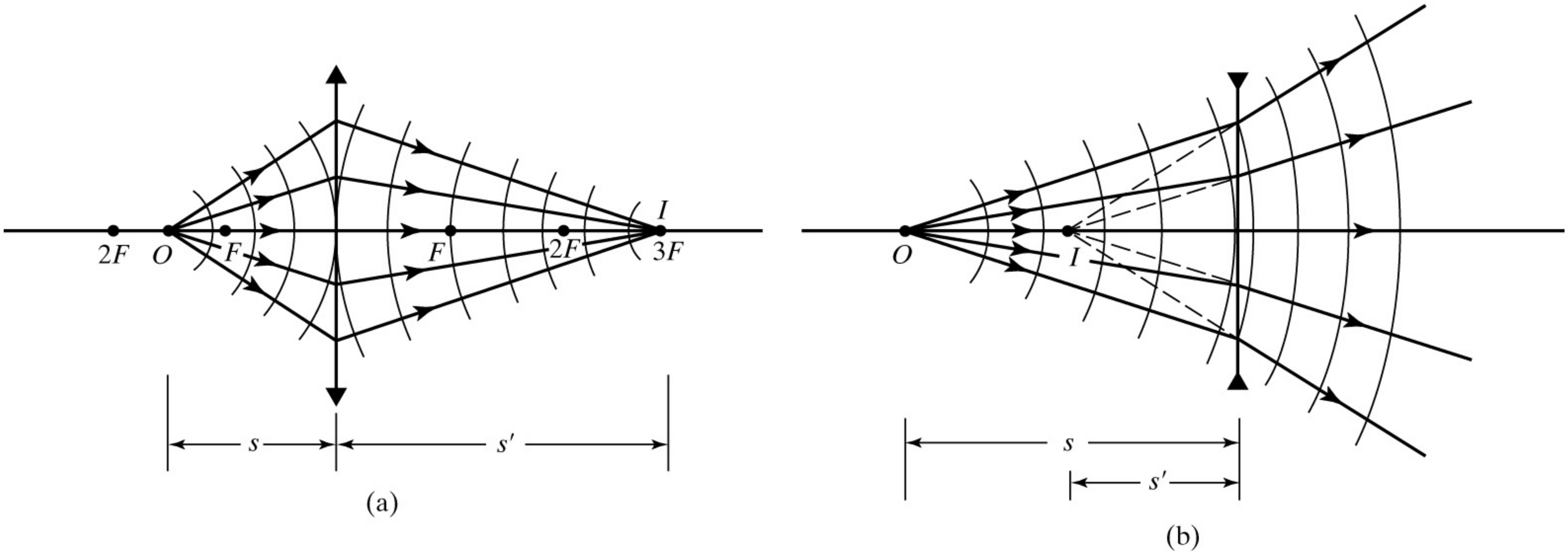
Imaging by an Optical System
Change in curvature of wavefronts by a thin lens



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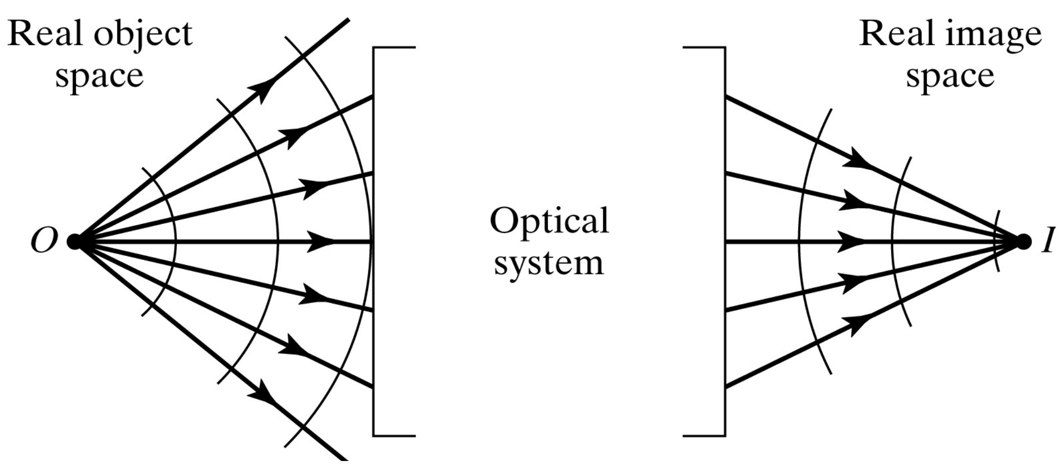


Chapter 3 Optical Instrumentation

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)*

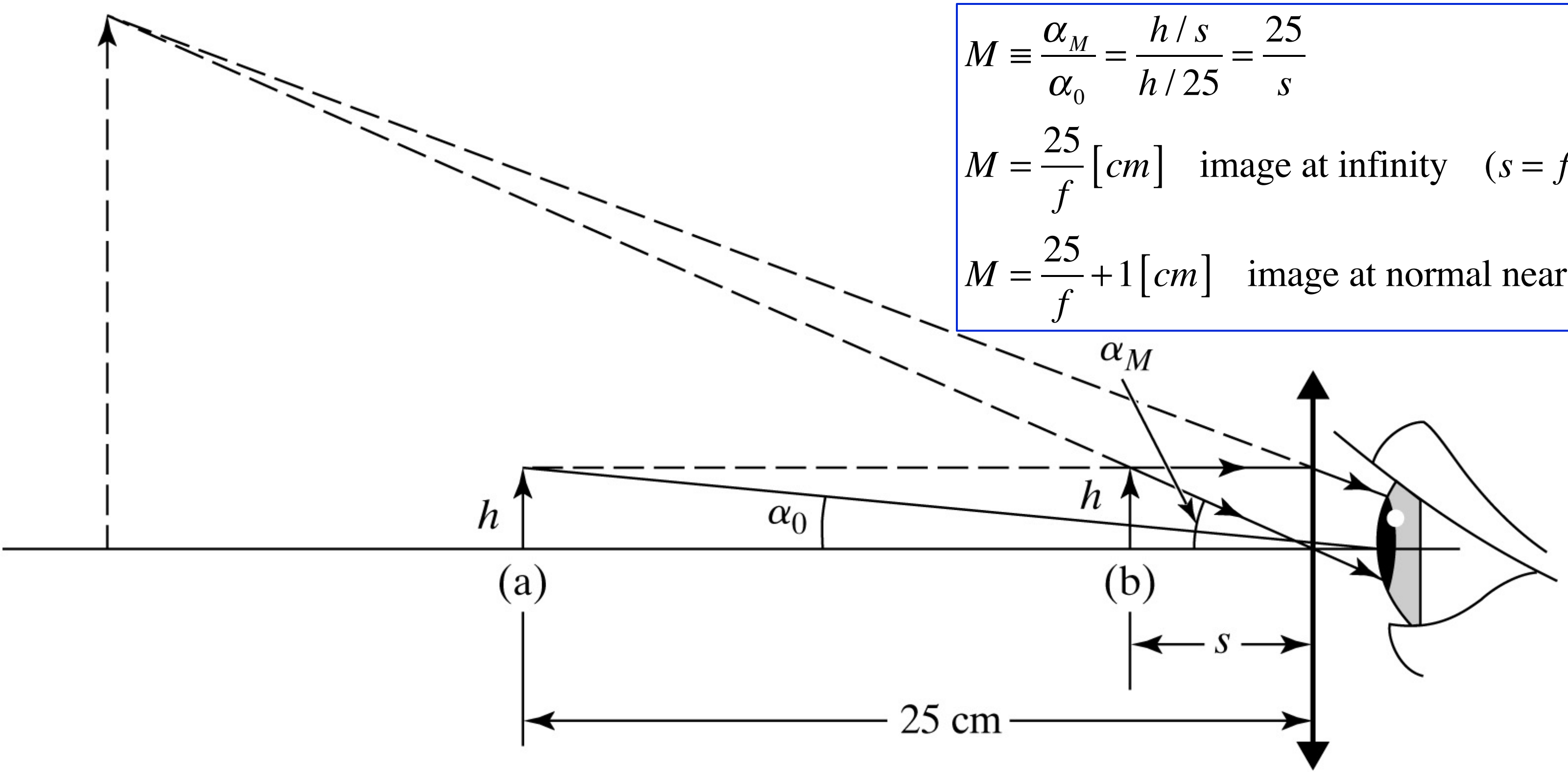
1. Magnifiers
2. Camera
3. Resolution limit
4. Microscopes
5. Telescopes

Simple Magnifiers

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

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

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



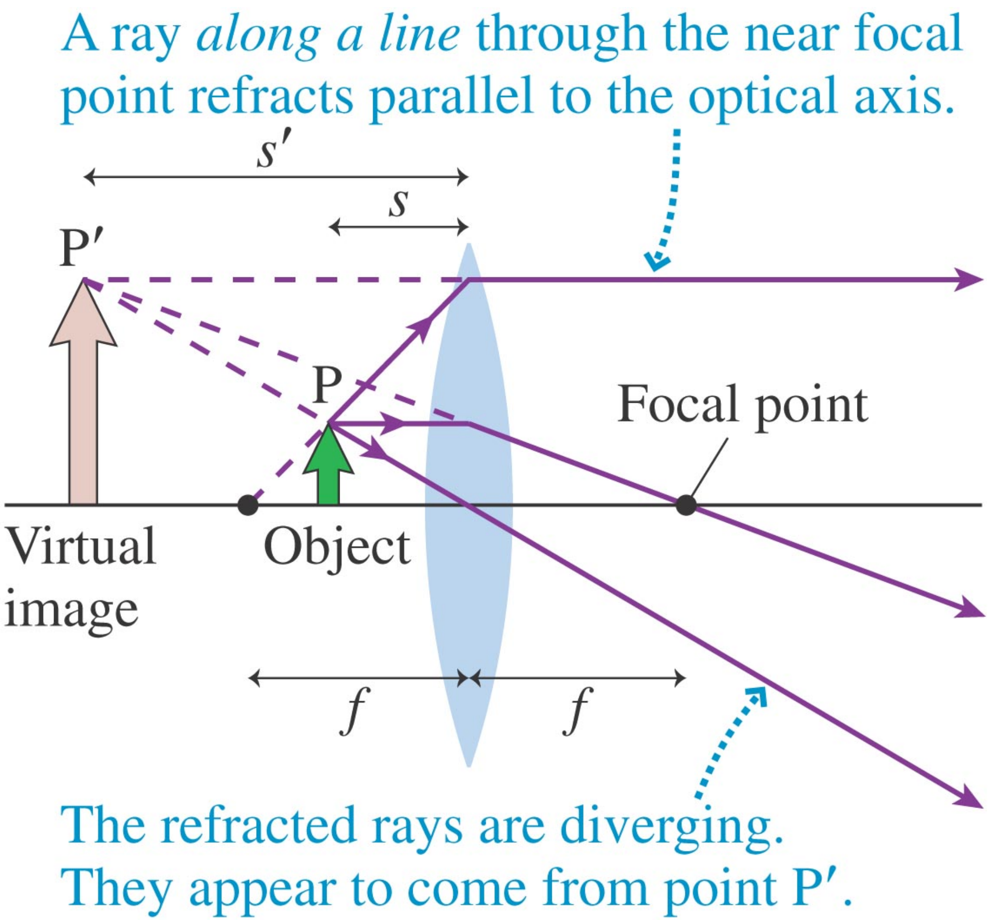
Magnifiers

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.

