DUT-RU ISE

DUT – RU International School of Information Science & Engineering

Topic # 6

Light and Optics

Lecture Course (online)
Dalian, 2021

Contents

The Subject of Optics

Light has a dual nature. In some experiments it acts like a particle, while in others it acts like a wave (aka wave-particle **duality**). The ability to manipulate light has greatly enhanced our capacity to investigate and understand the nature of the universe.

One goal of physics is to discover the basic laws governing light, such as the law of refraction. A broader goal is to put those laws to use, and perhaps the most important use is the production of **images**.

camera


telescope


microscope

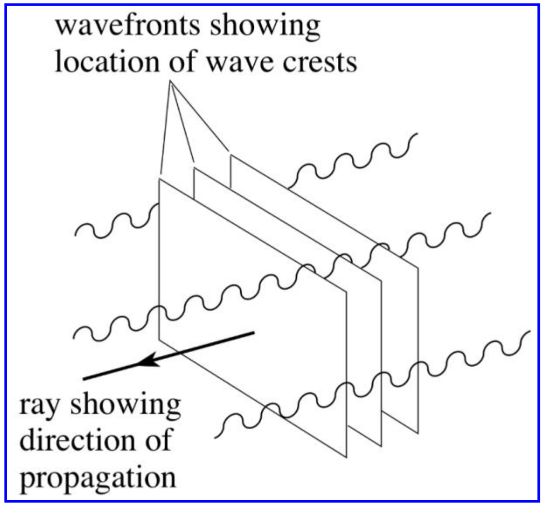

glasses and contact lenses

Reflection, Refraction, and Ray Approximation

When light travelling in one medium encounters a boundary leading into a second medium, the processes of **reflection** and **refraction** can occur.

- in **reflection**, part of the light encountering the second medium **bounces** off that medium
- in **refraction**, the light passing into the second medium **bends** through an angle with respect to the normal to the boundary

Note: Often, both processes occur at the same time, with part of the light being reflected and part refracted.

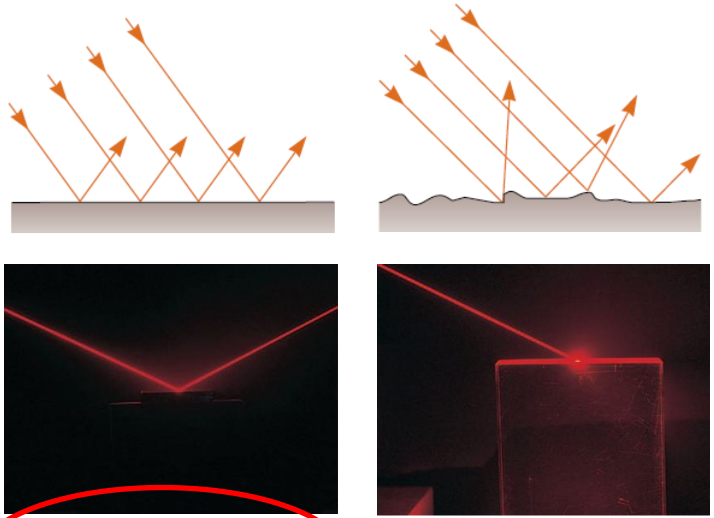


In order to study both phenomena, we use the **ray approximation** for light:

> light travels in a straight-line path in a homogeneous medium, until it encounters a boundary between two different materials

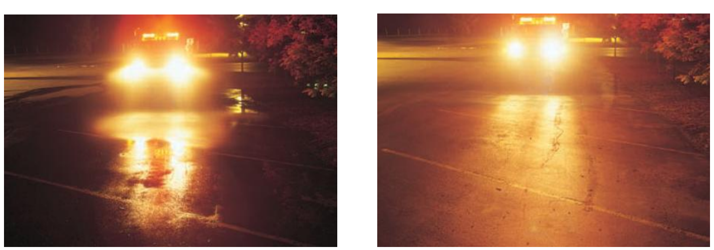
Reflection of Light

When a light ray traveling in a transparent medium encounters a boundary leading into a second medium, part of the incident ray is reflected back into the first medium.



specular reflection

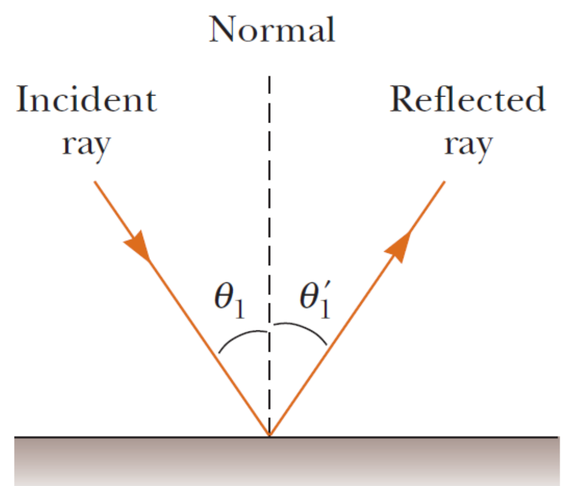
diffuse reflection



The **law of reflection**:
(deduced experimentally)

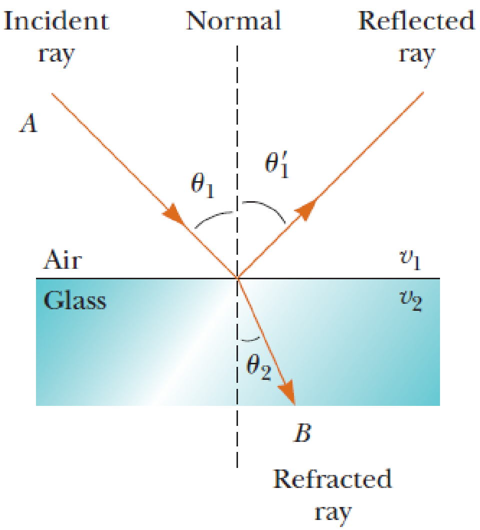
$$\theta_1' = \theta_1$$

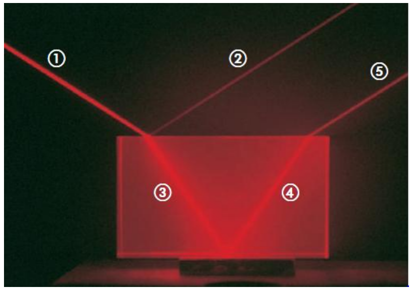
the angle of reflection equals the angle of incidence



Refraction of Light

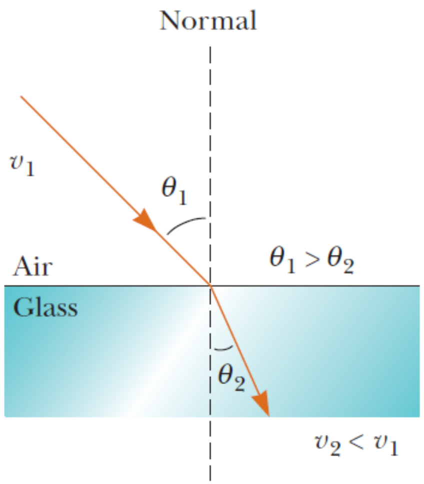
When a ray of light traveling through a transparent medium encounters a boundary leading into another transparent medium, part of the ray is reflected and part enters the second medium. The ray that enters the second medium is bent at the boundary and is said to be refracted.

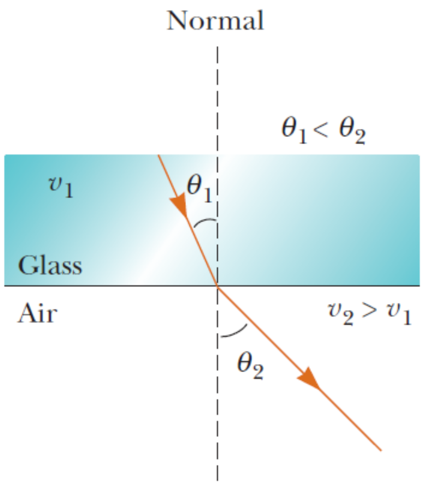




The incident ray, the reflected ray, the refracted ray, and the normal at the point of incidence all lie in the same plane

The path of a light ray through a refracting surface is reversible





Refraction of Light

When light passes from one transparent medium to another, it's refracted because the speed of light is different in the two media.

The **index of refraction**

$$n \equiv \frac{\text{speed of light in vacuum}}{\text{speed of light in a medium}} = \frac{c}{v}$$

The **law of refraction**

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} = \text{constant}$$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

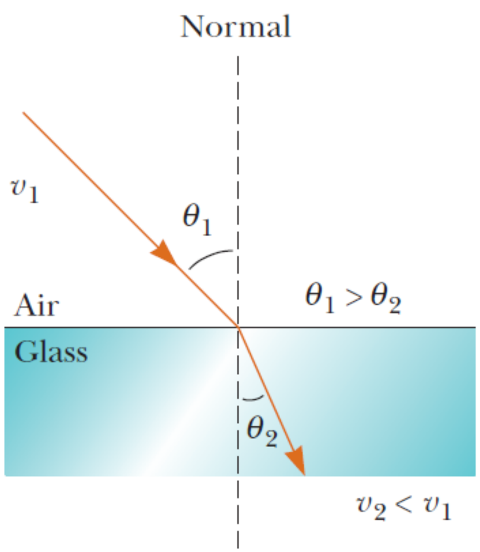
Snell's law of refraction

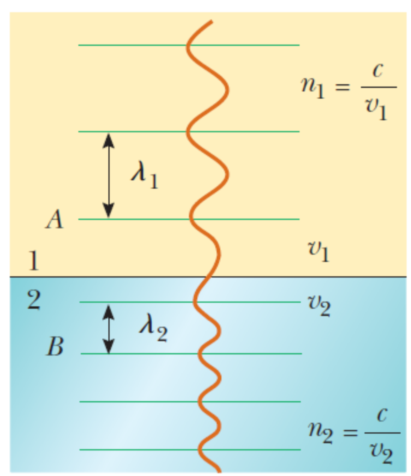
index of refraction and wave aspect of light

