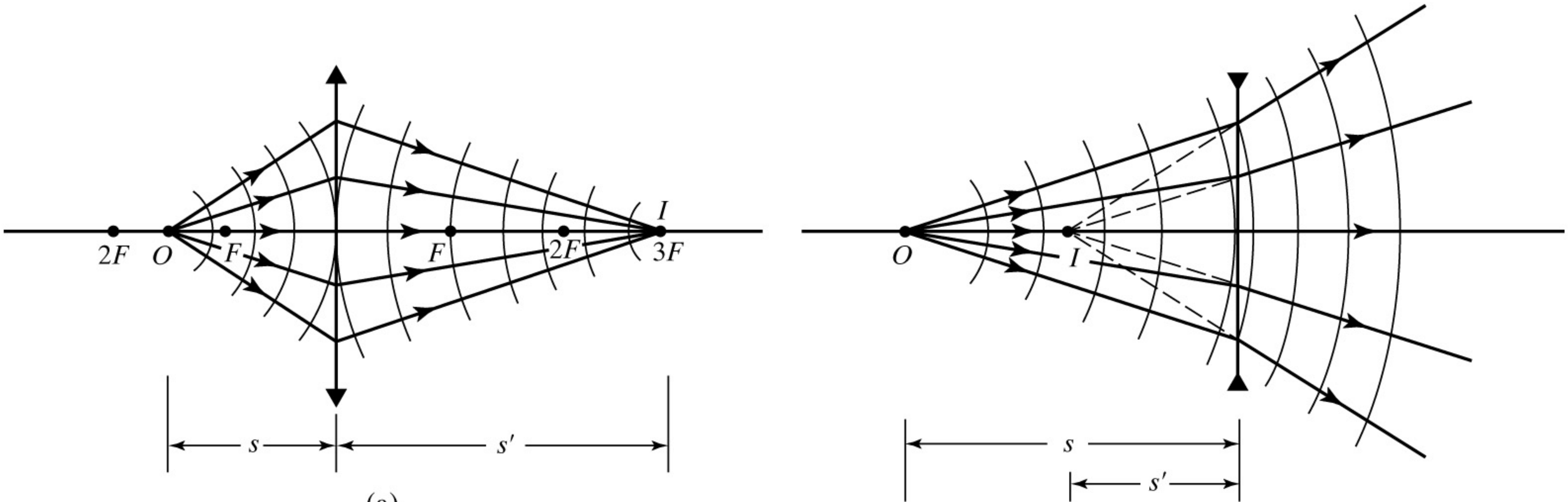
3-7 Telescopes

3-2 A brief look at aberrations
3-3 Prisms ➔ *next week (Sep 27)*

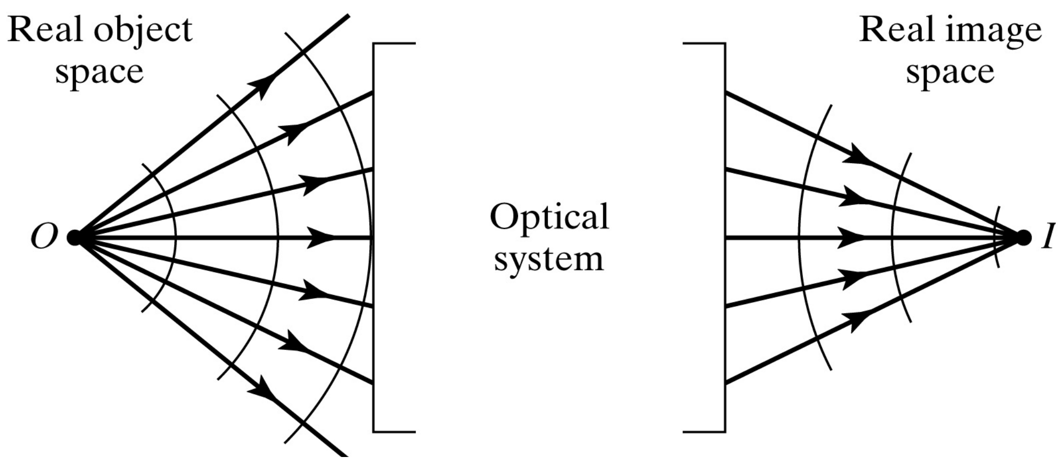
Today (2011-09-22)

1. Magnifiers
2. Camera
3. Resolution limit
4. Microscopes
5. Telescopes

Imaging by an Optical System
Change in curvature of wavefronts by a thin lens



(a) (b)

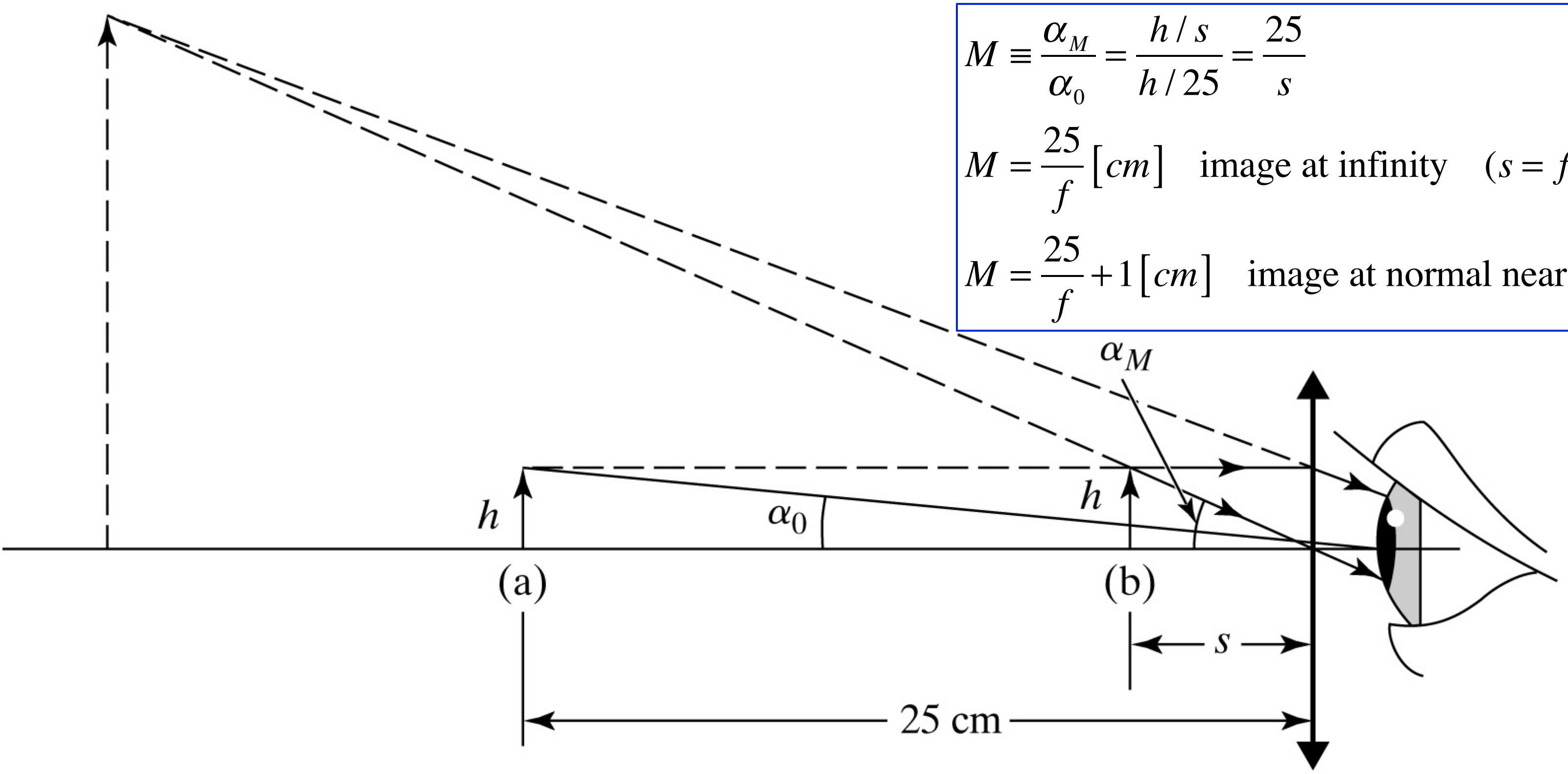


Simple Magnifiers

$$M \equiv \frac{\alpha_M}{\alpha_0} = \frac{h/s}{h/25} = \frac{25}{s}$$

$$M = \frac{25}{f}[cm] \quad \text{image at infinity} \quad (s = f)$$

$$M = \frac{25}{f} + 1[cm] \quad \text{image at normal near point } (s' = -25cm)$$



Magnifiers

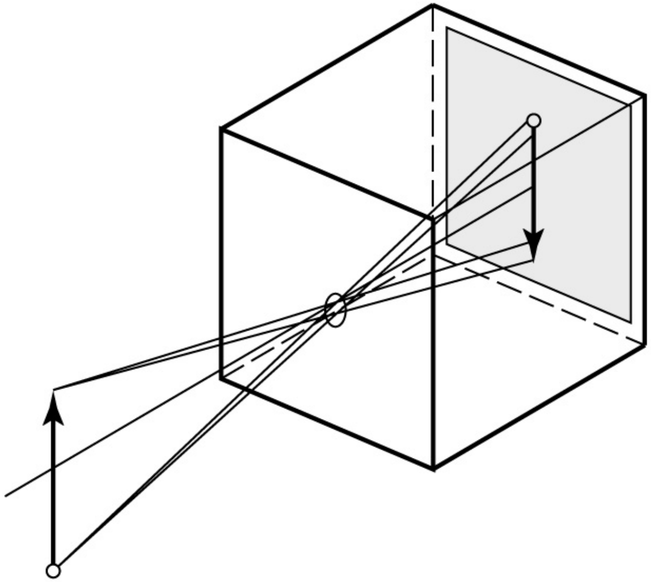
For relaxed-eye viewing, the angular magnification is