Magnifying Glass/Virtual Image



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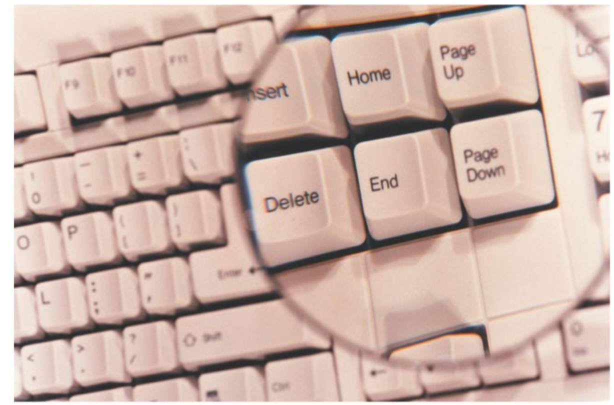

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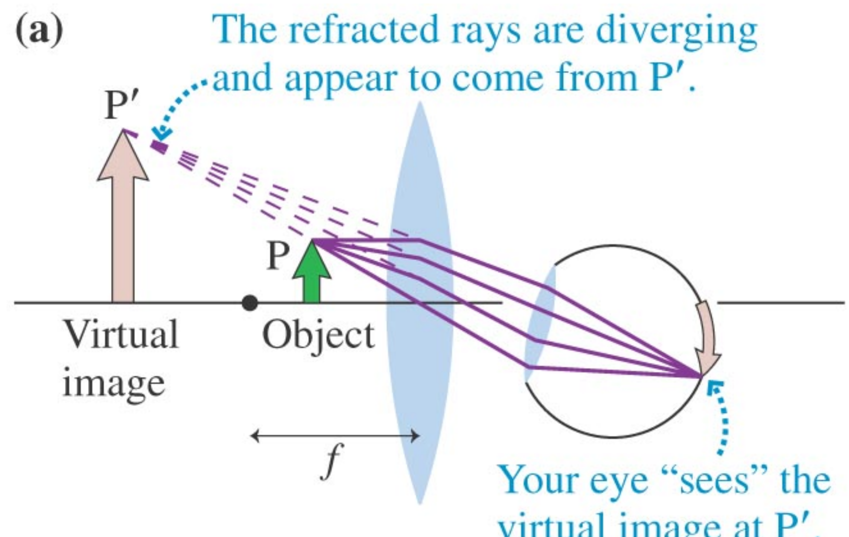

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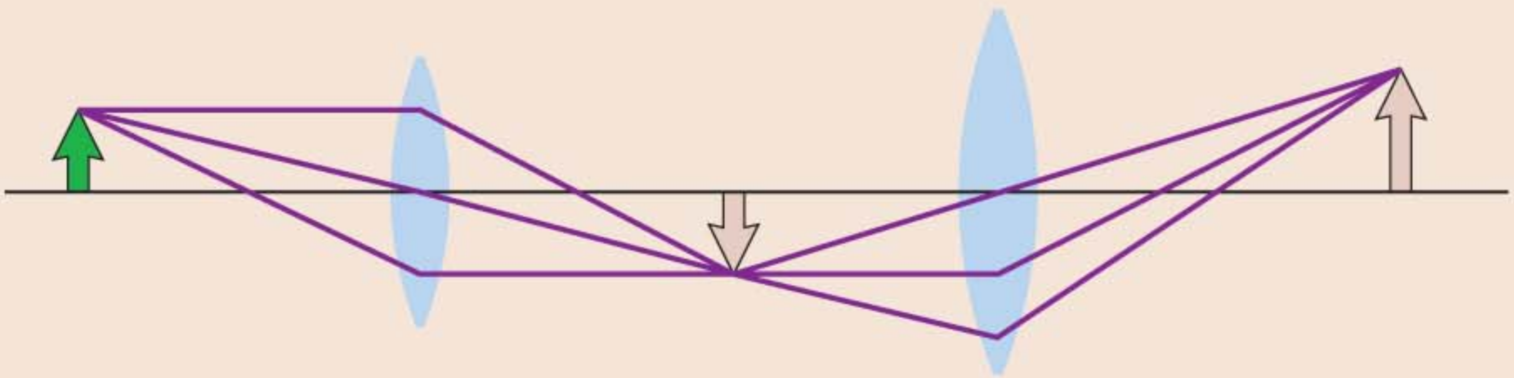
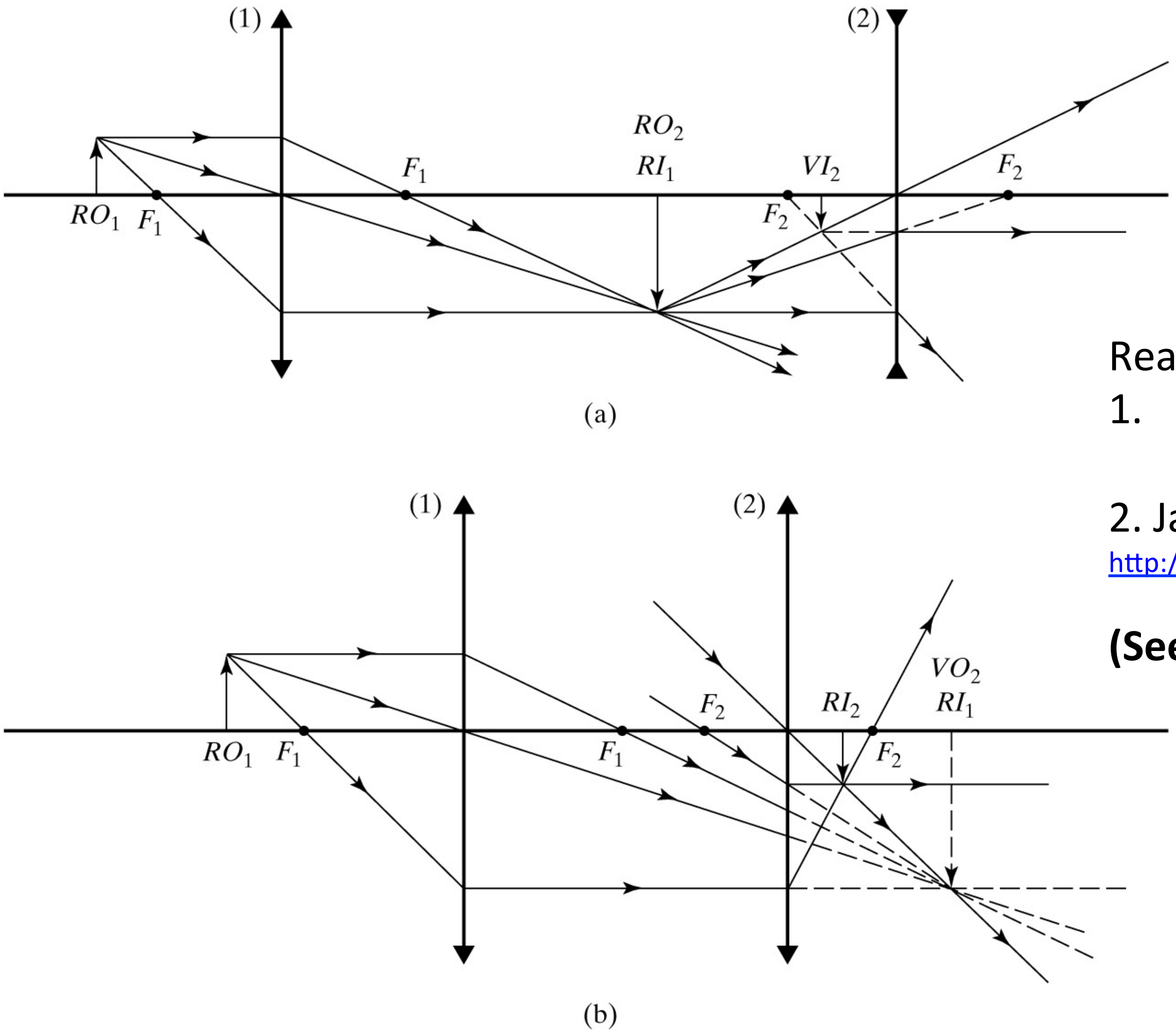
Important Concepts

Lens Combinations



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

Thin Lens Combination ➔ Sequential Imaging



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Reading Assignments

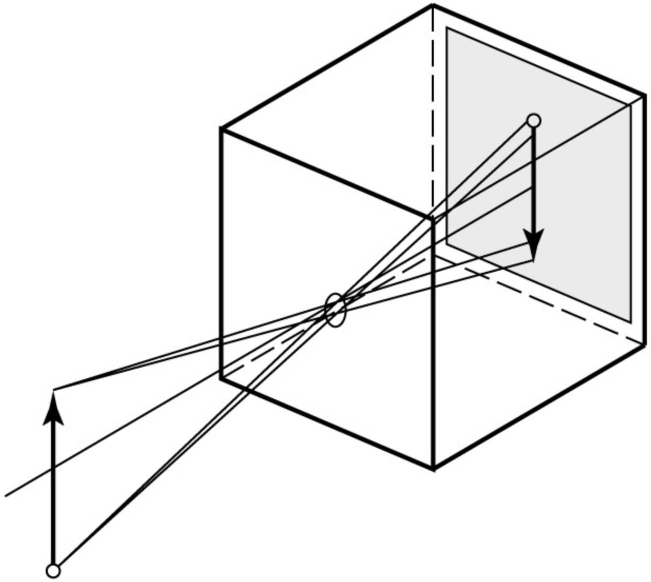
1. Example 2-3 (page 38)

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

(See also Lab #1 Appendix)