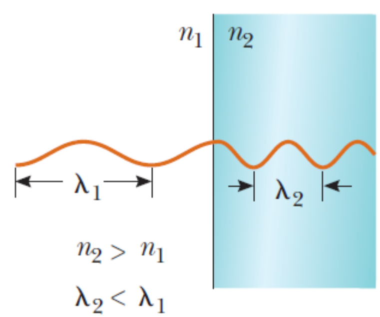
$$v_1 = f\lambda_1$$

$$v_2 = f\lambda_2$$

$$\boxed{\lambda_1 n_1 = \lambda_2 n_2}$$







Note: the frequency of the wave does **NOT** change as the wave passes from one medium to another

Refraction of Light

Indices of Refraction for Various Substances, Measured with Light of Vacuum Wavelength λ_0 = 589 mn

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		**Liquids at 20°C**	
Diamond (C)	2.419	Benzene	1.501
Fluorite (CaF_2)	1.434	Carbon disulfide	1.628
Fused quartz (SiO_2)	1.458	Carbon tetrachloride	1.461
Glass, crown	1.52	Ethyl alcohol	1.361
Glass, flint	1.66	Glycerine	1.473
Ice (H_2O) (at 0°C)	1.309	Water	1.333
Polystyrene	1.49		almost one
Sodium chloride (NaCl)	1.544	**Gases at 0°C, 1 atm**	
Zircon	1.923	Air	1.000 293
		Carbon dioxide	1.000 45

Reflection and Refraction of Light

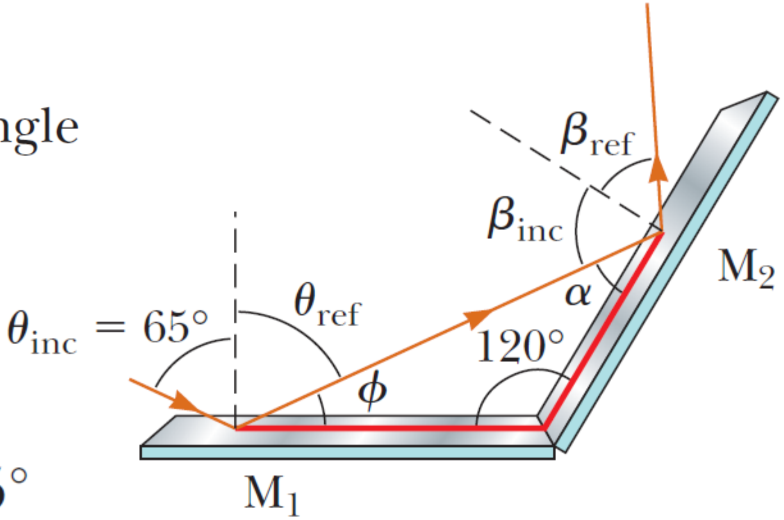
EXERCISE

Task #1: Two mirrors make an angle of 120° with each other, as shown of the figure. A ray is incident on mirror M_1 at an angle of 65° to the normal. Find the angle the ray makes with the normal to M_2 after it is reflected from both mirrors.

Solution:

Apply the law of reflection to M_1 to find the angle of reflection, θ_{ref}:

$$\theta_{\text{ref}} = \theta_{\text{inc}} = 65°$$



$$\phi = 90° - \theta_{\text{ref}} = 90° - 65° = 25°$$

$$180° = 25° + 120° + \alpha \quad \rightarrow \quad \alpha = 35°$$

$$\alpha + \beta_{\text{inc}} = 90° \quad \rightarrow \quad \beta_{\text{inc}} = 90° - 35° = 55°$$

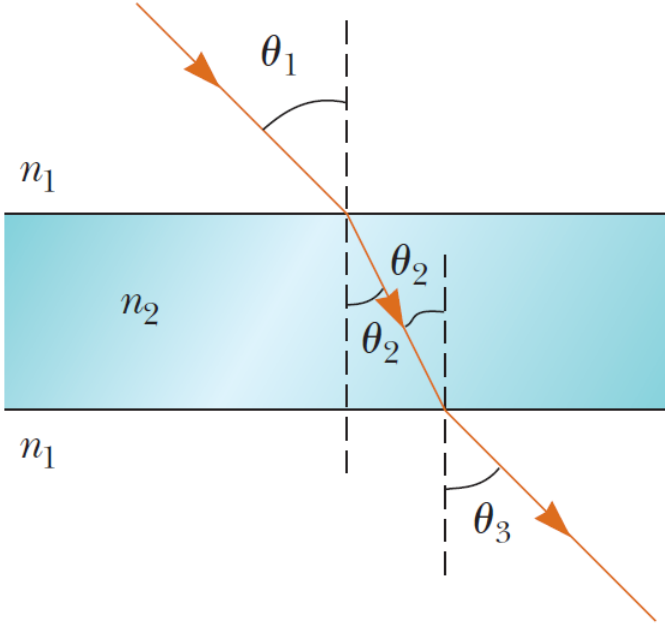
Apply the law of reflection a second time, obtaining β_{ref}: $\beta_{\text{ref}} = \beta_{\text{inc}} = \boxed{55°}$

Reflection and Refraction of Light

EXERCISE

Task #2: A light beam traveling through a transparent medium of index of refraction n_1 passes through a thick transparent slab with parallel faces and index of refraction n_2. Show that the emerging beam is parallel to the incident beam.

Solution:



Apply Snell's law to the upper surface:

$$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1$$

Apply Snell's law to the lower surface:

$$\sin\theta_3 = \frac{n_2}{n_1}\sin\theta_2$$

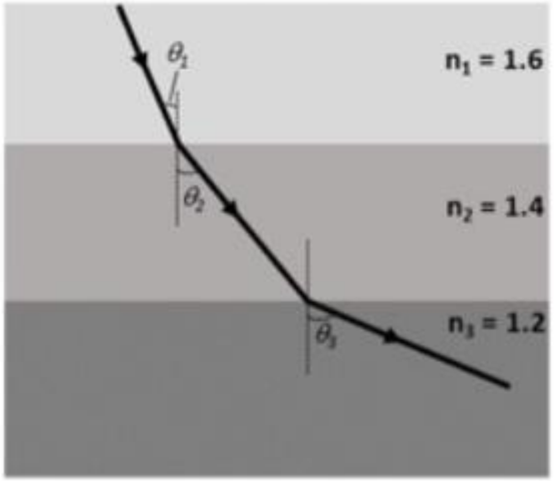
$$\Rightarrow \quad \sin\theta_3 = \frac{n_2}{n_1}\left(\frac{n_1}{n_2}\sin\theta_1\right) = \sin\theta_1 \quad \Rightarrow \quad \boxed{\theta_3 = \theta_1}$$

Reflection and Refraction of Light

EXERCISE

Task #2: A light beam traveling through a transparent medium of index of refraction n_1 passes through a thick transparent slab with parallel faces and index of refraction n_2. Show that the emerging beam is parallel to the incident beam.

Solution:



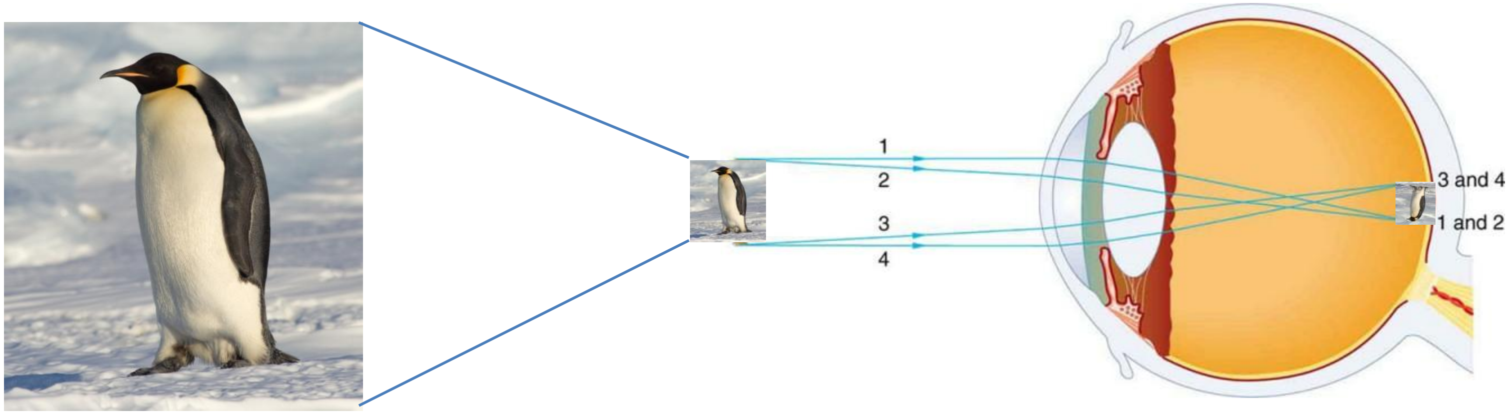
Important generalization:

$$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2 = \ldots = n_i \sin\theta_i = \ldots}$$

Mirrors and Lenses

The development of the technology of **mirrors** and **lenses** led to a revolution in the progress of science. These devices, relatively simple to construct from cheap materials, led to microscopes and telescopes, extending human sight and opening up new pathways to knowledge, from microbes to distant planets.

- **Images** can be formed by **reflection** from mirrors or by **refraction** through lenses.