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

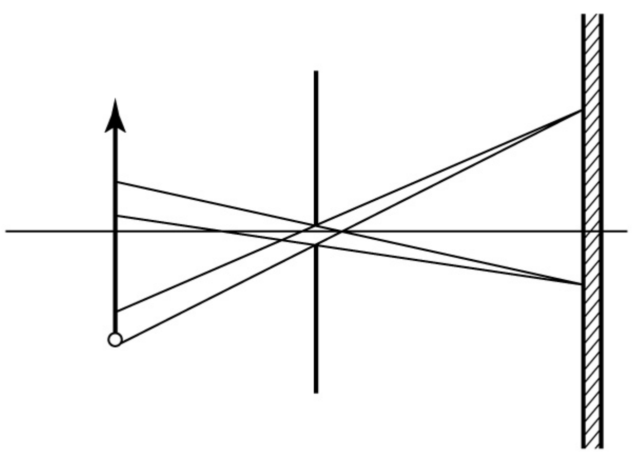
In microscopes and telescopes, the eyepiece acts as a magnifier to view the image of the objective.

The Camera

Pinhole Camera



(a)



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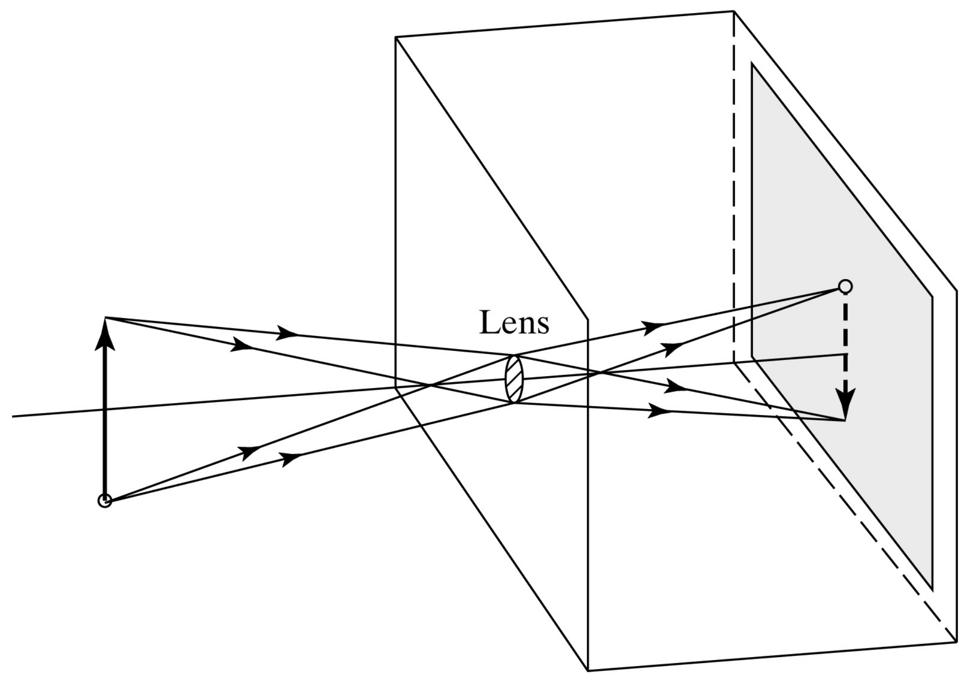
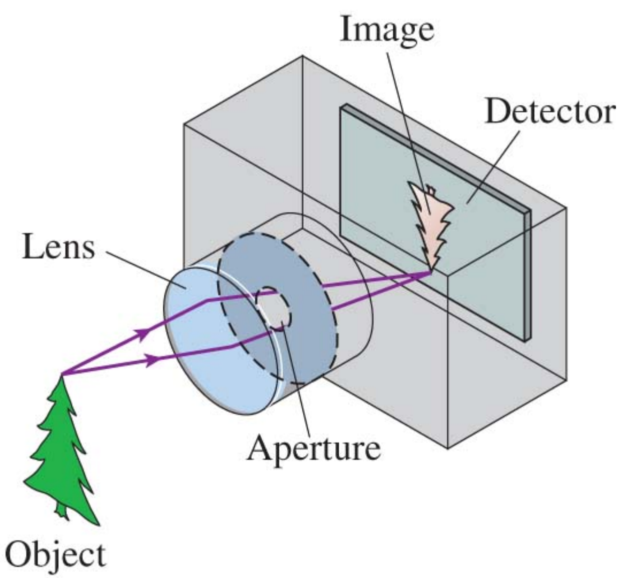
Simple Camera

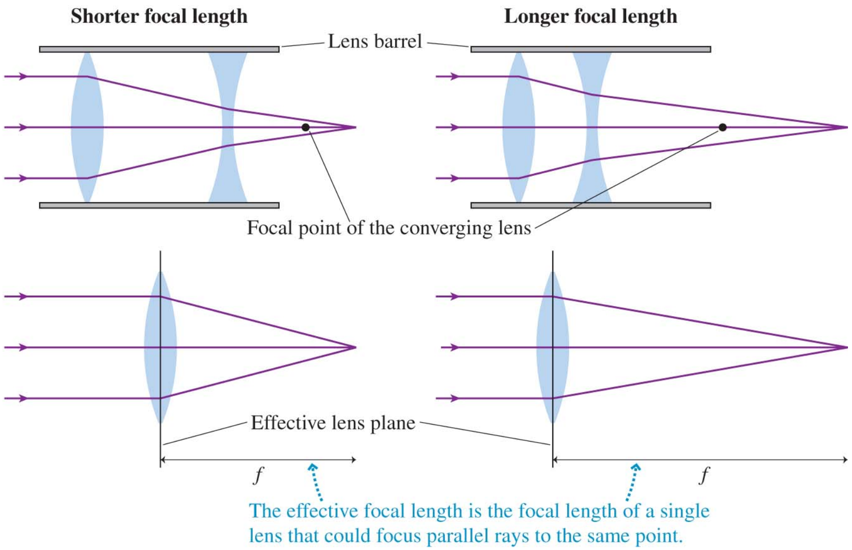


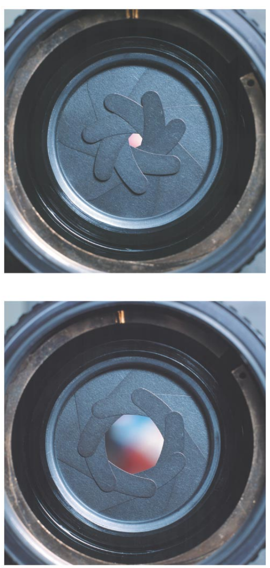
The Camera

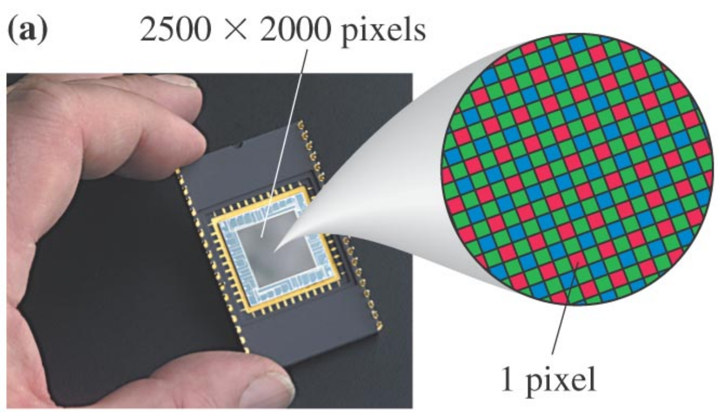


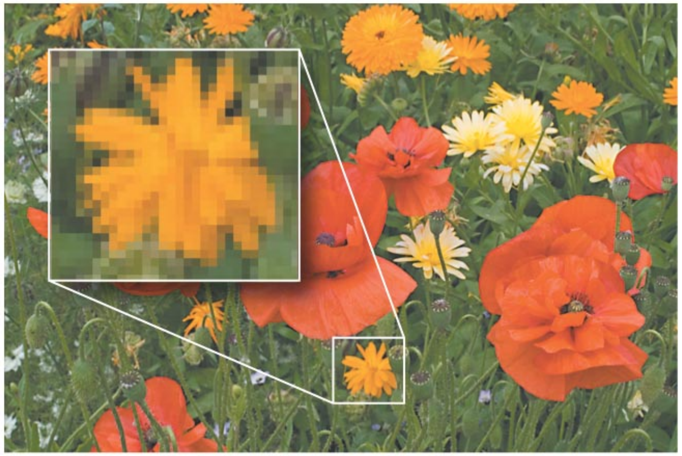
- A camera "takes a picture" by using a lens to form a real, inverted image on a light-sensitive detector in a light-tight box.
- We can model a combination lens as a single lens with an effective focal length (usually called simply "the focal length")
- A *zoom lens* changes the effective focal length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

The Camera: Components









Example Focusing a camera

QUESTION:

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

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

Example Focusing a camera

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

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

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

Zoom Lenses

- When cameras focus on objects that are more that 10 focal lengths away (roughly s > 20 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 $s \gg f$, 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.