Ch. 3-4 The Camera

Pinhole Camera



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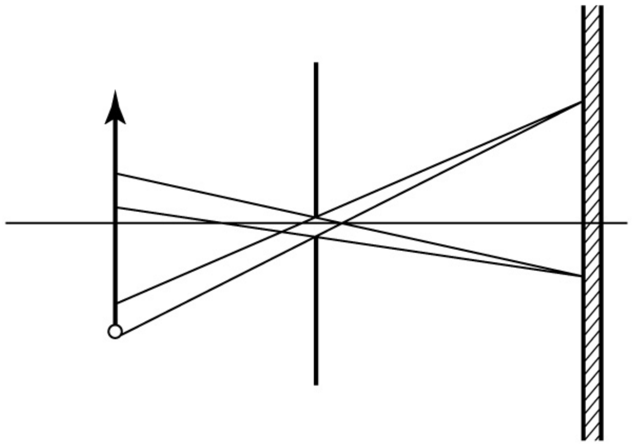
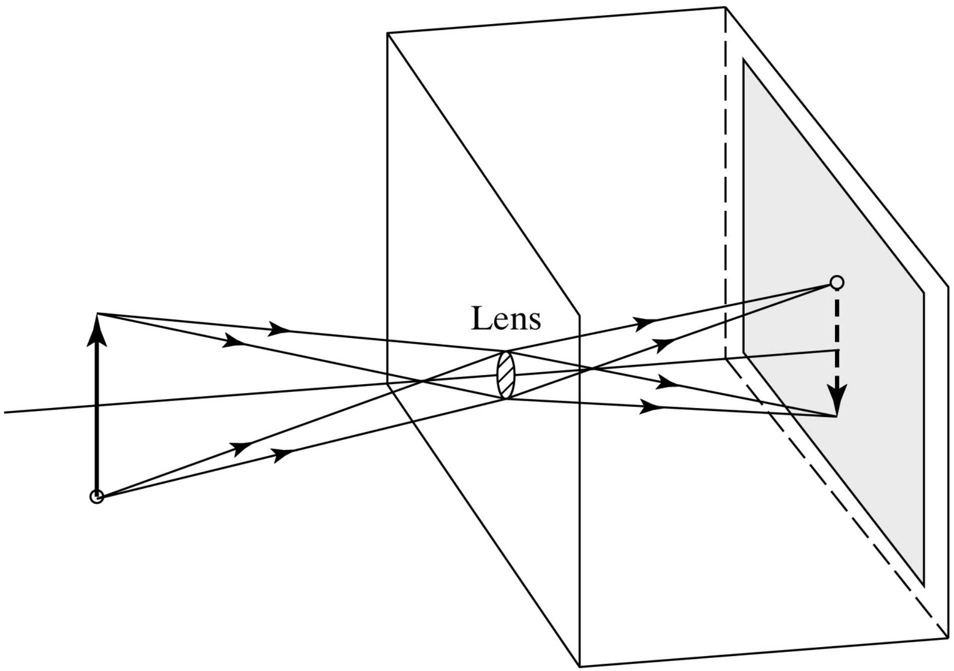


(b)

Simple Camera



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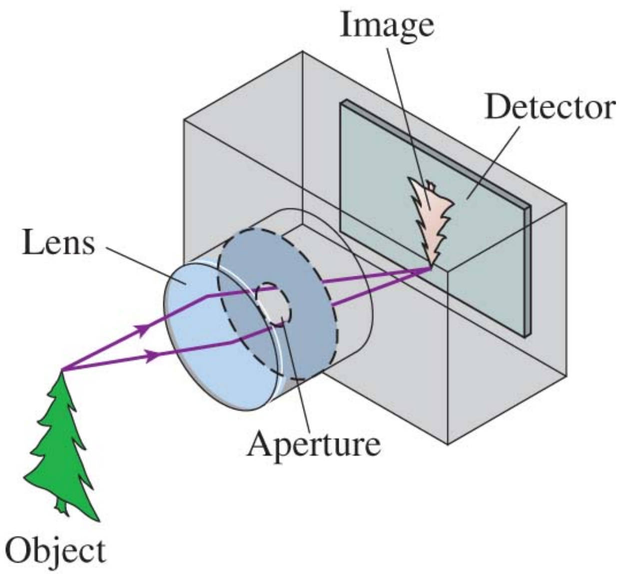
The Camera



- 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

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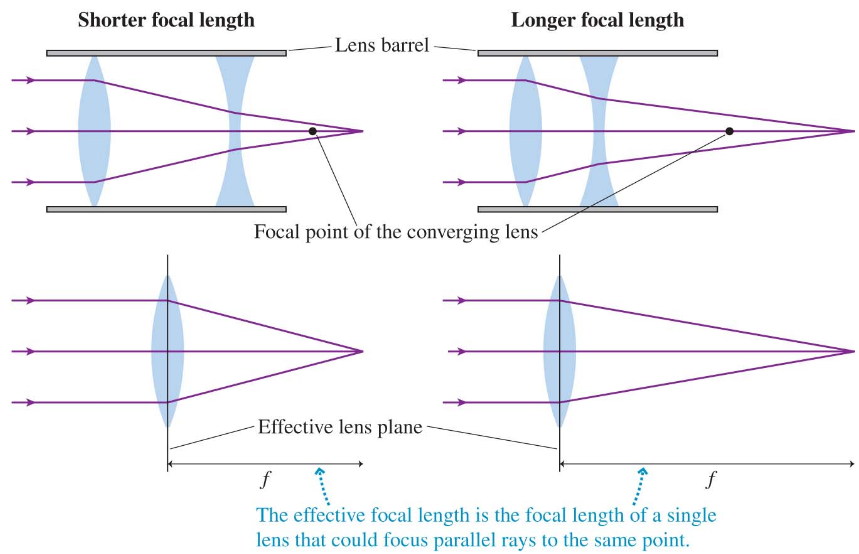

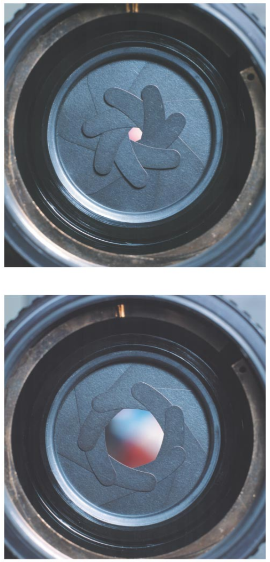

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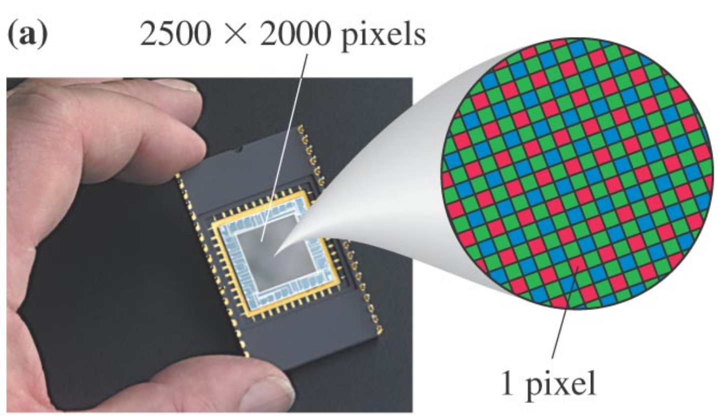

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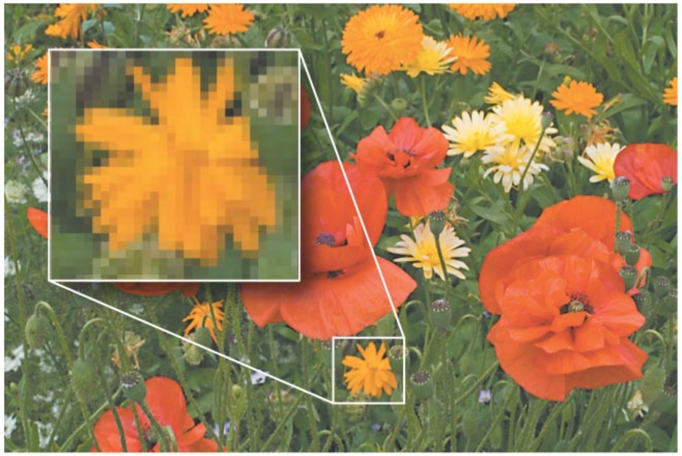


Zoom Lenses

- 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 $s >> f$, 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.

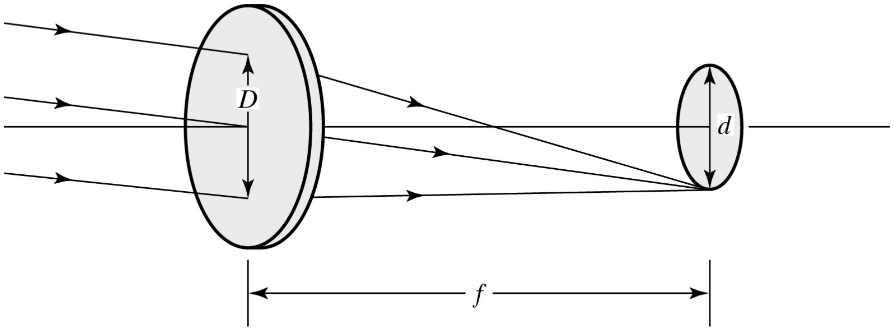
Controlling the Exposure

- 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

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



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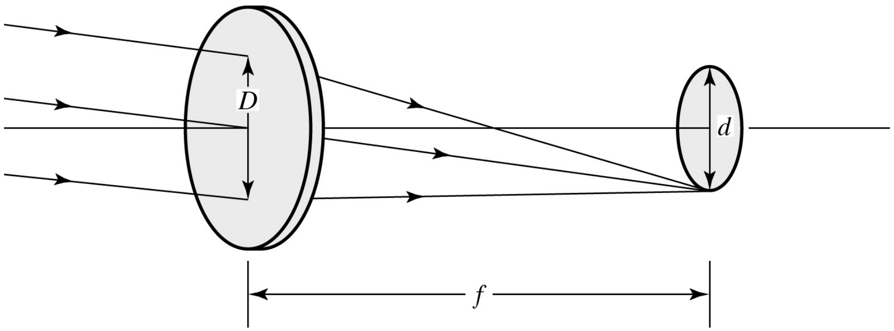
f-number and irradiance/intensity [W/m²]

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

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



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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	$E_0/512$

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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.

