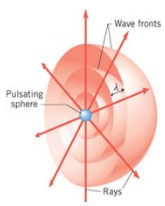
Chapter 25 The reflection of light

Goals for Chapter 25

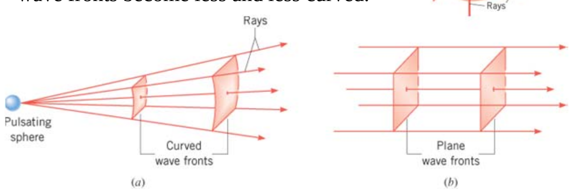
- **To study reflections from a plane mirror.**
- **To study reflections from a spherical mirror.**
- **To understand ray tracing and image formation.**
- **To understand mirror equation**
- **To study magnification equation**

25.1 Wave Fronts and Rays

A hemispherical view of a sound wave emitted by a pulsating sphere.
The rays are perpendicular to the wave fronts.



At large distances from the source, the wave fronts become less and less curved.

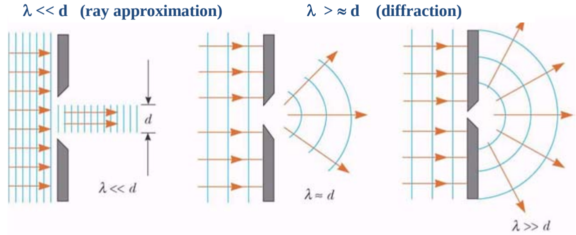


Geometrical Optics

Light can be described using geometrical optics as long as the objects with which it interacts are much larger than the wavelength of the light.

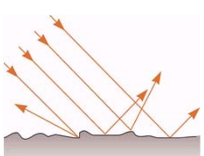
This can be described using geometrical optics
$\lambda << d$ (ray approximation)

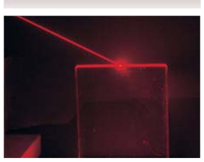
This requires the use of full wave optics (Maxwell's equations)
$\lambda > \approx d$ (diffraction)



25.2 The reflection of light

- **A ray of light, the *incident ray*, travels in a medium**
- **When it encounters a boundary with a second medium, part of the incident ray is *reflected* back into the first medium**

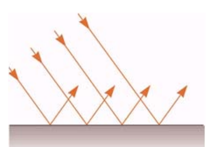




- **Diffuse reflection**
  is reflection from a rough surface
- **The reflected rays travel in a variety of directions**
- **A surface behaves as a smooth surface as long as the surface variations are much smaller than the wavelength of the light**

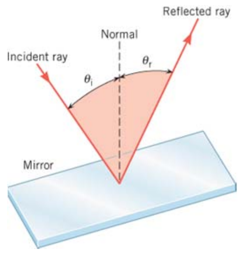
25.2 The reflection of light

- **A ray of light, the *incident ray*, travels in a medium**
- **When it encounters a boundary with a second medium, part of the incident ray is *reflected* back into the first medium**



- **Specular reflection**
  is reflection from a smooth surface
- **The reflected rays are parallel to each other**
- **All reflection in this text is assumed to be specular**

The Law of Reflection



- The normal is a line perpendicular to the surface
- The incident ray makes an angle of θ_1 with the normal
- The reflected ray makes an angle of θ_1' with the normal

The incident ray, the reflected ray, and the normal to the surface all lie in the same plane, and the angle of incidence equals the angle of reflection.

