

# AP PHYSICS – OPTICS

## LIGHT: (reflection, refraction, mirrors, lenses, diffraction/interference)

**Topics:** Plane mirrors, spherical mirrors (concave and convex), refraction, lenses (converging and diverging), multiple lens systems, diffraction, interference patterns through slits

### Worksheets/Labs/Quizzes:

1. Mirror Lab
2. Mirrors – Ray Diagram Practice
3. Index of refraction table
4. Refraction diagrams wksht
5. Mini labs (2) law of refraction / critical angle
6. Refraction Review
7. Concepts review – mirrors/refraction
8. Optics QUIZ mirrors/refraction
9. Multiple lenses 1
10. Multiple Lenses 2
11. Lenses wksht 3
12. Geo optics review
13. Unit Review sheet

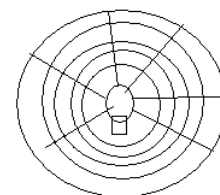
### Introduction:

Light has both wave and particle properties. We are going to look at the wave properties in this unit.

Another example of a wave is sound. If I talk, turned around, you still hear me. If I face one side of the room and talk, the other side still hears me. This is because waves naturally spread out as they propagate (travel).

Light is no different. For example, a light bulb, light propagates from the bulb in all directions.

If one follows a part of the wave, we can draw an arrow following its path. The line will be parallel to the wave front. This is called a Ray



**Ray** - An arrow drawn perpendicular to the wave front. The arrow points toward the direction of propagation of the wave.

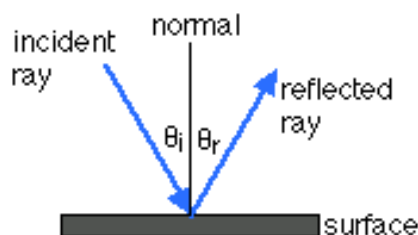
**Ray Diagram** – An easy way to visualize how waves reflect and refract.

Waves (Light waves in this case) can do three things:

Reflect, Refract, and Diffract

**Reflection:** The ray bounces off an object.

Law of Reflection: The angle of incidence = the angle of reflection.  $\theta_i = \theta_r$ .



law of reflection :  $\theta_r = \theta_i$

We base the angles on the “**Normal**”. Just like the normal force, the normal line is drawn Perpendicular to the surface.

The law of refraction is simply the conservation of momentum (It’s a collision at an angle).

Demo: Tennis ball bouncing off a surface, the incident = reflection

One can solve this as an angled collision

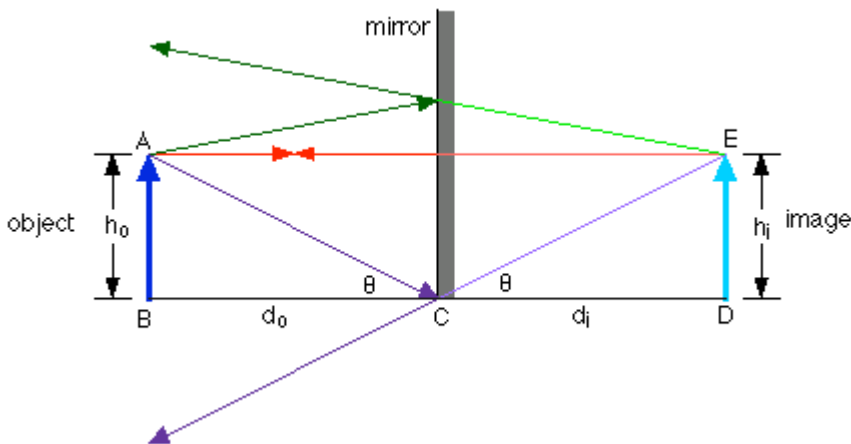
Lets look at Reflection with Mirrors:

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Plane Mirrors (flat mirrors)

With light, if one thinks of light bouncing off an object, it travels in all directions. When it hits an object, one that is not smooth, the rays will bounce at many different angles. (draw diagram)

However, if the surface is VERY smooth, the rays will all reflect obeying the law of reflection. The rays will bounce off and spread out. However, if we trace the reflected rays through the mirror, we notice all of the rays will intersect at a point, a focus. Anytime the points intersect, an image is formed.



Now, this image really doesn’t exist. It’s behind the mirror, in “virtual space”, the ”other side” or “Narnia”. This Image cannot be projected onto anything, you cant place the screen inside the mirror. This is called a Virtual image.