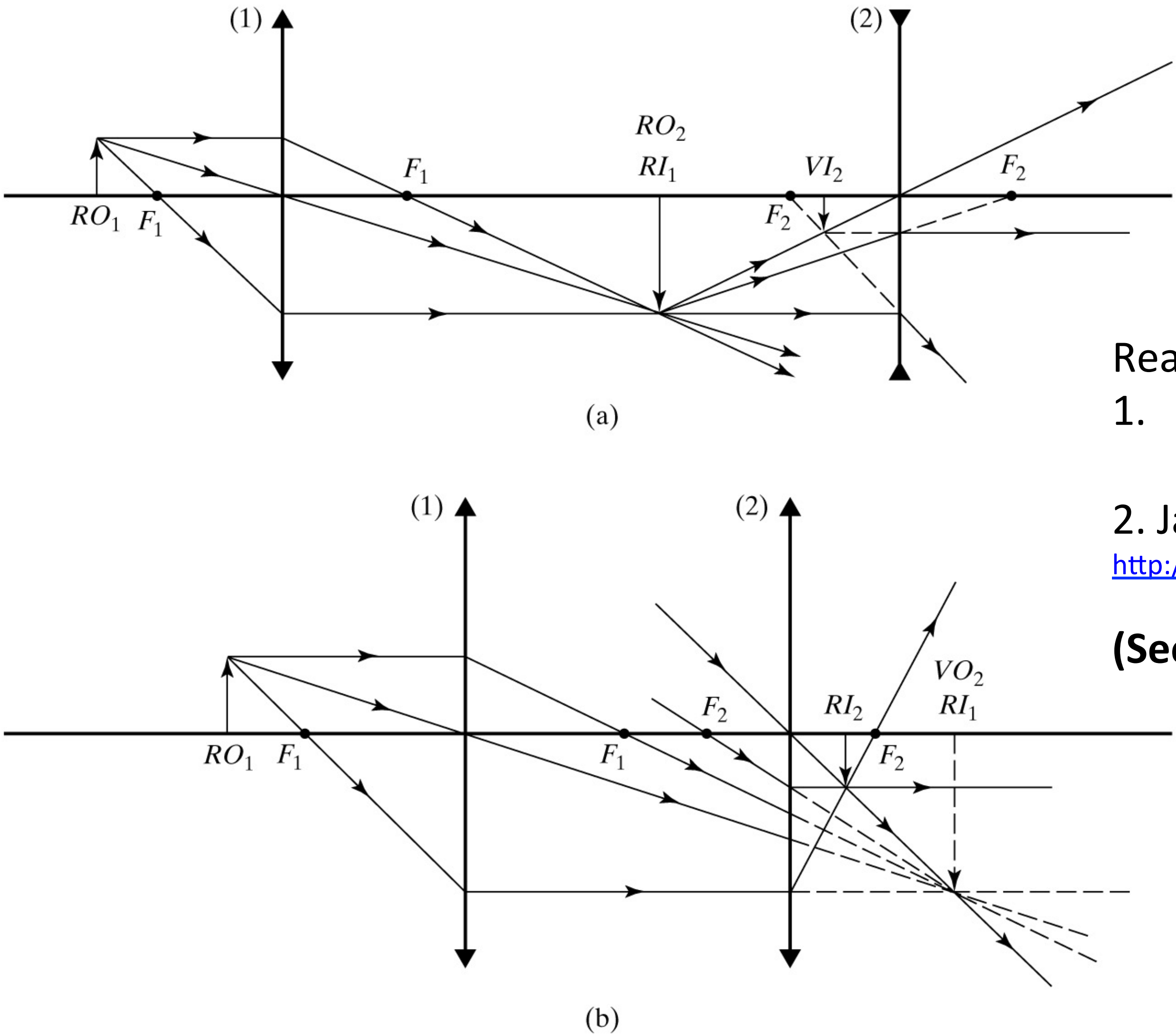
Example Focusing a camera

SOLVE The flower is at object distance $s = 20.0\text{ cm} = 200\text{ mm}$. 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 $s' = f = 10.0\text{ mm}$. To refocus as you shift scenes, the lens must move 0.5 mm closer to the detector.

Thin Lens Combination ➔ Sequential Imaging



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Reading Assignments

1. Example 2-3 (page 38)

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

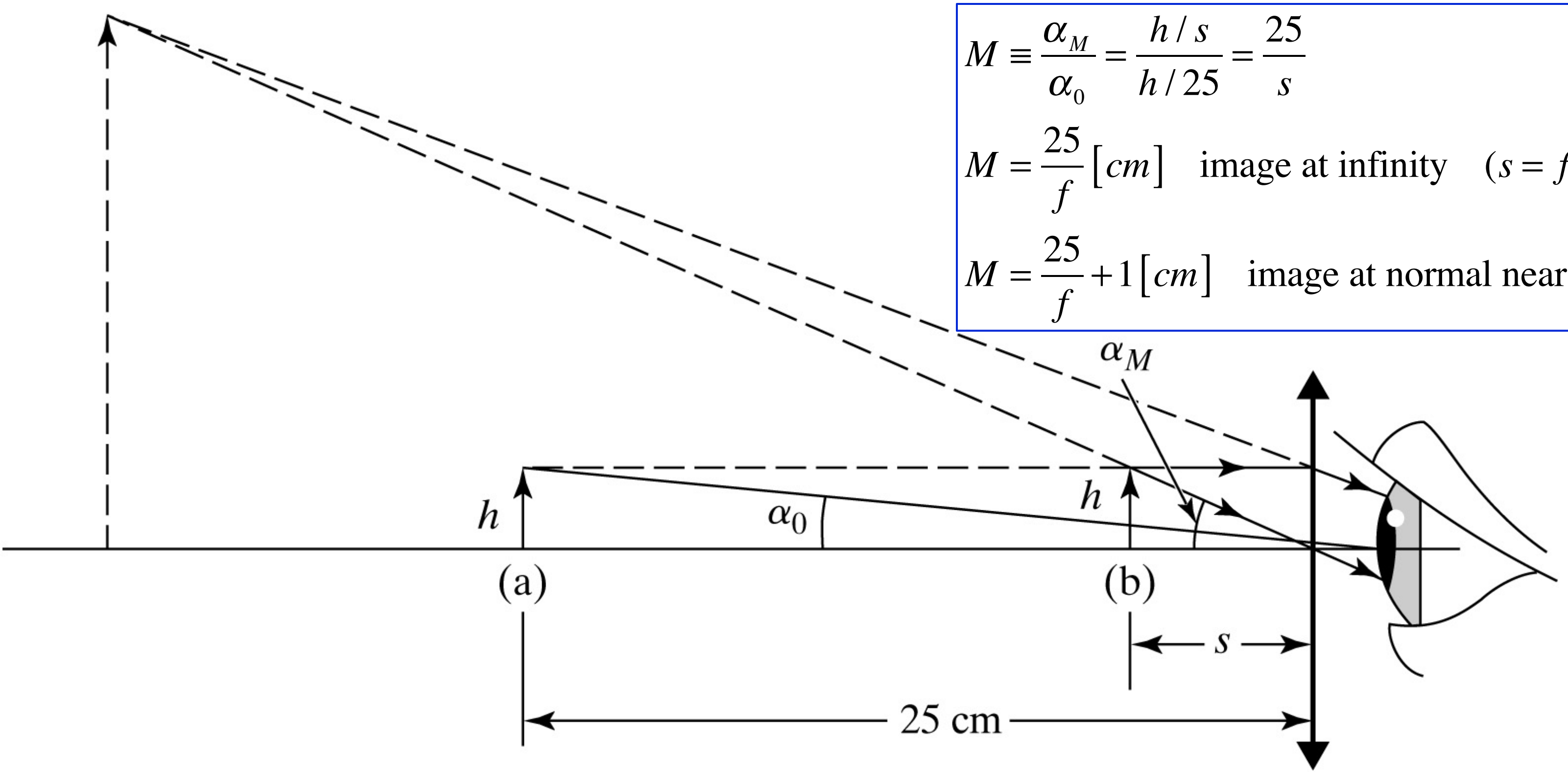
(See also Lab #1 Appendix)

Simple Magnifiers

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

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

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



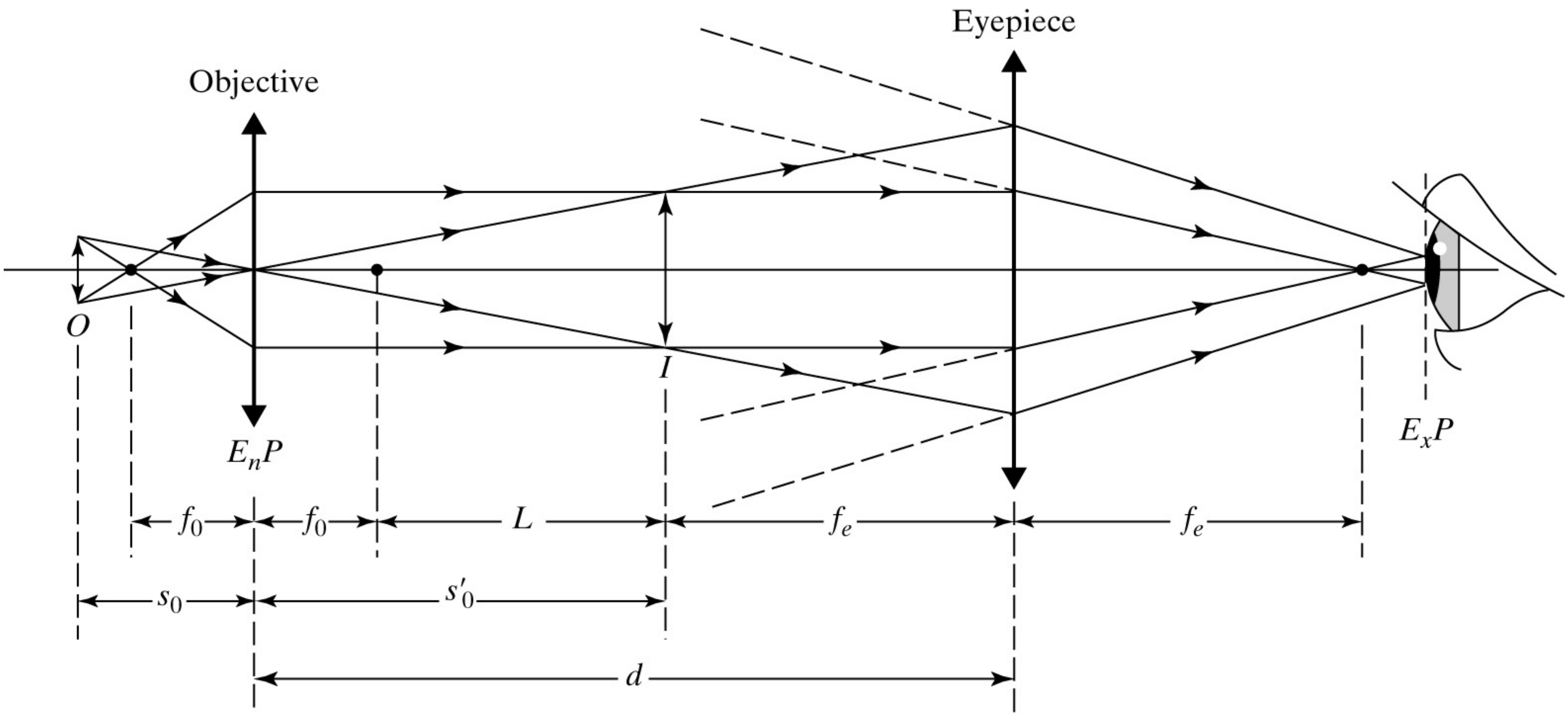
Magnifiers

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.