- Your visual system goes through this **processing** and recognition even if the light rays **do not come directly** from the penguin, but instead reflect toward you from a mirror or refract through the lenses in a pair of binoculars.

light actually passes through the image point

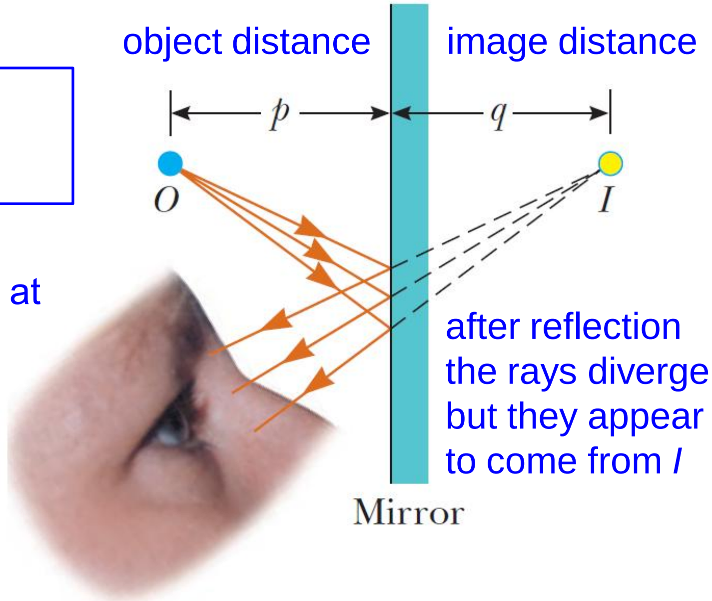
REAL IMAGE

VIRTUAL IMAGE

light diverges from the image point

Flat Mirrors

A **mirror** is a surface that can **reflect** a beam of light in one direction instead of either scattering it widely in many directions or absorbing it. **Flat** mirrors are the mirrors having the **flat reflecting surface**.



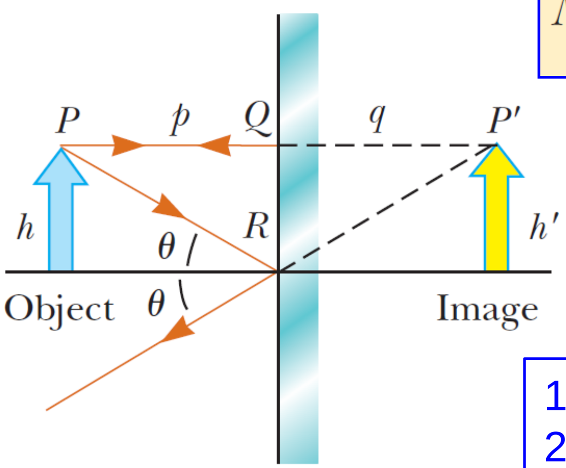
Images are formed at the point where rays of light actually intersect or where they appear to originate

To find out where an image is formed, it's necessary to follow at least two rays of light as they reflect from the mirror

lateral magnification

$$M \equiv \frac{\text{image height}}{\text{object height}} = \frac{h'}{h}$$

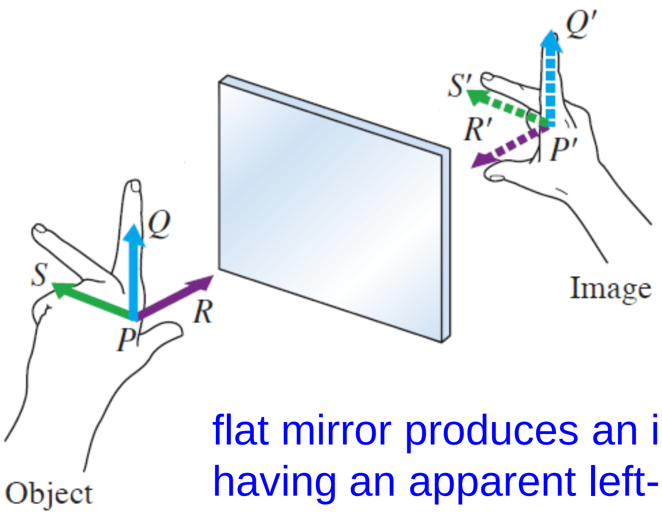
Flat mirror: $M = 1$



Note: word **magnification**, as used in optics, **doesn't** always mean **enlargement**, because the image could be smaller than the object.

1. The image is as far behind the mirror as the object is in front.
2. The image is unmagnified, virtual, and upright.

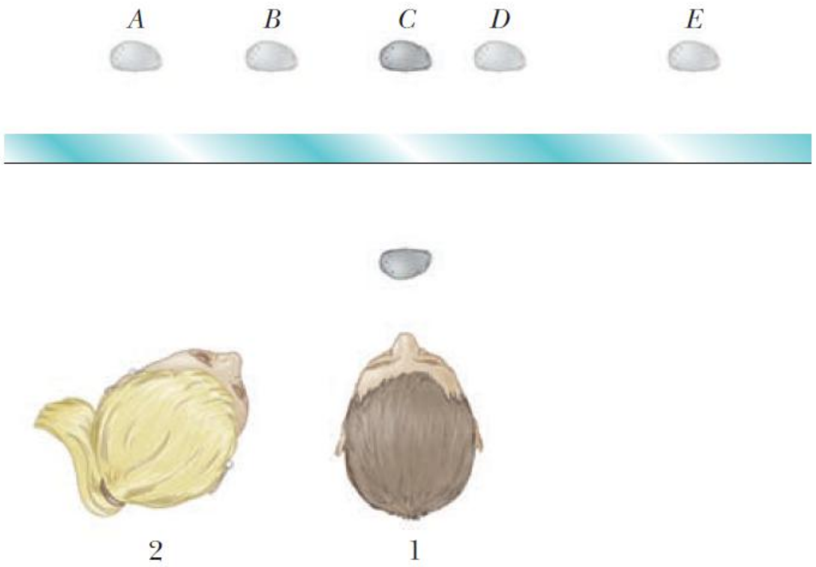
Flat Mirrors



flat mirror produces an image having an apparent left-right **reversal**

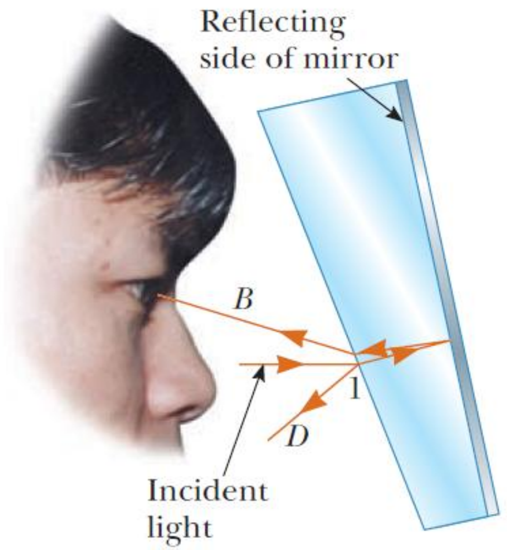
QUIZ Check your understanding:

In the overhead view, the image of the stone seen by observer 1 is at C. Where does observer 2 see the image – at A, at B, at C, at E, or not at all?



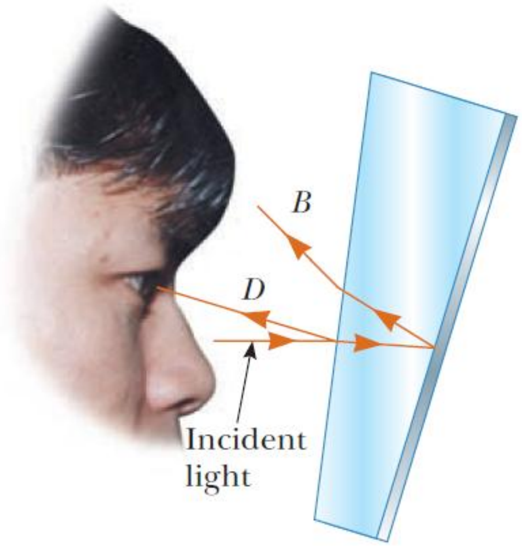
Flat Mirrors

Most **rearview** mirrors in cars have a day setting and a night setting. The night setting greatly diminishes the intensity of the image so that lights from trailing cars will not blind the driver.



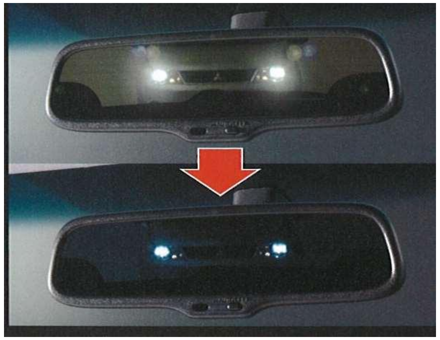
Daytime setting

the silvered back surface of the mirror reflects a bright ray B into the driver's eyes.



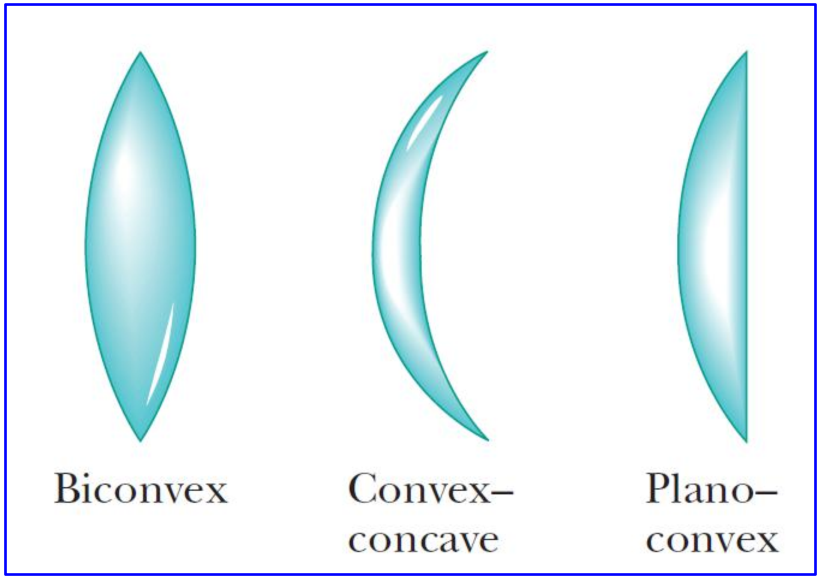
Nighttime setting

the glass of the unsilvered front surface of the mirror reflects a dim ray D into the driver's eyes.