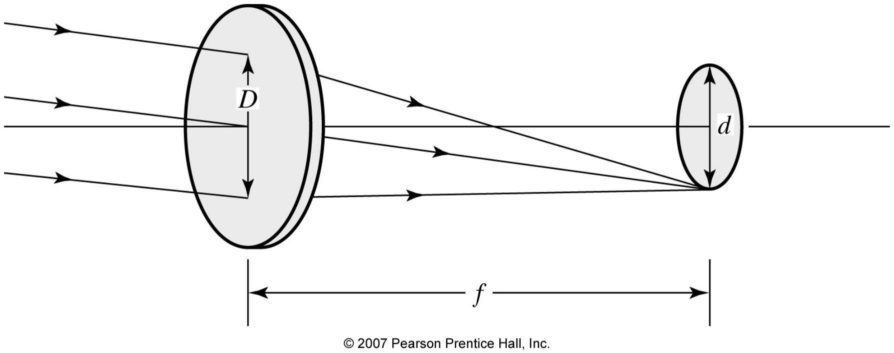
Controlling the Exposure

- The amount of light passing through the lens is controlled by an adjustable aperture, also called an *iris* because it functions much like the iris of your eye.

- The aperture sets the effective diameter *D* of the lens.

- By long tradition, the light-gathering ability of a lens is specified by its *f*-number, defined as

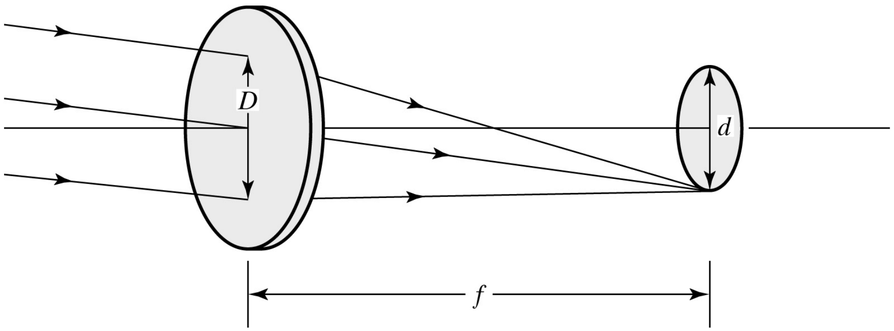
$$f\text{-number} = \frac{f}{D}$$



f-number and irradiance/intensity [W/m²]

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

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



Cameras

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

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

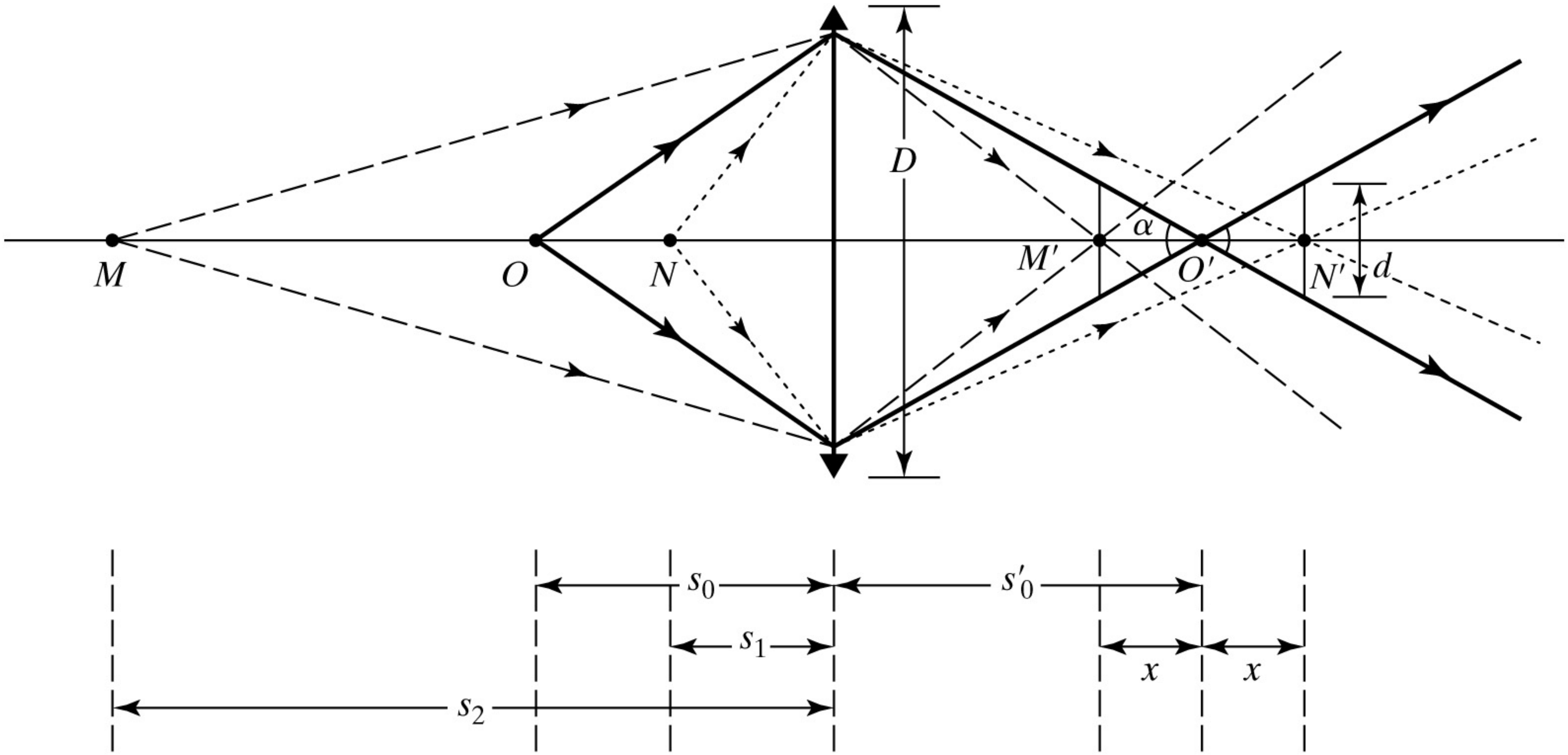
The light intensity on the detector is

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

TABLE 3-2 STANDARD RELATIVE APERTURES AND IRRADIANCE AVAILABLE ON CAMERAS

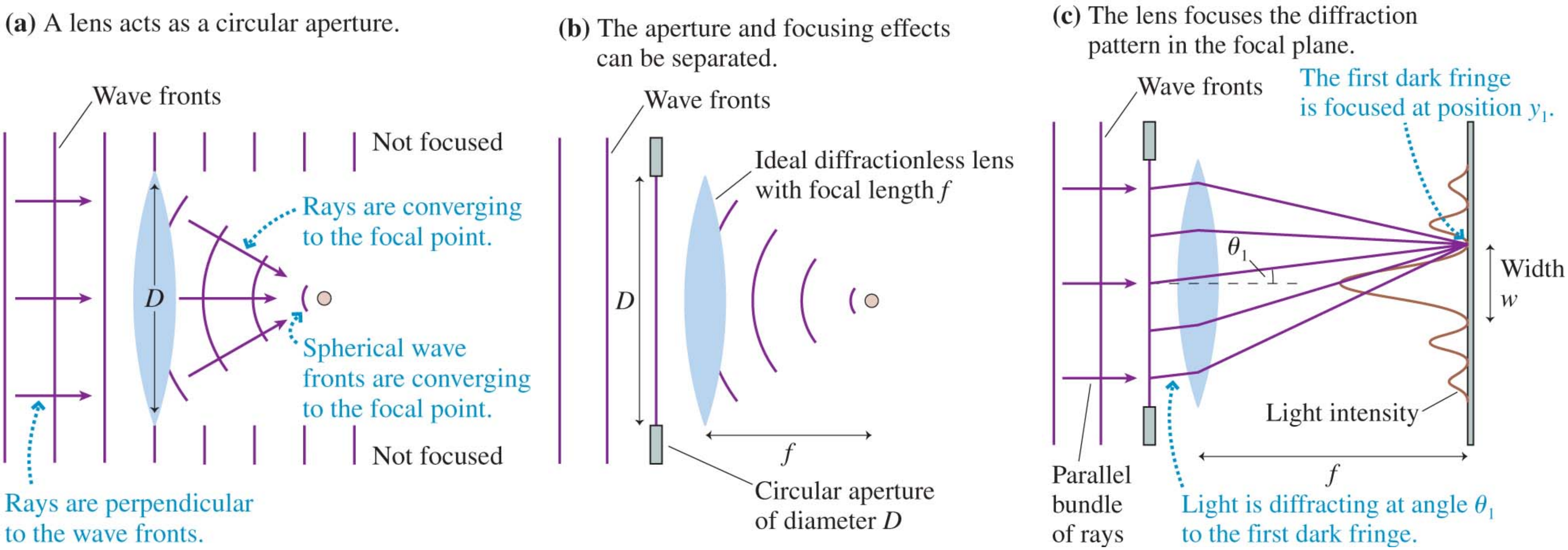
$A = f$-number		$(A = f\text{-number})^2$	E_e
1		1	E_0
1.4	$\sqrt{2} \approx 1.4$	2	$E_0/2$
2		4	$E_0/4$
2.8		8	$E_0/8$
4		16	$E_0/16$
5.6		32	$E_0/32$
8		64	$E_0/64$
11		128	$E_0/128$
16		256	$E_0/256$
22		512	$E_0/512$

Depth of Field & Example 3-3 (p. 73)



$$\text{depth of field} = \frac{2Ads_o\left(s_o - f\right)f^2}{f^4 - A^2d^2s_o^2}$$

A lens both focuses and diffracts the light



The Resolution of Optical Instruments

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

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

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

In order to resolve two points, their angular separation must be greater than $\theta_{\min}$, where

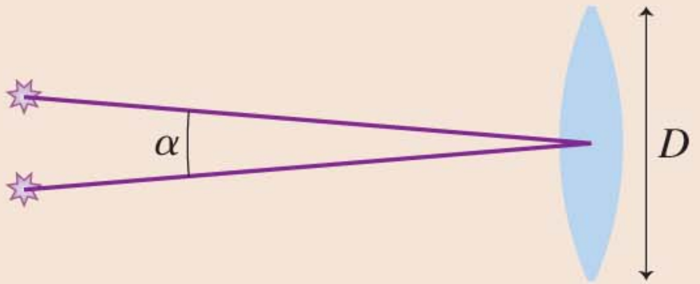
$$\theta_{\min} = \frac{1.22\lambda}{D} \qquad \text{(angular resolution of a lens)}$$

is called the angular resolution of the lens.