Microscope



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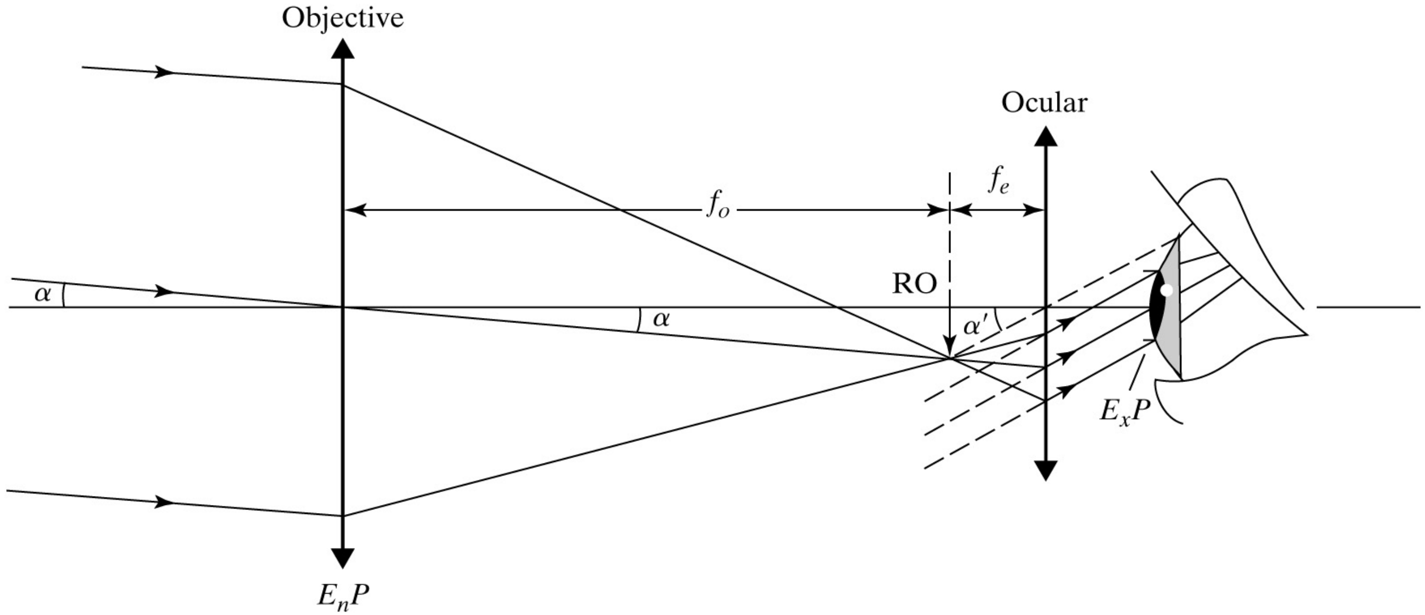
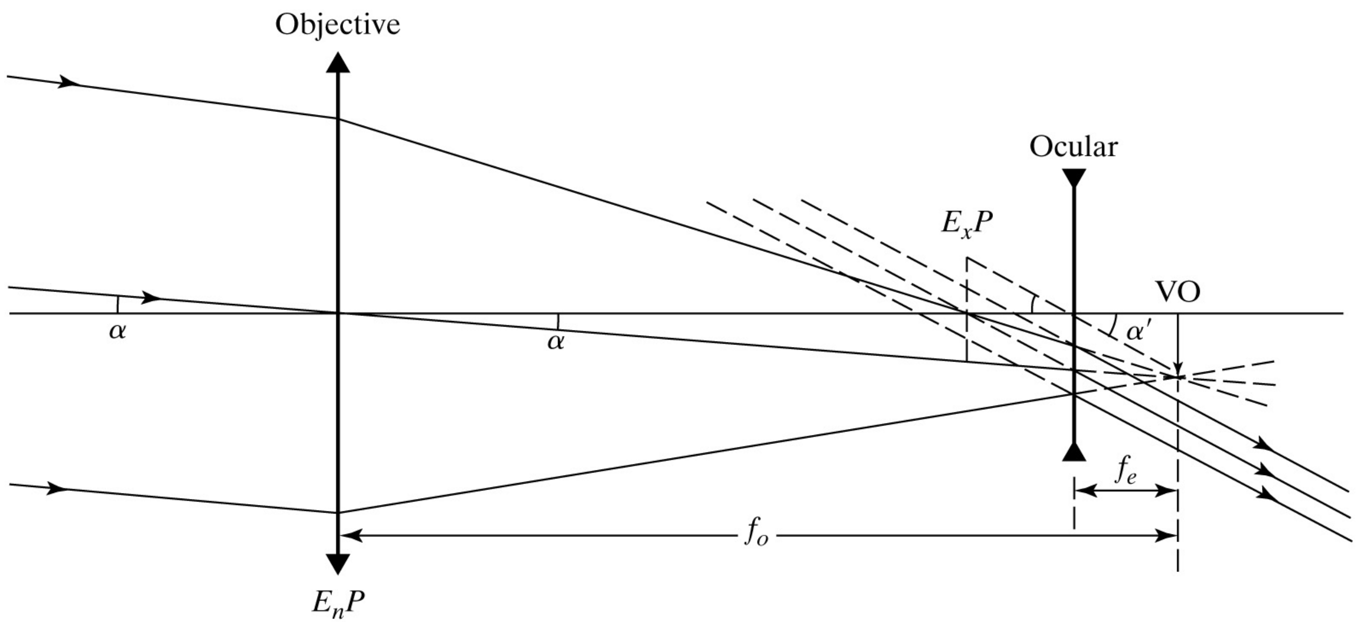
Telescope

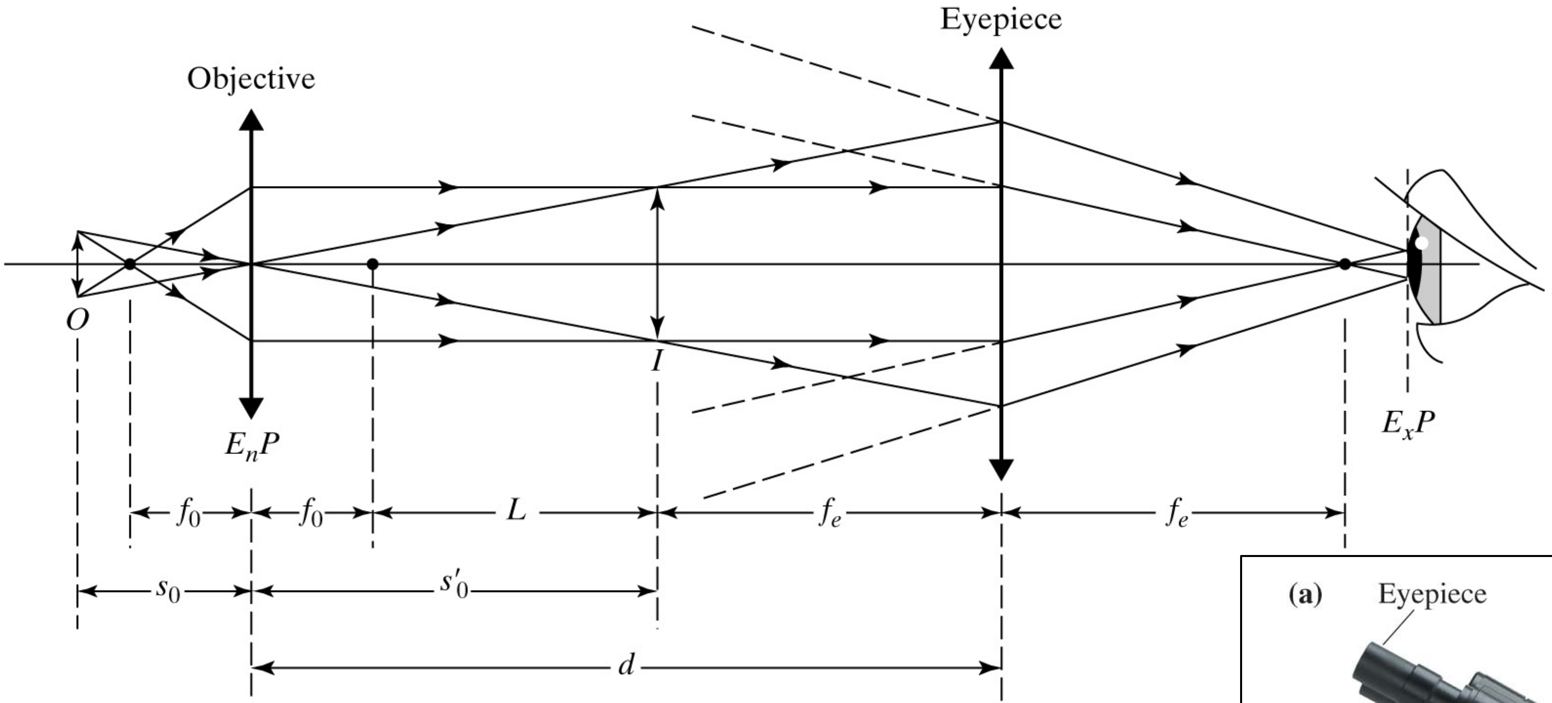


Objective
Ocular
f_o
f_e
RO
α
α
α'
E_xP
E_nP



Objective
Ocular
E_xP
VO
α
α
α'
f_e
f_o
E_nP

The Microscope



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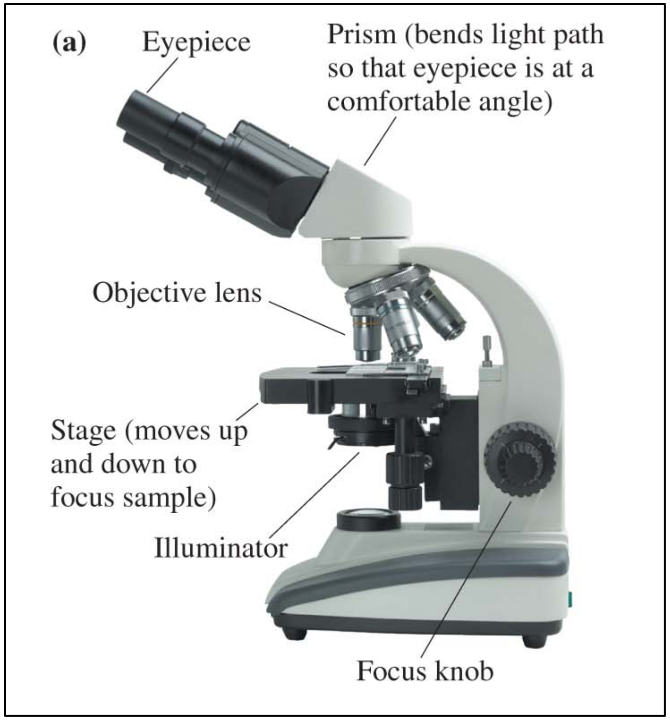


$$m_{\mathrm{obj}} = -\frac{s'}{s} \approx -\frac{L}{f_{\mathrm{obj}}}$$

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

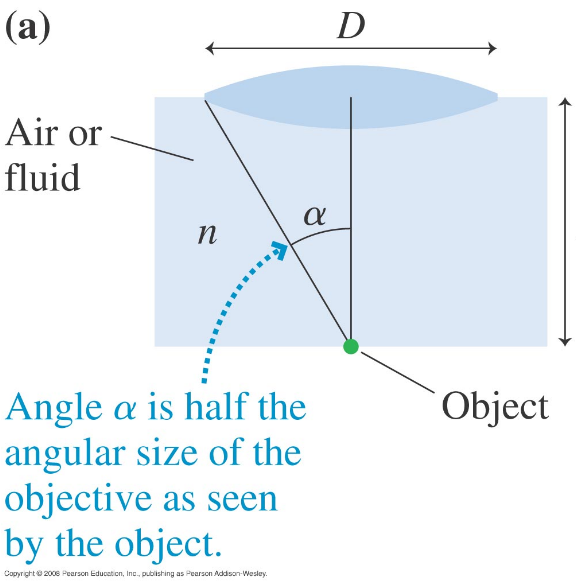
$$m_{\text{obj}} = -\frac{s'}{s} \approx -\frac{L}{f_{\text{obj}}}$$

