Chapter 1:

GEOMETRICAL OPTICS

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1.1 Reflection & Refraction

1.2 Images in Mirrors

1.3 Images in Lenses

1.4 Optical Instruments

Introduction

Can you read all the information schedule? Why?

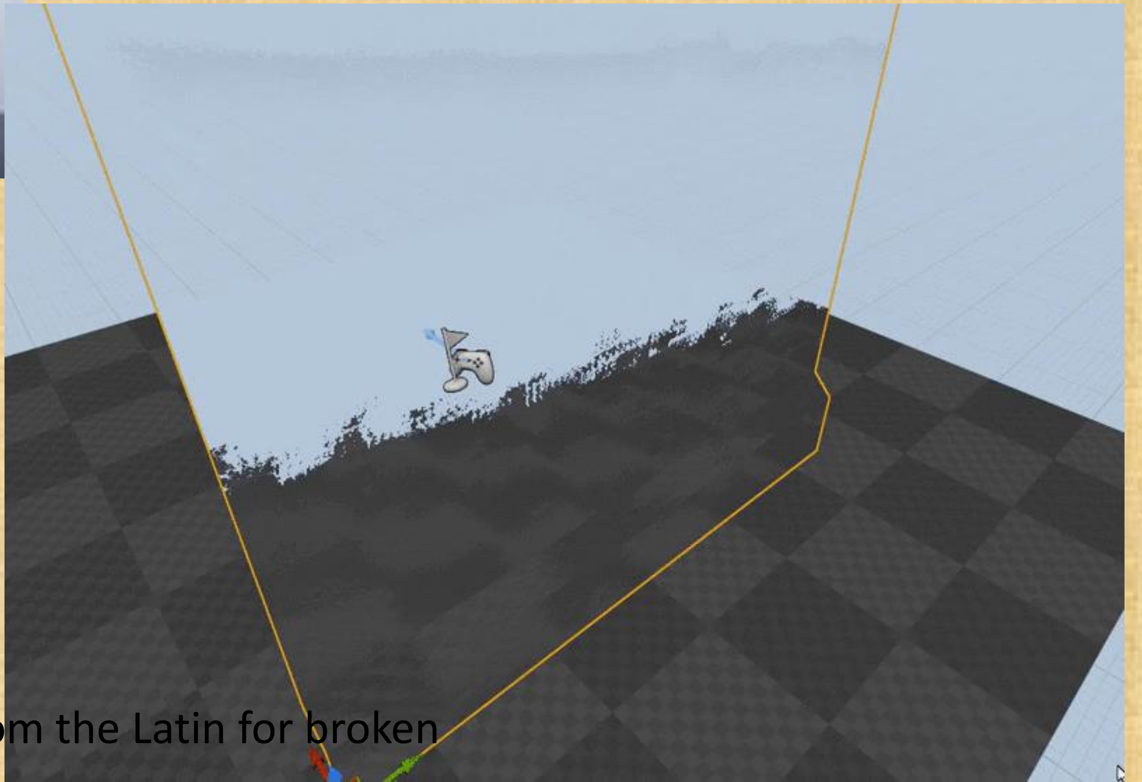
Optics can be divided into two areas:

Geometric optics

- Assume light travels in straight lines (‘rays’).
- Is valid when light meets objects which are large compared to the wavelength of the light.

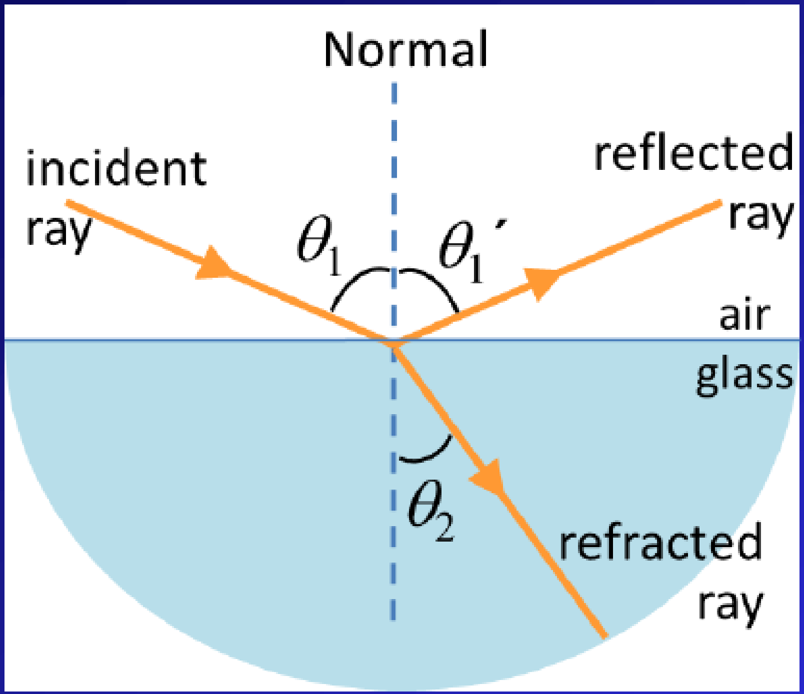
Wave optics (or physical optics)

- Includes phenomena such as interference and diffraction.
- Such phenomena reveal the wave nature of light.
- They occur when light meets objects with dimensions comparable to the wavelength of the light.



“Refraction” comes from the Latin for broken

Laws of Reflection



Normal: Line drawn perpendicular to the surface at the point of incidence

Plane of incidence: Plane containing the incident ray and the normal

θ_1: *angle of incidence*

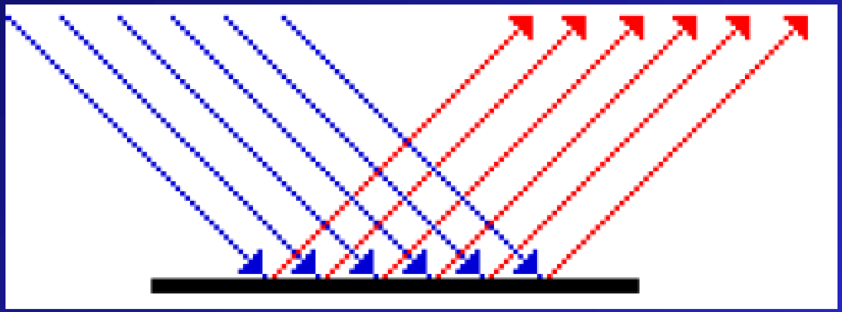
θ'_1 : *angle of reflection*

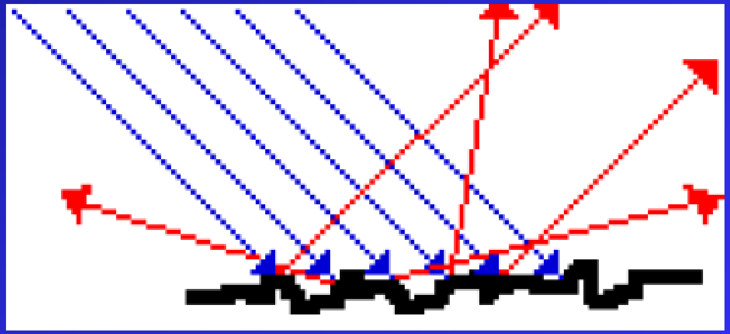
These are measured **relative to the *normal***

1. The reflected ray lies in the plane of incidence
2. The angle of incidence equals the angle of reflection: $\theta_1 = \theta'_1$

Specular and Diffuse Reflection

A 'parallel beam of light' can be considered to be a bundle of individual light rays traveling in parallel. When the beam meets a surface, each ray obeys the law of reflection.

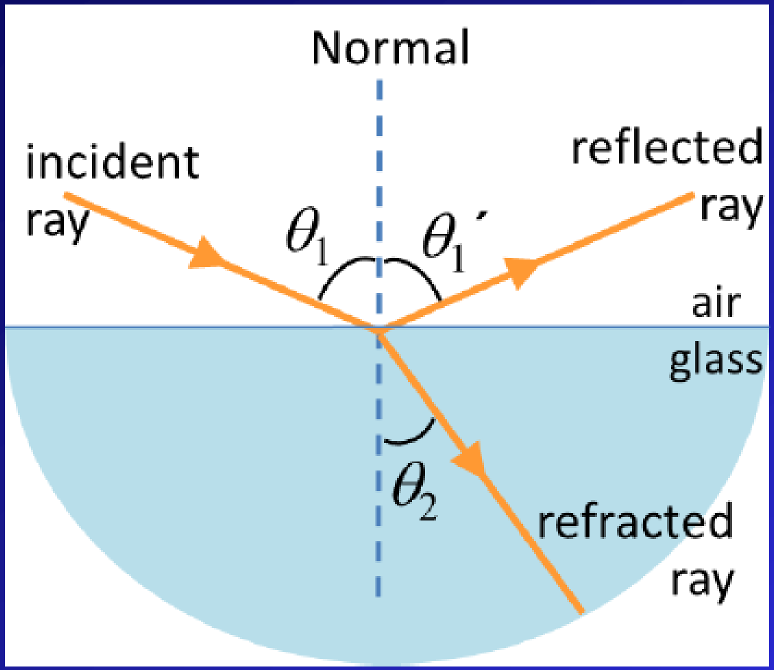




Smooth surface: all rays are reflected through the same angle giving a parallel reflected beam. This is called *specular* or *regular* reflection.

(Microscopically) rough surface: rays are reflected (*scattered*) in many different directions. This is called *diffuse* reflection.

Laws of Refraction



1. The refracted ray lies in the plane of incidence
2. The angle of refraction is related to the angle of incidence by:

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

(This is **Snell's Law**)

θ_1: *angle of incidence*

θ_2: *angle of refraction*

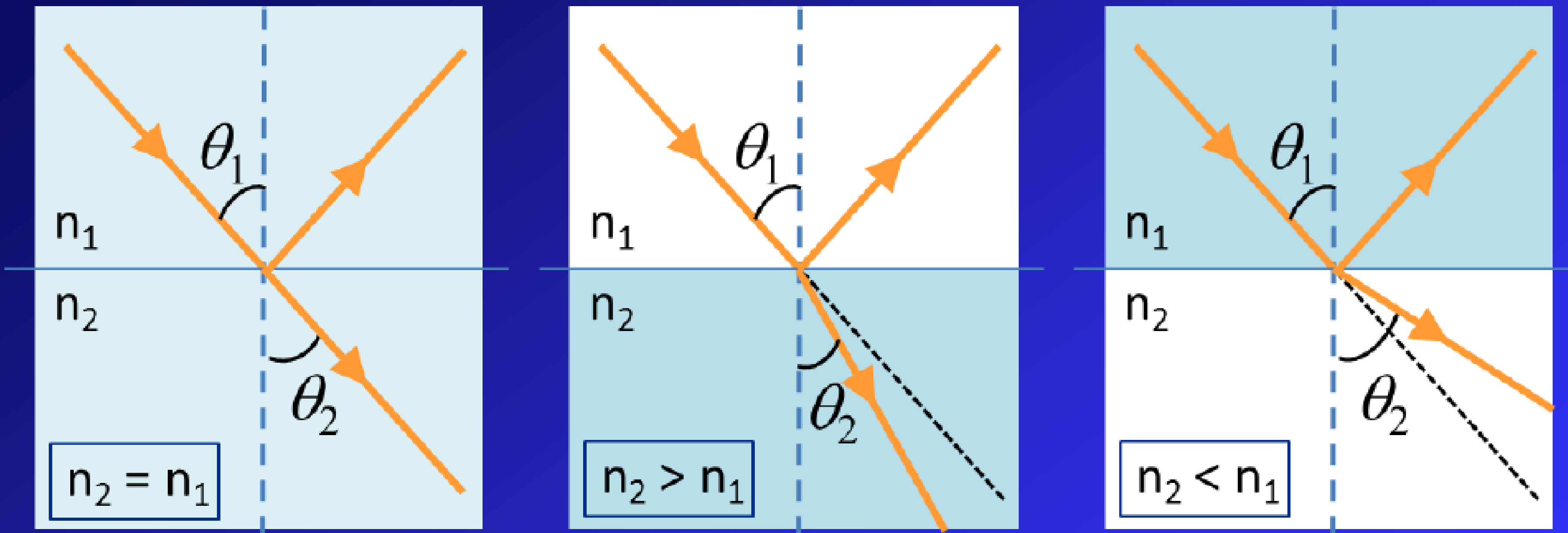
n_1: refractive index of air

n_2: refractive index of glass

n_i is a constant associated with the medium the light is passing through. It is called the ***index of refraction*** or ***refractive index*** of the medium.

Snell's Law, cont.

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



For a ray traveling from medium 1 to medium 2:

1. If $n_1 = n_2$ then $\theta_1 = \theta_2$, i.e. direction is unchanged
2. If $n_1 < n_2$ then $\theta_1 > \theta_2$: On entering an optically *denser* medium, the ray bends *towards* the normal.
3. If $n_1 > n_2$ then $\theta_1 < \theta_2$: On entering a *less* dense medium, the ray bends *away* from the normal.

Refractive Index Explained

$$n = \frac{c}{v}$$

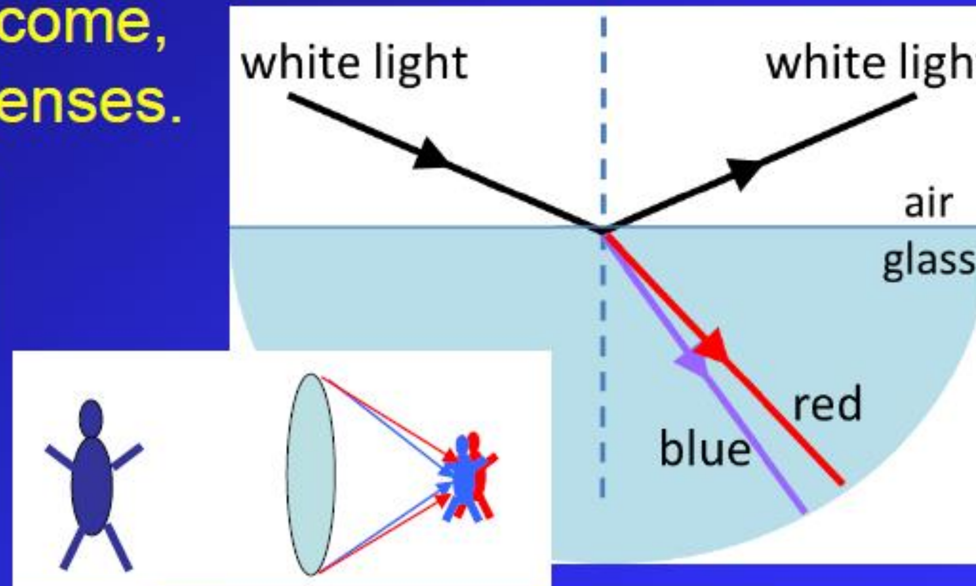
The refractive index (n) of a medium is defined as:
The speed of light in a vacuum (c) divided by the speed of light in the medium (v)

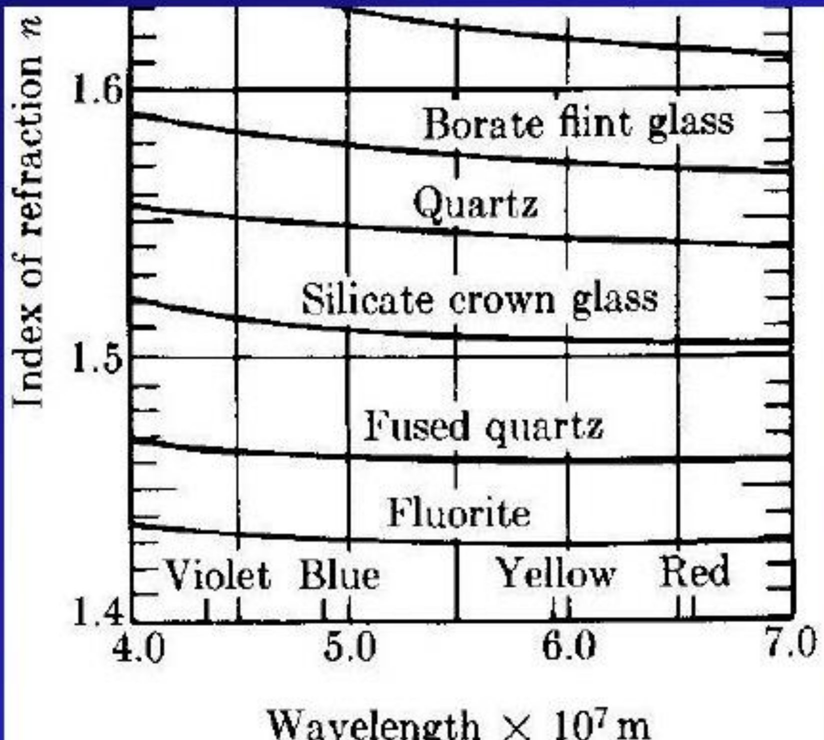
n = Refractive index (Index of refraction) of a medium
c = Speed of light in a vacuum = 299,792 kilometres per second
v = Speed of light of a medium = less than 299,792 kilometres per second

Optically rare material (eg. air) = smaller refractive index = faster medium
Optically dense medium (eg. glass) = larger refractive index = slower medium

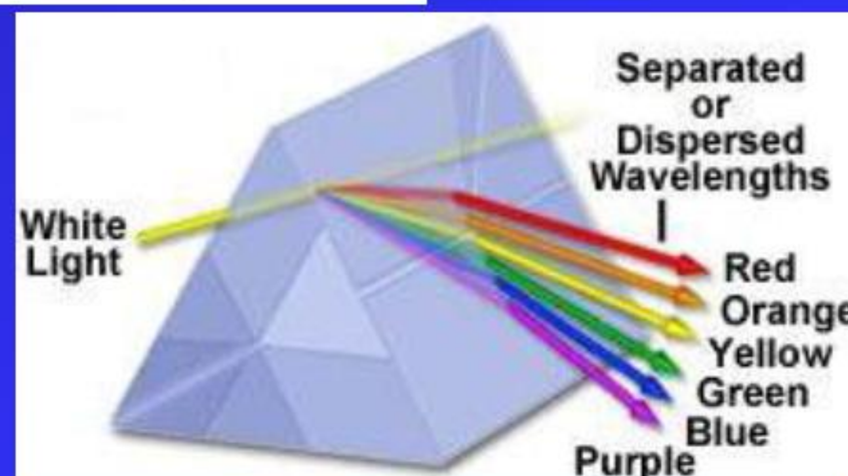
Chromatic Dispersion

When passing from air into glass, blue light may be deflected more than red. This can be desirable e.g. dispersing prisms, rainbows. Or it can be unwelcome, e.g. chromatic aberration in lenses.