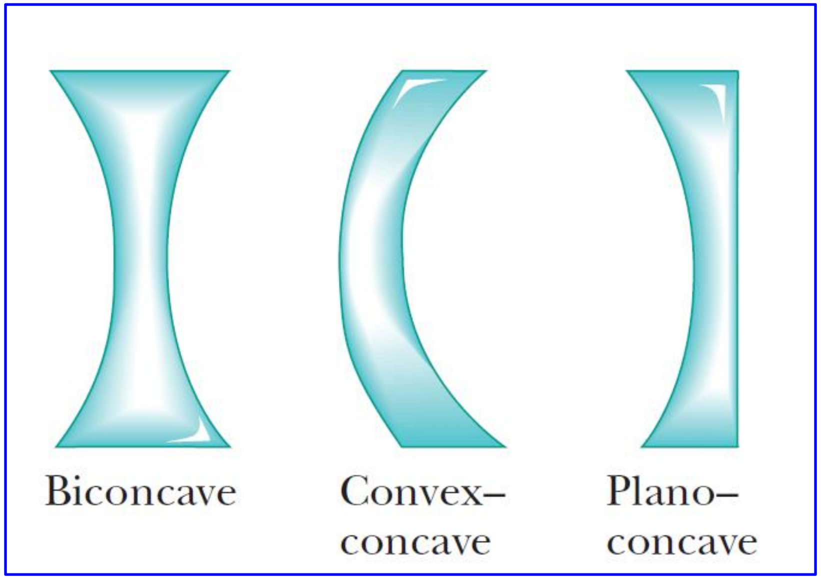


Thin Lenses

A typical **thin lens** consists of a piece of glass or plastic, ground so that each of its two refracting surfaces is a segment of either a sphere or a plane. Lenses are commonly used to form images by refraction in optical instruments, such as cameras, telescopes, and microscopes.



converging lenses



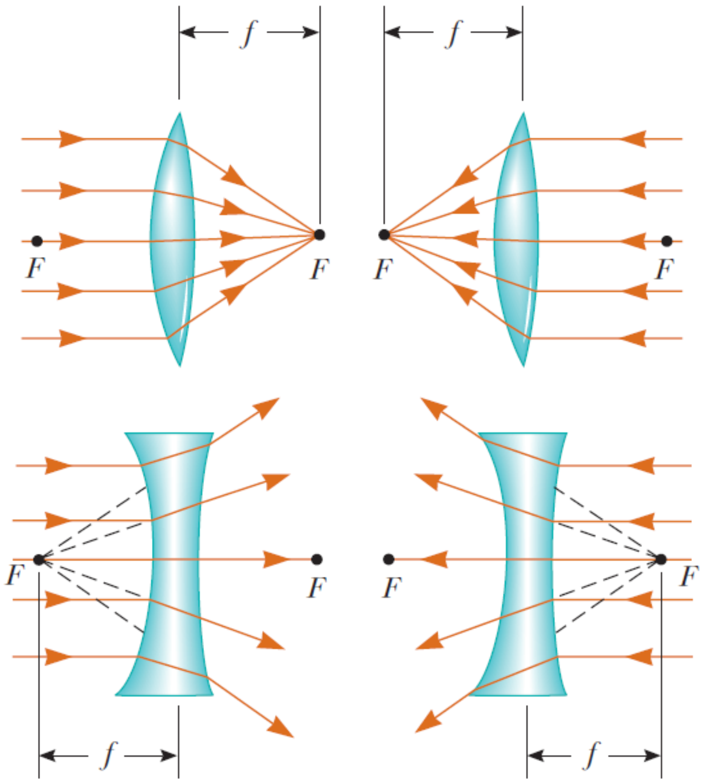
diverging lenses

Note: Converging lenses are thicker at the center than at the rim, whereas diverging lenses are thinner at the center than at the rim.

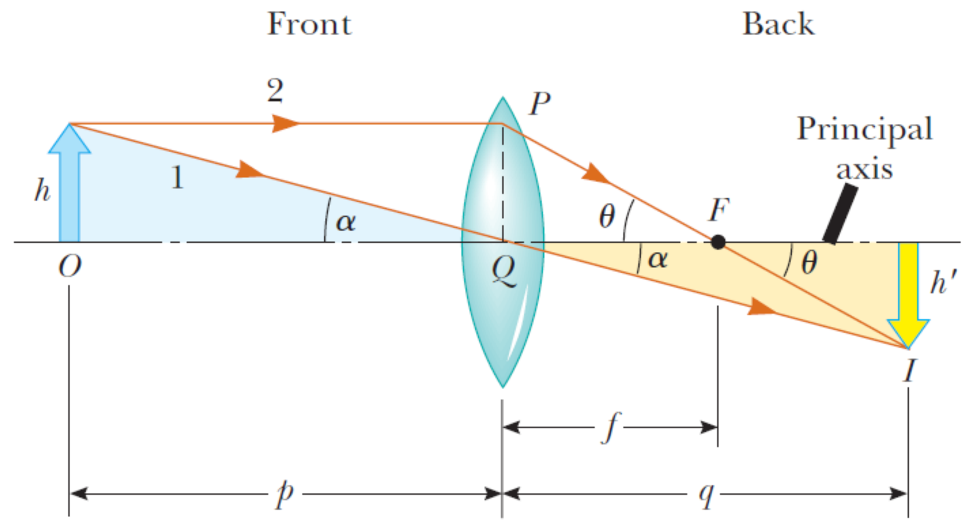
Thin Lenses

It is convenient to define a point called the **focal point** *F* for a lens. The distance from the focal point to the lens is called the **focal length** *f*.

The focal length is the image distance that corresponds to an **infinite** object distance



a thin lens has two focal points



$$\tan \alpha = \frac{h}{p}$$

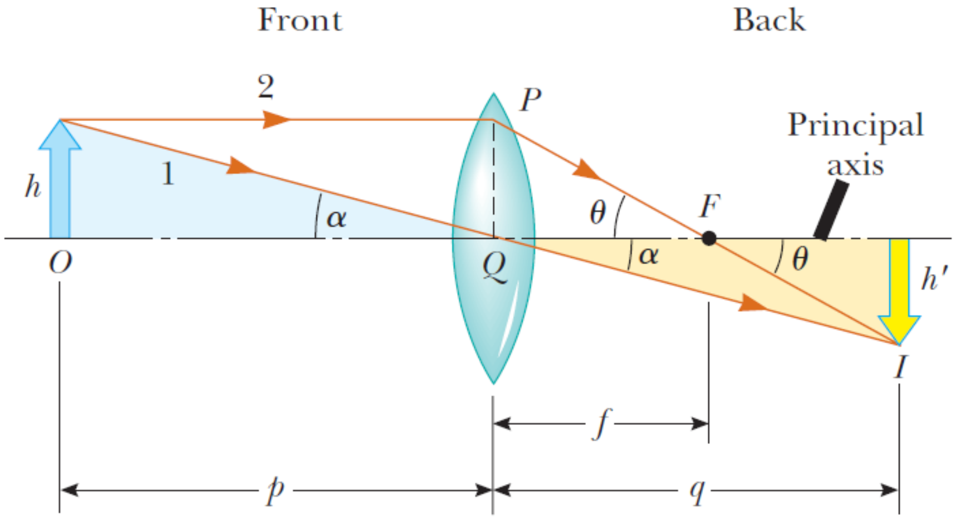
$$\tan \alpha = -\frac{h'}{q}$$

$$\boxed{M = \frac{h'}{h} = -\frac{q}{p}}$$

Thin Lenses

It is convenient to define a point called the **focal point** *F* for a lens. The distance from the focal point to the lens is called the **focal length** *f*.

The focal length is the image distance that corresponds to an **infinite** object distance



$$\tan\theta = \frac{PQ}{f} \qquad \tan\theta = -\frac{h'}{q-f}$$

$$\frac{h}{f} = -\frac{h'}{q-f} \qquad \frac{h'}{h} = -\frac{q-f}{f}$$

$$\frac{q}{p} = \frac{q-f}{f}$$

$$\boxed{\frac{1}{p} + \frac{1}{q} = \frac{1}{f}}$$

thin-lens equation

$$\tan\alpha = \frac{h}{p}$$

$$\tan\alpha = -\frac{h'}{q}$$

$$\boxed{M = \frac{h'}{h} = -\frac{q}{p}}$$

Thin Lenses

Thin-lens equation can be used with both converging and diverging lenses if we adhere to a set of sign conventions.

Sign Conventions for Thin Lenses

Quantity	Symbol	In Front	In Back	Convergent	Divergent
Object location	p	$+$	$-$		
Image location	q	$-$	$+$		
Lens Radii	R_1, R_2	$-$	$+$		
Focal Length	f			$+$	$-$

Note: a converging lens has a positive focal length under this convention and a diverging lens has a negative focal length.