Important Concepts

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

Resolution

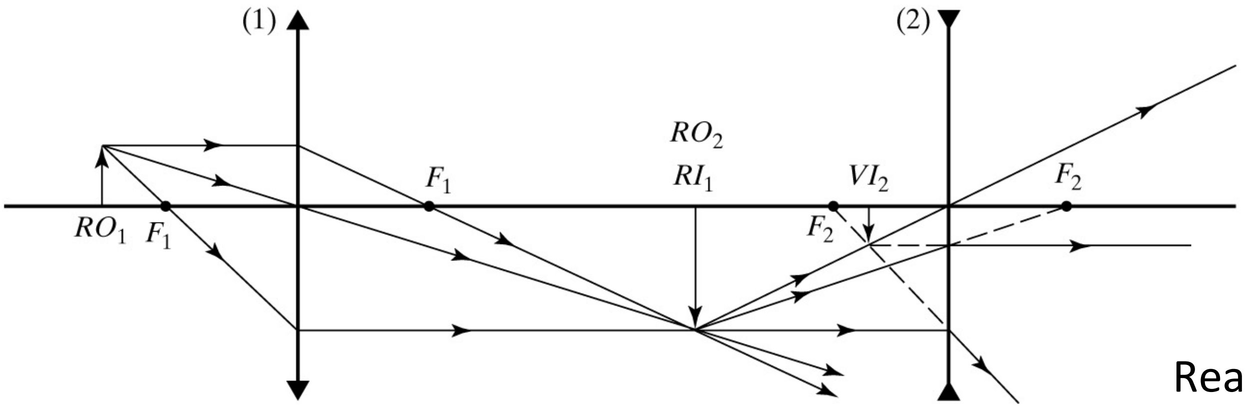


The angular resolution of a lens of diameter D is

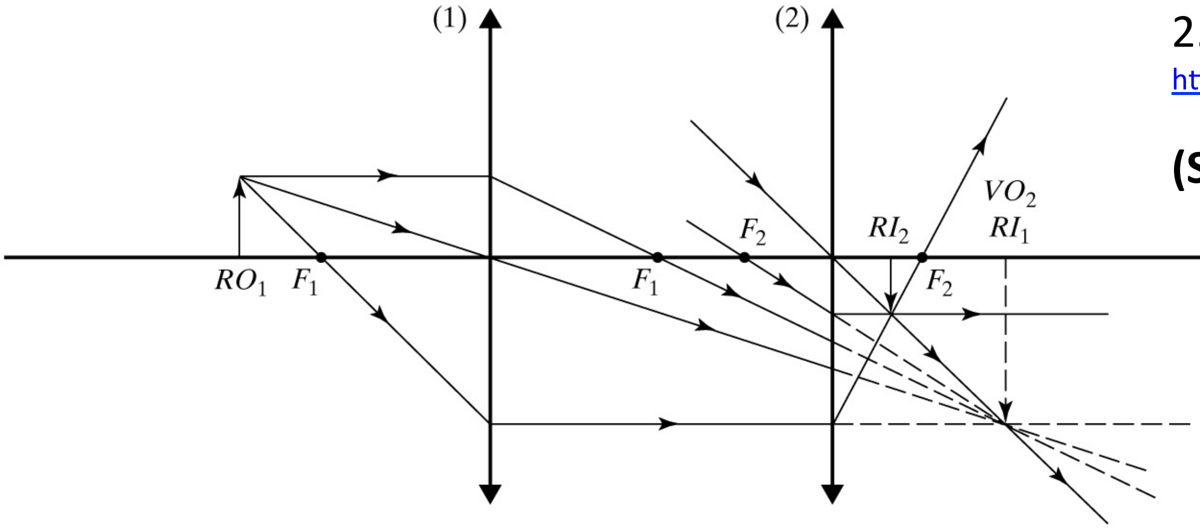
$$\theta_{\min} = 1.22\lambda/D$$

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

Thin Lens Combination ➔ Sequential Imaging



(a)



(b)

Reading Assignments

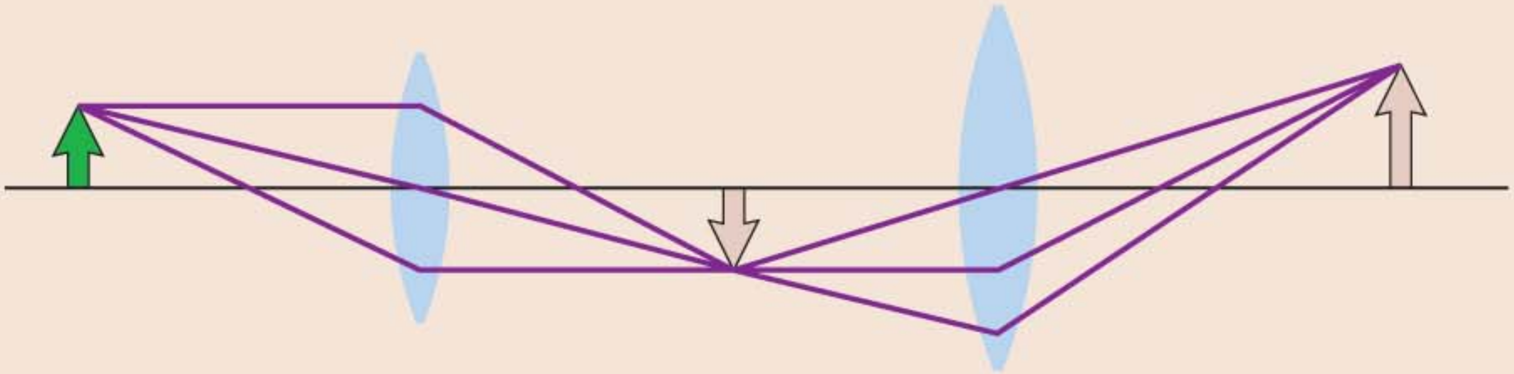
1. Example 2-3 (page 38)

2. Java Applets
http://silver.neep.wisc.edu/~shock/tools/ray.html

(See also Lab #1 Appendix)