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

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

The Microscope: Objective and Numerical Aperture (NA)

$$NA = n \sin\alpha$$



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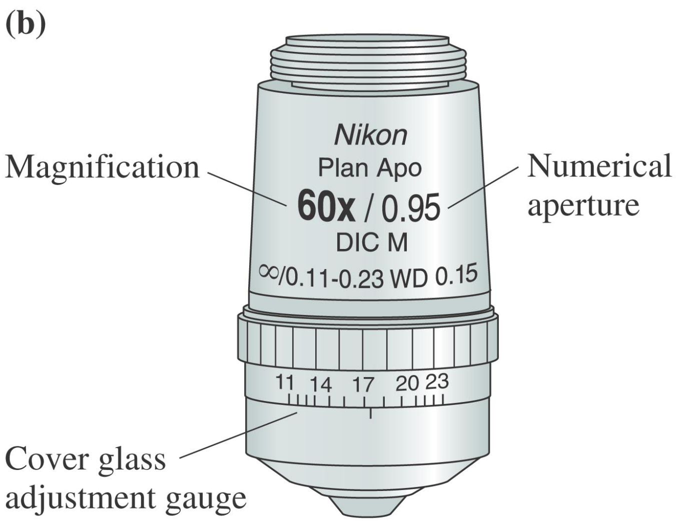

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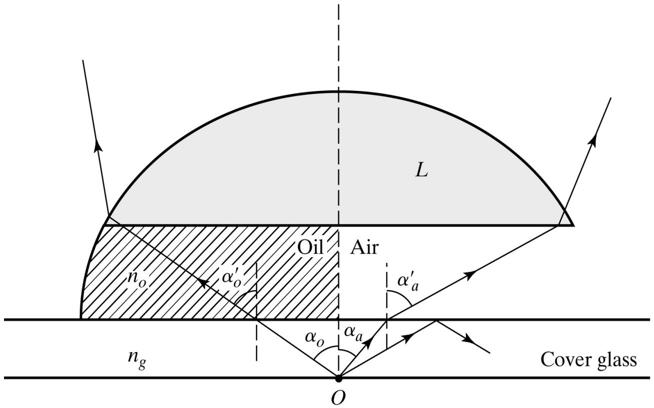
Oil-immersion microscope



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Microscopes

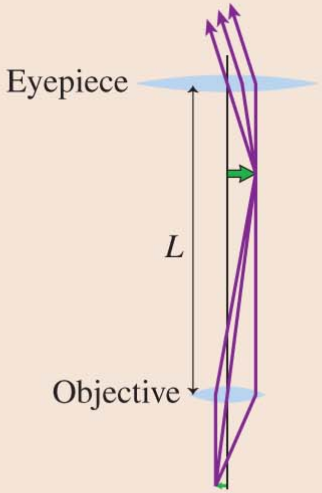
The object is very close to the focal point of the objective. The total magnification is

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

The spatial resolution is

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

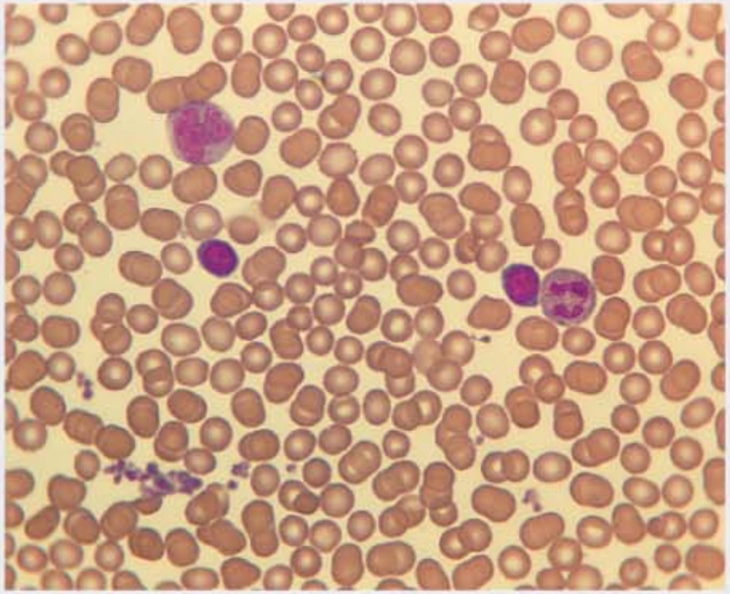
where NA is the numerical aperture of the objective lens.



Example: Viewing blood cells

QUESTION:

A pathologist inspects a sample of 7-μm-diameter human blood cells under a microscope. She selects a 40× 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?



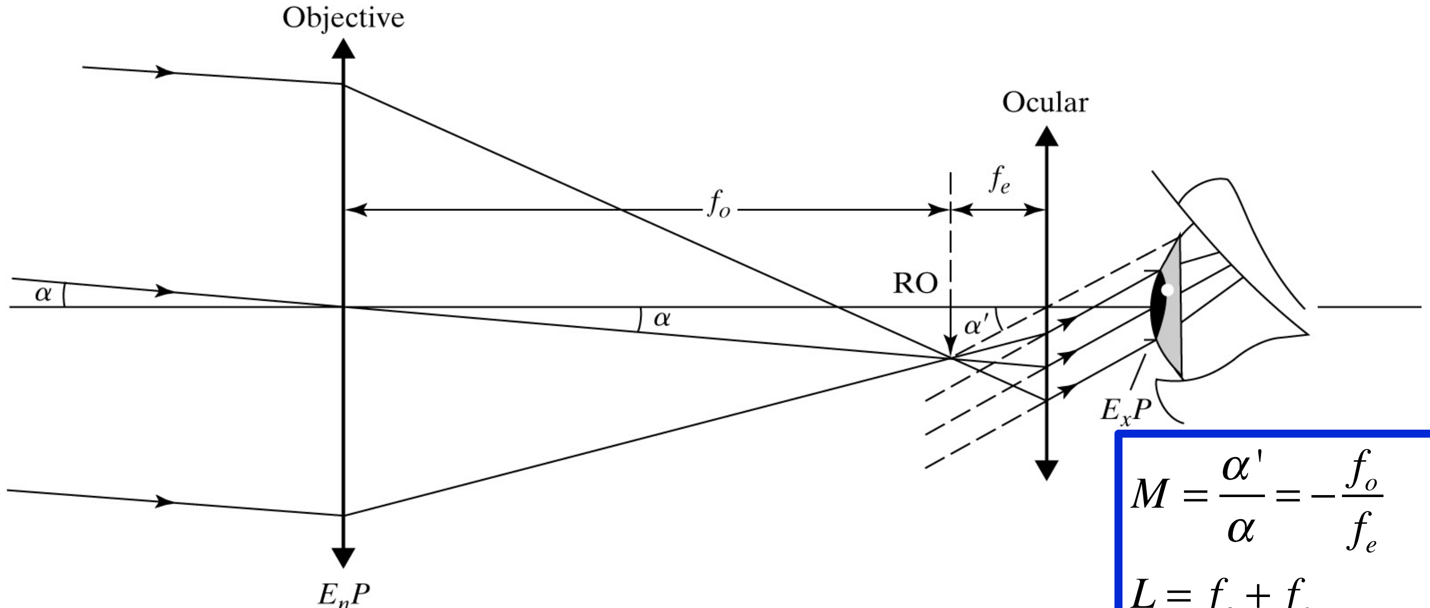
MODEL Angular magnification compares the magnified angular size to the angular size seen at the near-point distance of 25 cm.

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.

