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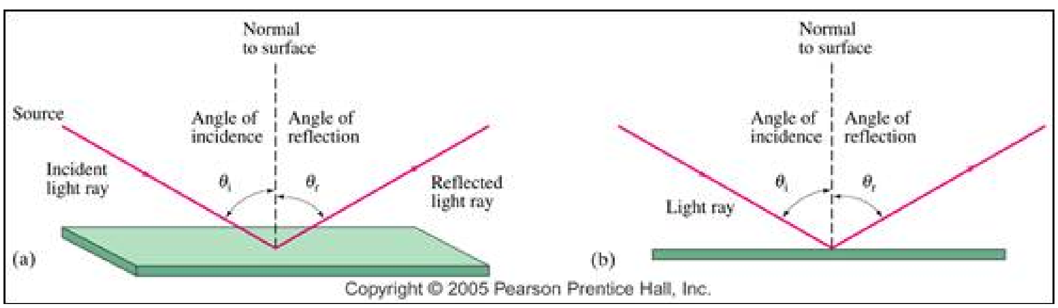
PROPERTIES OF LIGHT

Unit Overview

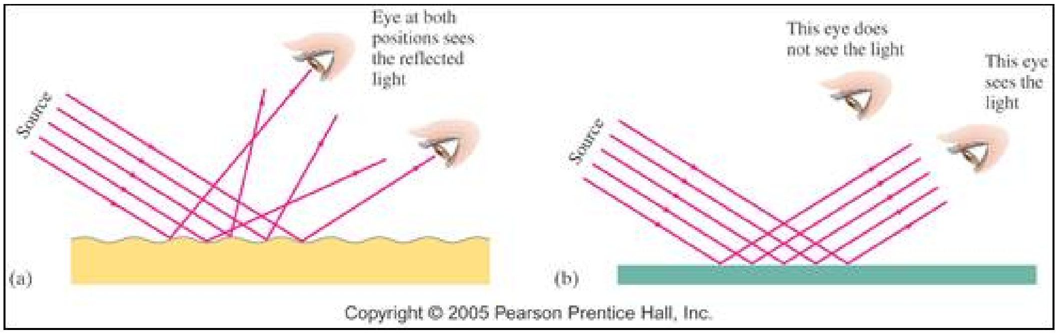
Now we know how light moves as a transverse wave, that speed depends on frequency and wavelength, we are now going to learn about how the speed or direction of light can change when different mediums get into it's path or as it is reflected off of a mirror. We have talked about the speed of light as it is traveling through air, but what about as it travels through water? Glass? These are all concepts that we are going to explore in this unit.

Reflection

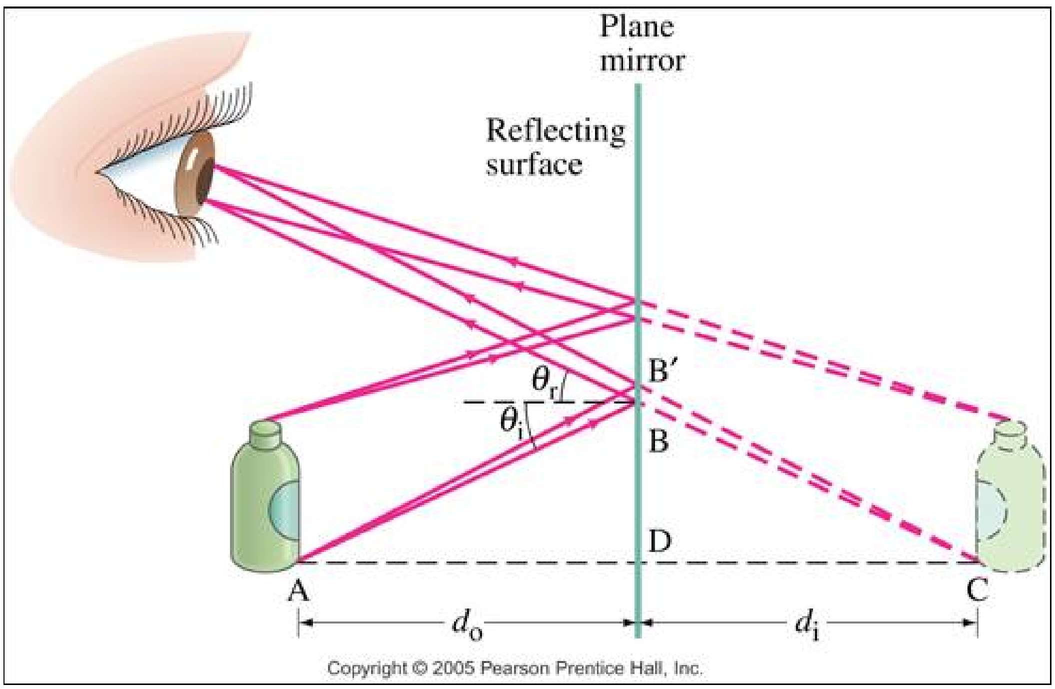
Light travels as a transverse wave in a straight line. The assumption that light travels in a straight path for most circumstances is called the ***ray model of light***. This model calls light's straight path a ***ray***, or an extremely narrow beam of light. As light rays strike the surface of an object, some light rays are always reflected, and some are absorbed by the object and converted to thermal energy. In this section we are going to focus on the light that is reflected. For shiny objects, like a mirror, 95% of light rays bounce off of the mirror and are reflected. When a light ray strikes a flat surface, like a mirror, the ***angle of incidence*** is the angle at which the light hits the mirror. An imaginary line that is perpendicular to the mirror is known as the ***normal line***. We will be using the normal line as a reference point. The angle at which light is reflected in relation to the normal line is known as the ***angle of reflection.*** The ***law of reflection*** states that the angle of incidence and the angle of reflection are always equal to one another, as seen in the picture below.