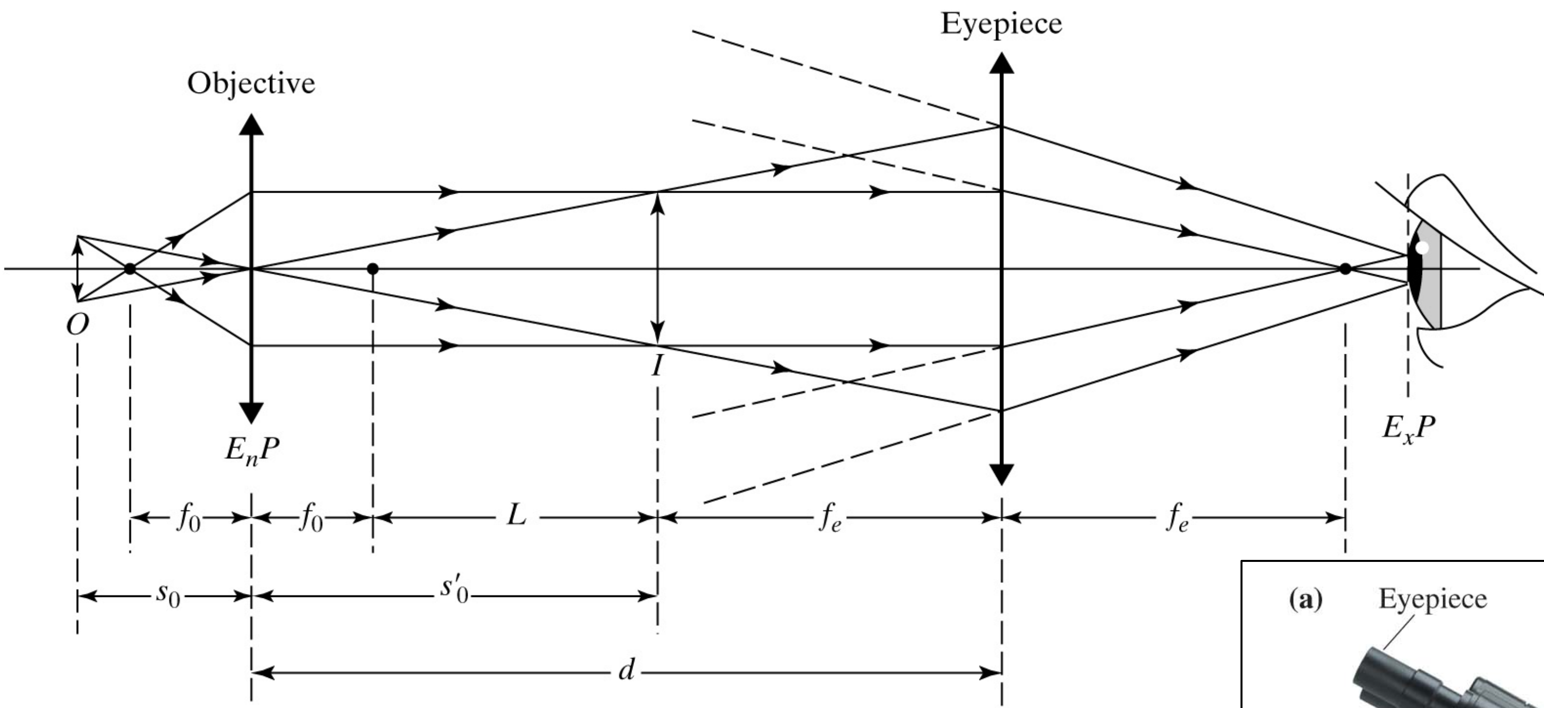
Important Concepts

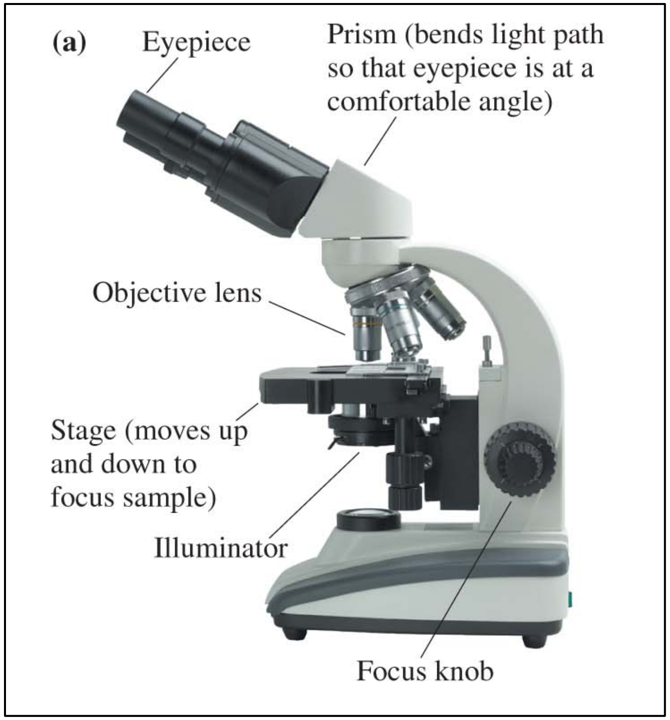
Lens Combinations



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

The Microscope





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

The Microscope

- A specimen to be observed is placed on the *stage* of a 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 lateral magnification of the objective is

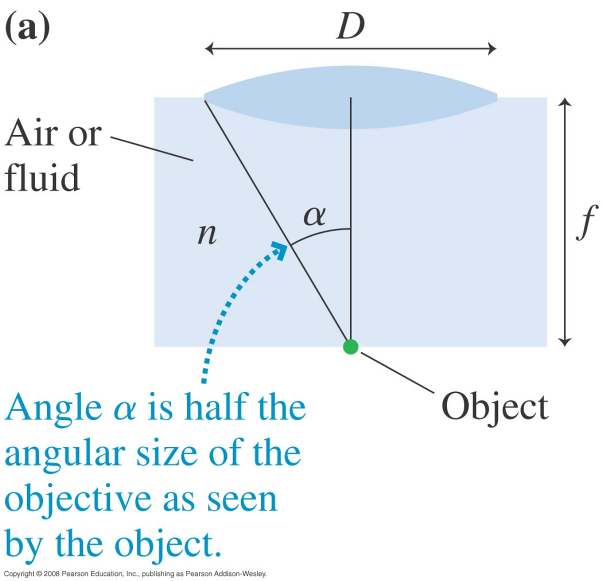
$$m_{obj} = -\frac{s'}{s} \approx -\frac{L}{f_{obj}}$$

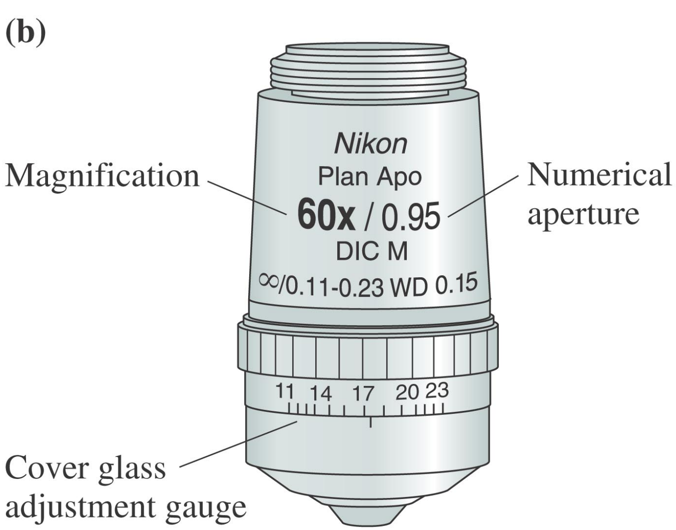
- Together, the objective and eyepiece produce a total angular magnification

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

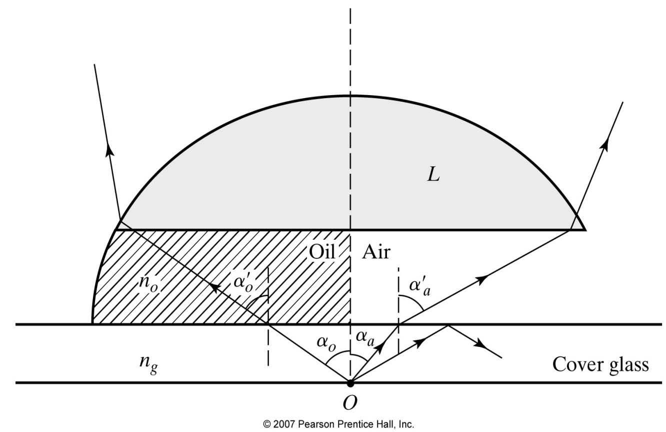
The Microscope: Objective and Numerical Aperture (NA)

$$NA = n \sin\alpha$$





Oil-immersion microscope



Microscopes

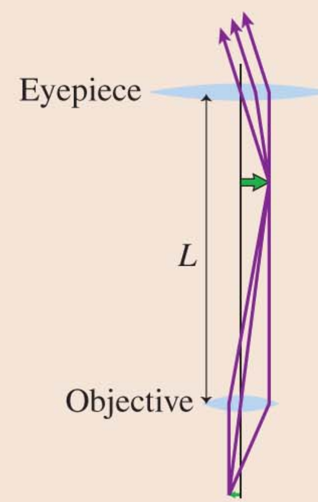
The object is very close to the focal point of the objective. The total magnification is

$$M = -\frac{L}{f_{\mathrm{obj}}}\frac{25\ \mathrm{cm}}{f_{\mathrm{eye}}}$$

The spatial resolution is

$$d_{\mathrm{min}} = 0.61\lambda/\mathrm{NA}$$

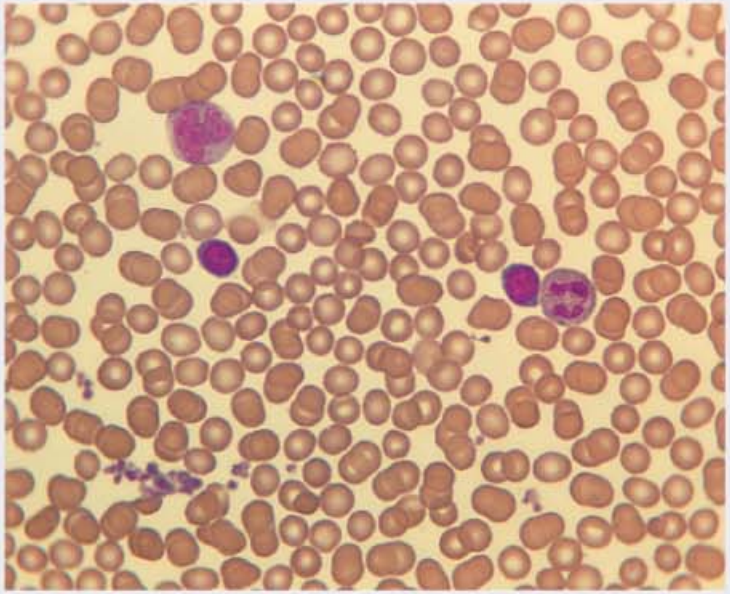
where NA is the numerical aperture of the objective lens.