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

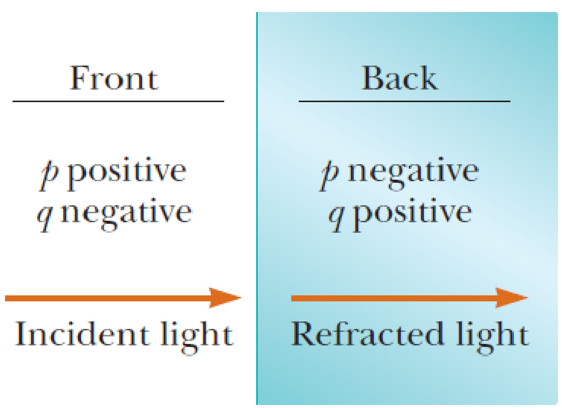
front curvature

back curvature

lens maker's equation

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

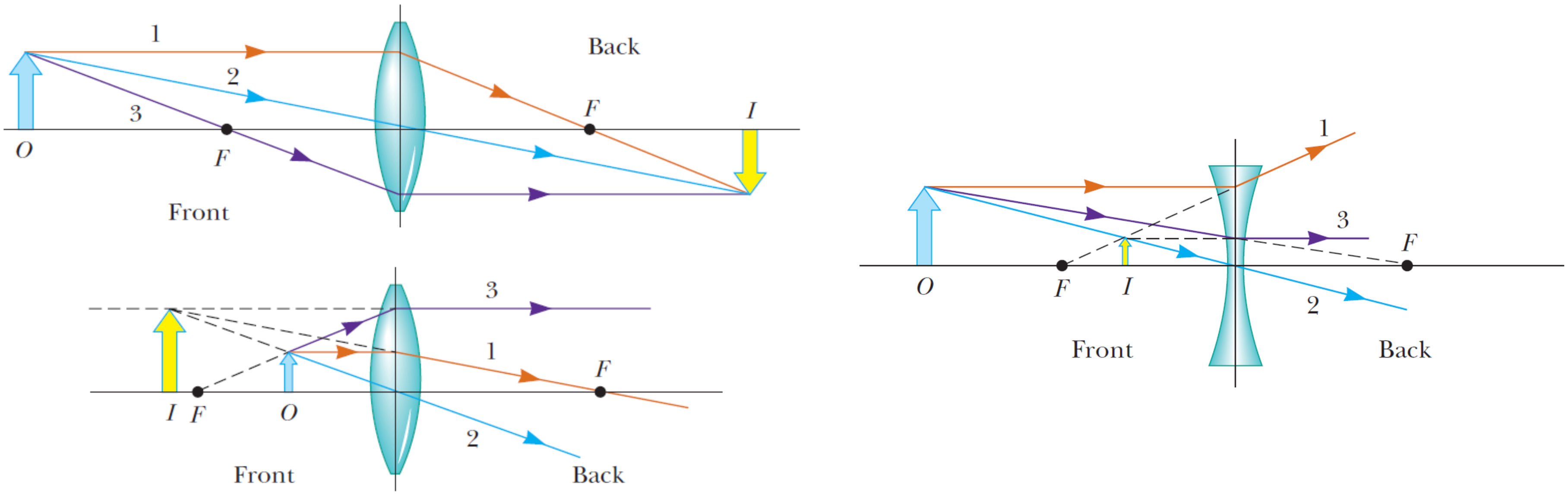
thin-lens equation



Ray Diagrams for Thin Lenses

To locate the image formed by a thin lens, the following three rays are drawn from the top of the objects:

1. The first ray is drawn parallel to the principal axis. After being refracted by the lens, this ray passes through (or appears to come from) one of the focal points.
2. The second ray is drawn through the center of the lens. This ray continues in a straight line.
3. The third ray is drawn through the other focal point and emerges from the lens parallel to the principal axis.



Thin Lenses

EXERCISE

Task #3: A converging lens of focal length 10.0 cm forms images of an object situated at various distances. (a) If the object is placed 30.0 cm from the lens, locate the image, state whether it's real or virtual, and find its magnification. (b) Repeat the problem when the object is at 10.0 cm and (c) again when the object is 5.00 cm from the lens.

Solution:

(a) $$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

$$\frac{1}{30.0\text{ cm}} + \frac{1}{q} = \frac{1}{10.0\text{ cm}}$$

$$q = \boxed{+15.0\text{ cm}}$$

$$M = -\frac{q}{p} = -\frac{15.0\text{ cm}}{30.0\text{ cm}} = \boxed{-0.500}$$

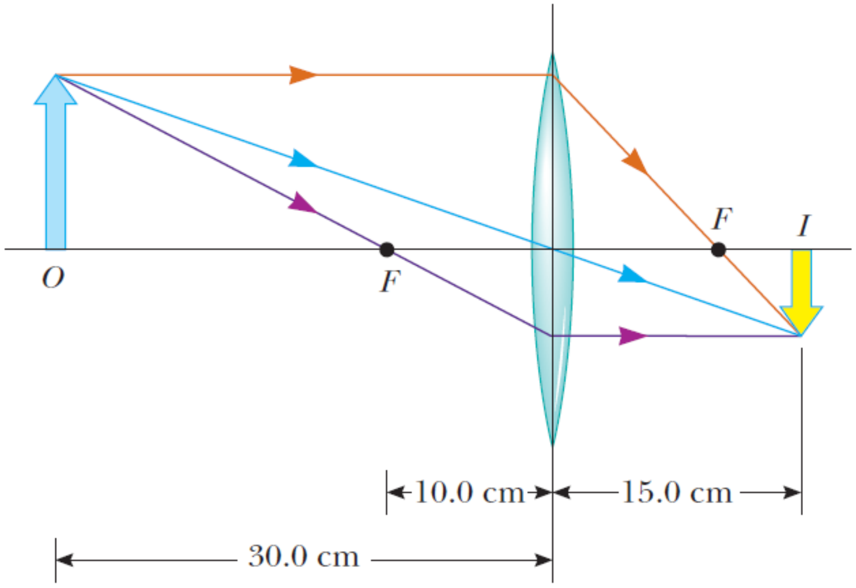


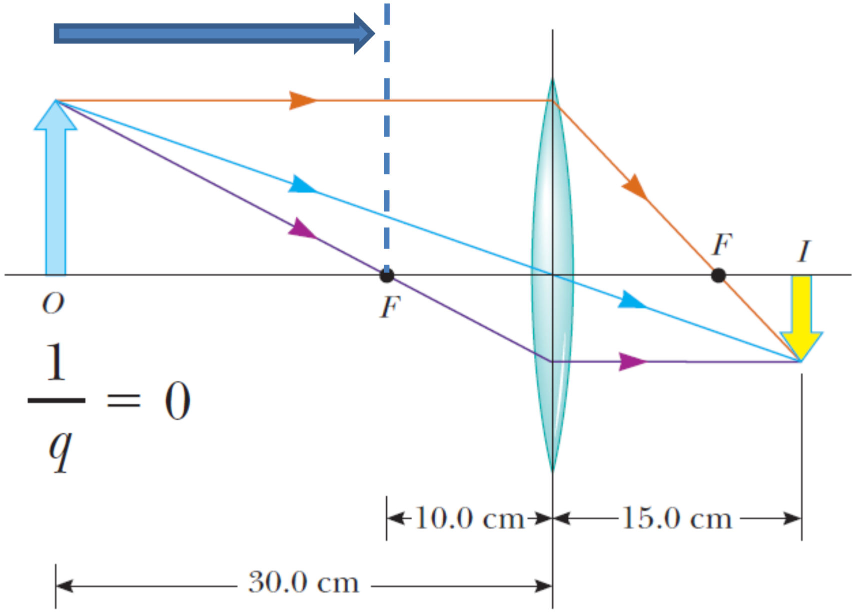
image real

(inverted and smaller than the object)

Thin Lenses

EXERCISE

Task #3: A converging lens of focal length 10.0 cm forms images of an object situated at various distances. (a) If the object is placed 30.0 cm from the lens, locate the image, state whether it's real or virtual, and find its magnification. (b) Repeat the problem when the object is at 10.0 cm and (c) again when the object is 5.00 cm from the lens.



Solution:

(b) $$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

$$\frac{1}{10.0 \text{ cm}} + \frac{1}{q} = \frac{1}{10.0 \text{ cm}} \rightarrow \frac{1}{q} = 0$$

$$q \rightarrow \infty$$

image at infinity

Thin Lenses

EXERCISE

Task #3: A converging lens of focal length 10.0 cm forms images of an object situated at various distances. (a) If the object is placed 30.0 cm from the lens, locate the image, state whether it's real or virtual, and find its magnification. (b) Repeat the problem when the object is at 10.0 cm and (c) again when the object is 5.00 cm from the lens.

Solution:

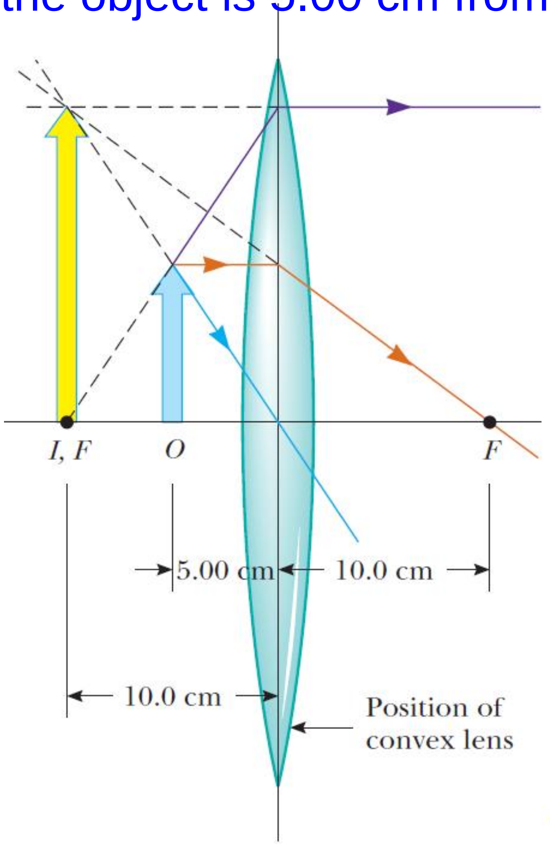
image virtual
(upright and double the object size)

(c) $$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

$$\frac{1}{5.00\text{ cm}} + \frac{1}{q} = \frac{1}{10.0\text{ cm}}$$

$$q = \boxed{-10.0\text{ cm}}$$

$$M = -\frac{q}{p} = -\left(\frac{-10.0\text{ cm}}{5.00\text{ cm}}\right) = \boxed{+2.00}$$