If light is shined on a rough surface, it will be reflected in many different directions and angles to the normal. This scattered reflection is called ***diffuse reflection***. Notice in the picture below the difference between a rough surface and perfectly flat, smooth surface.



When you look into a mirror, you see various objects that appear to be beyond the mirror, on the other side. But we all know this isn't true, the images are in front of the mirror, not behind the mirror. A mirror that has a smooth flat surface is called a plane mirror. The picture below shows what is happening to light rays as they bounce off of a mirror in order for us to see our reflection.



Looking at the picture above, light reflected from the bottle at two different points, hits the mirror and is reflected to the eye of the observer. This allows the observer to actually see the bottle in the mirror.

The bottle to the left is the placement of the actual bottle in front of the mirror. The bottle that we are actually seeing, or appear to be seeing, is the one of the right. So the bottle on the left is known as the ***real image*** and the bottle or the right is known as the ***virtual image.*** The image distance d_i is the same as the object distance d_o.

Knowing that the lines in the picture, ADB make a right angle, and the black dotted line is the normal line, we can find the angle of incidence and the angle of reflection. We will use this strategy in the example problem below.

Example: using a plane mirror to see an image

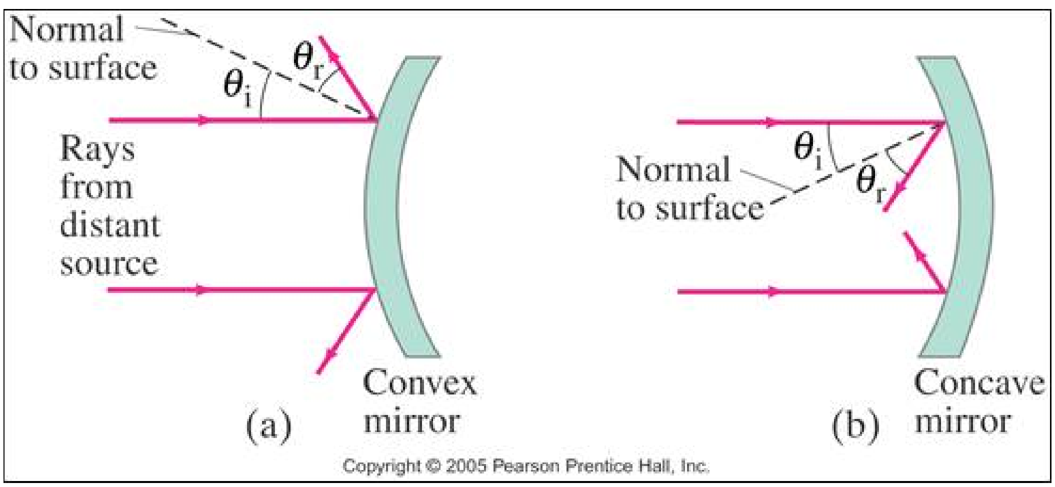
A child who is 1 meter tall stands in front of a plane mirror. What is the minimum height of the mirror, and how high must its lower edge be above the floor if she is able to see her whole body, assuming her eyes are 8 cm below the top of her head

Okay the first thing that you must do is draw a picture showing the light rays. Her eyes are approximately 92 cm or .92 m. above the ground. Where the child looks in the mirror to see her feet is half of the distance from her eyes to her feet. This is because the angle of incidence (her eye hitting the mirror) is the same as the angle of reflection (the mirror to her feet). Therefore the mirror does not need to be placed from her feet to half of the height from her eyes to her feet which is .92/2 = .46 cm off of the ground. So *the bottom of the mirror is placed at 46 cm from the ground.*