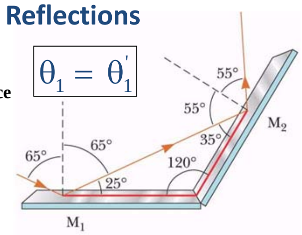
$$\theta_1 = \theta_1'$$

Multiple Reflections

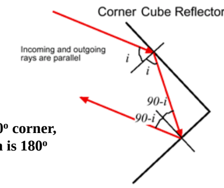
- 2 reflections on the 2 mirrors
- Apply the law of reflection twice

$$\theta_1 = \theta_1'$$

- Retroreflection: If the angle between the 2 mirrors is 90º, the reflected beam returns to the source parallel to its original path



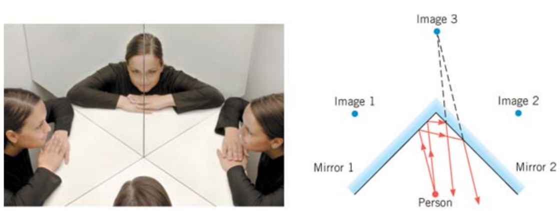
A retroreflector:
device to send light or other radiation back regardless of angle of incidence



For 90º corner, return is 180º

Example: Multiple Reflections

A person is sitting in front of two mirrors that intersect at a right angle. The person sees three images of herself. Why are there three, rather than two, images?



(a) (b)

Image Formation

We'll stick to geometrical optics: light propagates in straight lines until its direction is changed by reflection or refraction.

When we see an object directly, light comes to us straight from the object.

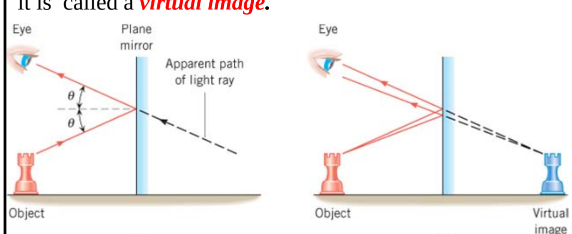
When we use mirrors and lenses, we see light that seems to come straight from the object but actually doesn't.

Thus we see an image, which may have a different position, size, or shape than the actual object.

25.3 Formation of Images by a Plane Mirror

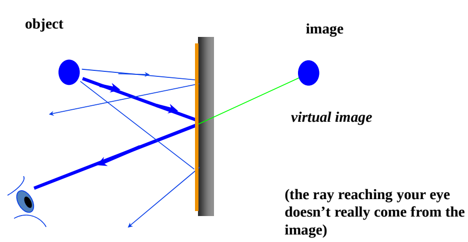
A ray of light from the top of the chess piece reflects from the mirror.
To the eye, the ray seems to come from behind the mirror.

Because none of the rays actually emanate from the image, it is called a ***virtual image***.



(a) (b)

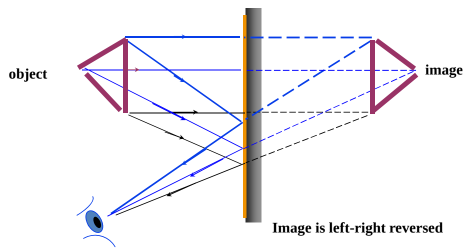
Images formed by plane mirrors



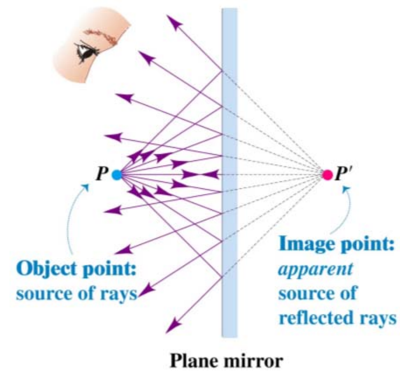
Your brain thinks the ray came from the image.

Images formed by plane mirrors

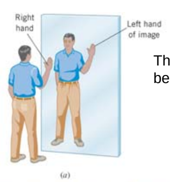
You can locate each point on the image with two rays.



Reflections at a plane surface



Formation of Images by a Plane Mirror

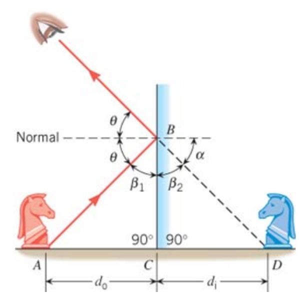


The person's right hand becomes the image's left hand.