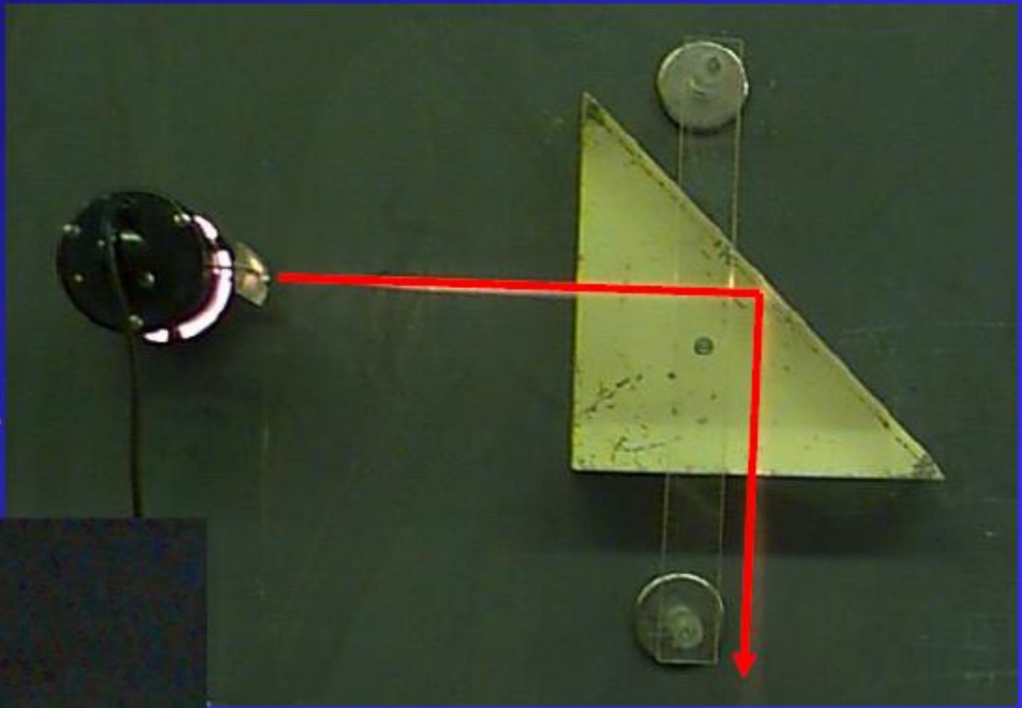


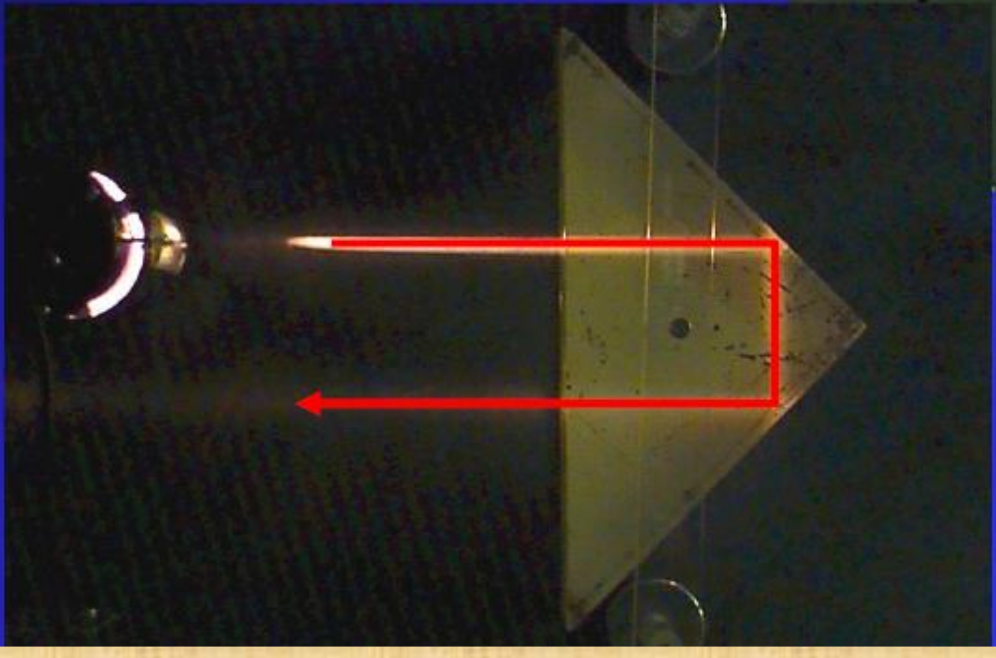
Wavelength dependence of *n* for various materials



Total Internal Reflection

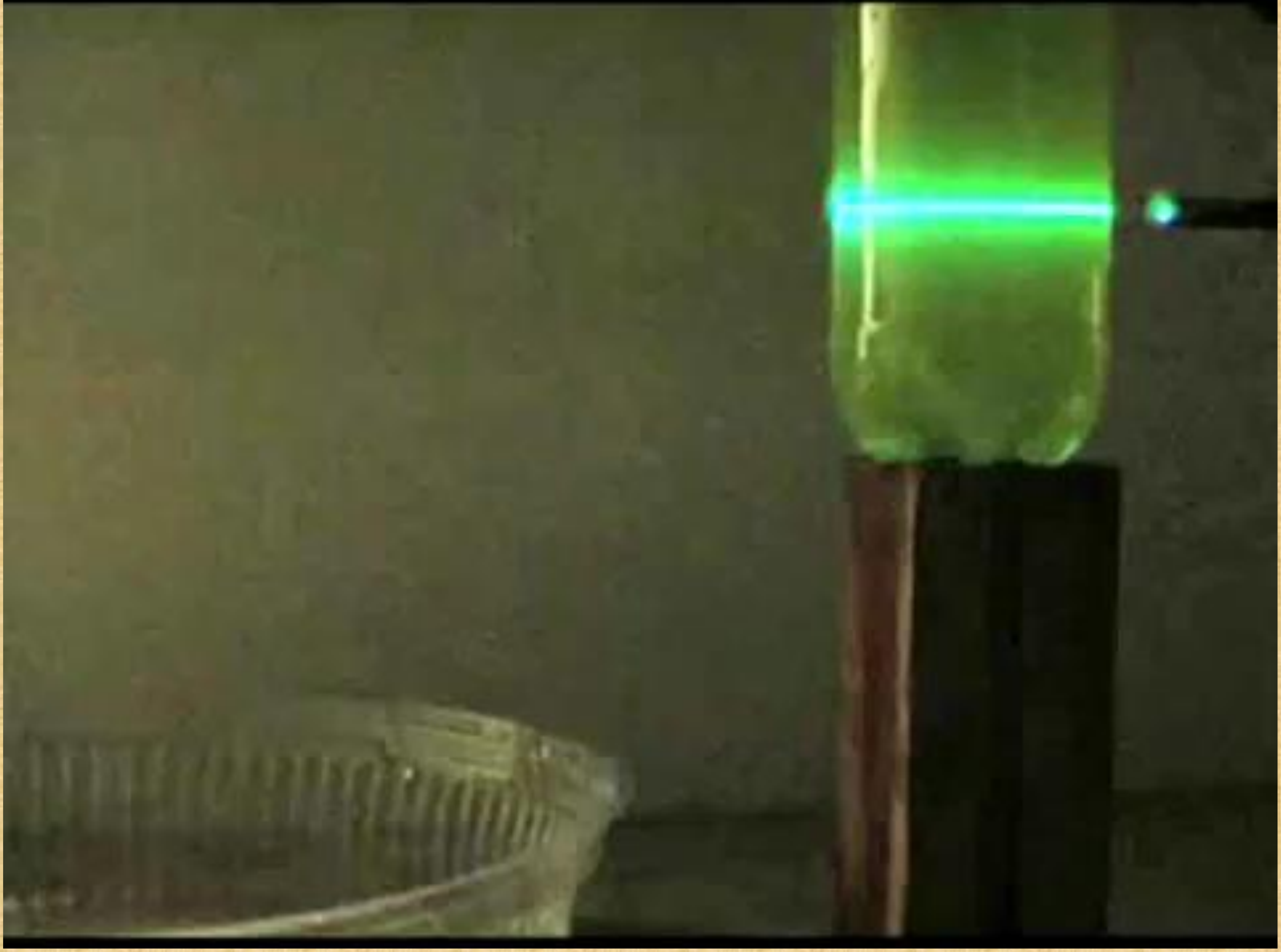
When light meets a boundary with an optically less dense medium, sometimes there is no refracted ray.



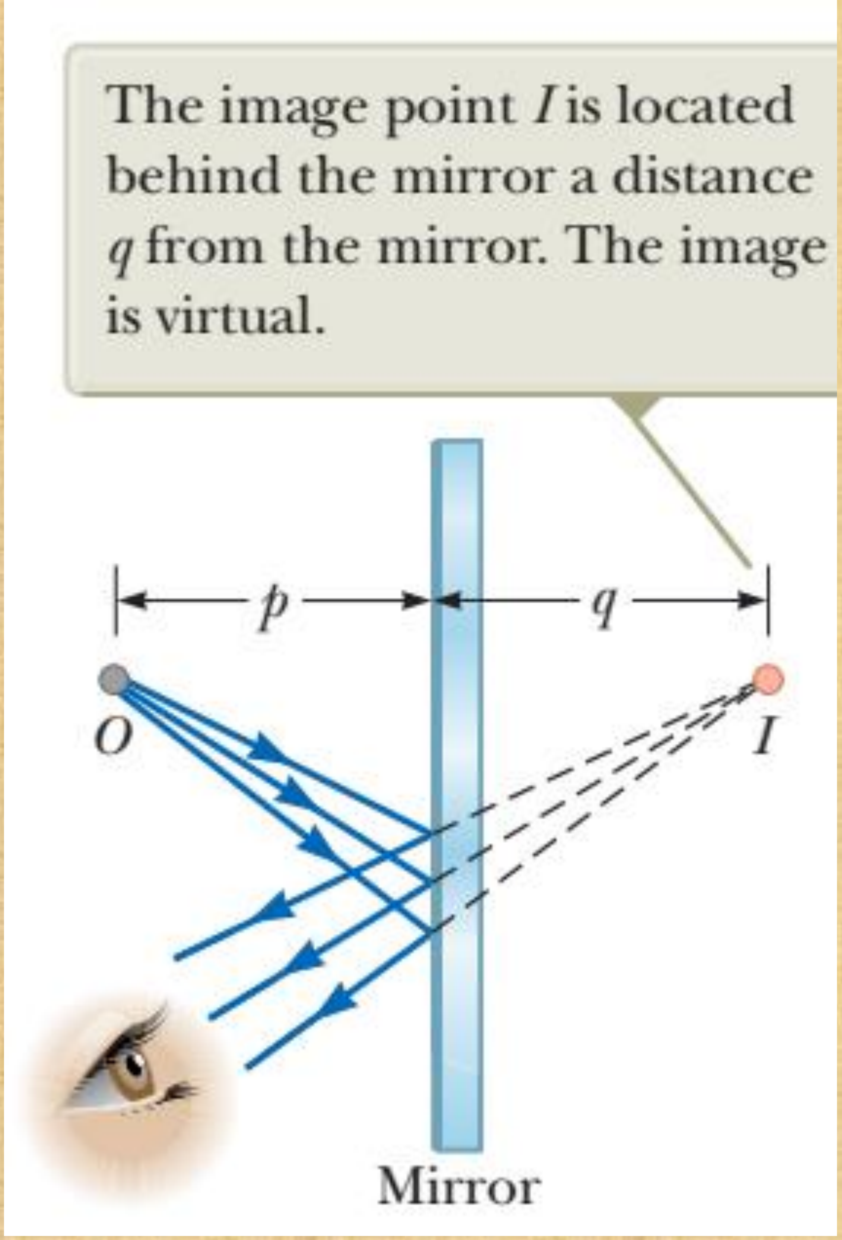


This is called **total internal reflection.**

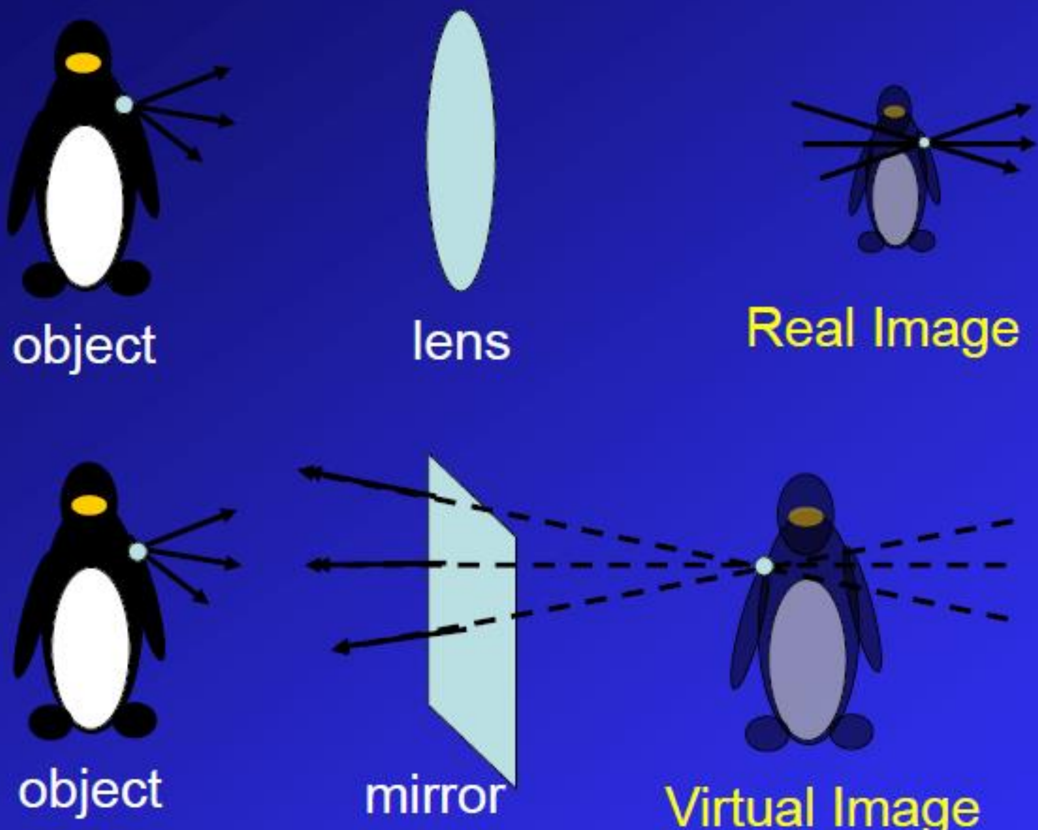
Why and when does it happen?