Example: Viewing blood cells

QUESTION:

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



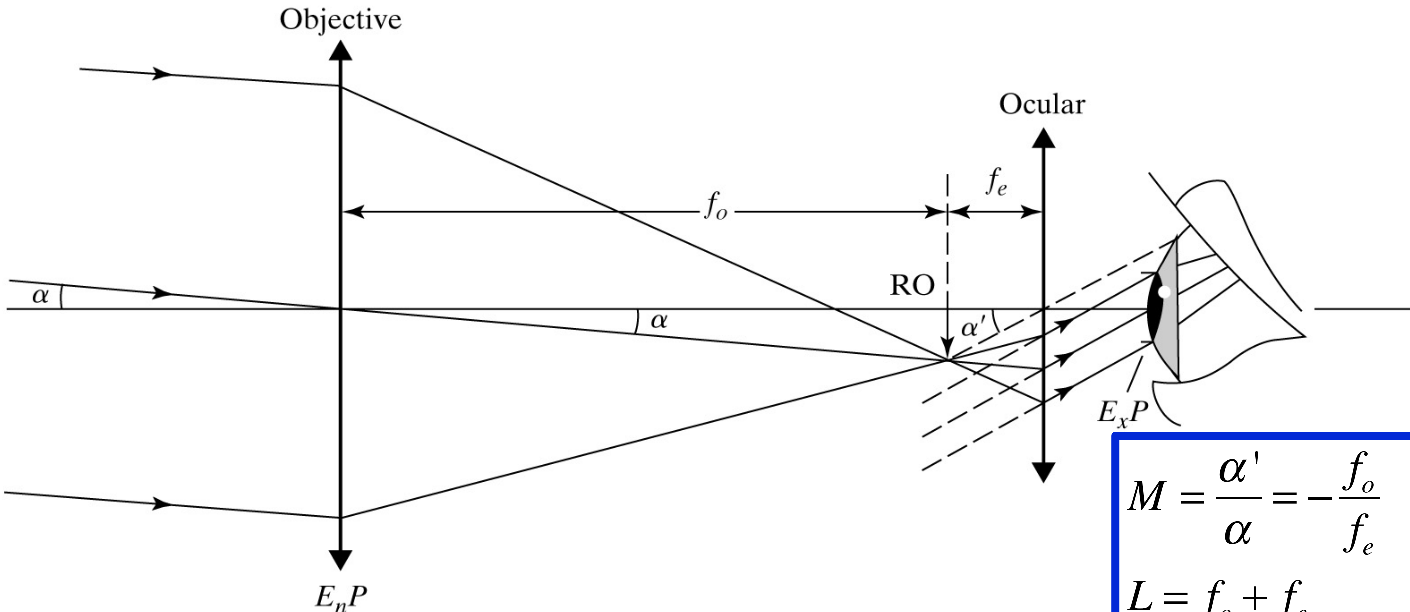
MODEL Angular magnification compares the magnified angular size to the angular size seen at the near-point distance of 25 cm.