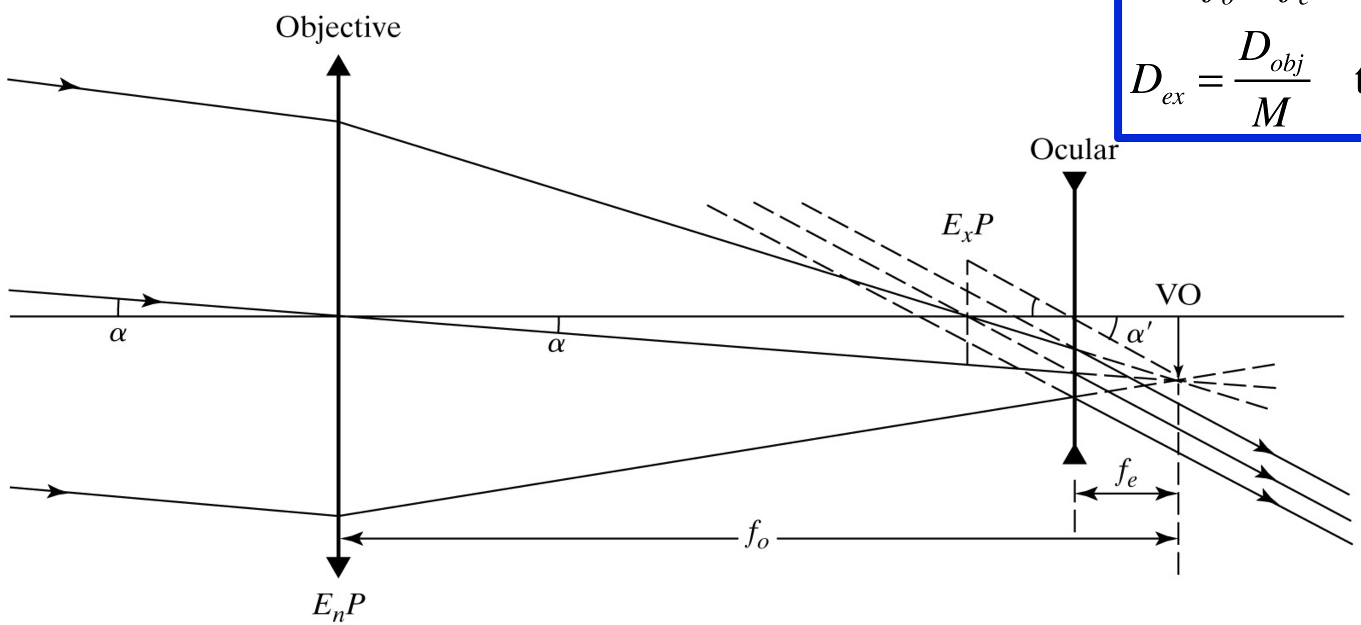
Telescope



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

$$L = f_o + f_e$$

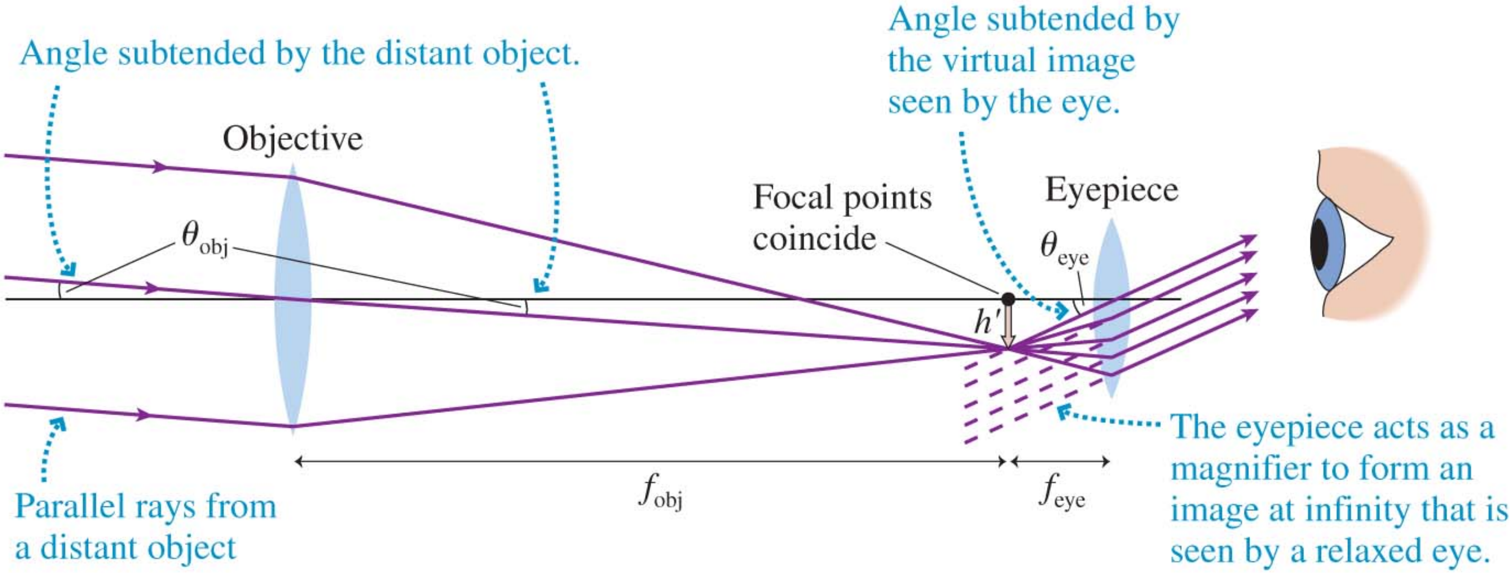
$$D_{ex} = \frac{D_{obj}}{M}$$ the diameter of the exit pupil



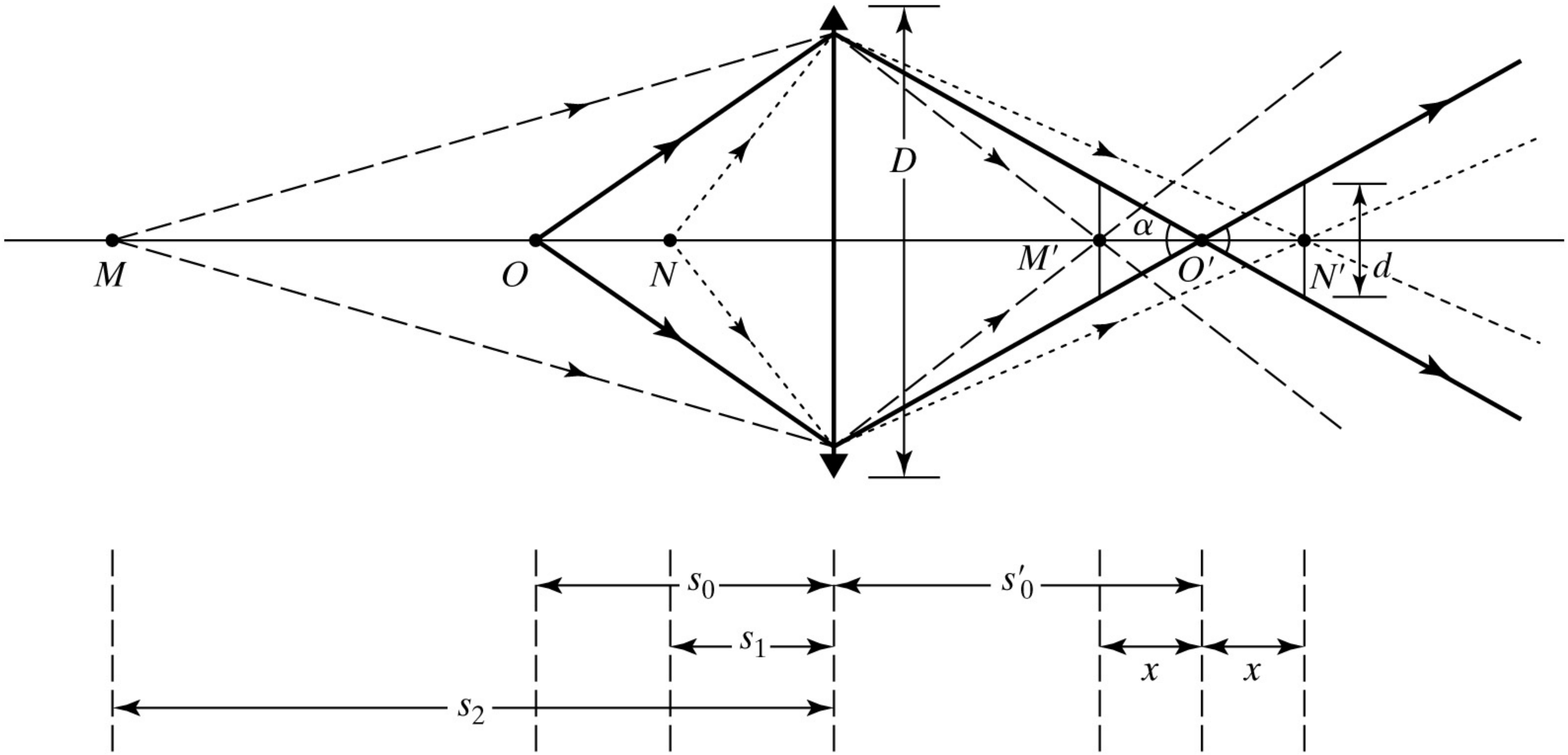
The Telescope

- 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

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



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



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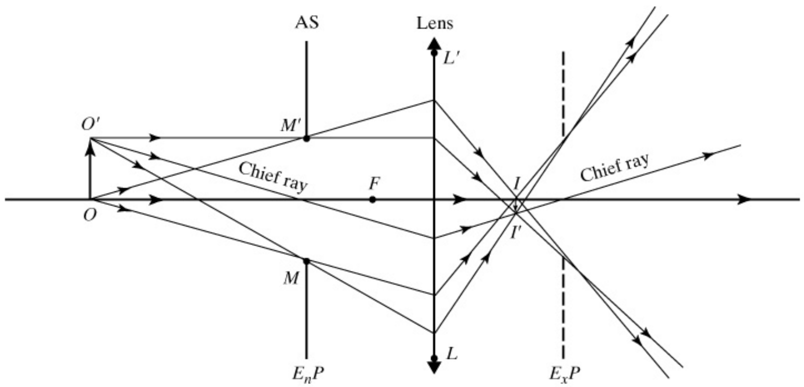
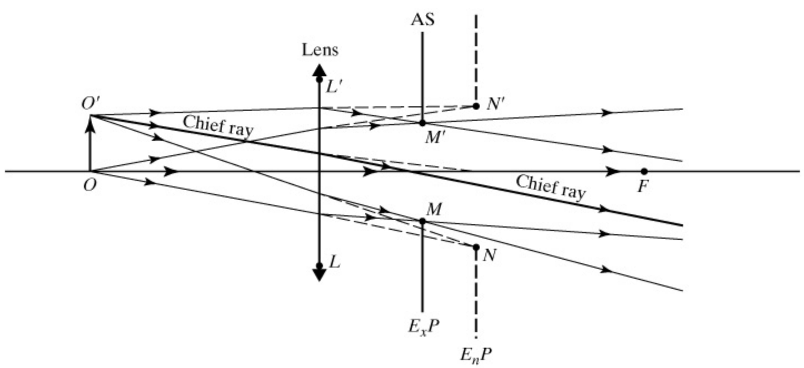
$$\text{depth of field} = \frac{2Ads_o\left(s_o - f\right)f^2}{f^4 - A^2d^2s_o^2}$$

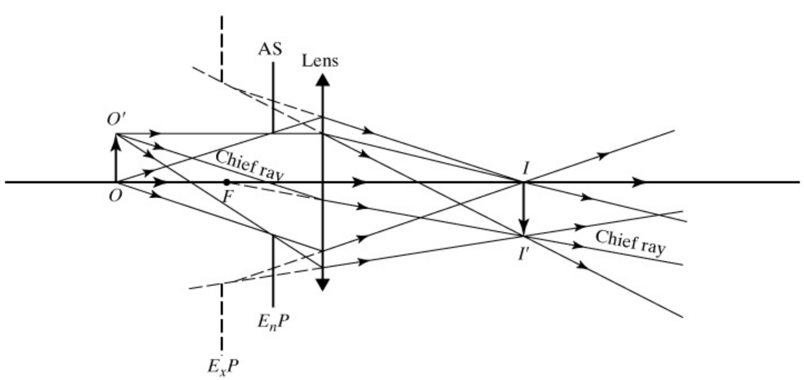
Stops, Pupils, and Windows



(a)



(b)



(c)

<u>*Summary of Terms*</u>

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.

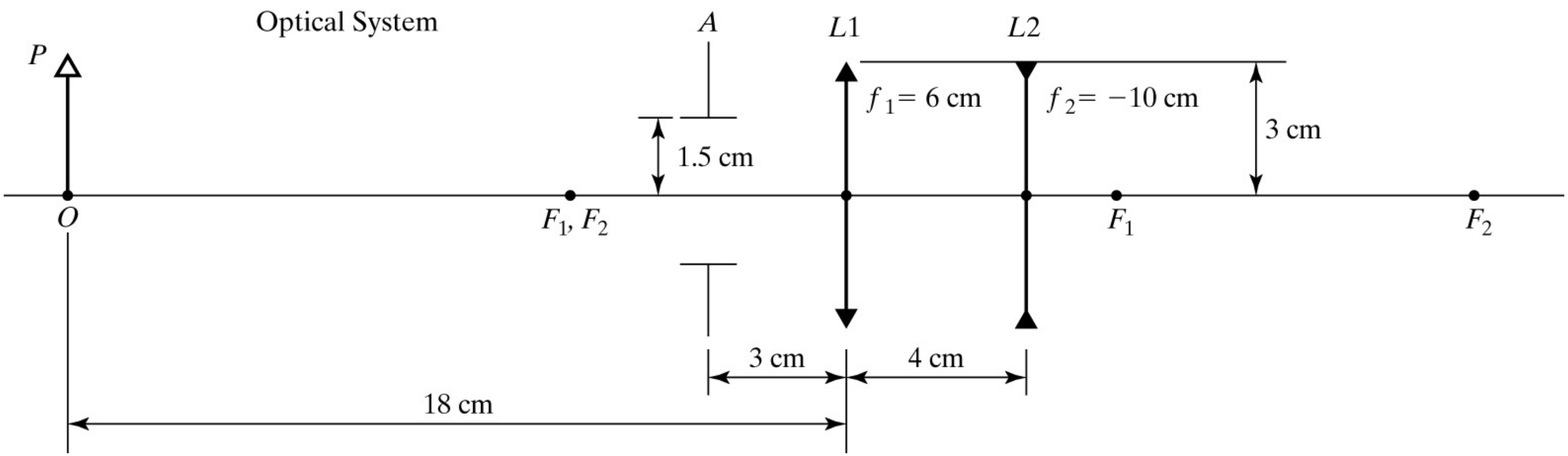
Entrance window E_nW: The image of the field stop formed by the optical elements (if any) that precede it.