1.2 Images in mirrors



Images: Real and Virtual



Real Image: Light rays actually pass through the image, it really exists (whether you are looking or not) and could be focused on a screen.

Virtual Image: Light rays do not actually pass through the image, they only appear to be coming from it. It cannot be focused on a screen.

$$N = (360/\theta) - 1$$

No.of reflections in the mirrors excluding object.

Total no. of images seen including the object.

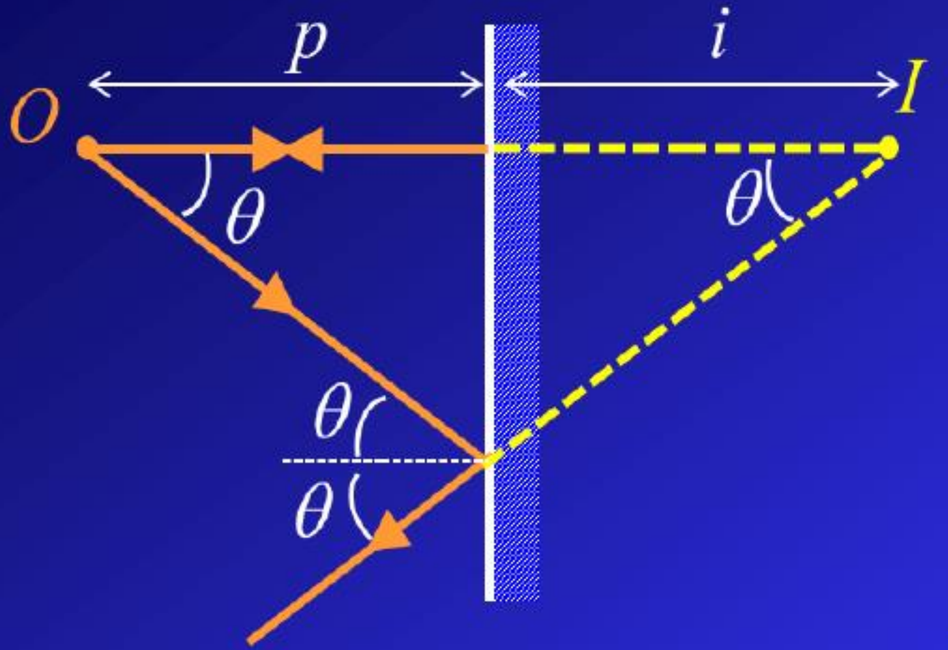
(To eclude the objec from total no. of images.)

Play (k)

where θ is the angle of inclination between mirrors...

p : object distance (perpendicular distance from mirror).

i : image distance



By geometry, $|p| = |i|$.

We use the "**real is positive**" rule:

- A *real* image or object distance is *positive*,
- A *virtual* image or object distance is *negative*.

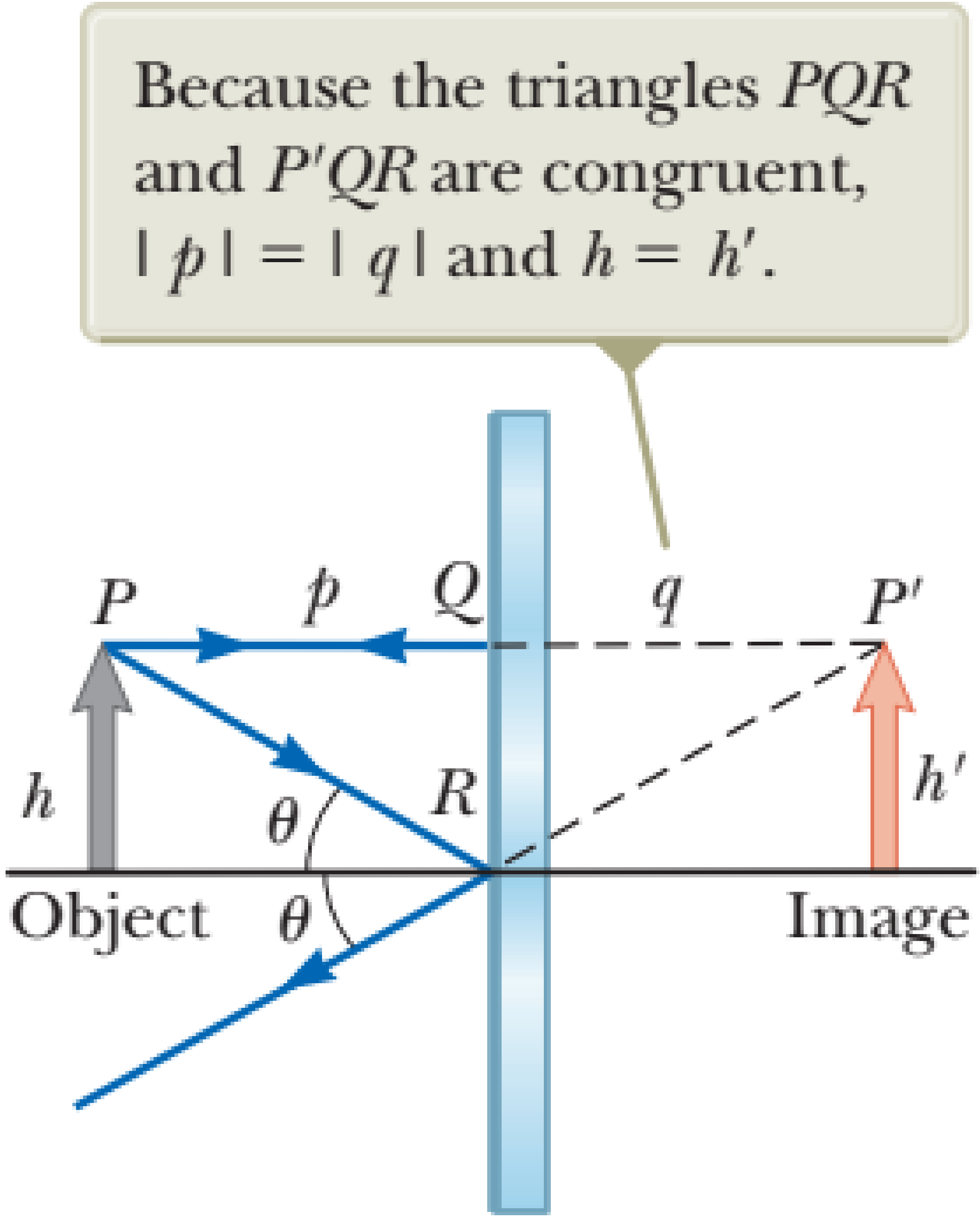
Here, p is +ve, i –ve, so

For a plane mirror, $i = -p$

Can a plane mirror to give a real image?

Lateral magnification M

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



Spherical Mirrors

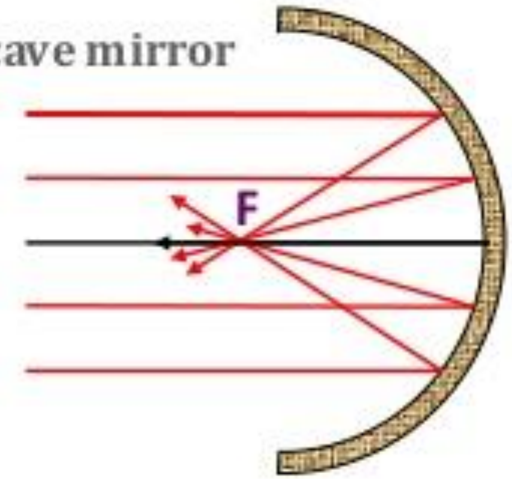
iTutor

- **Spherical Mirror :** A curved mirror formed by a part of a hollow glass sphere with a reflecting surface.

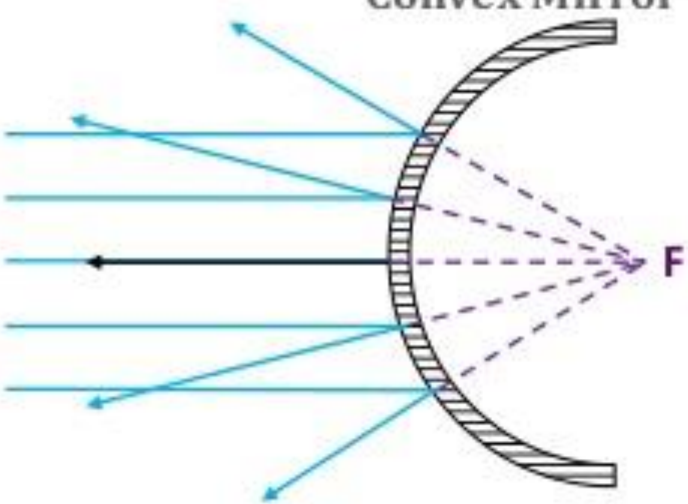
Two types of spherical mirrors:

- **Concave mirror:** A concave mirror is a curved mirror with the reflecting surface on the hollow side.
- **Convex Mirror** : A convex mirror is a curved mirror with the reflecting surface on the outer side