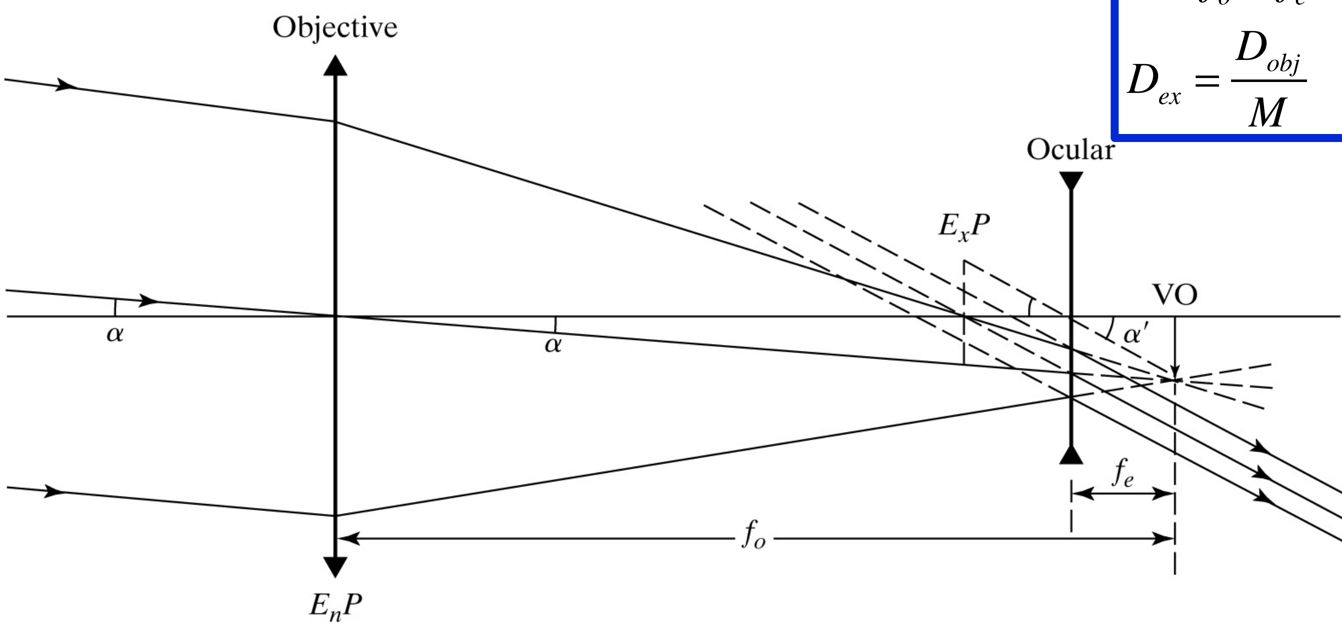
Example: Viewing blood cells

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

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

Telescope





$$M = \frac{\alpha'}{\alpha} = -\frac{f_o}{f_e}$$

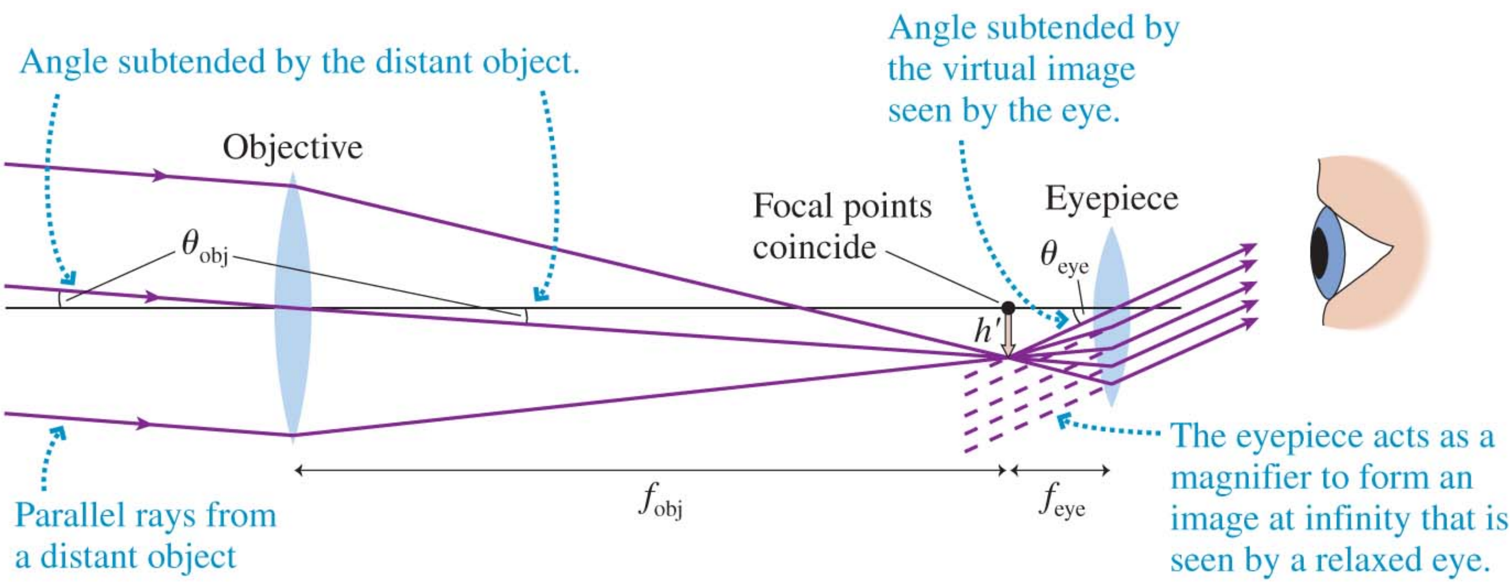
$$L = f_o + f_e$$

$$D_{ex} = \frac{D_{obj}}{M}$$ the diameter of the exit pupil

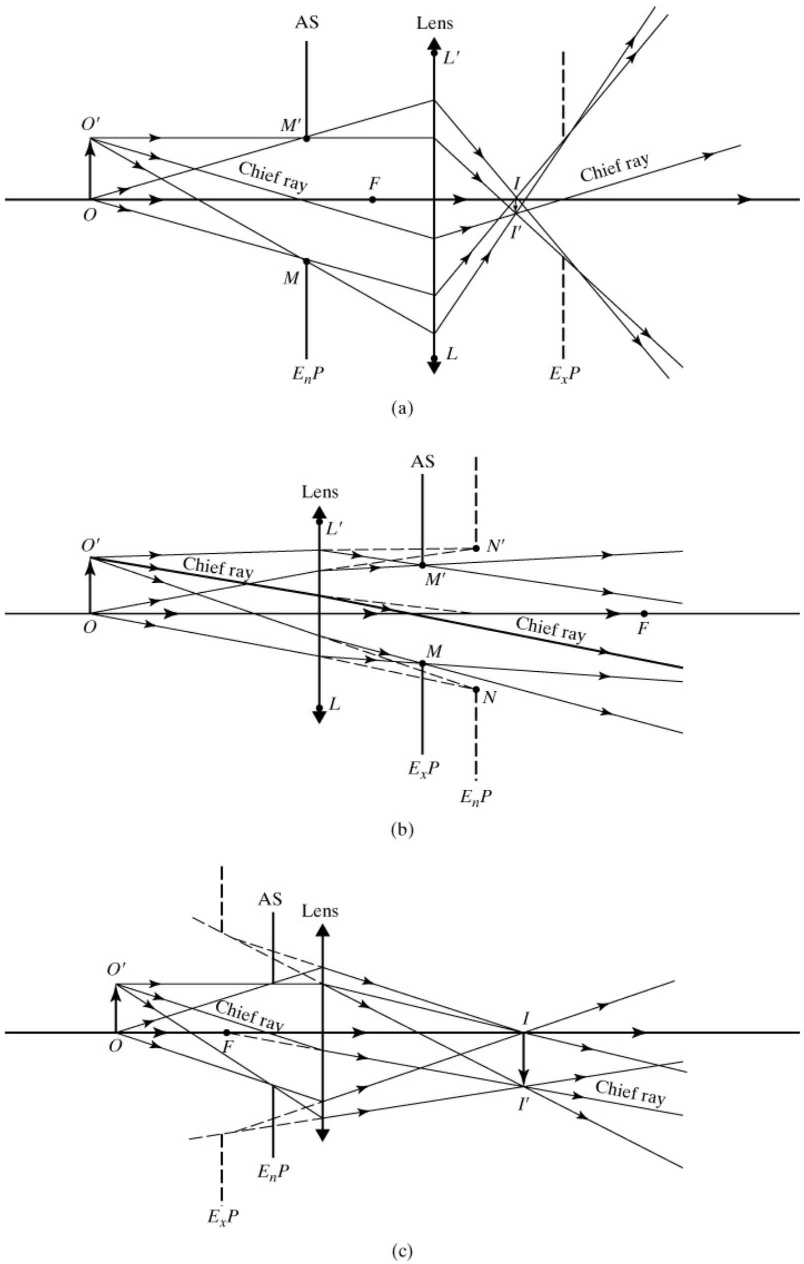
The Telescope

- 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 $s' = f_{\text{obj}}$.
- 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

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



Stops, Pupils, and Windows



Summary of Terms

Brightness

Aperture stop AS: The real element in an optical system that limits the size of the cone of rays accepted by the system from an axial object point.

Entrance pupil E_nP: The image of the aperture stop formed by the optical elements (if any) that precede it.

Exit pupil E_xP: The image of the aperture stop formed by the optical elements (if any) that follow it.

Field of view

Field stop ES: The real element that limits the angular field of view formed by an optical system.

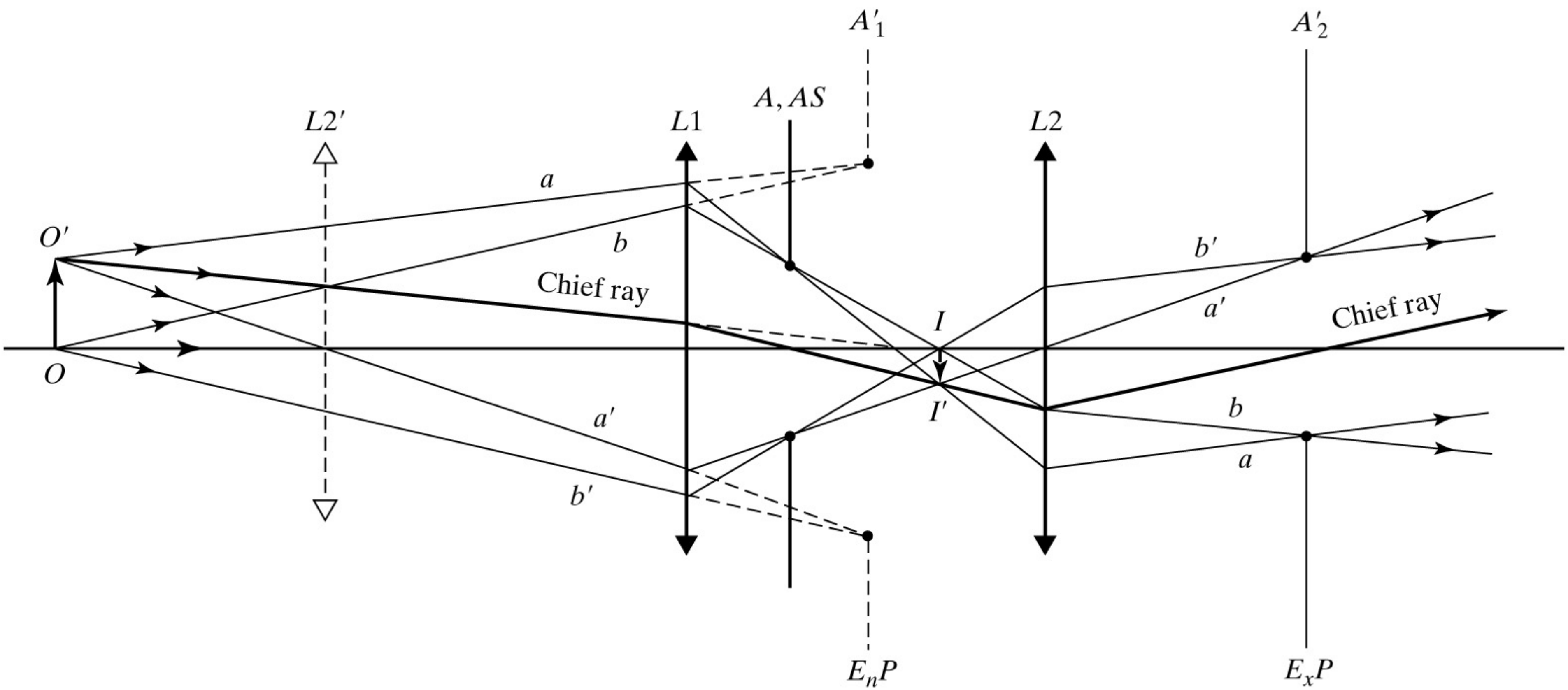
Entrance window E_nW: The image of the field stop formed by the optical elements (if any) that precede it.

Exit window E_xW: The image of the field stop formed by the optical elements (if any) that follow it.

Chief Ray

The chief, or principal, ray is a ray from an object point that passes through the axial point, in the plane of the entrance pupil.

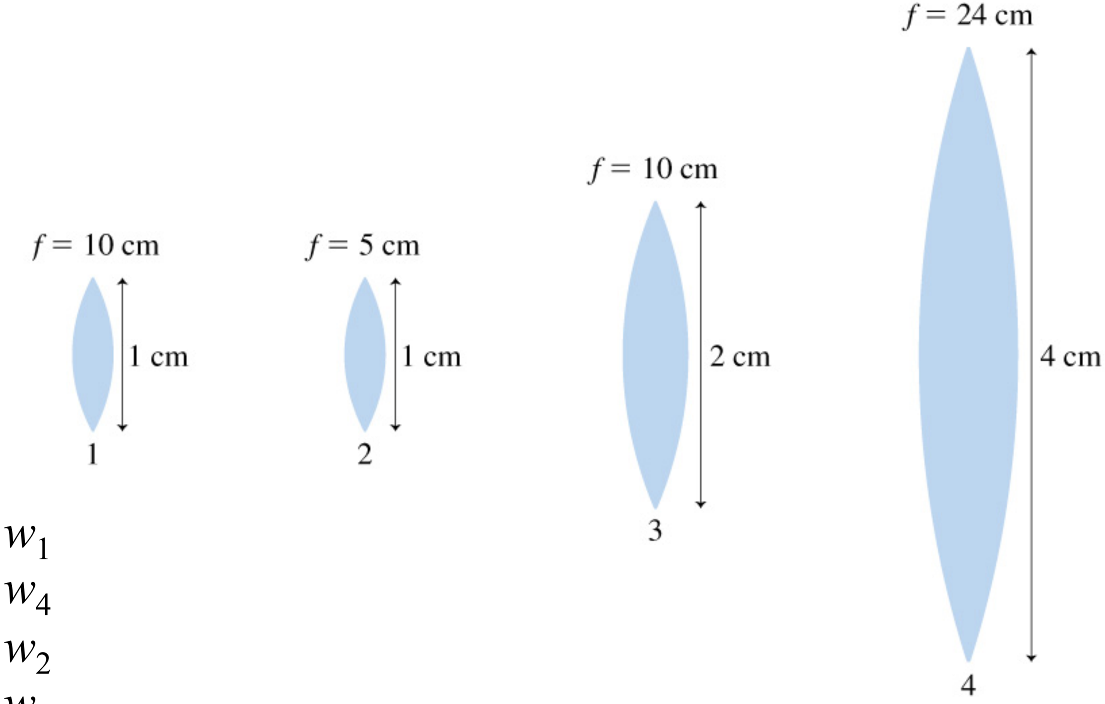
Limitation of light rays in a two-positive-lens system



A biologist rotates the turret of a microscope to replace a 20× objective with a 10× objective. To keep the same overall magnification, the focal length of the eyepiece must be