The image formed by a plane mirror has three properties:

1. It is upright.
2. It is the same size as you are.
3. The image is as far behind the mirror are you are in front of it.

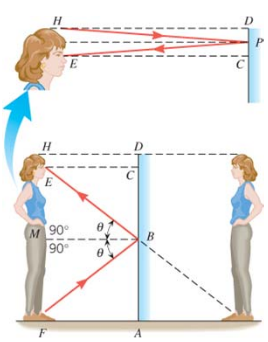
Formation of Images by a Plane Mirror



The geometry used to show that the image distance is equal to the object distance.

Example: Full-Length versus Half-Length Mirrors

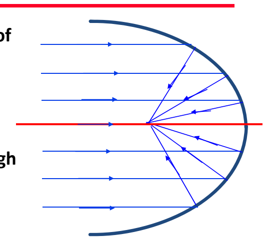
What is the minimum mirror height necessary for her to see her full image?



Mirror height has to be equal to her height

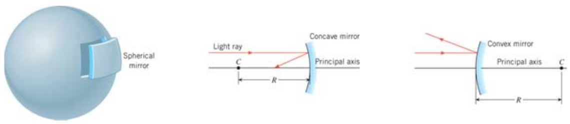
Ideal mirror---------Parabolic Mirror

- **Shape the mirror into a parabola of rotation (In one plane it has cross section given by $y = x^2$).**
- **All light going into such a mirror parallel to the principal axis of rotation is reflected to pass through a common point - the focus.**
- **What about the reverse?**



- **These present the concept of a focal point - the point to which the mirror brings a set of parallel rays together.**
- **Parallel rays come from objects that are very far away.**
- **Parabolas are hard to make. It's much easier to make spherical mirror, so that's what we'll examine next.**

25.4 Spherical Mirror

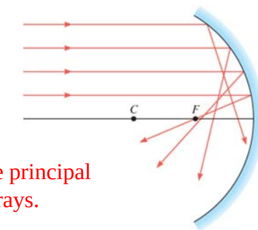


If the inside surface of the spherical mirror is polished, it is a ***concave mirror.*** If the outside surface is polished, is it a ***convex mirror.***

The law of reflection applies, just as it does for a plane mirror.

The ***principal axis*** of the mirror is a straight line drawn through the center and the midpoint of the mirror.

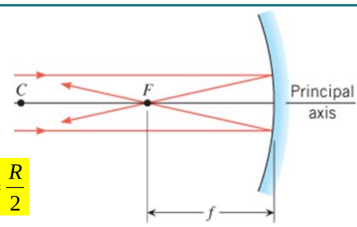
25.4 Spherical Mirror



Rays that lie close to the principal axis are called paraxial rays.

Rays that are far from the principal axis do not converge to a single point. The fact that a spherical mirror does not bring all parallel rays to a single point is known as ***spherical abberation.***

25.4 Spherical Mirror

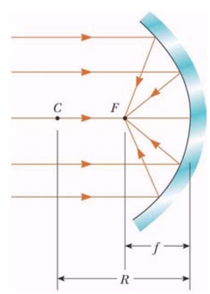


$f = \frac{R}{2}$

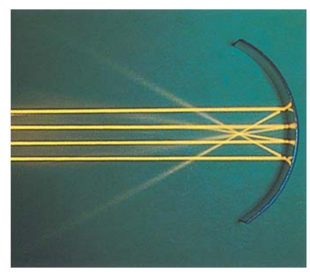
Light rays near and parallel to the principal axis (called paraxial rays) are reflected from the concave mirror and converge at the focal point.

The focal length is the distance between the focal point and the mirror.

Concave Mirror (spherical)

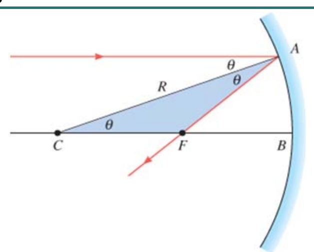


Concave mirror of radius R. The center of curvature C is located on the principal axis. The focal point F is also located on the principal axis.