The same reasoning as the child being able to see her feet is used to see the top of her head. So if her eyes are 8 cm from the top of her head, the mirror needs to be 4 cm above her eyes. So *the top of the mirror must be placed 96 cm off of the ground.*

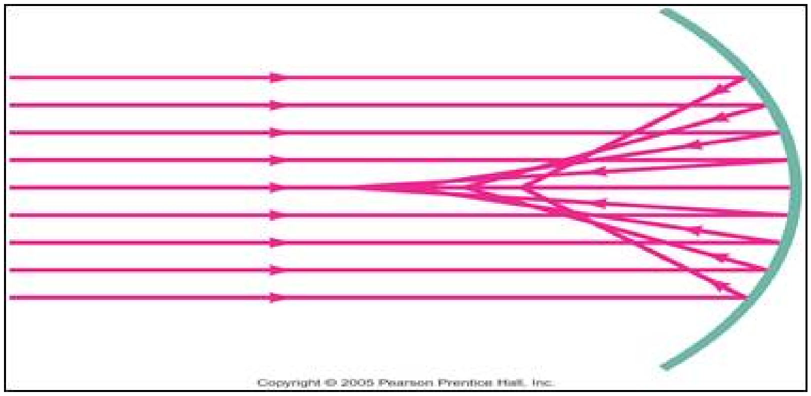
Spherical Mirrors

Not all mirrors are perfectly flat or plane, some are curved and resemble sections of a sphere. If a mirror is called ***convex***, this means that the reflection occurs on the outer surface of the mirror that bulges out towards the person looking into it. If the center of the mirror is going away from the viewer, this is called ***concave***. Because of the mirrors shape, they will produce different images from one another, as well as a different image opposed to looking at a plane mirror. When looking into a convex mirror, it will reduce the size of the images allowing the mirror to show a larger field of view. A concave mirror will magnify the image.

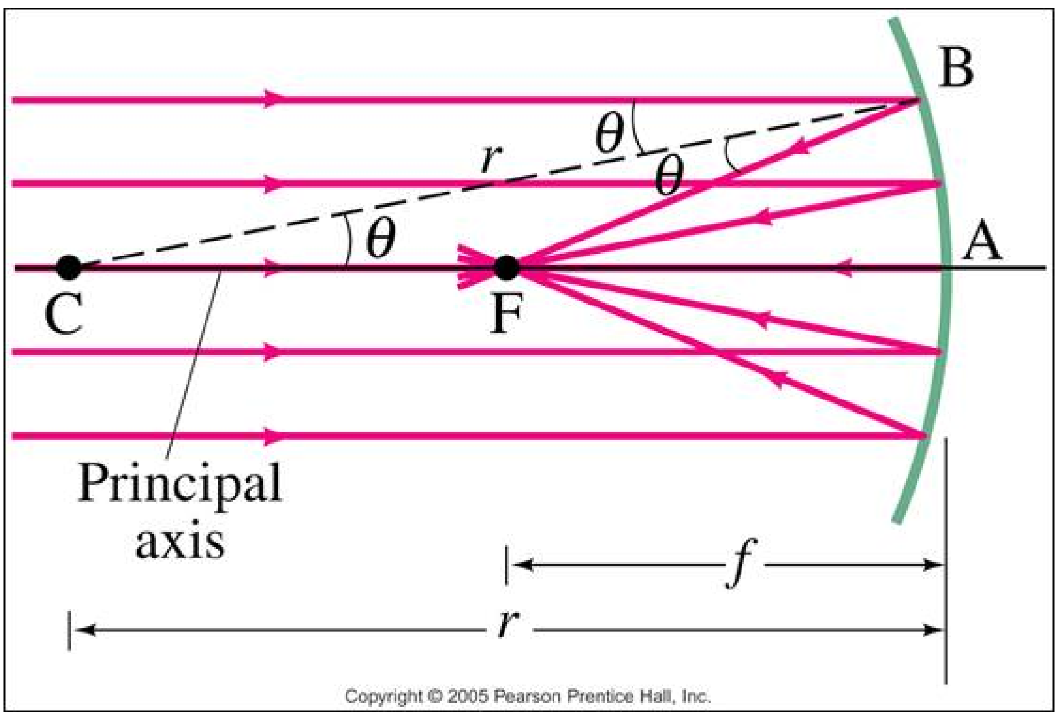


In the picture above, notice the black dotted normal line is still perpendicular to the surface and the incident and reflective angles are the same.