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.

Example 3-1



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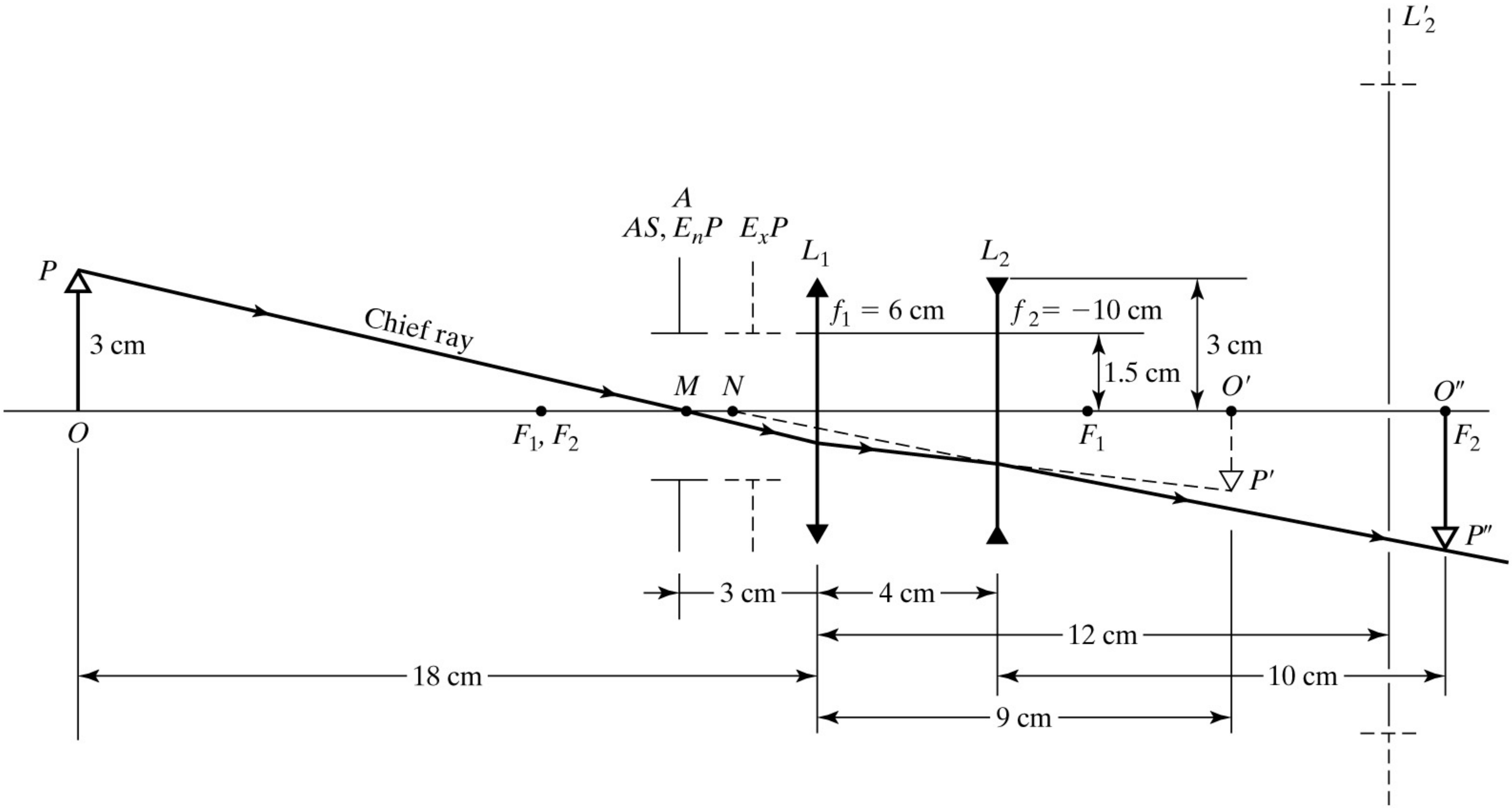
Example 3-1: Solution



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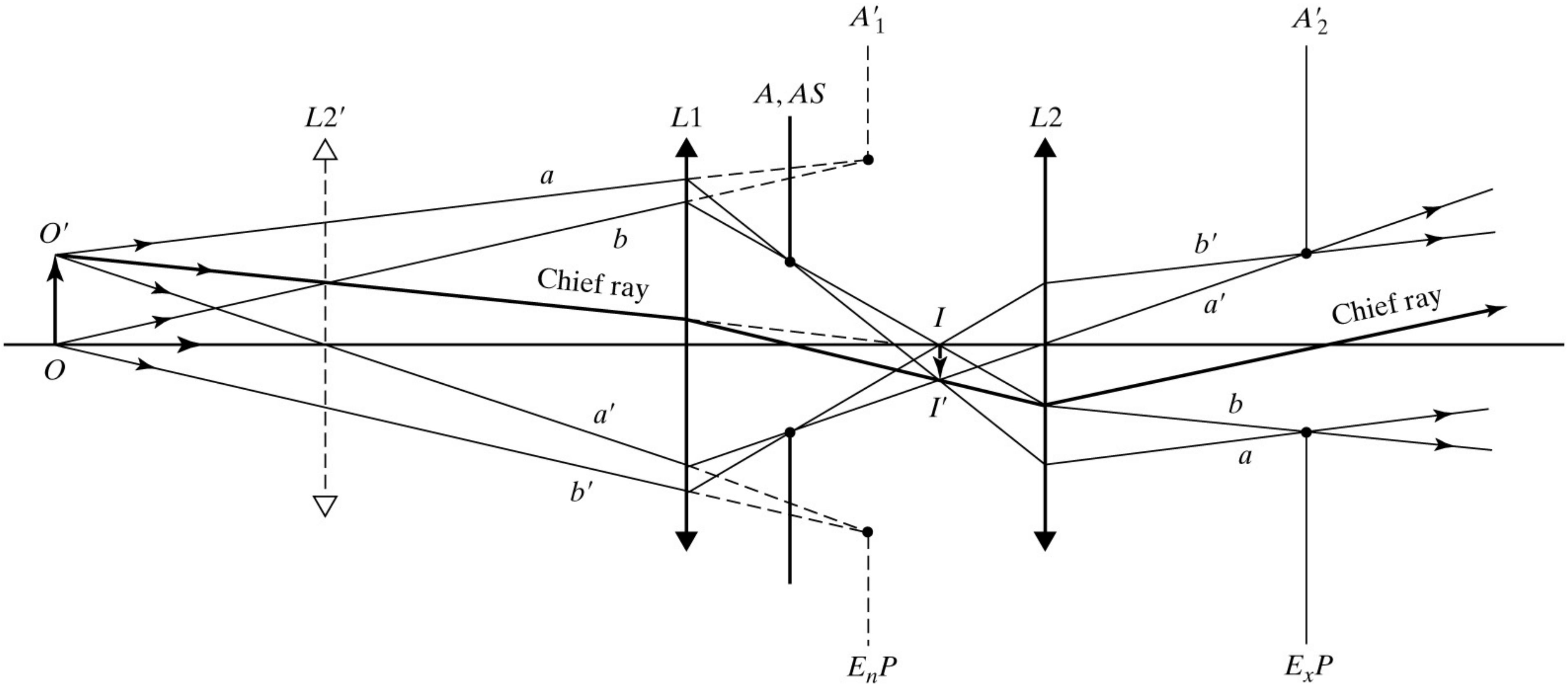
Limitation of light rays in a two-positive-lens system



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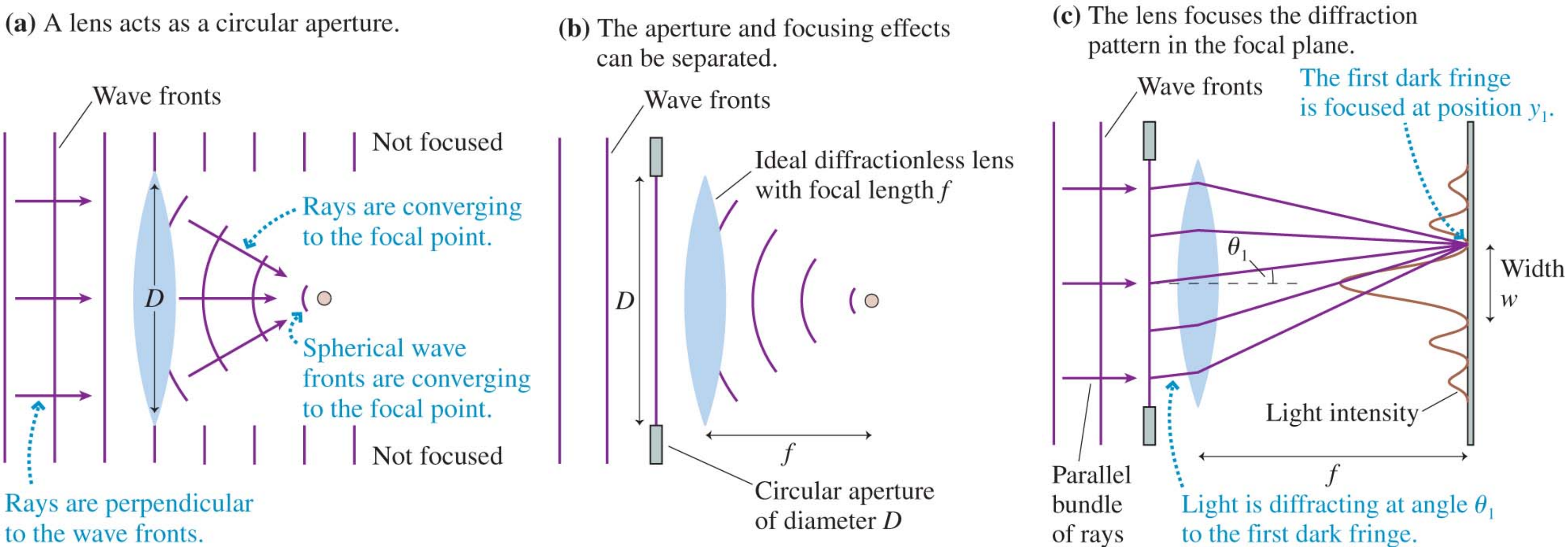
A lens both focuses and diffracts the light



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

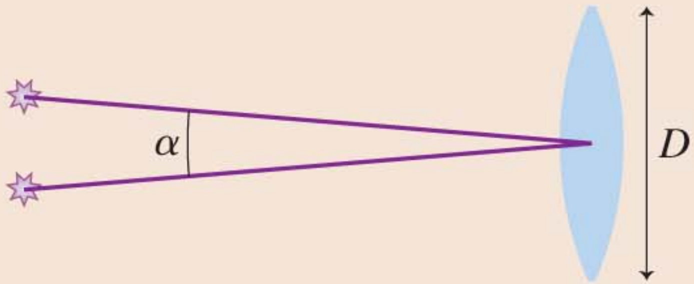
$$\theta_{\min} = \frac{1.22\lambda}{D} \qquad \text{(angular resolution of a lens)}$$

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

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

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