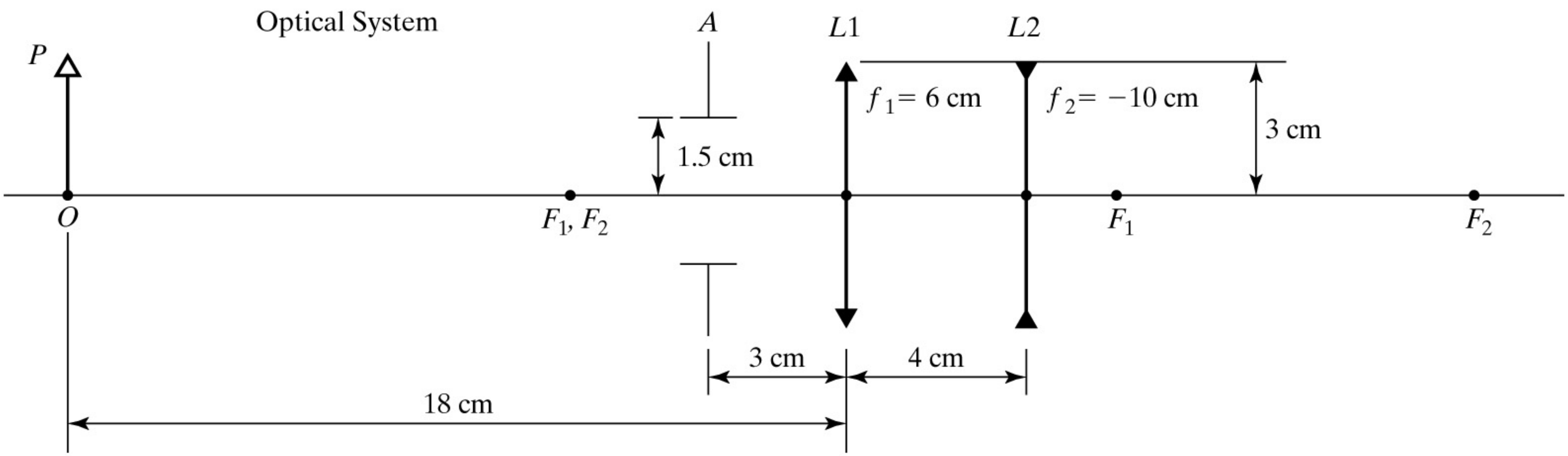
A. Halved.
B. Doubled.
C. Kept the same.
D. The magnification cannot be kept the same if the objective is changed.

Four diffraction-limited lenses focus plane waves of light with the same wavelength *l*. Rank order, from largest to smallest, the spot sizes w_1 to w_4.



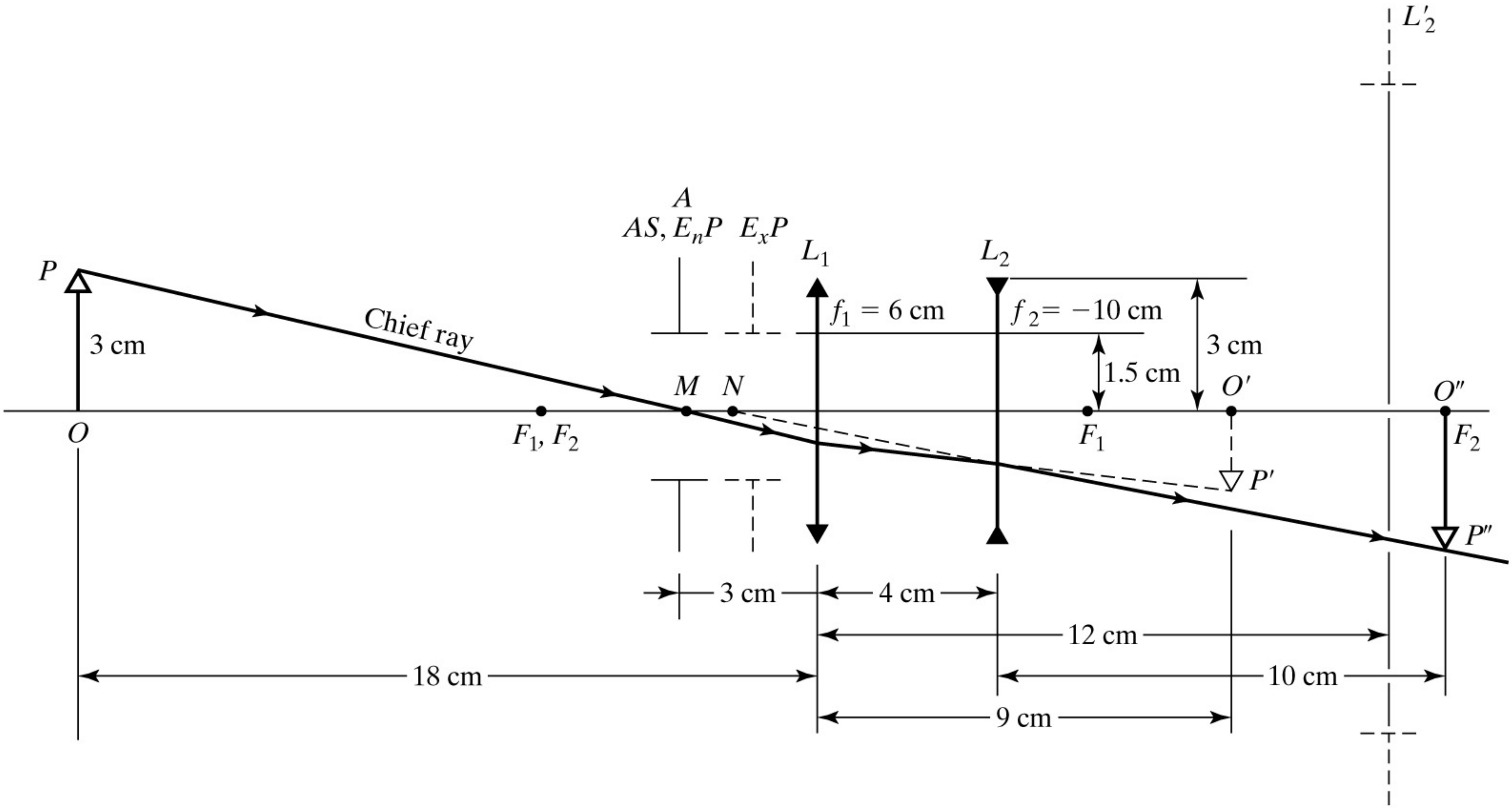
A. $w_2 = w_3 > w_4 > w_1$
B. $w_1 = w_2 > w_3 > w_4$
C. $w_4 > w_3 > w_1 = w_2$
D. $w_1 > w_4 > w_2 = w_3$
E. $w_2 > w_1 = w_3 > w_4$

Example 3-1



Optical System
P
A
L1
L2
$f_1 = 6$ cm
$f_2 = -10$ cm
3 cm
1.5 cm
O
F_1, F_2
F_1
F_2
3 cm
4 cm
18 cm

Example 3-1: Solution



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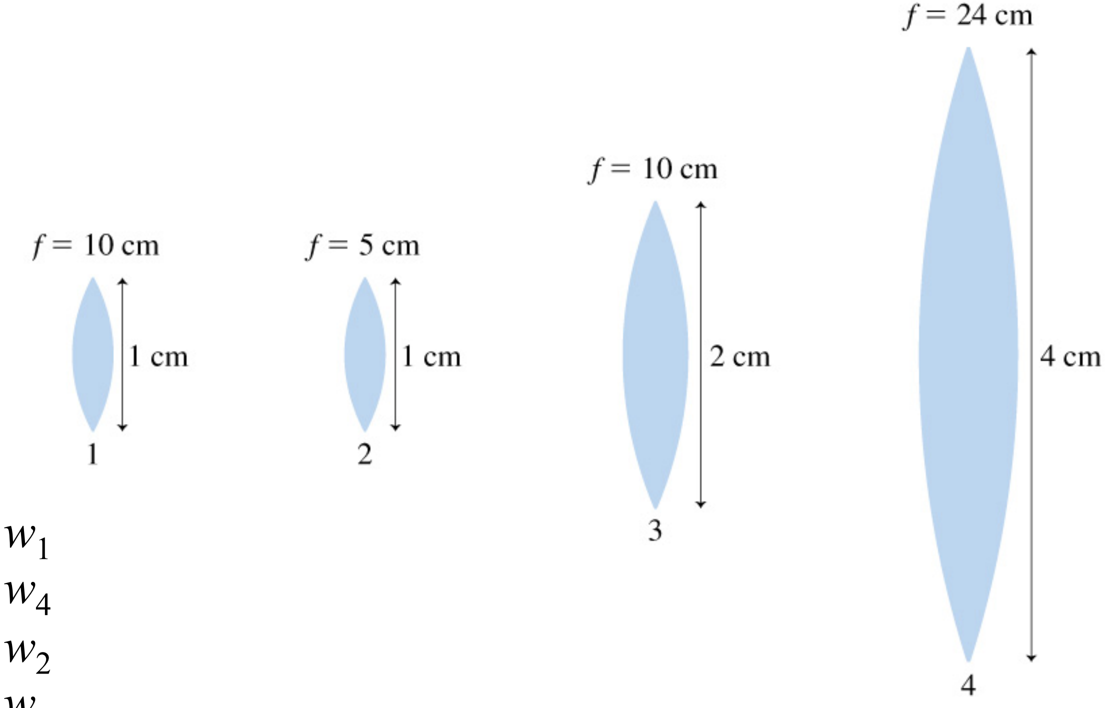

A. $w_2 = w_3 > w_4 > w_1$
B. $w_1 = w_2 > w_3 > w_4$
C. $w_4 > w_3 > w_1 = w_2$
D. $w_1 > w_4 > w_2 = w_3$
✔ E. $w_2 > w_1 = w_3 > w_4$