In order to understand how spherical mirrors change the image that you see when you look into it, we need to look at the path of the light rays coming in and reflecting from the mirror. Light rays coming off of an object and striking a spherical mirror are almost always parallel when they reach the mirror. For a concave mirror, the rays bouncing off of the mirror converge at a single point almost in the center of the mirror. Where the reflected rays cross each other, it is called the ***focus.*** If the mirror is larger with a greater curvature, not all rays will intersect at the focus point. This occurrence is called a ***spherical abrasion***. As seen below



If the curvature of the mirror is smaller then the focus is much more precise and all light rays will reflect and meet at the focus like the picture below



In the picture above, F will always represent the focal point where all lines meet when reflected from a spherical mirror. The dark line that is labeled as the ***principle axis*** indicates the line that all other light rays are parallel to and is perfectly in the center of mirror and this line is labeled CA. The distance between the focal point and the center of the mirror (FA) is the focal length, labeled *f*. The radial distance of the waves is from point C to A and is labeled *r* above.

Calculating the Focal Point

In order to calculate the focal point we need to look at the light rays coming in. Specifically, the top ray that strikes point B on the mirror. The black dashed line is showing the normal line, or perpendicular line, of the mirror at point B. Remember that C is the center of the curvature. The dashed line that connects points B and C is equal in distance to *r*, the radius of curvature. The incoming ray that hits the mirror at B makes an angle with this normal dashed line and the reflected ray BF also makes an angle to the normal. These angles are the same according to the law of reflection and are labeled, θ**,** in the picture above. Notice also in the picture, that BCF is also labeled as the same angle θ. Because these angles are the same, this means that the distance from C to F is the same distance from B to F. So CF = BF and this also means then that the distance from FB is the same distance as FA or *f*. CA is equal to 2 C X FA which is *r*. Therefore the focal length is half the radius of curvature.

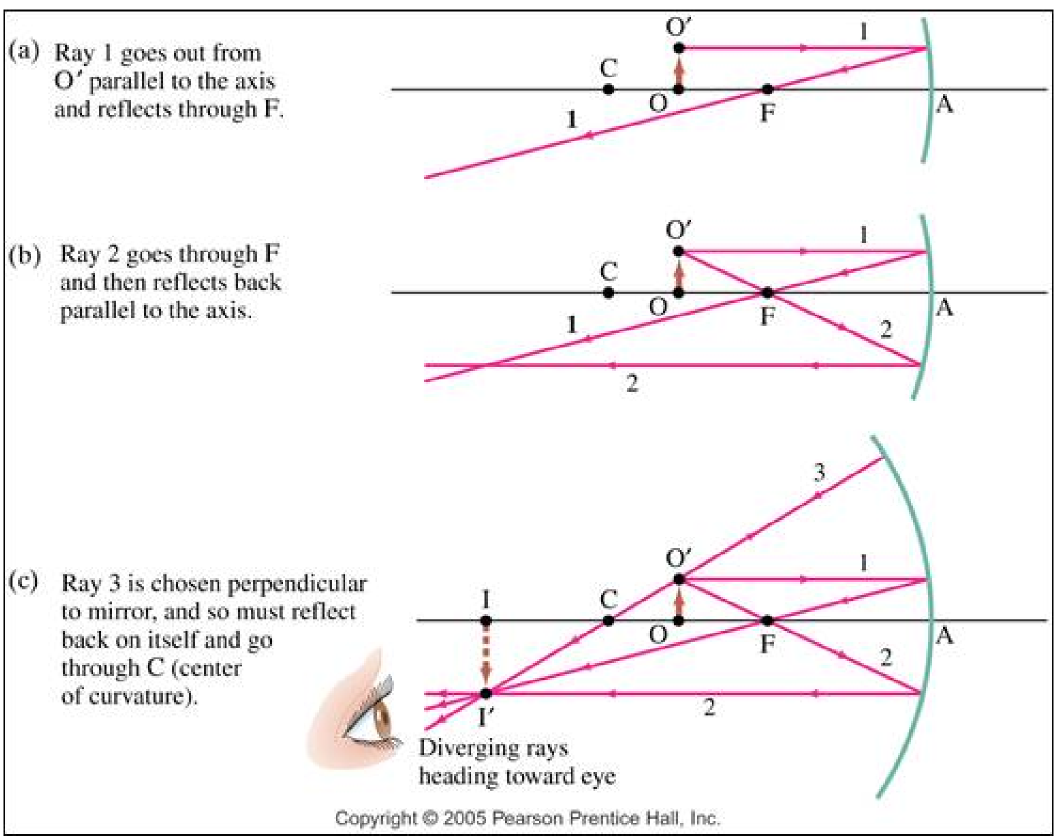
Simplifying it into the equation below:

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

We use ray diagrams to determine where an image will be. For mirrors, we use three key rays, all of which begin on the object:

1. A ray parallel to the axis; after reflection it passes through the focal point
2. A ray through the focal point; after reflection it is parallel to the axis
3. A ray perpendicular to the mirror; it reflects back on itself

(see the image below for clarification)

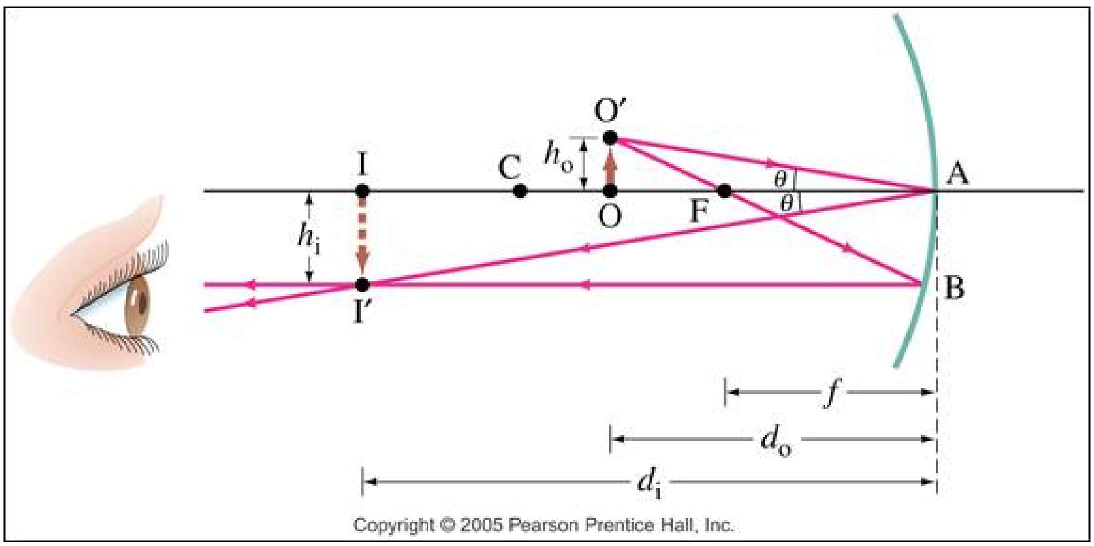


In the picture of, diagram (c), showing the intersection of all three rays, it also shows a point on an object which is the *real image* placed in front of the mirror, or where all rays will be directed toward your eye.

If we want to see the entire real image and not just a point on it, we can form an equation used to find the image distance of you have two or more points on a mirror. To do this, the equation must relate the object distance, the image distance and the focal length of the mirror.

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

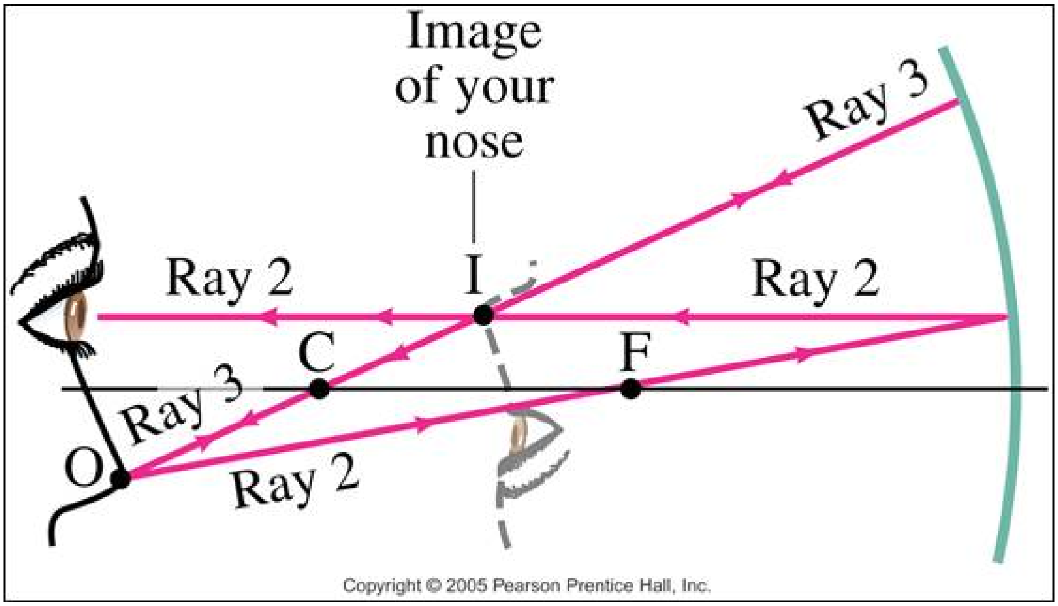
The picture below shows these distances all together. The above equation is called the ***mirror equation*** and relates the object and image distances to the focal length, which remember is $r/2$.