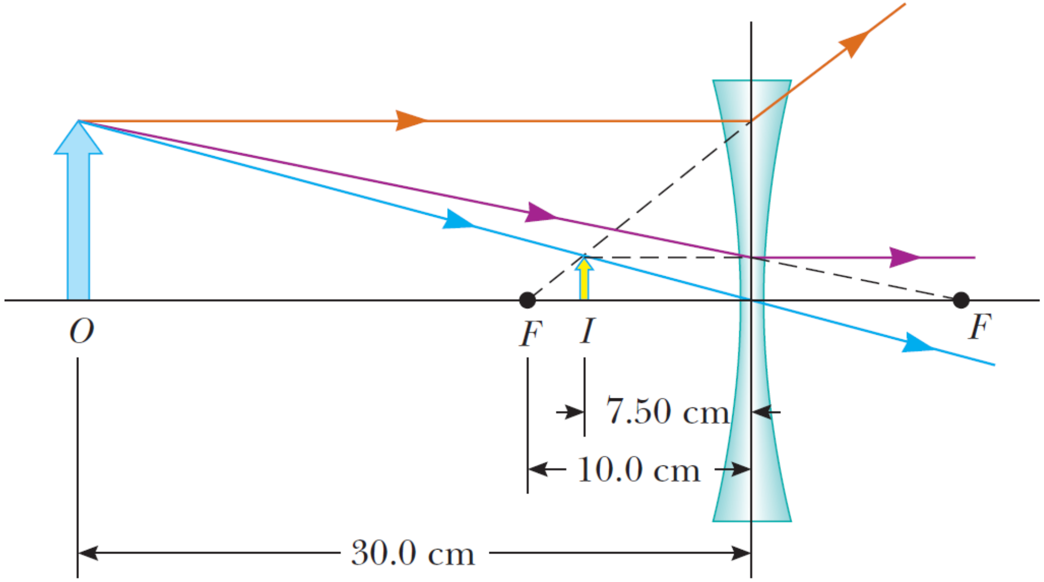


Thin Lenses

EXERCISE

Task #4: A diverging lens of focal length 10.0 cm forms images of an object situated at various distances. (a) If the object is placed 30.0 cm from the lens, locate the image, state whether it's real or virtual, and find its magnification. (b) Repeat the problem when the object is at 10.0 cm and (c) again when the object is 5.00 cm from the lens.

Solution:



(a) $$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}$$

$$\frac{1}{30.0\text{ cm}}+\frac{1}{q}=-\frac{1}{10.0\text{ cm}}$$

$$q=\boxed{-7.50\text{ cm}}$$

$$M=-\frac{q}{p}=-\left(\frac{-7.50\text{ cm}}{30.0\text{ cm}}\right)=\boxed{+0.250}$$

image virtual

(upright and smaller than the object)

Thin Lenses

EXERCISE

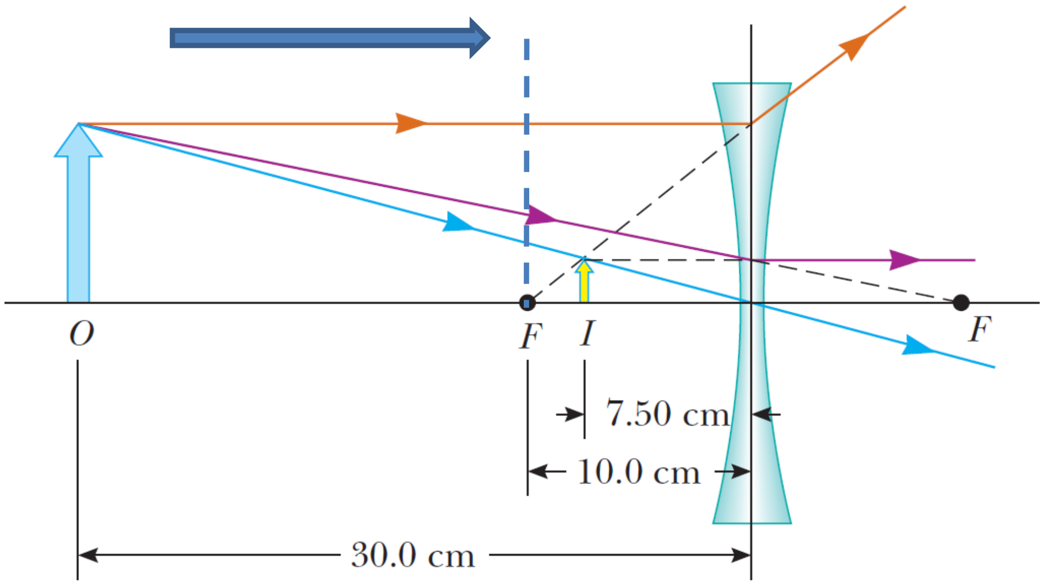
Task #4: A diverging lens of focal length 10.0 cm forms images of an object situated at various distances. (a) If the object is placed 30.0 cm from the lens, locate the image, state whether it's real or virtual, and find its magnification. (b) Repeat the problem when the object is at 10.0 cm and (c) again when the object is 5.00 cm from the lens.

Solution:

(b) $$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

$$\frac{1}{10.0\text{ cm}} + \frac{1}{q} = -\frac{1}{10.0\text{ cm}}$$

$$q = \boxed{-5.00\text{ cm}}$$



$$M = -\frac{q}{p} = -\left(\frac{-5.00\text{ cm}}{10.0\text{ cm}}\right) = \boxed{+0.500}$$

image virtual

(upright and smaller than the object)

Thin Lenses

EXERCISE

Task #4: A diverging lens of focal length 10.0 cm forms images of an object situated at various distances. (a) If the object is placed 30.0 cm from the lens, locate the image, state whether it's real or virtual, and find its magnification. (b) Repeat the problem when the object is at 10.0 cm and (c) again when the object is 5.00 cm from the lens.

Solution:

(c) $$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

$$\frac{1}{5.00\text{ cm}} + \frac{1}{q} = -\frac{1}{10.0\text{ cm}}$$

$$q = \boxed{-3.33\text{ cm}}$$

$$M = -\left(\frac{-3.33\text{ cm}}{5.00\text{ cm}}\right) = \boxed{+0.666}$$

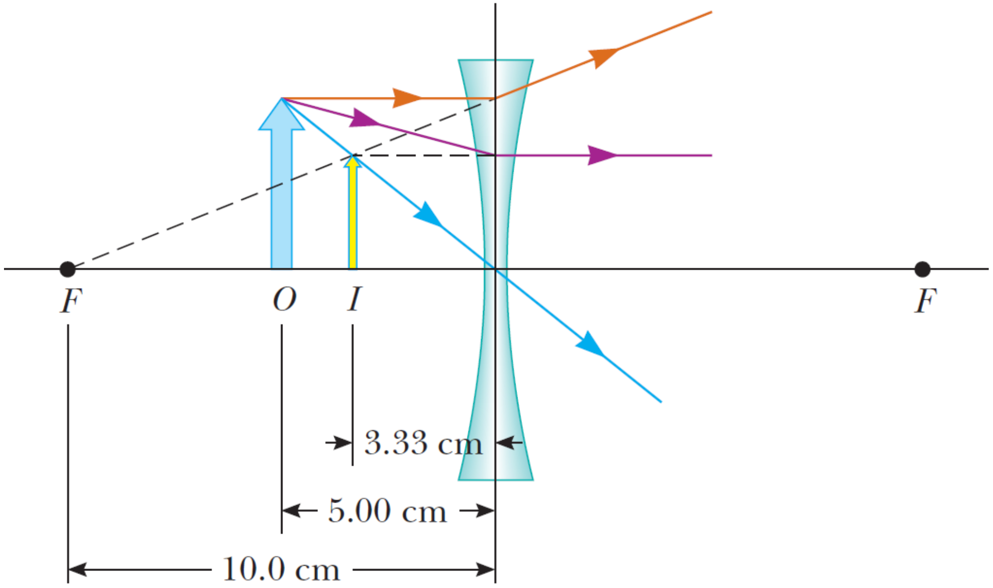


image virtual
(upright and smaller than the object)

Optical Instruments (optional part)

We use devices made from lenses, mirrors, or other optical components every time we put on a pair of eyeglasses or contact lenses, take a photograph, look at the sky through a telescope, and so on. Let us examine how these and other optical instruments work. For the considered devices, our analyses will involve the laws of reflection and refraction and the procedures of geometric optics.

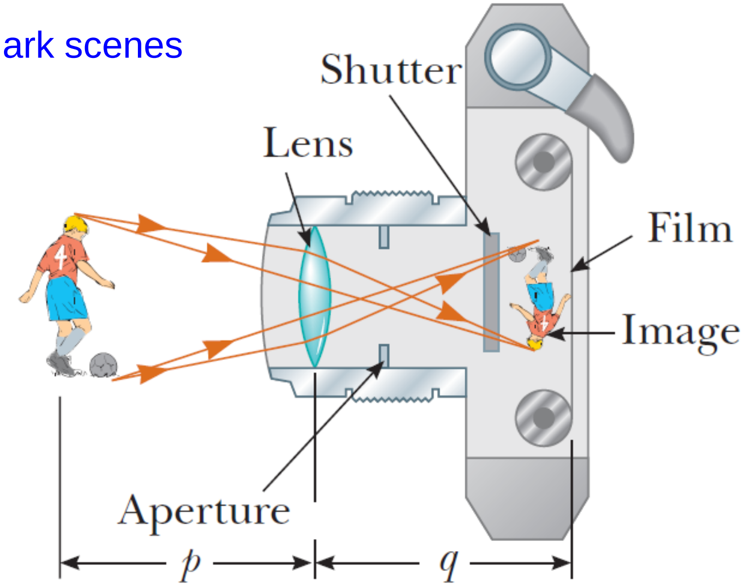
This part is NOT included in the test

The Camera

The single-lens photographic **camera** is a simple optical instrument. It consists of: an **opaque box**, a **converging lens** that produces a real image, and a **“film”** behind the lens to receive the image.

- Focusing is accomplished by varying the distance between lens and film.
- Adjustable exposure time to make photos either of the dark scenes or moving objects (and shaking hands)

$$1/30,\ 1/60,\ 1/125,\ \text{and}\ 1/250\ \text{s}$$



- Adjusting the aperture we control the intensity of the light reaching the film
- The ratio of focal length to the lens diameter is called the f-number. This number is often given as a description of the lens “speed”. A lens with a low f - number is a “fast” lens.