**Virtual image:** Image that cannot be focused onto a screen, or an image that forms behind the mirror.

**\*\*\* Anything on the virtual side of the mirror is considered negative (-)**

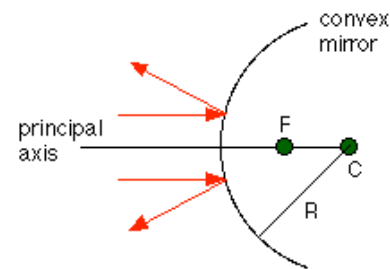
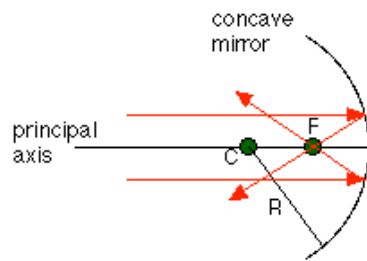
If we analyze the diagram, we can make a few properties for a plane (flat) mirror:

1. Image is upright
  2. Image is same size as the object (magnification  $m = 1$ )
  3. Image is the same distance form the mirror as the object appears to be. (Image distance = object distance)
  4. Image is Virtual
-

Spherical Mirrors – like the ones on sharp corners on roads, in grocery stores, etc...

A spherical mirror is simply a piece of a mirrored sphere. Therefore it has a radius, center point, circumference, etc...

Lets make ray diagrams:



### Terminology of spherical

**Concave** – s. mirrors that light (caved inward)

**Convex** – s. mirrors that diverge the light (bent outward)

C – center of curvature - center of the sphere

R – radius of curvature – radius of the sphere

f – Focal Length – If make a very good ray diagram, one will notice  $f = 1/2R$ , half the radius.

The focal length is where the rays converge to form an image – all rays go through the focal point)

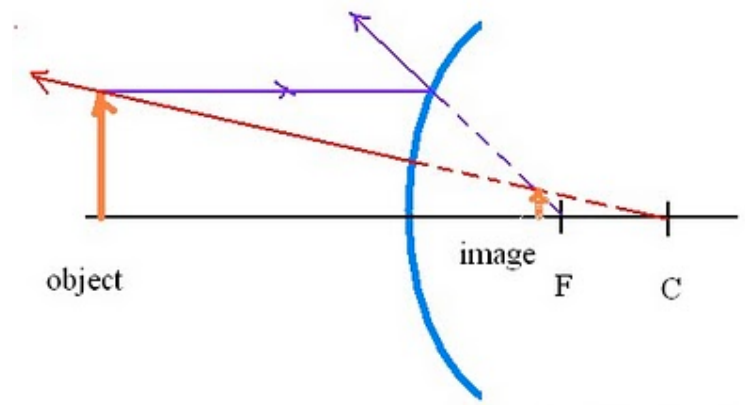
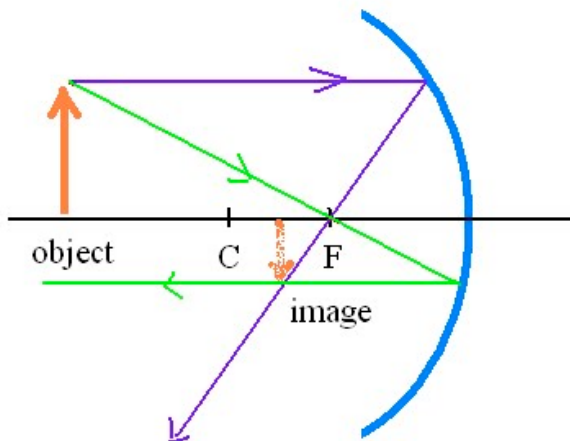
\*\*\*(If the above terms are on the Virtual side of the mirror, they are considered Negative (-). )

A good reason to make ray diagrams is to see where the image forms real or virtual, and which orientation it is upright or upside down)

Strategic Ray Diagrams – make 3 rays:

1. Parallel to axis – reflection will be through F
2. Through F – reflection will be parallel to axis
3. Through C – reflection will bounce back through C

The point where all 3 reflected rays converge is where the image will be formed. One can then tell if its real/virtual, upright/upside down, magnified, etc...



**mirrors:**  
converge the

## Mirror mini lab

Review of drawing ray diagrams

## Mirror worksheet 1 – ray diagrams

### Refraction:

If one has ever used a pool skimmer, gone fishing, played with a stick in the water one would notice objects in the water tend to bend. They are not where they are suppose to be. This is refraction.

The light rays are bending when they go from the air to the water.

Why?

Car demo: Think of a car that hits a mud puddle on the road. The tires that hit the puddle slow down (resistance), while the tires that don't, continue at the same speed.

If the left side hits the puddle, the left tires will slow, causing the car to rotate. Same thing happens when light enters a different medium, its speed slows, and if it enters at an angle, it will change direction, or refract.