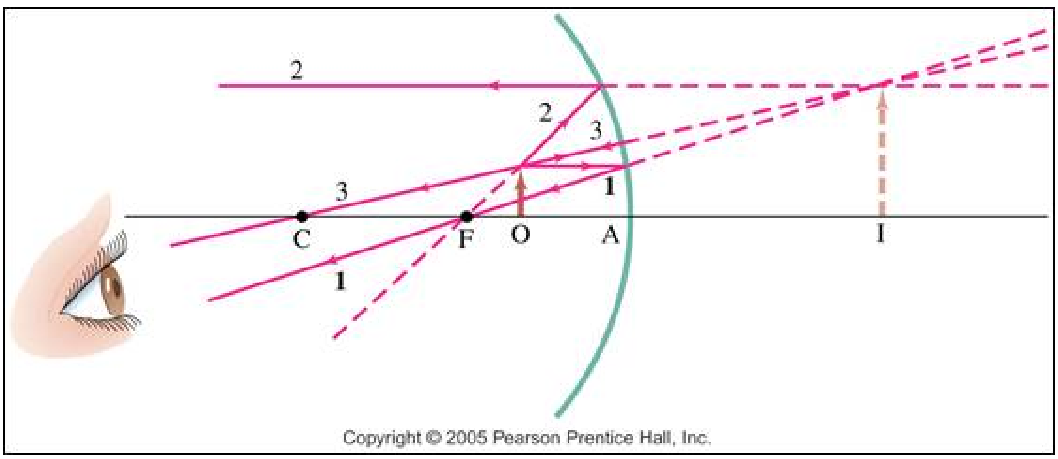
The magnification, m, of a mirror can be found by dividing the height of the image by the height of the object which is also related to distances.   So our magnification equation is the following.

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

The negative sign just means that the image in inverted. This object, O, is between the center of curvature, C, and the focal point, F, and its image is larger, inverted, and real. If the object, O, is not in between C and F it will appear smaller, inverted and real. The diagram will look like the one below.



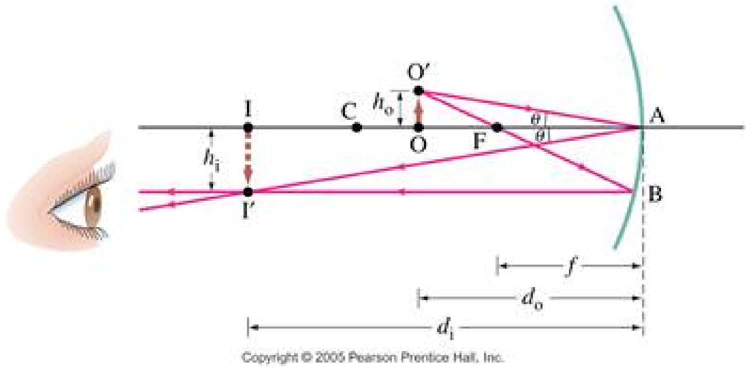
If an object is inside the focal point, its image will be upright, larger, and virtual. As seen in the picture below.



EXAMPLE
1. A 1.3 cm high wad of paper is placed 18.0 cm away from a concave mirror with a radius curvature of 25 cm. Determine (A) the position of the image and (B) the size of the image.

A. GIVEN	SOLVING FOR
Object height = 1.3 cm	position of image, d_i =?
d_o = 18.0 cm	
r = 25 cm	

The object is between C and F so a diagram that we would draw would look like…



which means we can use our mirror equation to solve for d*i*.

$1/d_o + 1/d_i = 1/f$ *and* f is $r/2$. Which is 25 / 2 = 12.5 cm

$1/18 + 1/d_i = 1/12.5$
solving for di we get
$1/d_i = 1/12.5 - 1/18$
$1/d_i = .024$
$d_i = 1/.024$
d_i = 40.9 cm from the mirror

B. Now that we know where the image is located we can find how much it is magnified which then we can figure out it's size.