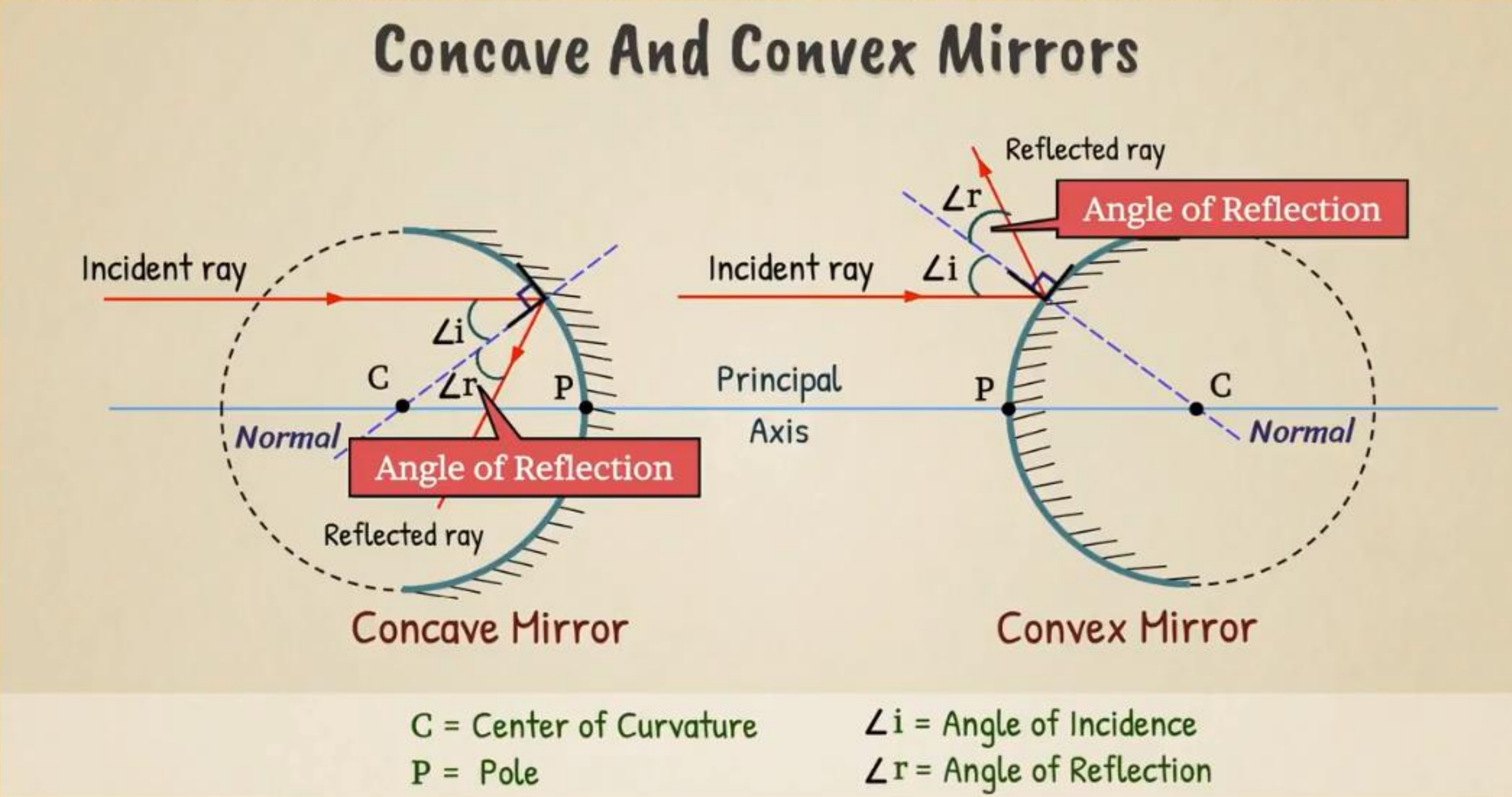
Concave mirror



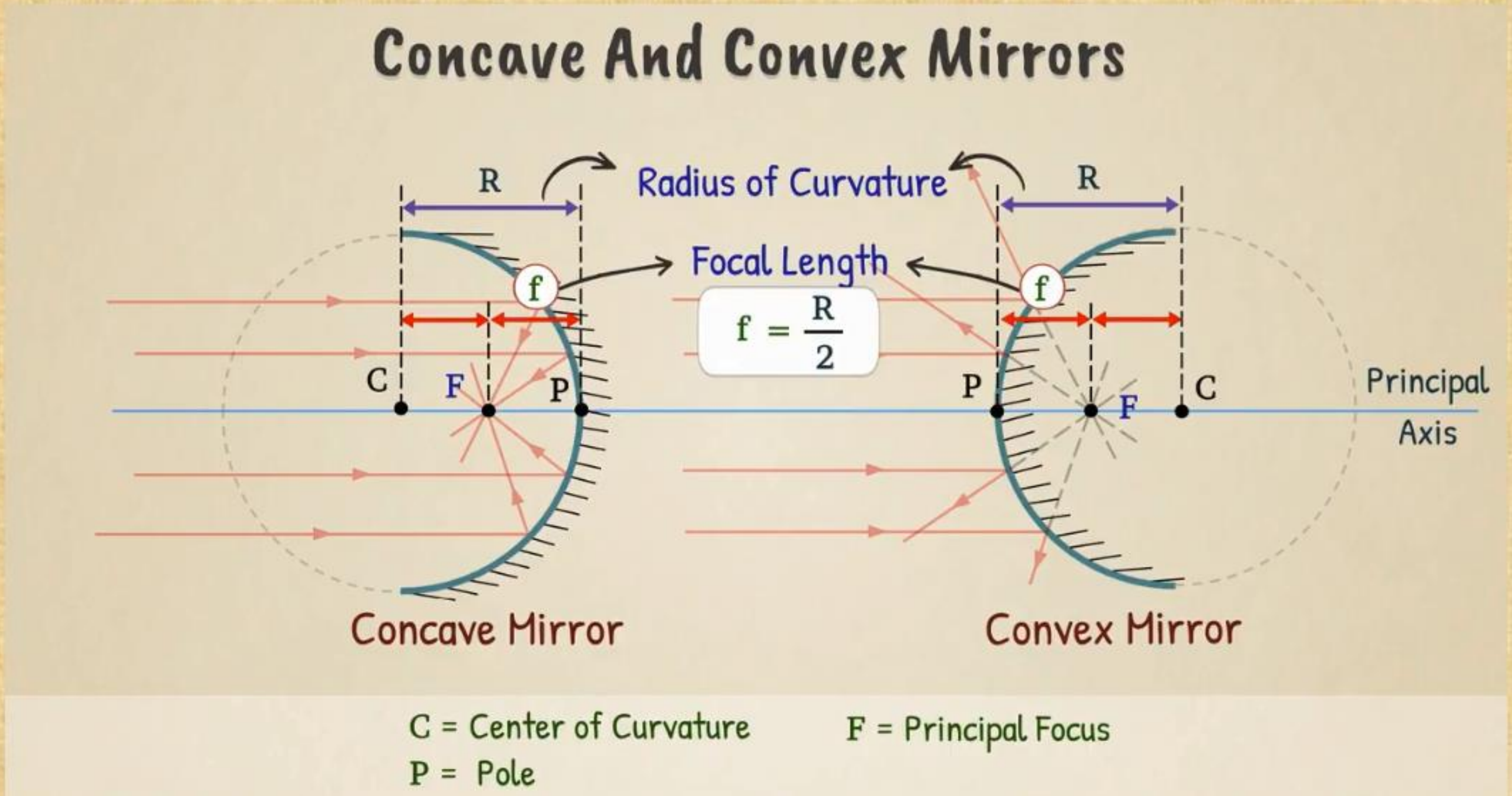
Convex Mirror



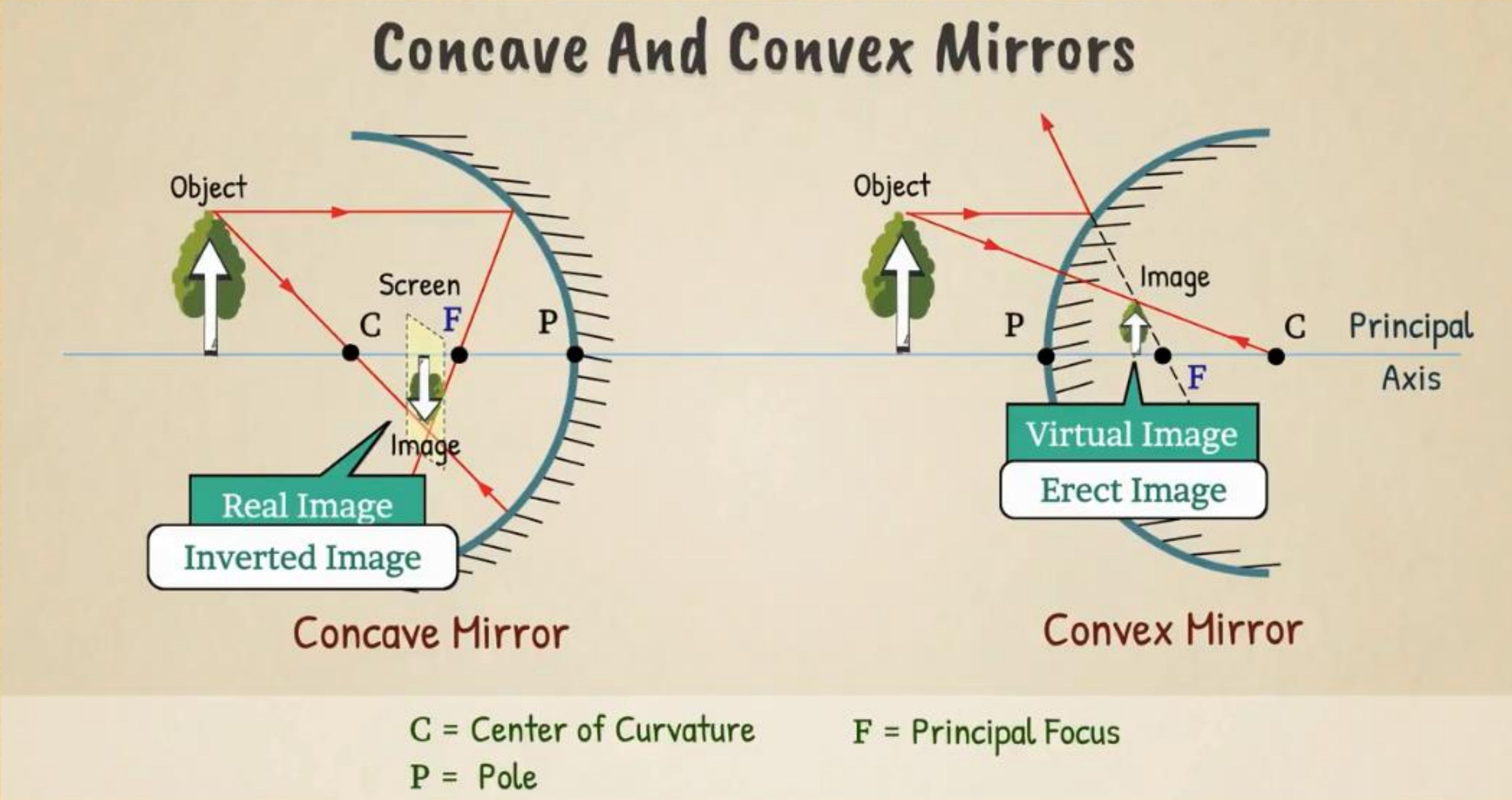
Spherical Mirrors



Spherical Mirrors



Spherical Mirrors



Images in Spherical Mirrors

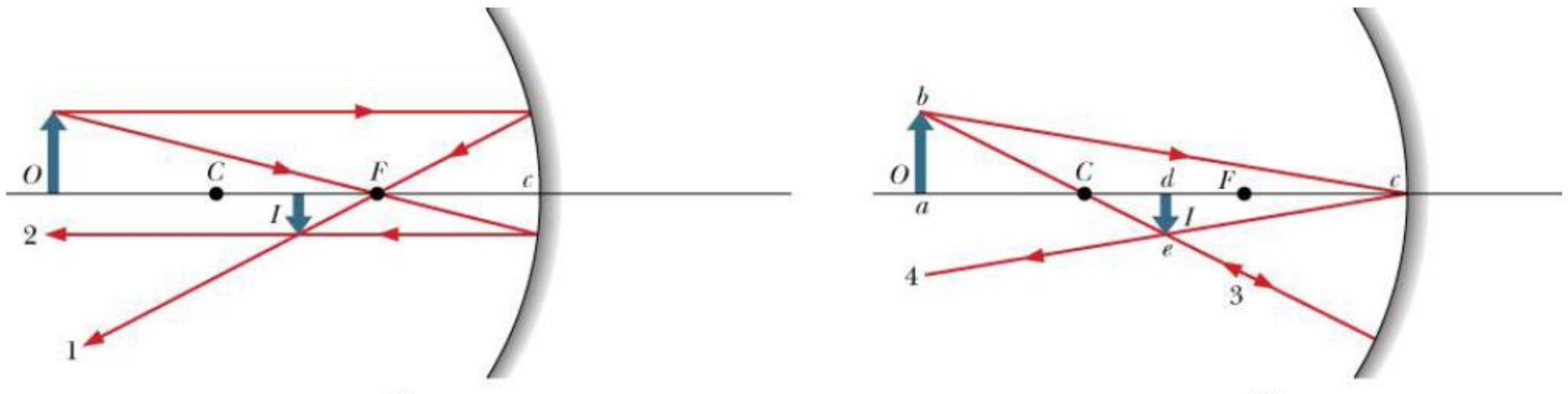
The location and nature of the image of a given object can be obtained by drawing a ray diagram or by using formulae.

<u>Drawing Ray Diagrams</u>

Draw rays from a (non-axial) point on the object. Where the rays intersect, or appear to intersect, is the corresponding point on the image. It is sufficient to draw *two* of the following:

1. A ray parallel to principal axis which after reflection passes through, or appears to diverge from, the principal focus, F.
2. A ray which passes through F and after reflection travels parallel to the principal axis.
3. A ray through the centre of curvature, C, which strikes the mirror normally and is reflected back along the same path.
4. A ray which reflects from the mirror at the pole P and is reflected symmetrically about the principal axis.

Ray Diagrams: Examples



(a) (b)

1. A ray parallel to principal axis which after reflection passes through, or appears to diverge from, the principal focus, F.
2. A ray which passes through F and after reflection travels parallel to the principal axis.
3. A ray through the centre of curvature, C, which strikes the mirror normally and is reflected back along the same path.
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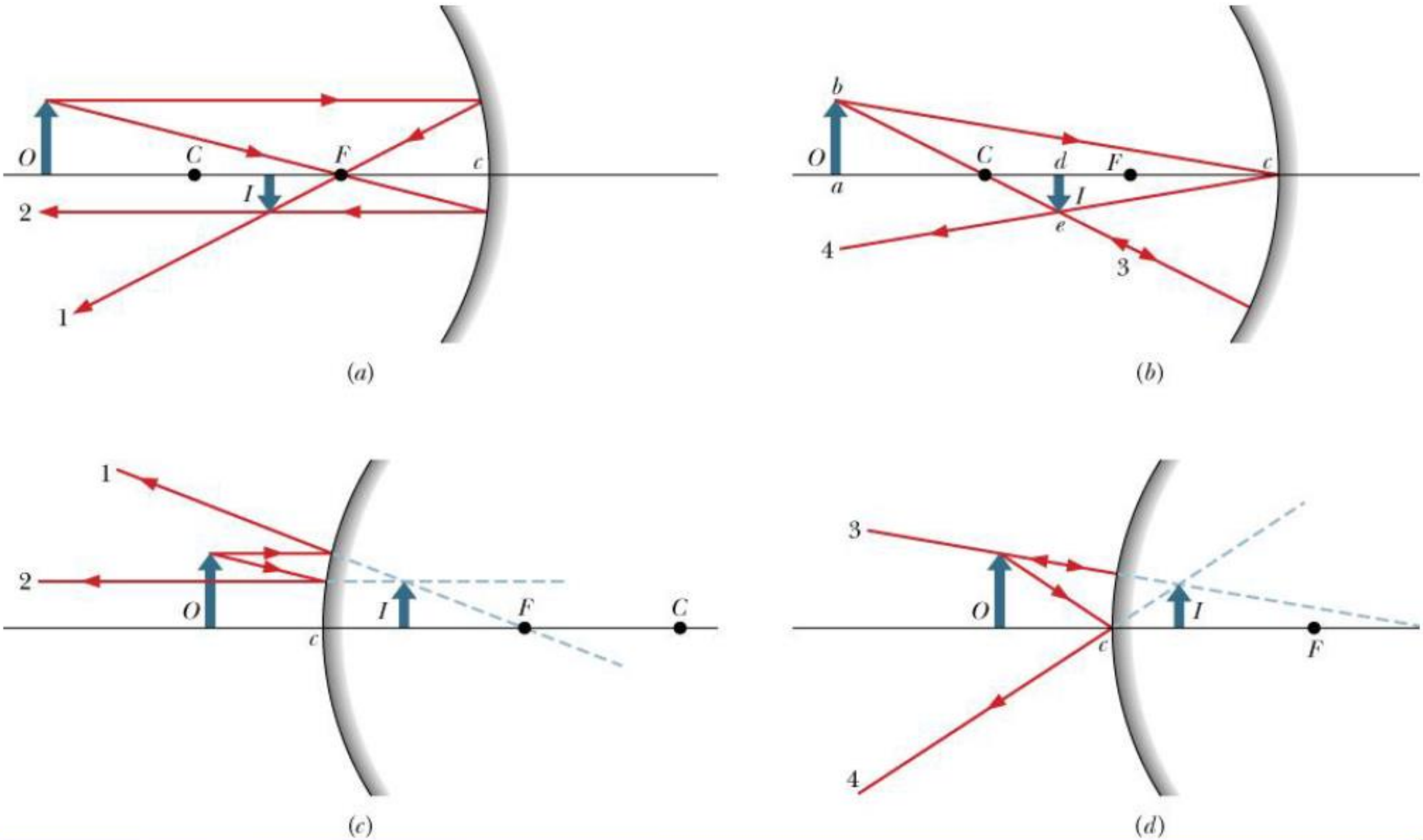
Ray Diagrams: Examples



Formulae for Spherical Mirrors

Mirror formulae:

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

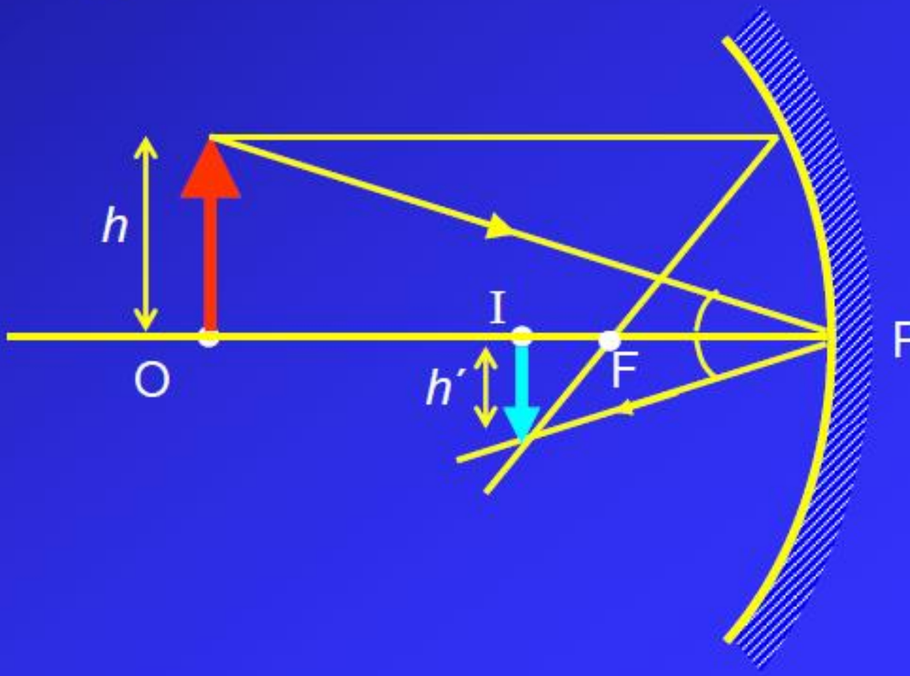
p object distance

i image distance

f focal length

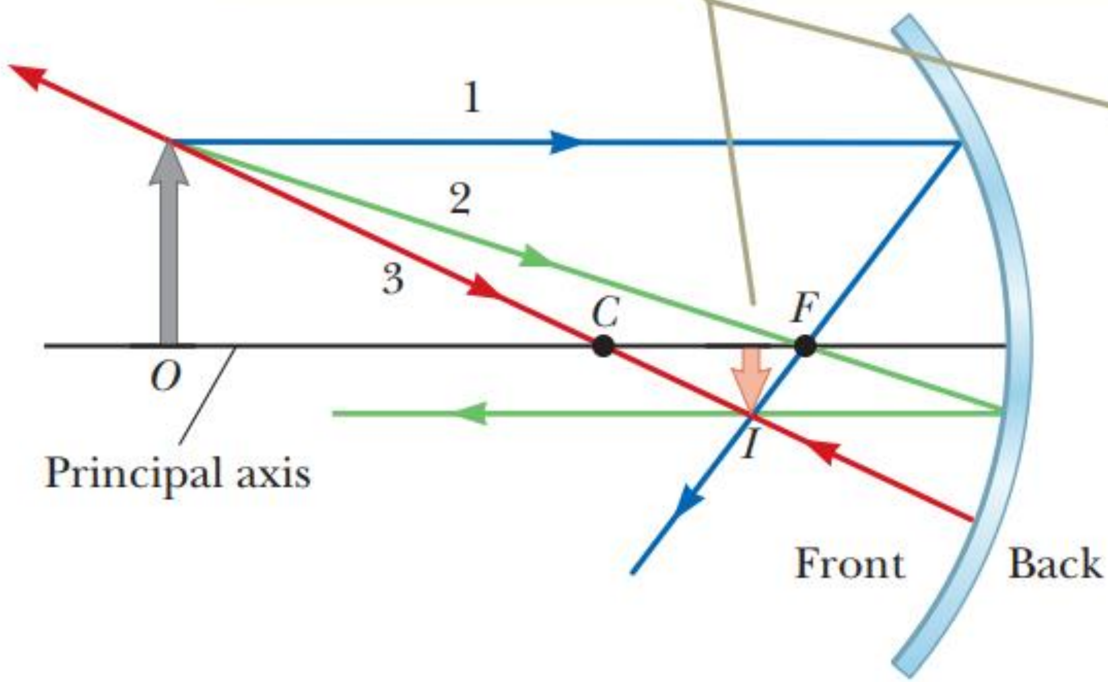
** Remember **
'Real is Positive'

$$m=-\frac{i}{p}$$



Can you convince yourself that for spherical mirrors, erect images are always virtual, real images always inverted?

When the object is located so that the center of curvature lies between the object and a concave mirror surface, the image is real, inverted, and reduced in size.