Paraxial rays reflected from a concave mirror, converge to a focal point.

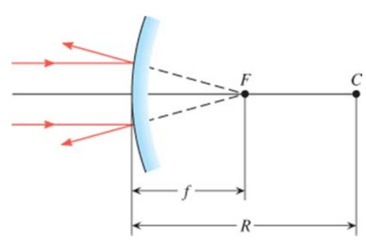
Focal length of a concave mirror



The focal point of a concave mirror is halfway between the center of curvature of the mirror C and the center of the mirror at B.

$$f = \tfrac{1}{2}R$$

Focal length of a convex mirror

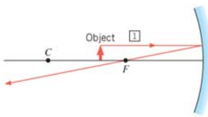


When paraxial light rays that are parallel to the principal axis strike a convex mirror, the rays appear to originate from the focal point.

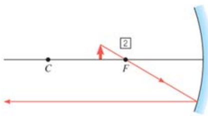
$$f = -\tfrac{1}{2}R$$

25.5 Formation of images by spherical mirrors

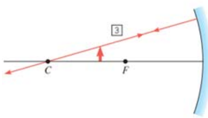
CONCAVE MIRRORS



This ray is initially parallel to the principal axis and passes through the focal point.



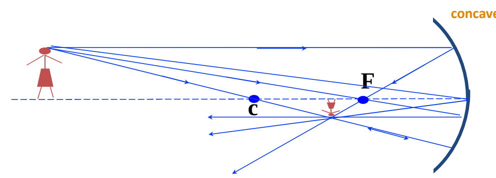
This ray initially passes through the focal point, then emerges parallel to the principal axis.



This ray travels along a line that passes through the center.

Spherical Mirrors

To analyze how a spherical mirror works we draw some special rays, apply the law of reflection where they strike the spherical surface, and find out where they intersect.

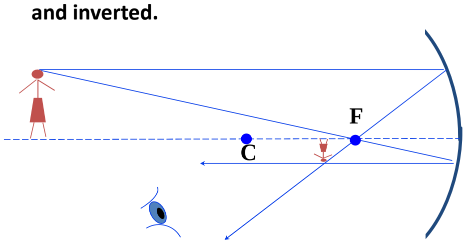


A ray passing through the center of curvature c, returns on itself.
A ray parallel to the mirror axis reflects through the focal point F.
A ray passing through the focal point reflects parallel to the axis.
A ray that strikes the center of the mirror reflects symmetrically according to law of reflection.

Concave Mirrors

When the object is beyond the center of curvature C, the image is:

real (on the same side as the object), reduced, and inverted.



Concave Mirrors

Object between C and F.

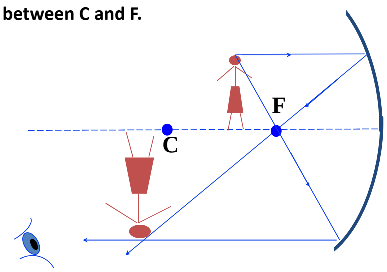


Image is real, inverted, magnified

Concave Mirrors

Object between F and the mirror.

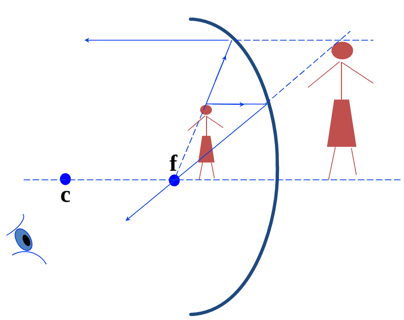
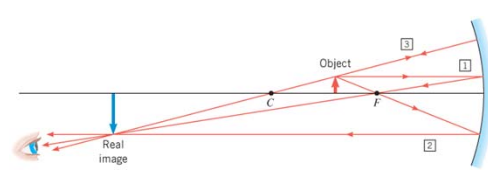
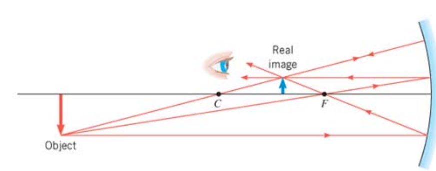