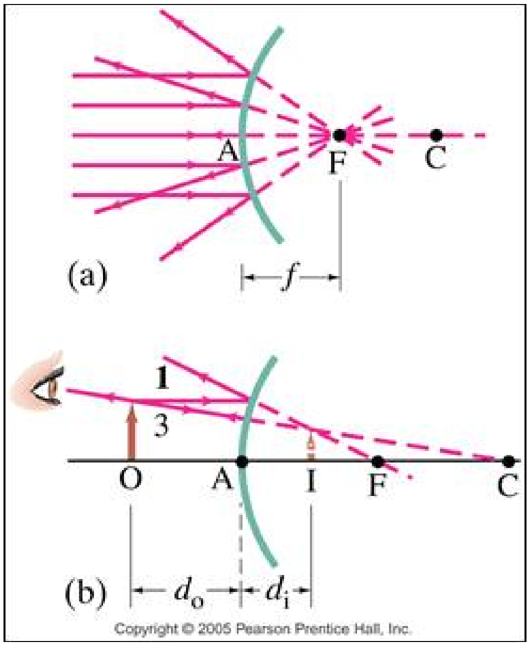
$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

so $m = -d_I / d_o$
$m = -40.9 / 18$
$m = -2.27$ times bigger

So the image height is 2.27 times the object height.
Height of image is - 2.27(1.3) =**- 2.95 cm,** the negative sign reminds us that the image is inverted.

Convex Mirrors

Solving for convex mirrors is very similar to concave mirrors. In the case of a convex mirror, the rays diverge instead on come together when they are reflected off of the mirror. So now we have to think if terms of the rays coming from behind the mirror. The focal point, F, comes from behind the mirror, as well as the focal length, *f*. No matter where the object is placed on in front of a convex mirror, the image is always upright and virtual. To find the image we will draw rays 1 and 3 that we drew earlier for concave mirrors. Because these lines don't actually pass behind the mirror, they are drawn as dotted lines. The focal length, *f*, is always negative when solving for convex mirrors, as well as the radius of curvature. C.



We will be using the same mirror equation as before.
Problem Solving Tips:

1. Draw a ray diagram; the image is where the rays intersect.
2. Apply the mirror and magnification equations.
3. Sign conventions: if the object, image, or focal point is on the reflective side of the mirror, its distance is positive, and negative otherwise. Magnification is positive if image is upright, negative otherwise.
4. Check that your solution agrees with the ray diagram.

EXAMPLE
A side mirror on the outside of a car is a convex mirror with a radius of curvature of 15.0 m. Determine the (A) location of the image and its (B) magnification for an object 9.0 m from the mirror.

(A) GIVEN
r = -15 meters (because it is behind the mirror)
f = -7.5 m
d_o = 9 m

SOLVING FOR
location of image (d_i) =?

EQUATION
$1/d_o + 1/d_i = 1/f$
solving for di
$d_i = 1 / (1/f - 1/d_o)$
$d_i = 1 / (1/-7.5 – 1/9)$
$d_i = 1 / (-.2444)$
d_i = **-4.1 m** → this is negative, meaning the image is behind the mirror

(B) $m = - di/ d_o$
$m = - (-4.1 / 9)$
m = .45 + → this is a positive magnification meaning the image is upright and less than half as tall as the object.

Refraction

We learned in unit 28 that the speed of light is approximately 3 $X10^8$ m/s in a vacuum. We also learned that this speed applies to all electromagnetic waves. In air the speed of light is slightly less than in a vacuum. When light travels through water, the speed decreases to 3/4c. The ratio of the speed of light in a vacuum compared the speed of light traveling through different mediums is known as the ***index of refraction, n,*** of that material. In order to find the index of refraction we can use the equation below.

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

Below is a chart showing various indices of refraction depending upon the medium that the waves are traveling through, which are never less than 1, because 3 $X10^8$ m/s, is the absolute fastest light can travel, it only slows down from there.

Snell's Law

TABLE 23–1
Indices of Refraction[†]

Medium	$n = c/v$
Vacuum	1.0000
Air (at STP)	1.0003
Water	1.33
Ethyl alcohol	1.36
Glass	
Fused quartz	1.46
Crown glass	1.52
Light flint	1.58
Lucite or Plexiglas	1.51
Sodium chloride	1.53
Diamond	2.42

[†] $\lambda = 589$ nm.