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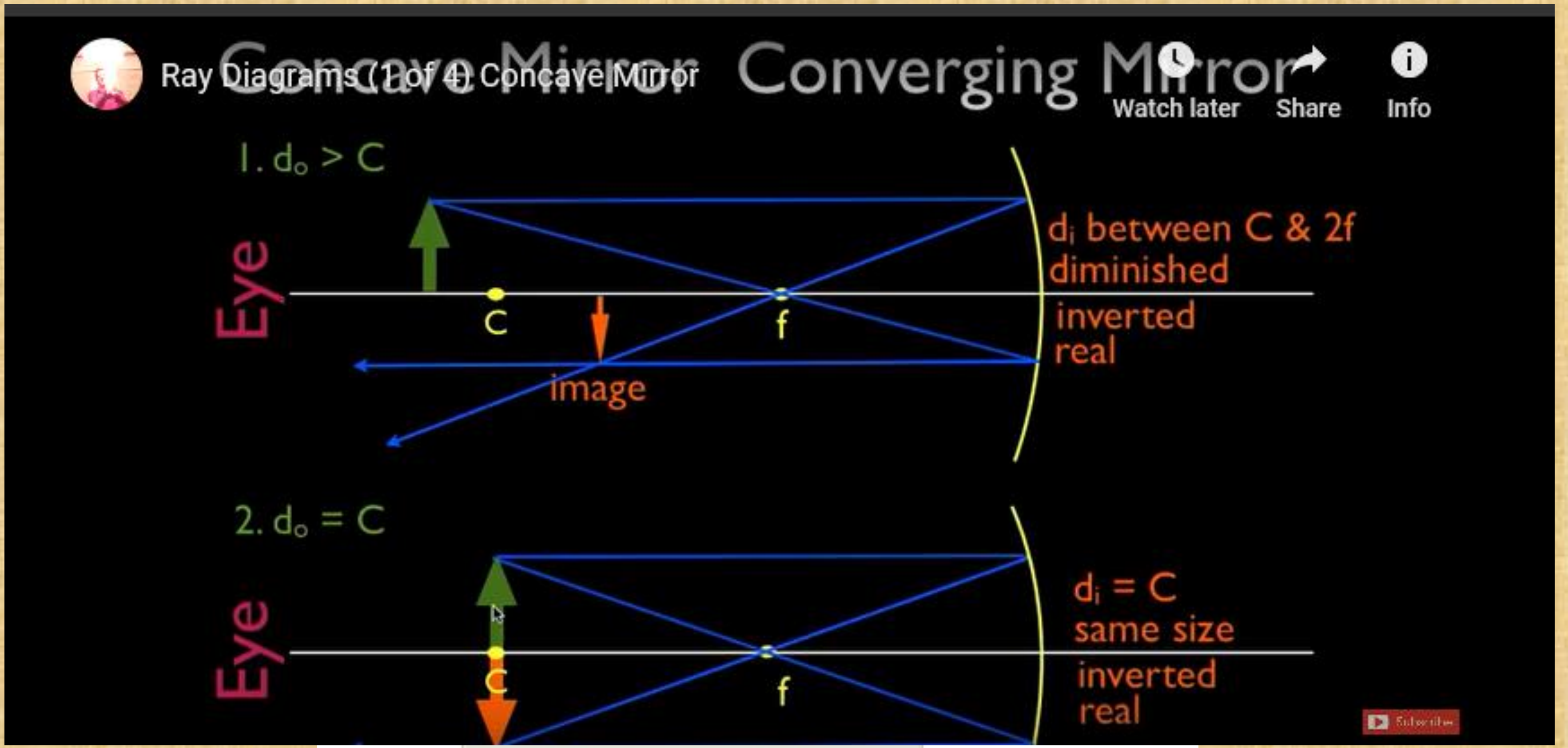
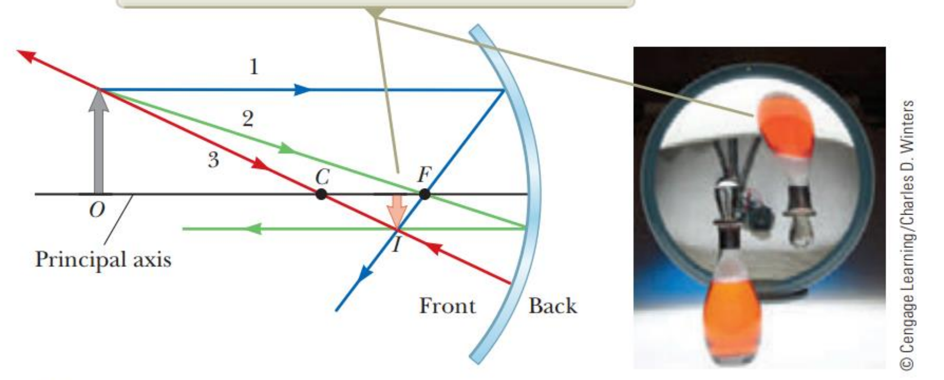
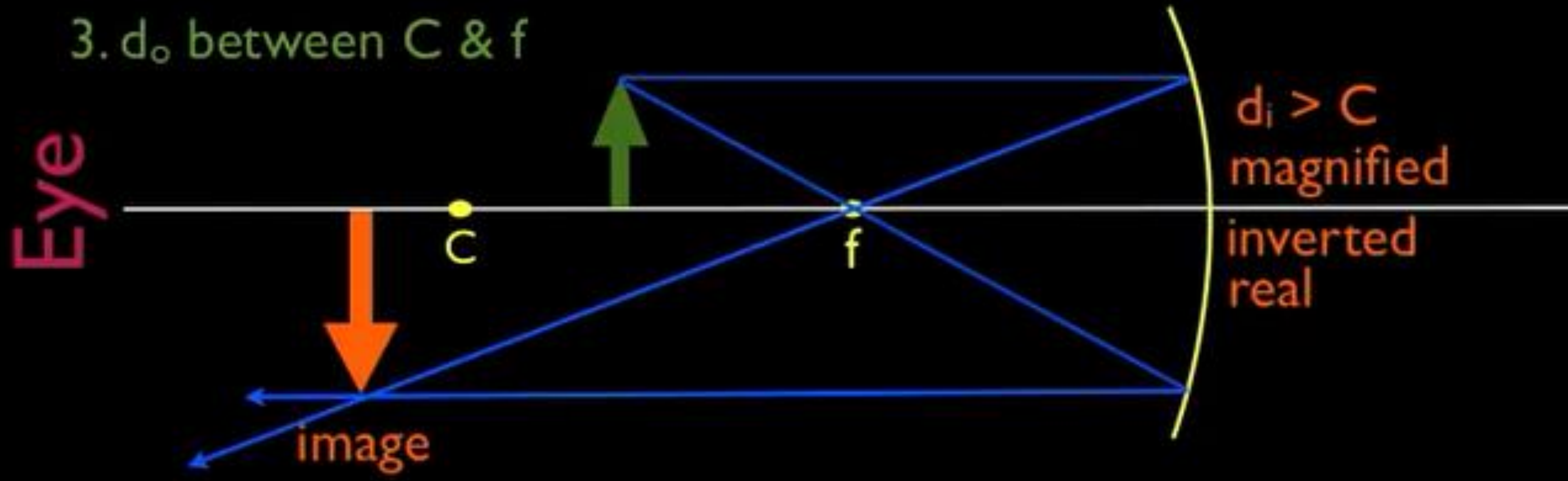
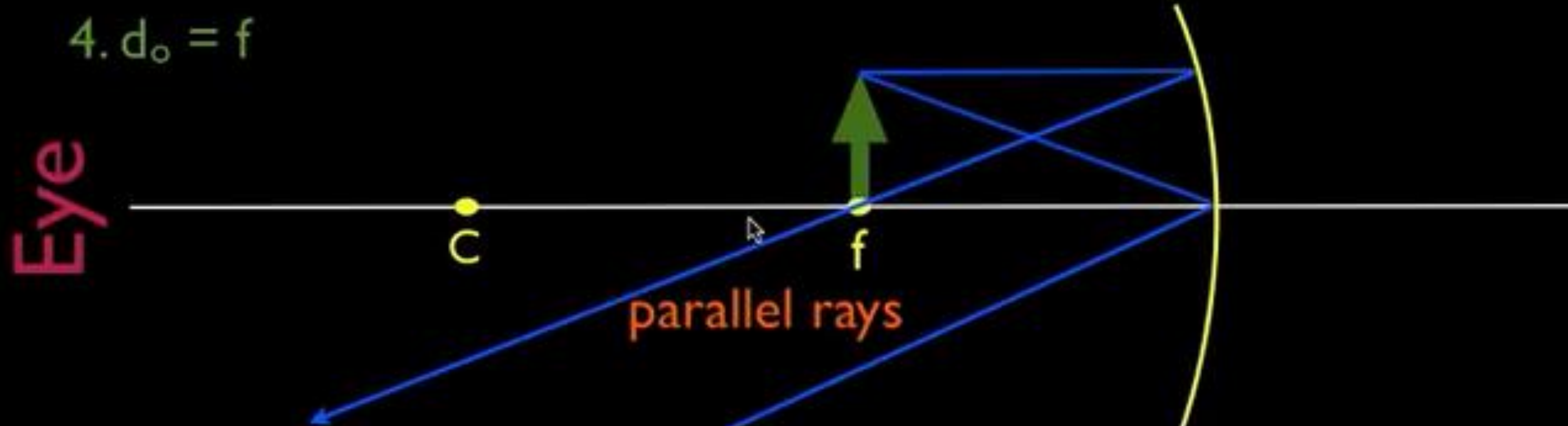


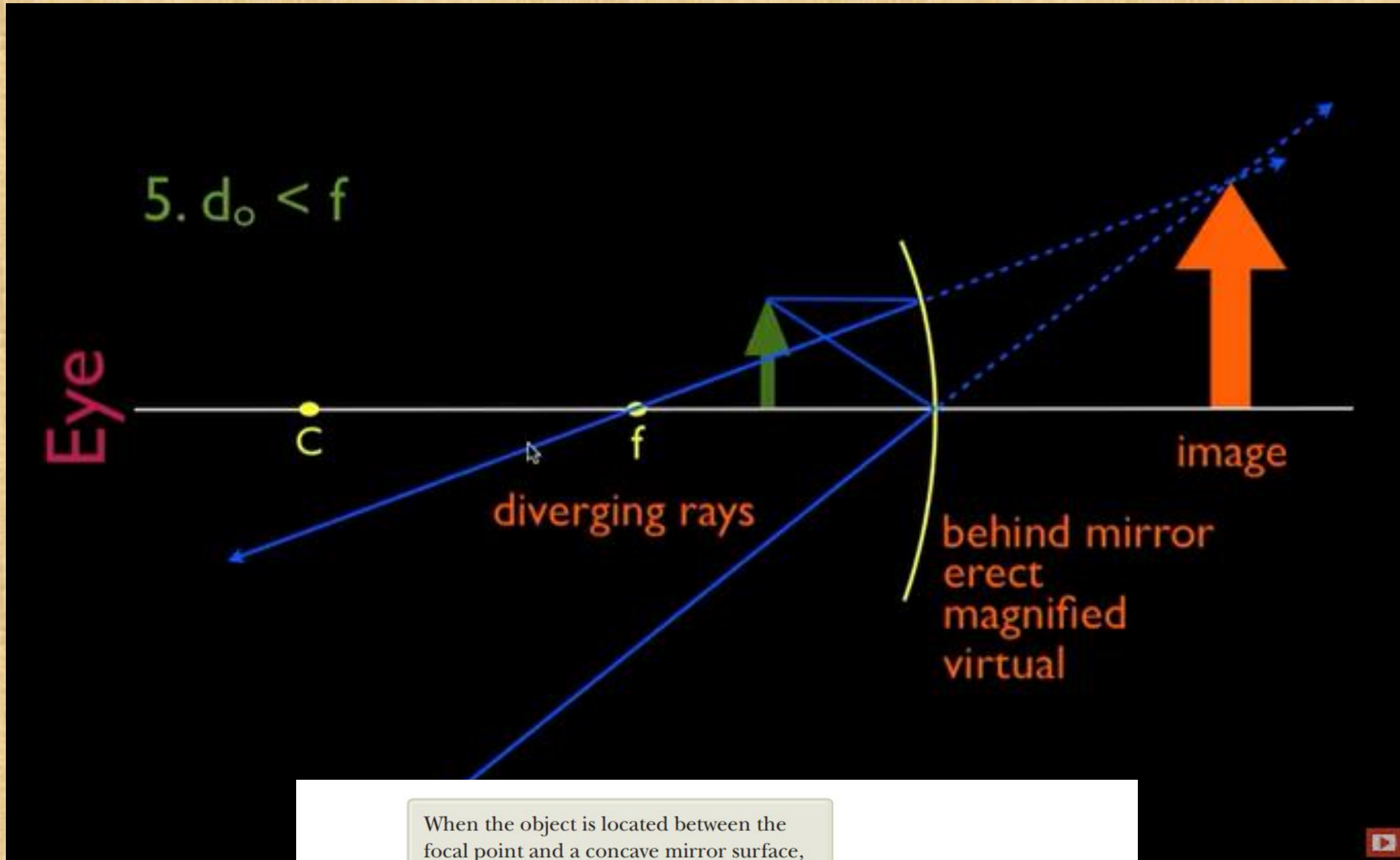
When the object is located so that the center of curvature lies between the object and a concave mirror surface, the image is real, inverted, and reduced in size.



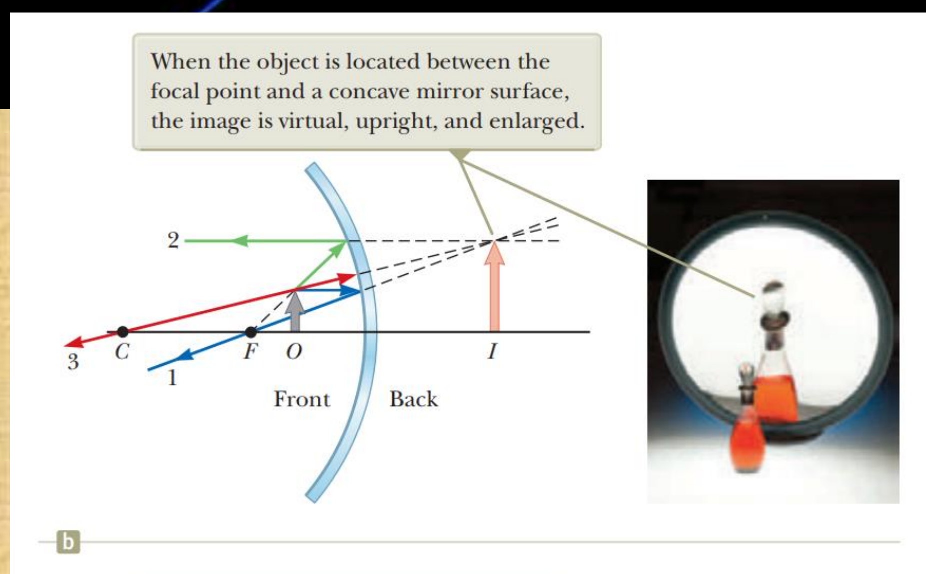
Concave Mirror Converging Mirror







5. $d_o < f$
Eye
C
f
diverging rays
image
behind mirror
erect
magnified
virtual



When the object is located between the focal point and a concave mirror surface, the image is virtual, upright, and enlarged.
2
3
C
1
F
O
I
Front
Back
b

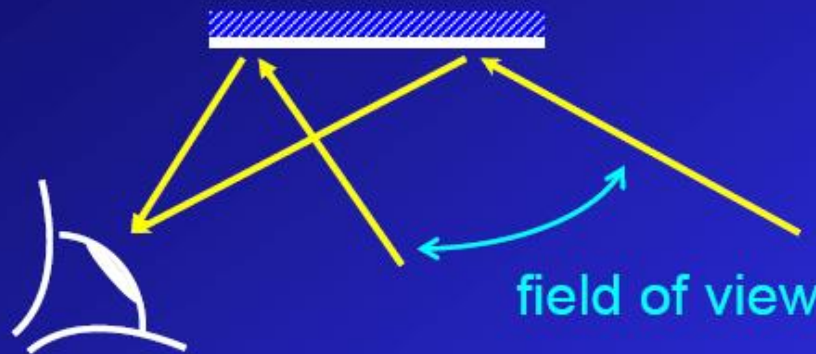
Table 36.1 Sign Conventions for Mirrors

Quantity	Positive When . . .	Negative When . . .
Object location (p)	object is in front of mirror (real object).	object is in back of mirror (virtual object).
Image location (q)	image is in front of mirror (real image).	image is in back of mirror (virtual image).
Image height (h')	image is upright.	image is inverted.
Focal length (f) and radius (R)	mirror is concave.	mirror is convex.
Magnification (M)	image is upright.	image is inverted.