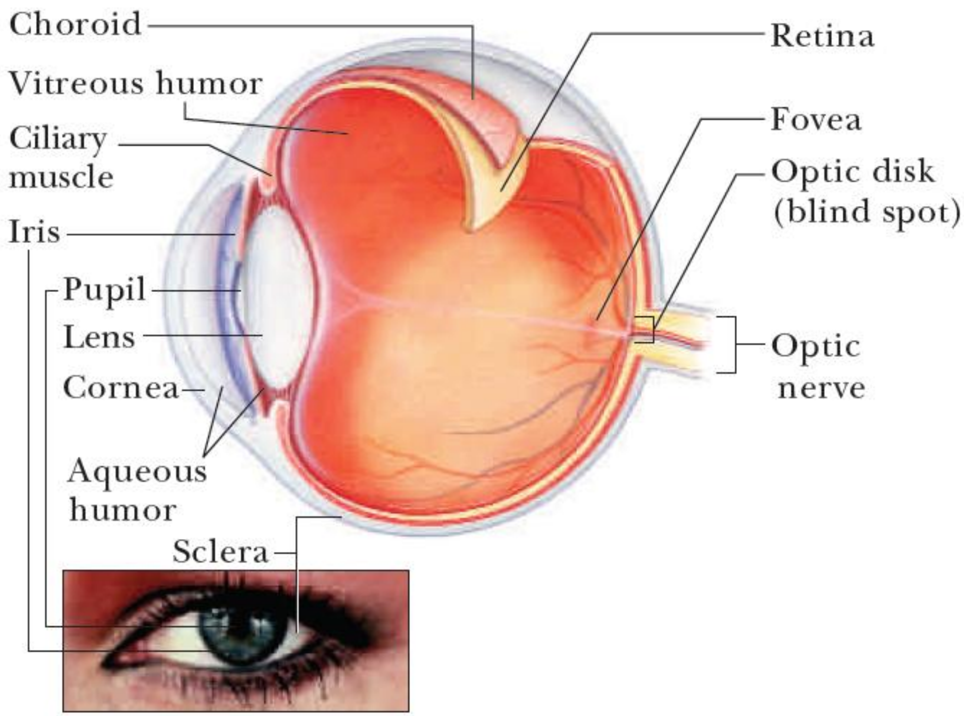
$$f\text{-number} \equiv \frac{f}{D}$$

The lowest f-number setting on a camera corresponds to a wide open aperture, and the use of the maximum possible lens area

Extremely fast: 1.2; simple cameras: ~11

The Eye

Like a camera, a **normal eye** focuses light and produces a sharp image. However, the mechanisms by which the eye controls the amount of light admitted and adjusts to produce correctly focused images are far more complex, intricate, and effective than those in even the most sophisticated camera.



Light enters **cornea**
(a transparent structure)

↓

Aqueous humor
(liquid)

↓

Pupil
(variable aperture)

↓

Crystalline lens

↓

Retina
(receptors: **rods** and **cones**)

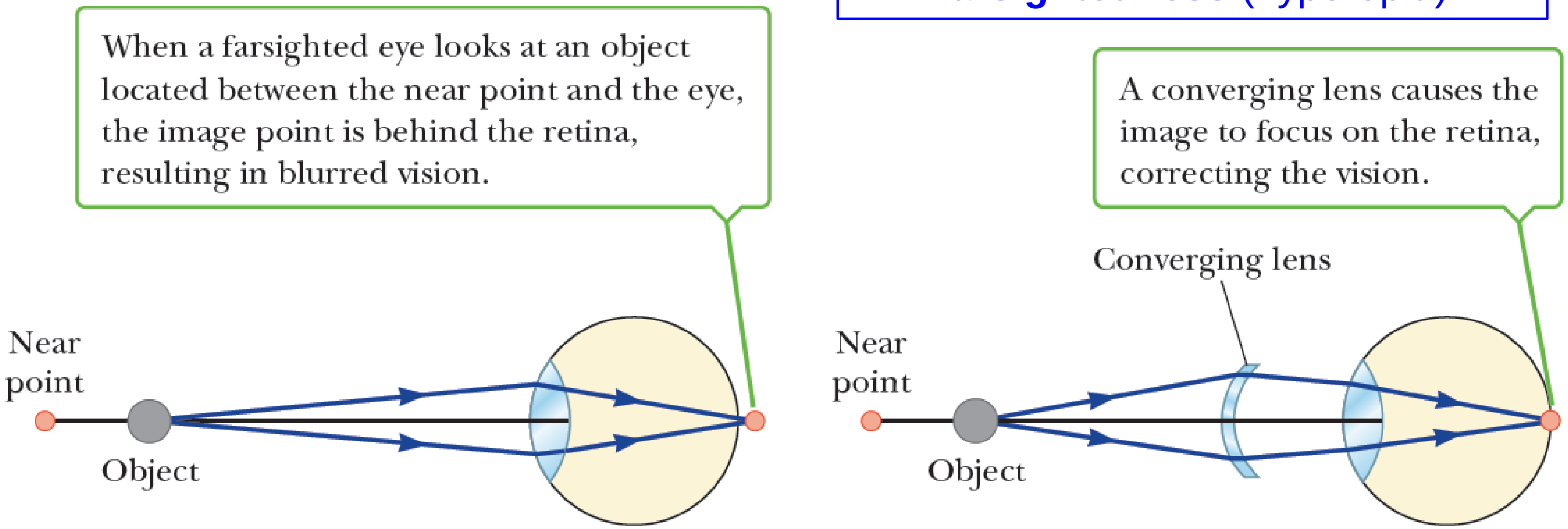
The Eye

The eye focuses on an object by varying the shape of the pliable crystalline lens through an amazing process called **accommodation**. An important component in accommodation is the **ciliary muscle**, which is situated in a circle around the rim of the lens.

- 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.

- The **far point** of the eye represents the farthest distance for which the lens of the relaxed eye can focus light on the retina. A person with normal vision is able to see very distant objects, such as the Moon, and so has a far point at infinity.

farsightedness (hyperopia)



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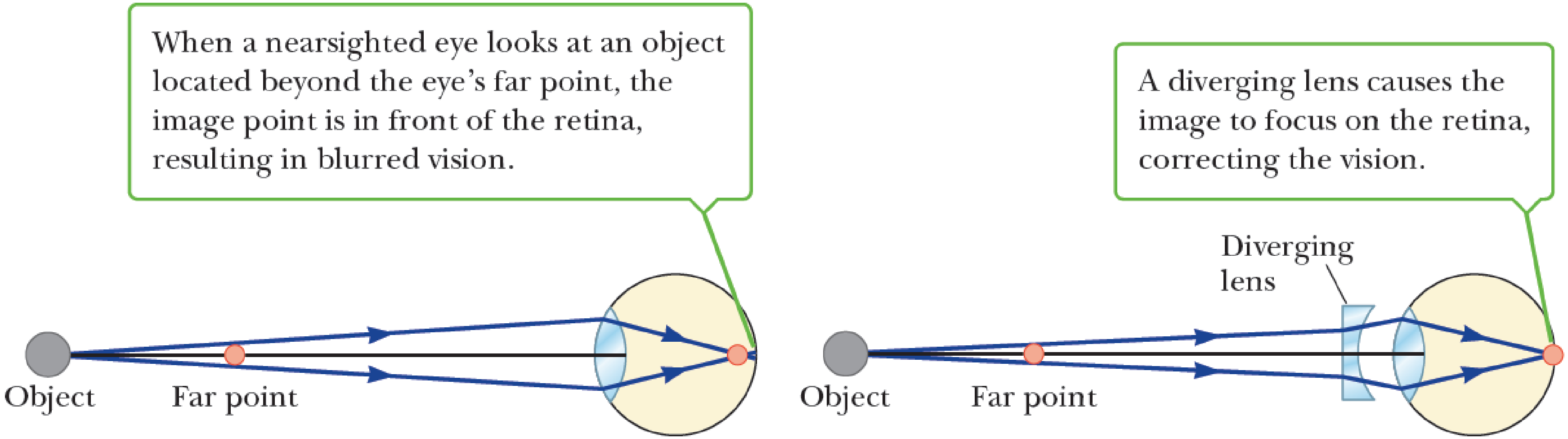
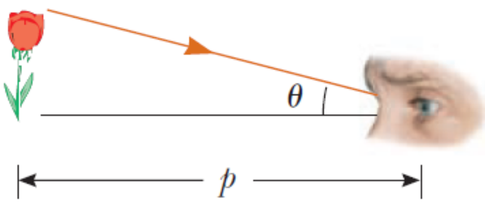
nearsightedness (myopia)



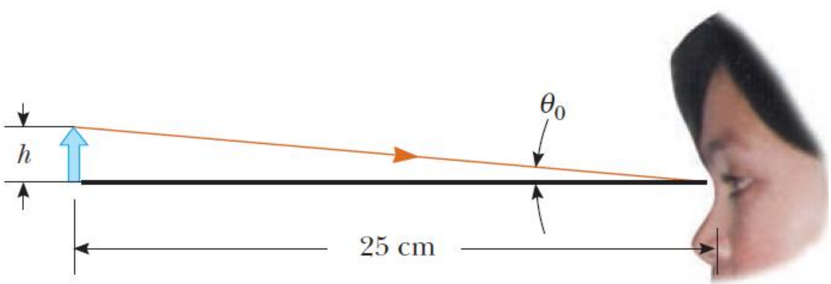
The Simple Magnifier

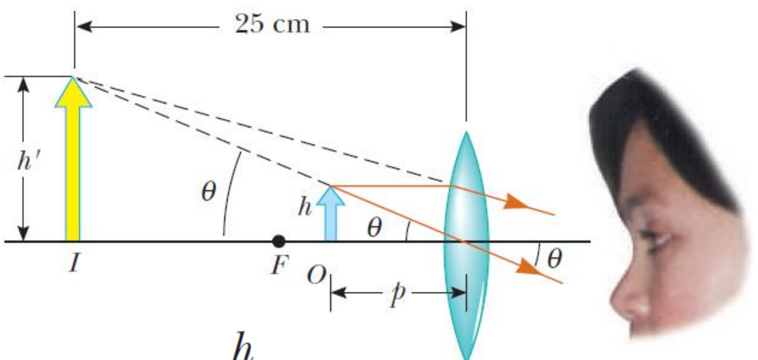
The **simple magnifier** is one of the most basic of all optical instruments because it consists only of a single converging lens. As the name implies, this device is used to increase the apparent size of an object.