Image is virtual, upright, magnified

Image formation and the principle of reversibility

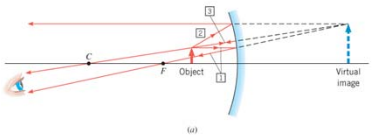


(a)



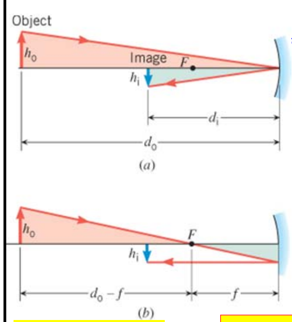
(b)

Formation of images by spherical mirrors



When an object is located between the focal point and a concave mirror, and enlarged, upright, and virtual image is produced.

25.6 Mirror equation and magnification



f = focal length

d_o = object distance

d_i = image distance

m = magnification

$$\frac{h_o}{-h_i} = \frac{d_o}{d_i}$$

$$\frac{h_o}{-h_i} = \frac{d_o - f}{f}$$

$$\Rightarrow \frac{d_o}{d_i} = \frac{d_o - f}{f}$$

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

Example 4: Virtual image formed by convex mirror

A convex mirror is used to reflect light from an object placed 66 cm in front of the mirror. The focal length of the mirror is f = -46 cm. Find (a) the location of the image and (b) the magnification.

$$\frac{1}{d_i} + \frac{1}{d_o} = \frac{1}{f} \quad \Rightarrow \quad \frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o} = \frac{1}{-46\text{ cm}} - \frac{1}{66\text{ cm}}$$

$$= -0.037\text{ cm}^{-1}$$

$$\Rightarrow \quad d_i = -27 \text{ cm}$$

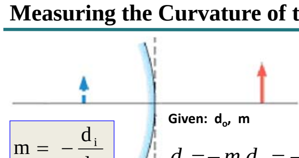
$$m = \frac{\text{Image height } h_i}{\text{Object height } h_o} = -\frac{d_i}{d_o} \quad \Rightarrow \quad m = -\frac{-27\text{cm}}{66\text{ cm}} = 0.41$$

Measuring the Curvature of the Cornea of the Eye

A contact lens rests against the cornea of the eye. An optometrist uses a keratometer to measure the radius of curvature of the cornea, thereby ensuring that the prescribed lenses fit accurately. In the keratometer, light from an illuminated object reflects from the corneal surface, which acts like a convex mirror and forms an upright virtual image that is smaller than the object.

With the object placed 9.0 cm in front of the cornea, the magnification of the corneal surface is measured to be 0.046. Determine the radius of the cornea.

Measuring the Curvature of the Cornea of the Eye



$$f = -\frac{|R|}{2} = \frac{R}{2} \qquad R < 0$$

Given: d_o, m

$$m = -\frac{d_i}{d_o}$$

$$d_i = -m\, d_o = -(0.046)(9.0cm) = -0.414cm$$

$$\frac{1}{d_i} + \frac{1}{d_o} = \frac{1}{f} \qquad \frac{1}{-0.414} + \frac{1}{9.0} = \frac{1}{f}, \quad f = -0.434 \ cm$$

$$\Rightarrow \quad |R| = -2\ f = 0.87\ cm$$

Summary of Sign Conventions for Spherical Mirrors

Focal length

f is + for a concave mirror.

f is - for a convex mirror.

Object distance

d_o is + if the object is in front of the mirror (real object).

d_o is - if the object is behind the mirror (virtual object).*

Image distance

d_i is + if the image is in front of the mirror (real image).

d_i is - if the image is behind the mirror (virtual image).

Magnification

m is + for an image that is upright with respect to the object.

m is - for an image that is inverted with respect to the object.