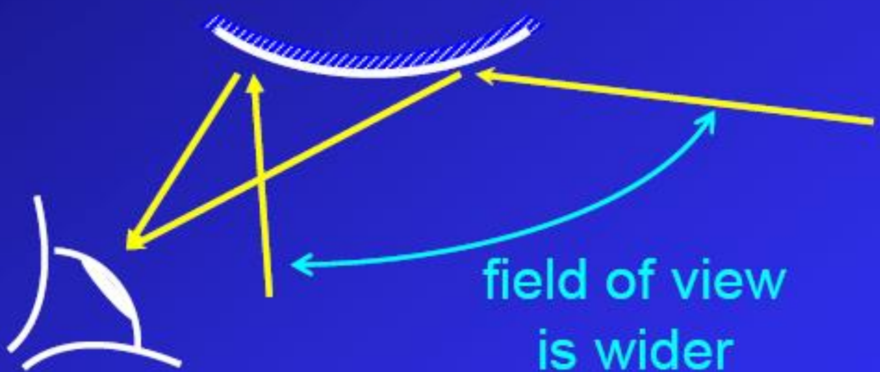
Concave Mirror (Converging Mirror)

d_o	d_i	orientation	size	type
> C	btwn C and f	inverted	diminished	real
at C	at C	inverted	equal	real
btwn C and f	> C	inverted	magnified	real
at f	no image	no image	no image	no image
< f	behind mirror	erect	magnified	virtual

Field of View

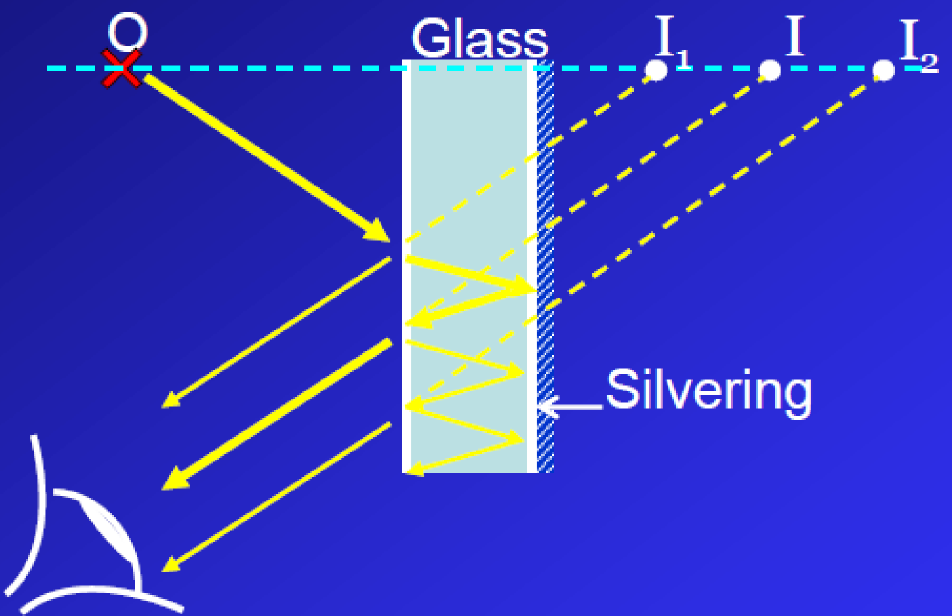


Convex mirror



Concave mirror

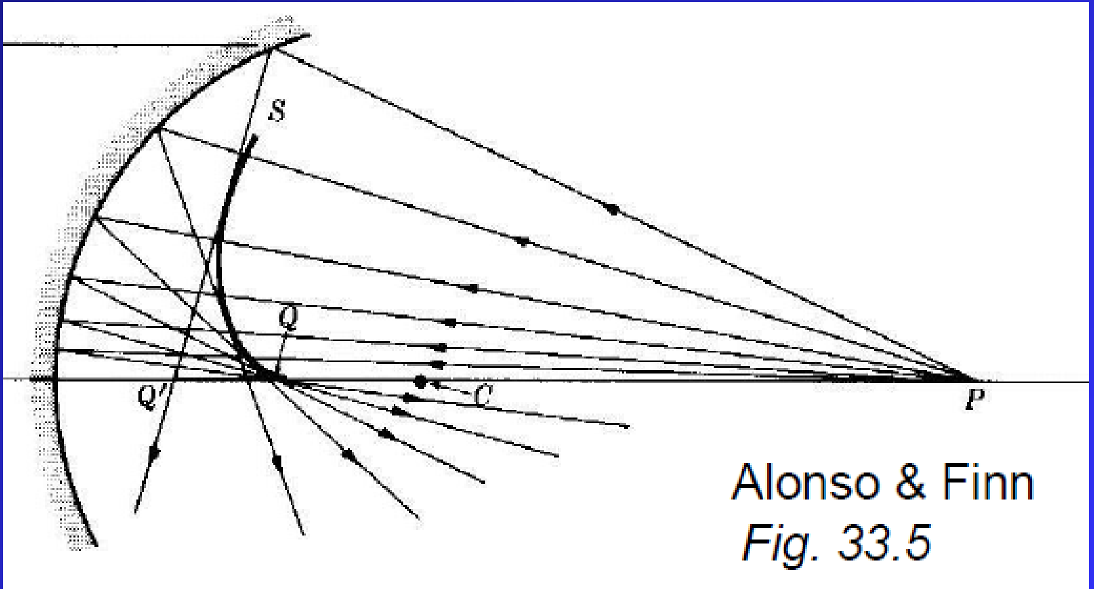
Problems with Mirrors



1. Multiple Images

Looking at an angle into a mirror made of thick glass with silvering on the back surface, you may notice multiple weak images.

2. Spherical Aberrations



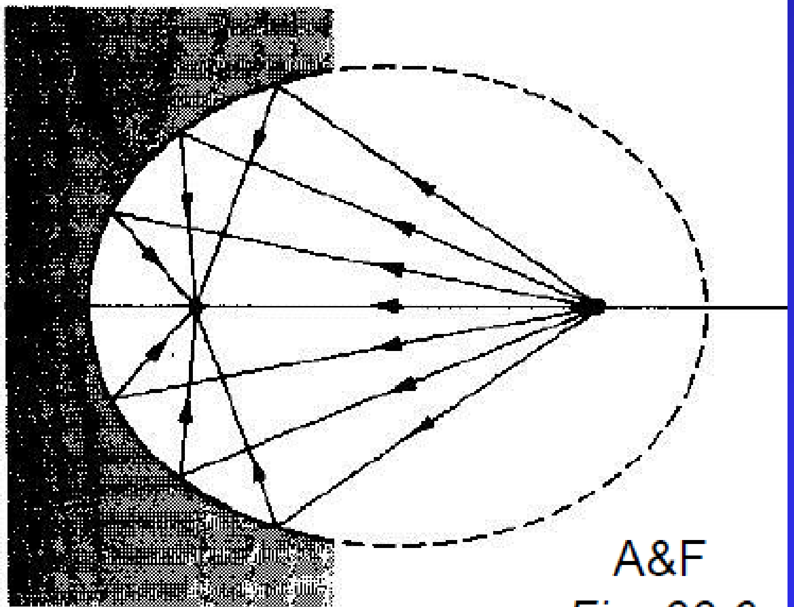
Alonso & Finn
Fig. 33.5

For spherical mirrors with non- paraxial rays / large apertures, reflected rays do *not* all intersect at one point so images are blurred.

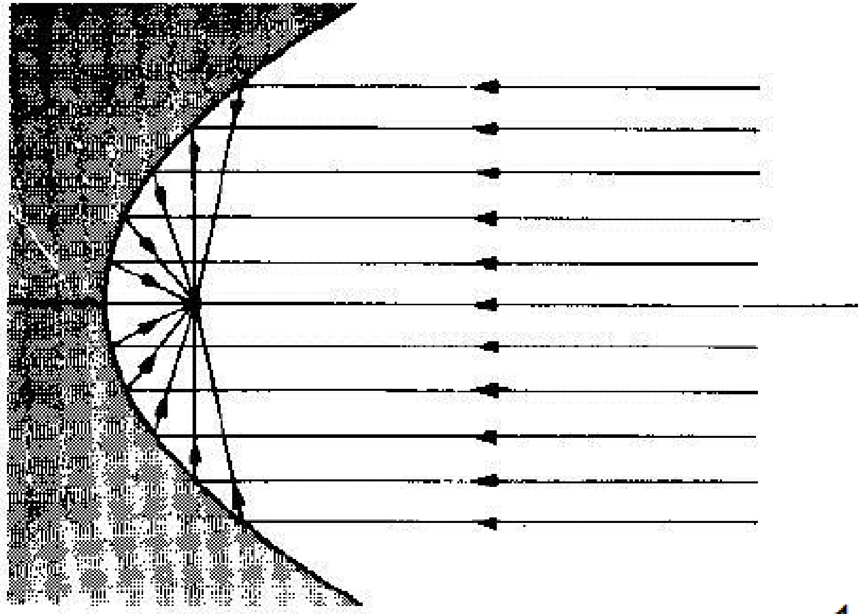
Most telescopes use parabolic mirrors. Why?

Spherical aberration cannot be totally eliminated but it can be reduced. Different shapes of mirror give different amounts of aberration for different object distances, e.g.

- An elliptical mirror gives a sharp image of an object placed at one focus of the ellipse
- A parabolic mirror gives no aberration for rays parallel to the principal axis

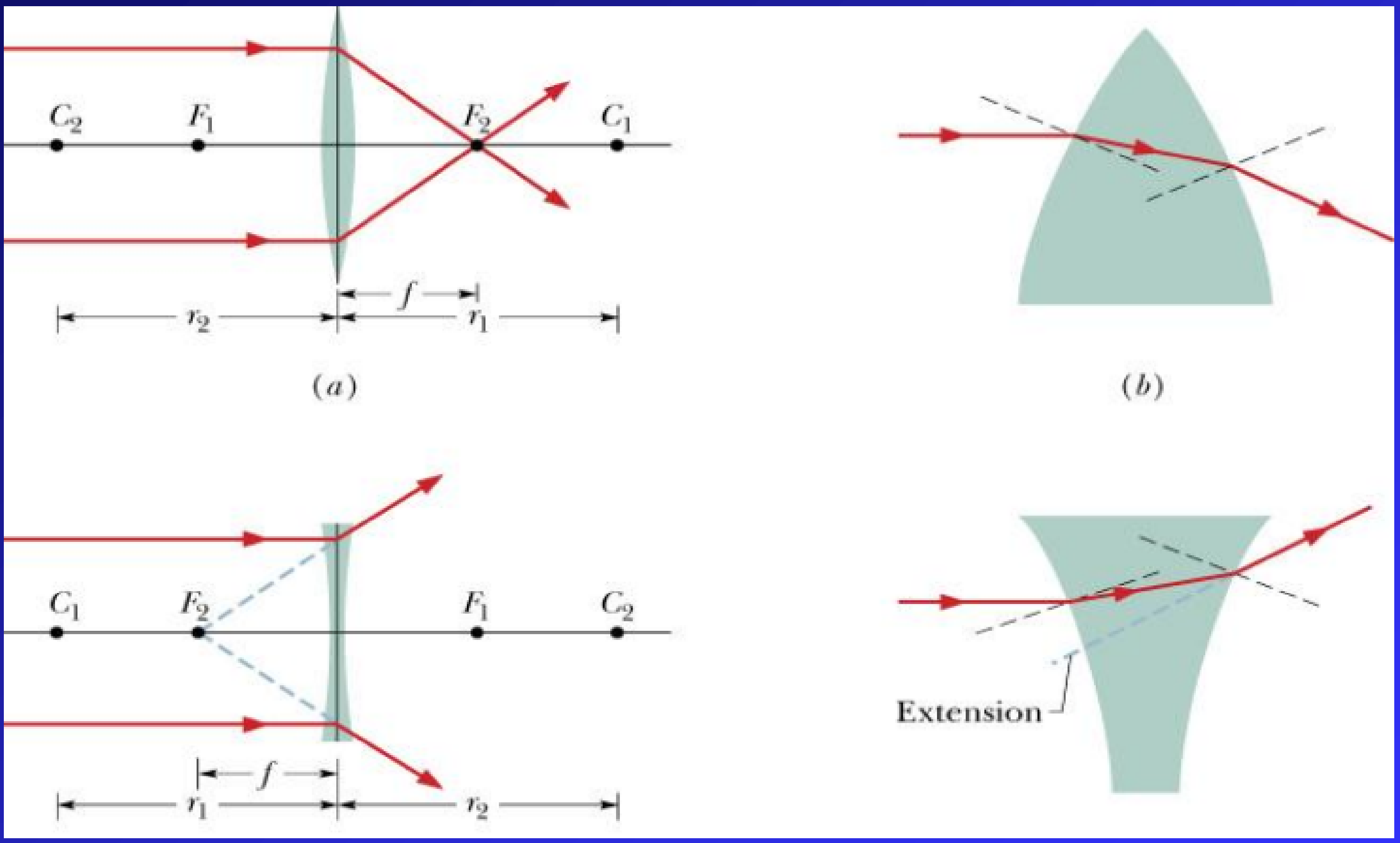


A&F
Fig. 33.6



1.3 Images in Lenses

A *lens* has two refracting surfaces whose principal axes coincide. So light rays may be bent twice.



Convex
Converging
f positive

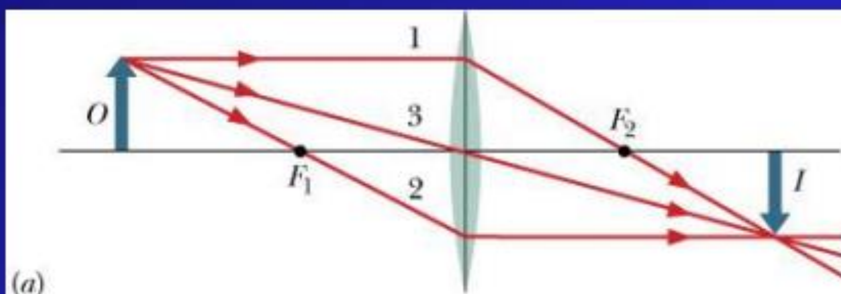
Concave
Diverging
f negative

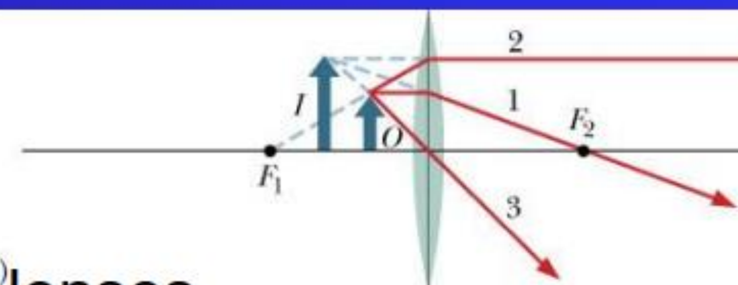
Lenses have two focal points: one on each side of the lens.

Ray Diagrams

For any off-axis point on an object, draw two of the following rays. The image point is located where the rays intersect.

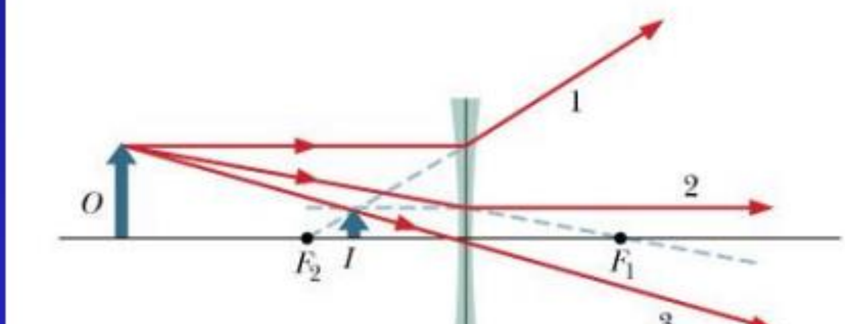
1. A ray initially parallel to central axis will pass through or appear to diverge from F_2
2. A ray that initially passes through or appears to diverge from F_1 will emerge parallel to the principal axis
3. A ray through the centre of the lens will emerge unchanged





For lenses,

- ***real*** images form on the *opposite* side of the lens from the object,
- ***virtual*** images on the *same* side



Thin Lens Formulae

- A *thin lens* has a thickness which is small compared to the object distance, the image distance and the radii of curvature of the two surfaces.
- We again only consider paraxial rays.

Then for lenses, as for mirrors, we have

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

And lateral magnification

$$|m|=\frac{h'}{h}$$

$$m=-\frac{i}{p}$$

where i and p are positive if real, negative if virtual

(For proofs, see textbooks).