EXAMPLE

Calculate the speed of light in Plexiglas

Equation

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

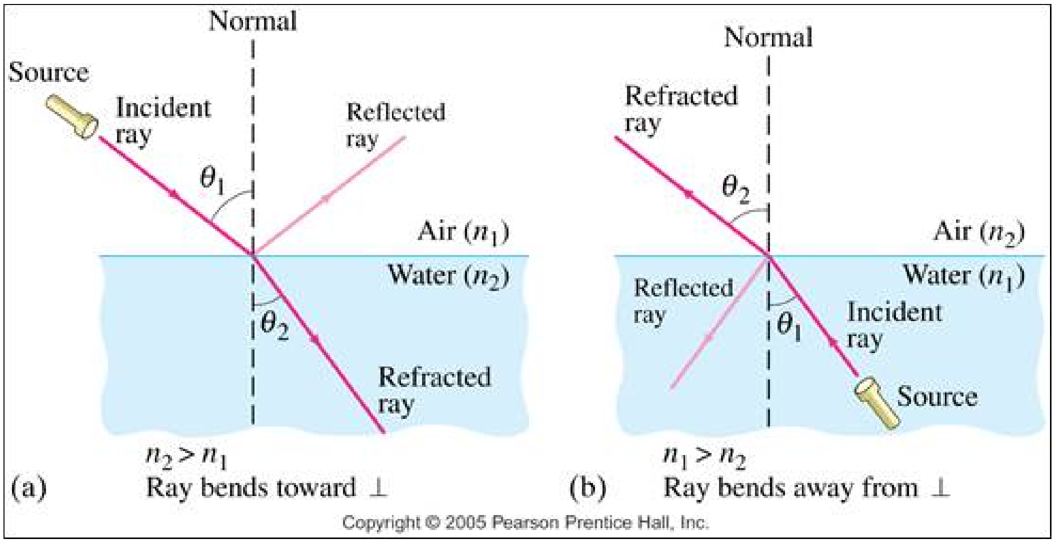
We can look up the index of refraction of Plexiglas in the chart above, which is 1.51, and the speed of light is 3 X10^8 m/s.

$1.51 = 3\text{ X}10^8 / v$

$\mathbf{v = 1.98 \text{ X } 10^8}$ **m/s**

Snell's Law

When light travels from one medium to another, some of the light is reflected at that boundary between mediums and some light travels through the new medium. If the incident ray hitting the boundary is at an angle at anything other than perpendicular, the ray changes direction as it enters the new medium because the speed of the ray is changing. This bending of light as it travels through a new medium is called ***refraction.*** The angle the outgoing ray makes with the normal is called the angle of refraction**.** The picture below shows the incident ray, the normal perpendicular line, the reflected ray as well as the refracted ray. Notice the light starts in air and enters water. Water is the new medium causing refraction.



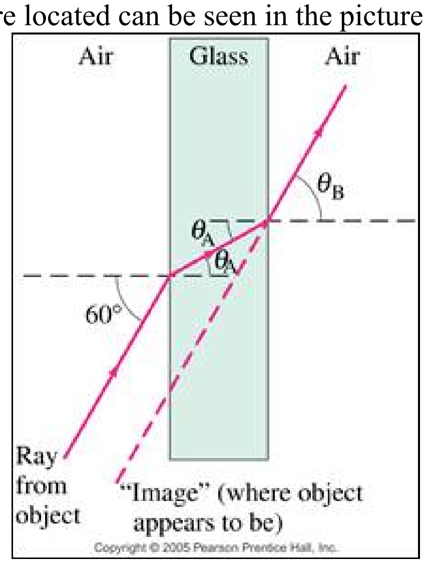
Notice above that the ray bends *towards* the normal line when it enters the water in diagram (a), this is ALWAYS the case when a ray enters a medium where light travels slower. Notices in diagram (b) the wave starts in water then enters air. As it travels in the air it bends *away* from the normal line. This is ALWAYS the case when light travels from a slower medium to a faster medium.

Refraction is what makes objects have submerged in a different medium look weird or cut in half.

The angle of refraction depends on the speed of light in the two different media and on the incident angle. A relationship between the incident angle and the refracted angle can be seen in Snell's equation:

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

An example of where these angles are located can be seen in the picture below



By examining Snell's equation, if the second medium has a greater index of refraction, then the second angle will be less than the first angle and the ray will be bent towards the normal.

EXAMPLES

Light traveling in air (n = 1) strikes a flat piece of glass with an incident angle of 60°. (A) What is the angle of refraction in the glass (n = 1.5)? And (B) what is the angle of the ray refracted out of the glass? (this scenario is shown in the picture above)

(A) GIVEN
n air = 1
n glass = 1.5
θi = 60

SOLVING FOR
θr in the glass =?

EQUATION

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

1(sin60) = 1.5 (sinθ)
.866 = 1.5 (sinθ)
.578 = sinθ
^{1}-sin (.578) = **35.2° towards the normal from air to glass**

(B) $n_1 \sin\theta_1 = n_2 \sin\theta_2$

(1.5) sin35.2 = 1(sinθ)
.871 = 1 (sinθ)
.871 = sinθ
^{1}-sin (.871) = θ
θ = 60°

A Look Ahead

In the next unit we will shift gears to learn about electricity, where we will focus on electric charge and electric field. We will learn what an electric charge is made from and how we can induce a charge on an object. We will also explore Coulomb's Law and how the distance between charges effects the force between them. Finally we will talk about the electric field and field lines.

Below are additional educational resources and activities for this unit.

Unit 30 Resource 1

Unit 30 Resource 2