The size of the image formed on the retina depends on the angle u subtended at the eye. As the object moves closer to the eye, angle increases and a larger image is observed.

Note: a **normal** eye can't focus on an object closer than about 25 cm, the near point. Therefore, angle is maximal at the near point.





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

angular magnification

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

$$\tan\theta_0 \approx \theta_0 \approx \frac{h}{25}$$

$$\tan\theta \approx \theta \approx \frac{h}{p}$$

$$\boxed{m_{\max} = 1 + \frac{25\text{ cm}}{f}}$$

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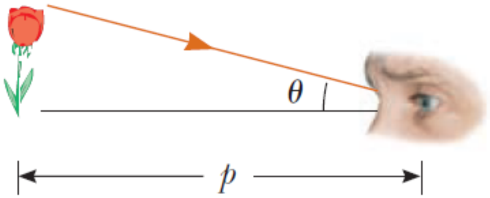

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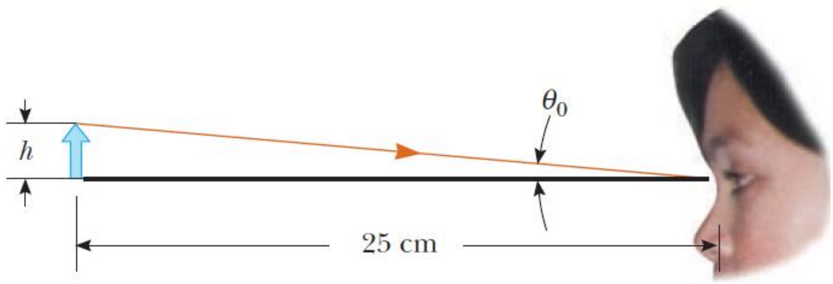
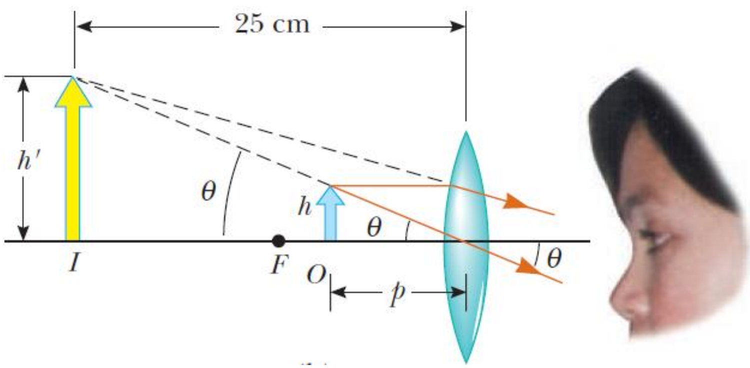




To make the eye relaxed image should be at the infinity: $p = f$

$$\theta_0 \approx \frac{h}{25} \qquad \theta \approx \frac{h}{f}$$

$$\boxed{m = \frac{\theta}{\theta_0} = \frac{25\text{ cm}}{f}}$$

The Compound Microscope

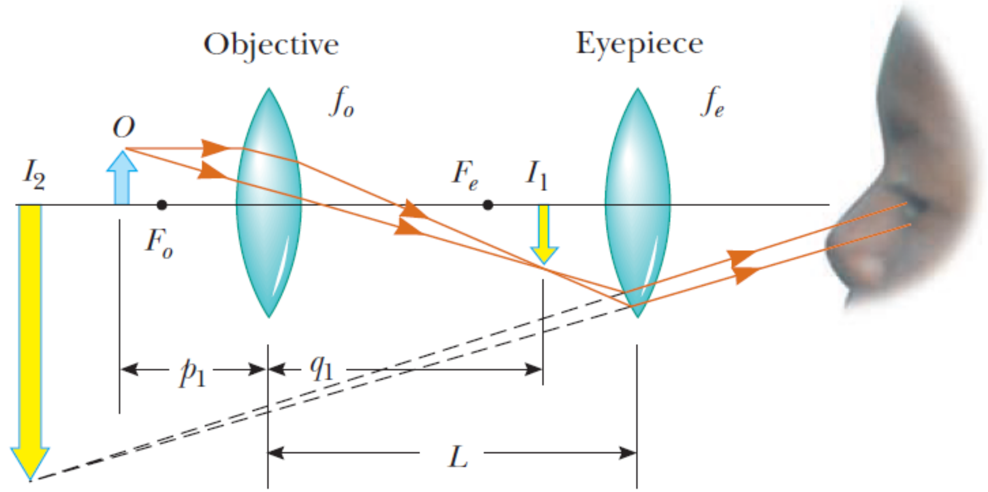
A simple magnifier provides only limited assistance with inspection of the minute details of an object. Greater magnification can be achieved by combining two lenses in a device called a **compound microscope**.

The basic approach used to analyze the image formation properties of a microscope is that of two lenses in a row: the image formed by the first becomes the object for the second.

$$q_1 \approx L \qquad p \approx f_0$$

$$M_1 = -\frac{q_1}{p_1} \approx -\frac{L}{f_o}$$

$$m_e = \frac{25\text{ cm}}{f_e}$$



Total magnification:

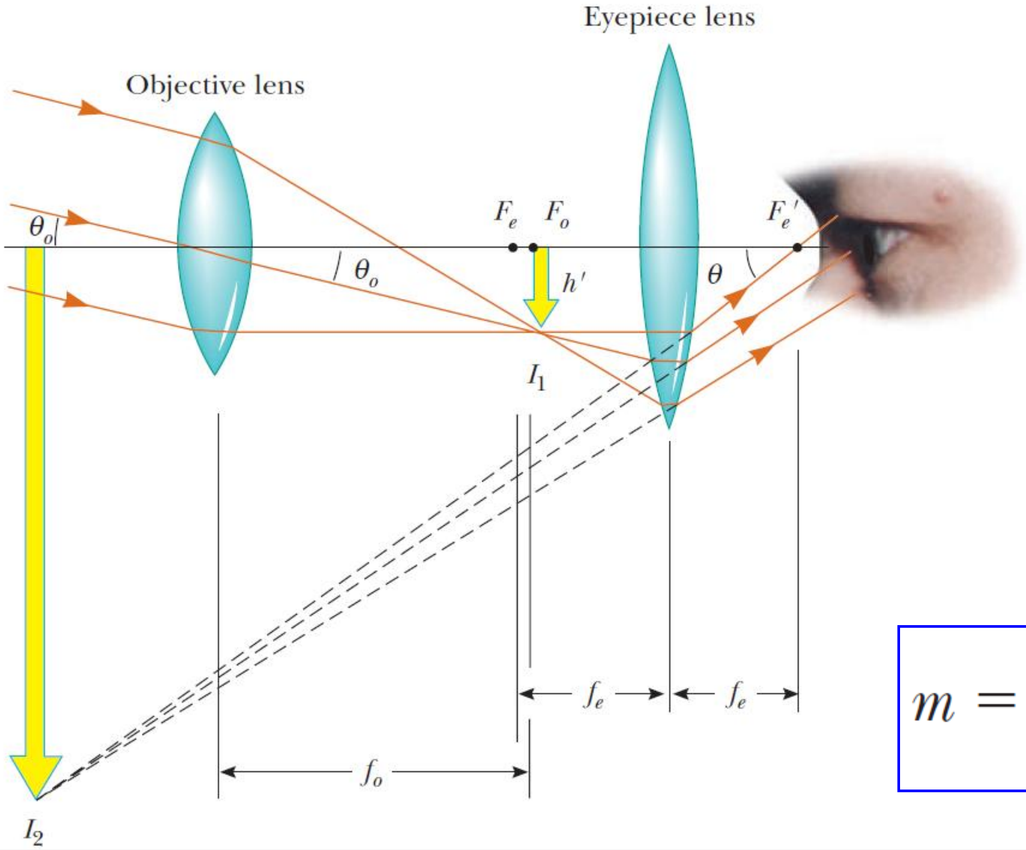
$$\boxed{m = M_1 m_e = -\frac{L}{f_o}\left(\frac{25\text{ cm}}{f_e}\right)}$$

image virtual

(inverted and very much enlarged)

The Telescope

There are two fundamentally different types of **telescopes**, both designed to help us view distant objects such as the planets in our Solar System. These two types are (1) the **refracting** telescope, which uses a combination of lenses to form an image, and (2) the **reflecting** telescope, which uses a curved mirror and a lens to form an image. Once again, we will be able to analyze the telescope by considering it to be a system of two optical elements in a row.



Two lenses are arranged so that the objective forms a real, inverted image of the distant object very near the focal point of the eyepiece

Further, the image at I_1 is formed at the focal point of the objective because the object is essentially at infinity

$$\theta \approx \frac{h'}{f_e} \qquad \theta_o \approx \frac{h'}{f_o}$$

$$\boxed{m = \frac{\theta}{\theta_o} = \frac{h'/f_e}{h'/f_o} = \frac{f_o}{f_e}}$$

image
virtual
(inverted)

Conclusions

- Light has a **dual** nature. In some experiments it acts like a wave, in others like a particle, called a **photon** by Einstein

- **reflection** and **refraction** are the phenomena which occur when the light travelling in one medium encounters a boundary leading into a second medium. The physics of both is governed by the **law of reflection** and **law of refraction** correspondingly

- the **index of refraction** of a material the ratio of the **speed of light** in the **vacuum** to the speed of light in the **material**

- **images** can be formed by **reflection** from mirrors or by **refraction** through lenses. We considered the basic cases of such mechanisms as **flat mirrors** and **thin lenses**

- there exist **two types** of images – real and virtual. A **real image** is formed when light intersects, or passes through, an image point. In a **virtual image** the light doesn't pass through the image point, but appears to diverge from it.

- the basic principles of ray optics can be put into basis of some **optical devices** which can significantly extend the scope of our vision as well as fix some eye diseases