Table 36.1 Sign Conventions for Mirrors

Quantity	Positive When . . .	Negative When . . .
Object location (p)	object is in front of mirror (real object).	object is in back of mirror (virtual object).
Image location (q)	image is in front of mirror (real image).	image is in back of mirror (virtual image).
Image height (h')	image is upright.	image is inverted.
Focal length (f) and radius (R)	mirror is concave.	mirror is convex.
Magnification (M)	image is upright.	image is inverted.

Table 36.3 Sign Conventions for Thin Lenses

Quantity	Positive When . . .	Negative When . . .
Object location (p)	object is in front of lens (real object).	object is in back of lens (virtual object).
Image location (q)	image is in back of lens (real image).	image is in front of lens (virtual image).
Image height (h')	image is upright.	image is inverted.
R_1 and R_2	center of curvature is in back of lens.	center of curvature is in front of lens.
Focal length (f)	a converging lens.	a diverging lens.

Convex Lens (Converging Lens)

d_o	d_i	orientation	size	type
> 2f	btwn 2f and f	inverted	diminished	real
at 2f	at 2f	inverted	equal	real
btwn 2f and f	> 2f	inverted	magnified	real
at f	no image	no image	no image	no image
< f	behind lens	erect	magnified	virtual

Concave Mirror (Converging Mirror)

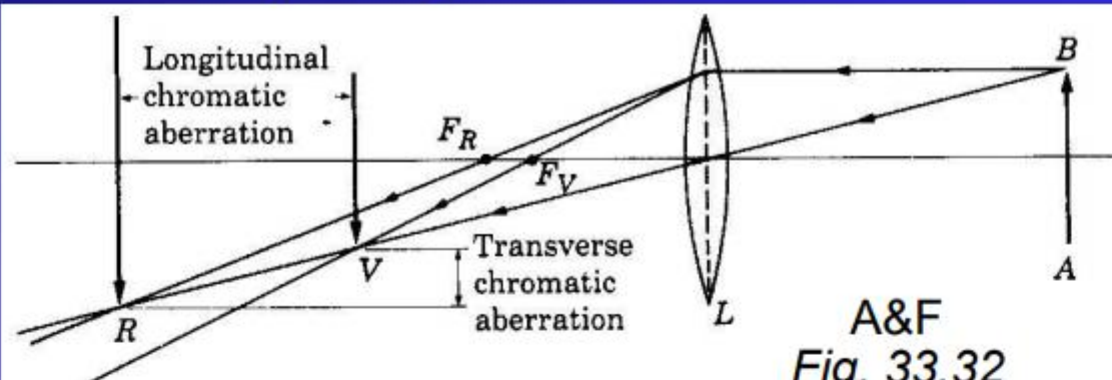
d_o	d_i	orientation	size	type
> C	btwn C and f	inverted	diminished	real
at C	at C	inverted	equal	real
btwn C and f	> C	inverted	magnified	real
at f	no image	no image	no image	no image
< f	behind mirror	erect	magnified	virtual

Aberrations

Spherical Aberration – As for mirrors

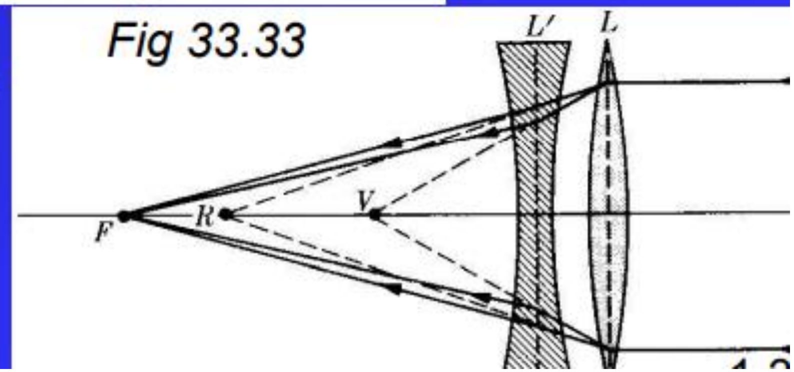
Chromatic Aberrations

- Focal length of a lens depends on *n,* so varies with wavelength
- From a white object, red and violet images will be formed at different distances (longitudinal aberration) and with different sizes (transverse aberration). Image looks blurred with coloured edges.

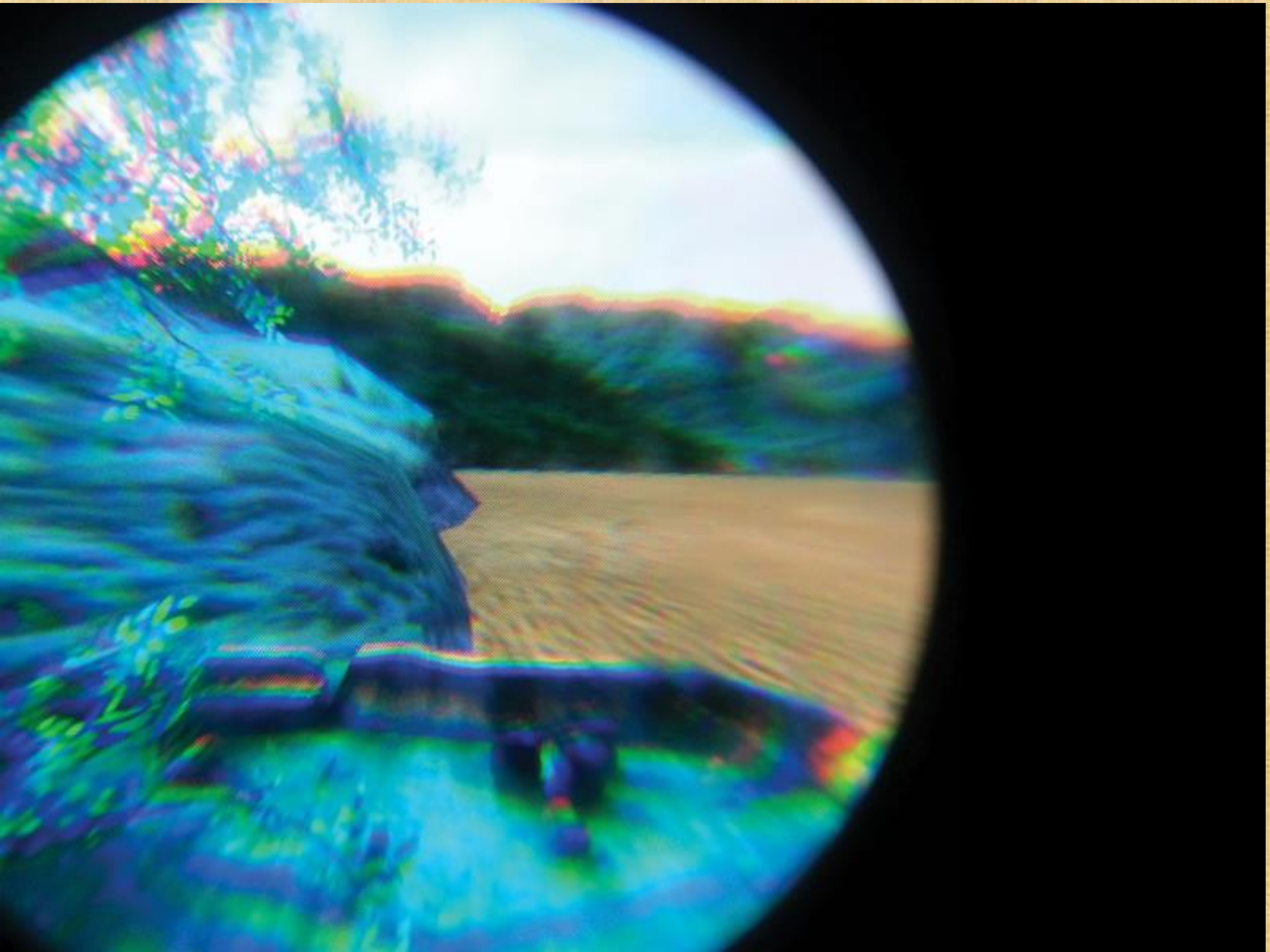


A&F
Fig. 33.32

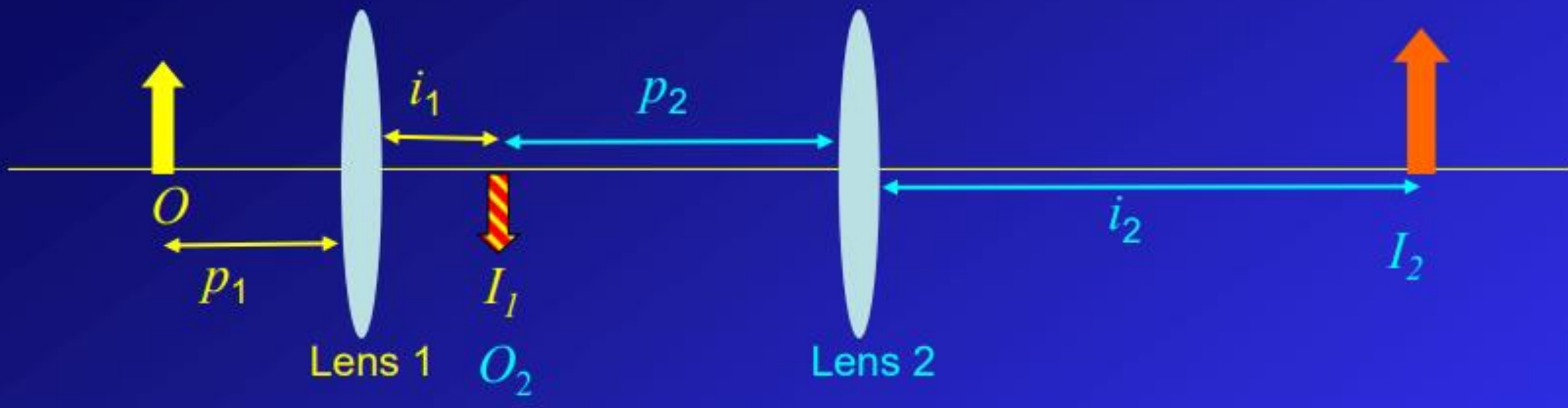
Fig 33.33



- Can be reduced using an *achromatic doublet:* two lenses of different materials giving approximately equal and opposite amounts of dispersion.



Two Lens Systems



1. First consider lens 1 only.
   Let p_1 be the distance of the object O from lens 1.
   Calculate the image distance i_1.

2. Now consider lens 2 only. Use I_1 as the object O_2.
   From the geometry, determine p_2. (If O_2 is located to the right of lens 2, take p_2 to be negative.)
   Calculate i_2 to locate the final image I_2.

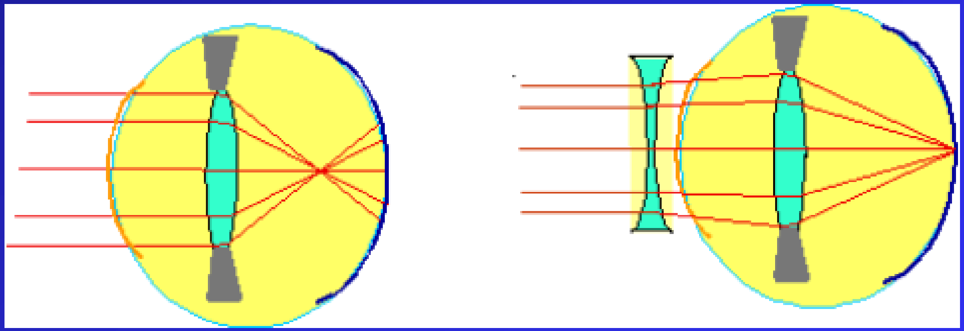
The net magnification is $M = m_1 m_2$

1.4 Optical Instruments

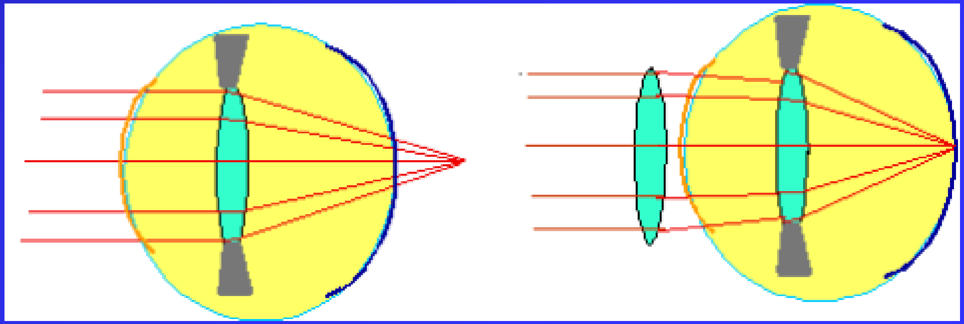
- The range of the human eye can be extended in many ways by optical instruments such as magnifiers, microscopes, telescopes, cameras, projectors, etc.
- Instruments can also be constructed to operate beyond the visible range of the spectrum, e.g. infrared cameras, x-ray microscopes.
- To understand the basic principles of such instruments we will continue to use thin lens formulae. However in practice, most instruments use compound lenses with several components and non-spherical interfaces, so more complex calculations are needed.

Eye Defects

- **Short-sight** / Near-sightedness / myopia:
  Distant objects not seen clearly
  Caused by too strong a lens
  Corrected by concave lens



- **Long-sight** / far-sightedness / hypermetropia:
  Near objects not seen clearly
  Caused by too weak a lens
  Corrected by convex lens



Angular Magnification

Of objects A and B:
- which is bigger?
- which *appears* bigger to the observer?

The *apparent* size of an object depends on the *angle* the object subtends at the eye.

The ***angular magnification*** of an optical instrument is:

$$\boxed{m_\theta = \frac{\theta'}{\theta}}$$

θ: angle subtended at eye by object (without instrument)

θ´: angle subtended at eye by image (with instrument)

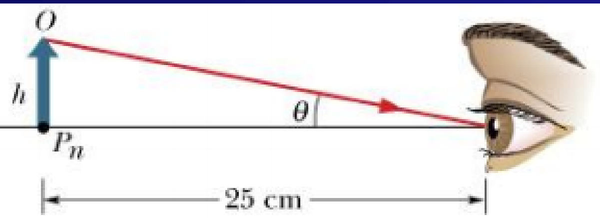
Usually we can take $\theta \approx \frac{h}{d}$

h: height of object

d: distance of object from eye

The Simple Magnifier

(a)



$$\theta \approx \frac{h}{25\,cm}$$

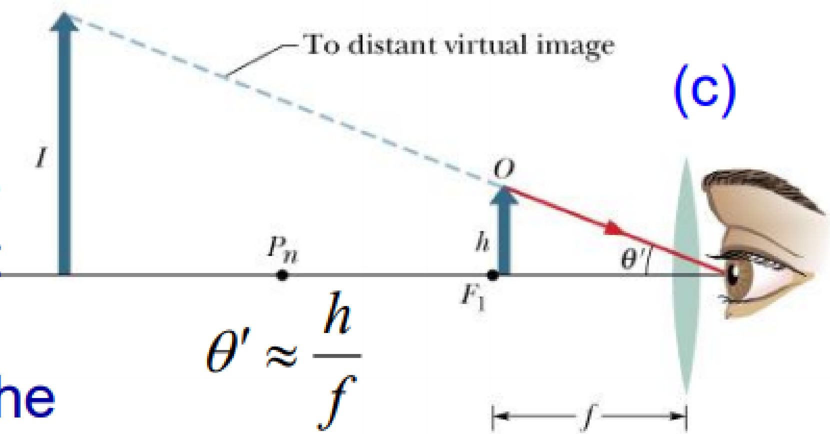
(b)

(a) An object appears larger as it is brought closer to the eye.

(b) But if it is brought closer than the near point $P_n \sim 25$ cm, the eye cannot focus so the image is blurred.

(c) Insert a converging lens so that the object is just inside its focal point. The lens produces a large, distant, virtual image which the eye can see clearly.

(c)

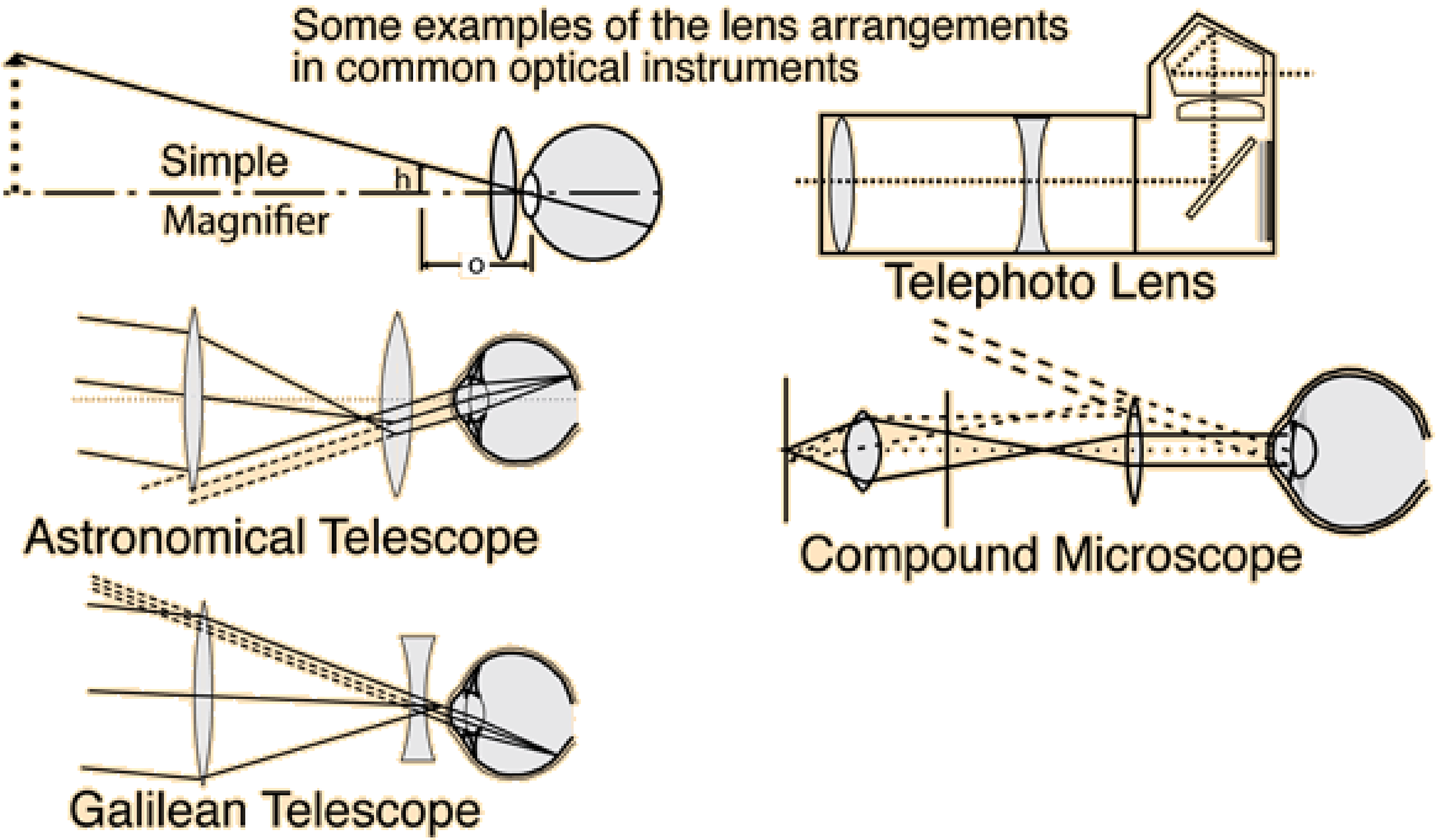


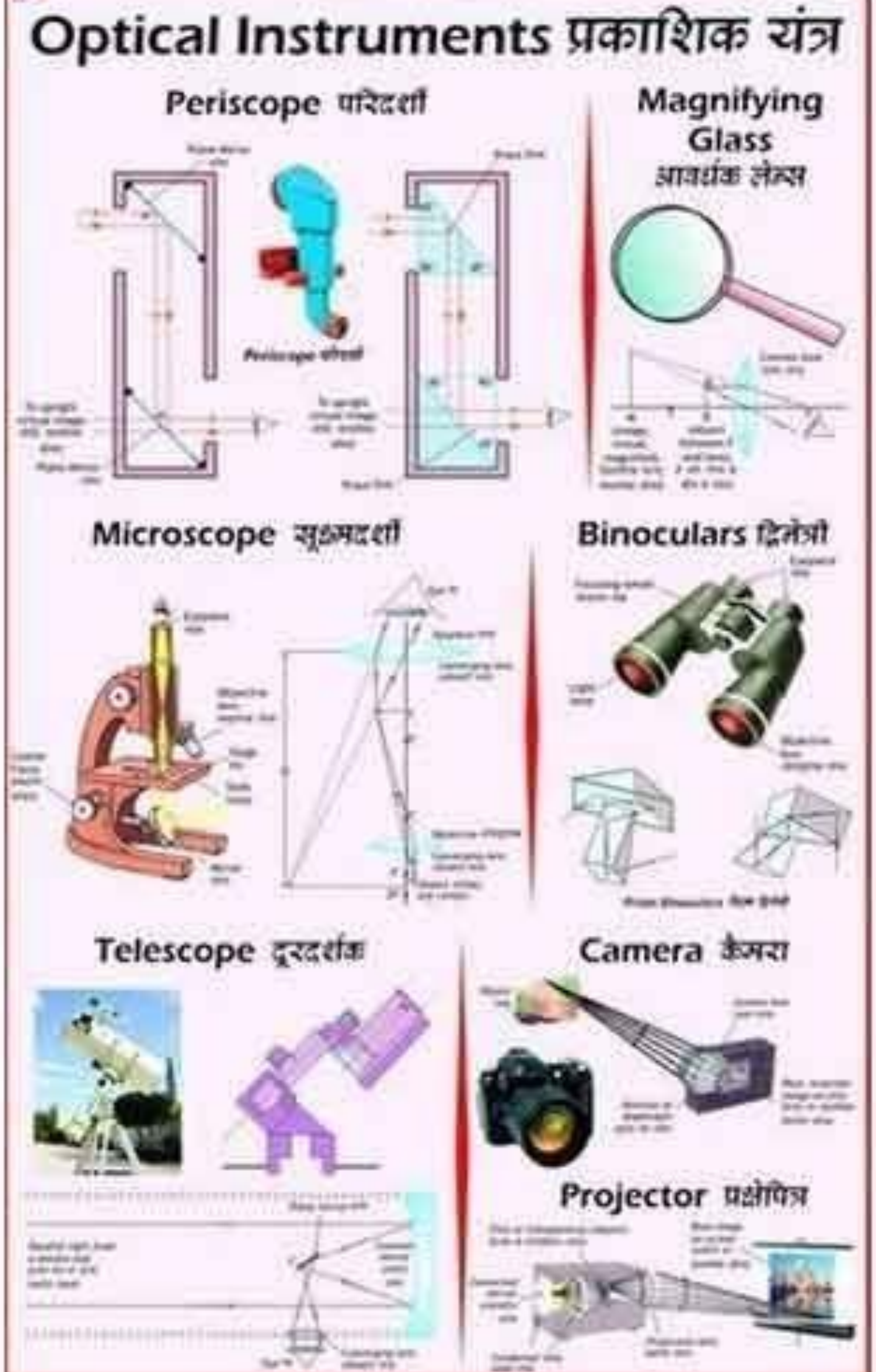
$$\theta' \approx \frac{h}{f}$$

When the simple magnifier is used to give an image at **infinity**, the angular magnification (compared with viewing the object at the near point), is

$$m_\theta = \frac{\theta'}{\theta} \approx \frac{h/f}{h/25\,cm} = \boxed{\frac{25\,cm}{f}}$$

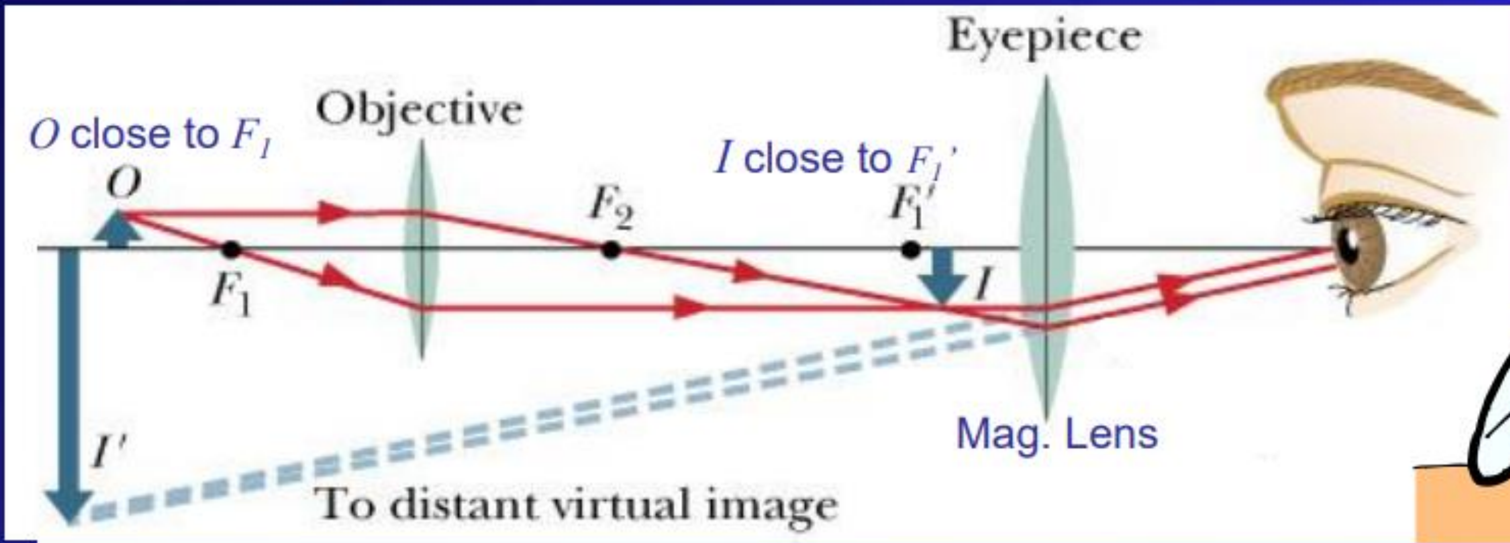
(In this case, angular magnification = linear magnification.)


Some examples of the lens arrangements
in common optical instruments
Simple
Magnifier
h
o
Telephoto Lens
Astronomical Telescope
Compound Microscope
Galilean Telescope

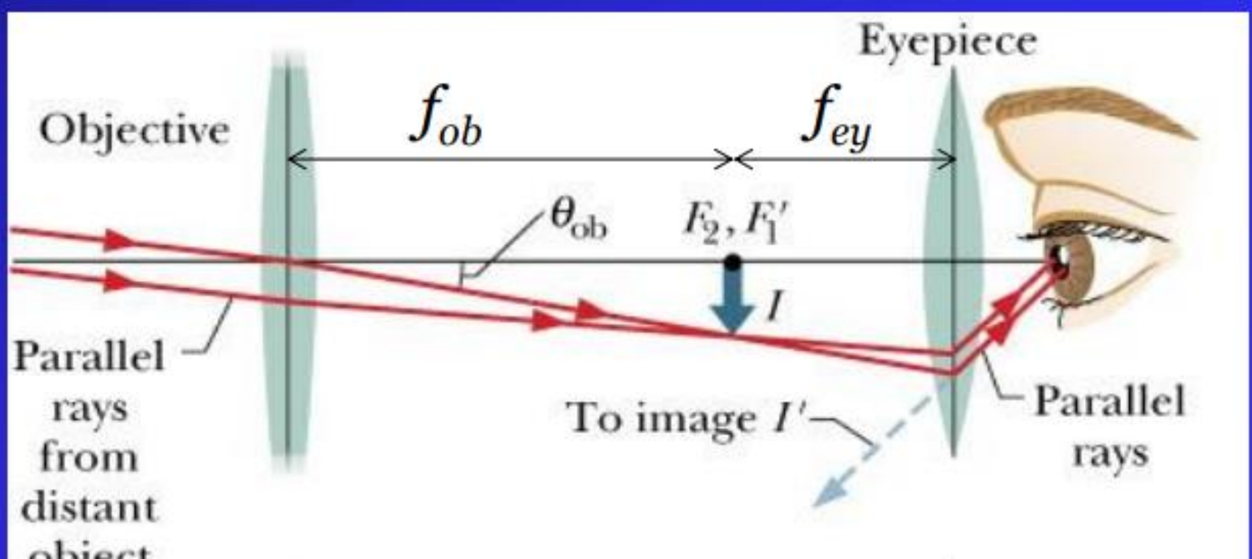


Optical Instruments प्रकाशिक यंत्र
Periscope परिदर्शी
Magnifying Glass आवर्धक लेन्स
Microscope सूक्ष्मदर्शी
Binoculars द्विनेत्री
Telescope दूरदर्शक
Camera कैमरा
Projector प्रक्षेपित्र

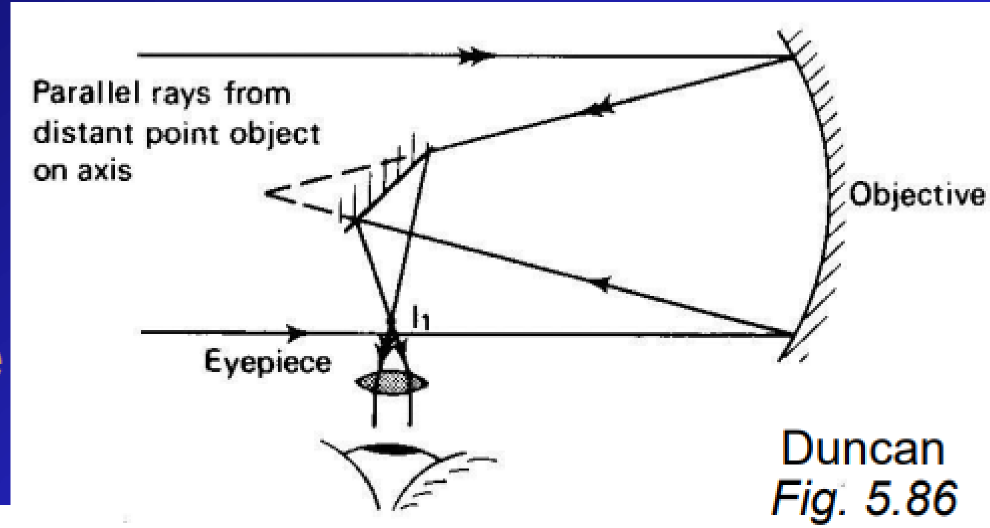
Microscope : Produces an enlarged, virtual image of a small objec



Telescope: produces a near image of a distant object



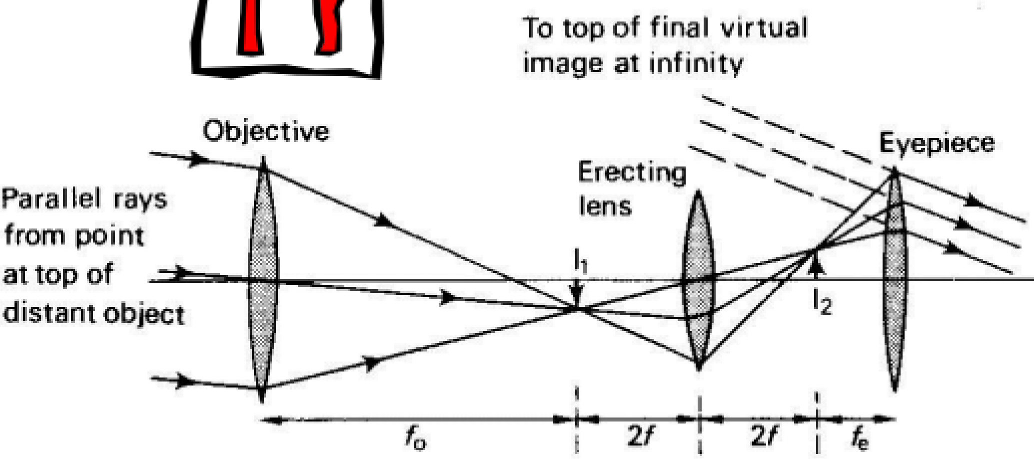
Other Types of Telescope:



Duncan
Fig. 5.86

Reflecting Telescope

Modern astronomical telescopes use a parabolic *mirror* in place of the objective lens.



Terrestrial Telescope

An extra 'erecting' lens is inserted.

Prism Binoculars

Reflecting prisms between the objective and eyepiece make the image erect and increase the effective length.