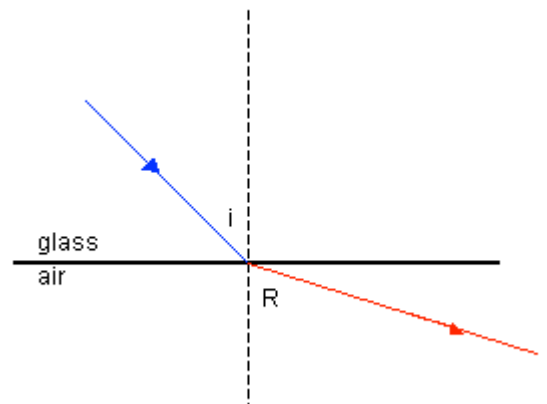
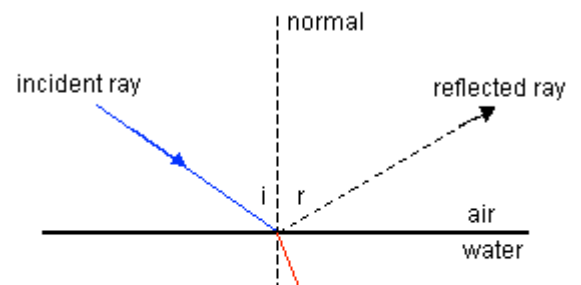
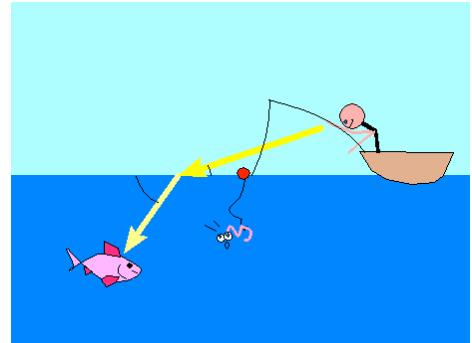
### Students with rulers/hallway refraction demo.

When a wave travels from one medium into another, the speed changes. This causes a change in direction, or refraction.

$i$  - angle of incidence  
 $r$  - angle of partial reflection  
 $R$  - angle of refraction

Light slows down as it passes from air to glass, and so bends toward the normal. Glass is a more optically dense medium.

Light speeds up as it passes from glass to air, and so bends away from the normal.



When light passes from one medium to another at  $0^\circ$ , or directly along the normal, no refraction occurs.

The relationship between these quantities, the change in speed, and angle is expressed in SNELL'S LAW

Snell studied refraction angles and different materials and came up with this relationship:

Snell's Law states:  $\sin i / \sin r = v_1 / v_2 = n_2 / n_1$

Usually it is solved as:

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

Remember, the angles are always measured from the NORMAL line.

Where  $n$  is the **index of refraction**. Every material has a different index of refraction.

Substance	Index of Refraction
Air (vacuum)	1.00
Water	1.33
Alcohol	1.36
Quartz	1.46
Lucite	1.50
Benzene	1.50
Glass – Crown	1.52
Plexiglas	1.55
Glass – Flint	1.61
Diamond	2.42

The **absolute index of refraction** is the  $n$  of a material when light travels from a vacuum into it.

$n$  for a vacuum is 1.00

So, the absolute index of refraction is defined as:

$n_2/n_1 = v_1/v_2 = c/v$  if  $n_1 = 1$ , we get  $n_2 = v_1/v_2$  or...

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

where  $c$  is the speed of light in a vacuum

$v$  is the speed of light in the medium

$n$  is the index of refraction

The speed of light in a vacuum is  $3.00 \times 10^8$  m/s.

The greater the value of  $n$ , the slower the speed of light in that medium.

## Total internal reflection & Critical angle

### Critical Angle & Total Internal Reflection

When light travels into a more optically dense medium at a very special incident angle, the resulting refracted angle is  $90^\circ$ . It follows the surface. This special angle of incidence is called the **critical angle** of that medium.

How to find the critical angle:

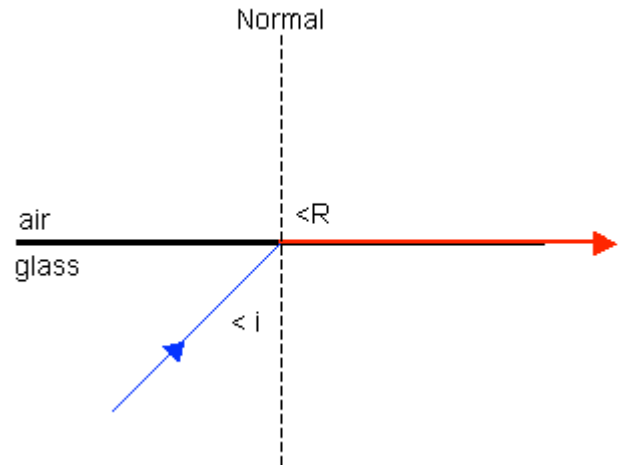
$$n_1 \sin \theta_c = n_2 \sin \theta_2$$

$\theta_2$  is  $90$  degrees, so...

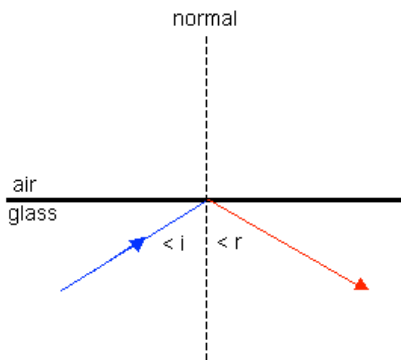
$$n_1 \sin \theta_c = n_2$$

$$\text{Therefore, } \sin \theta_c = \frac{n_2}{n_1}$$

Substances that have a high index of refraction ( $n$ ) have a low critical angle. Diamond has an index of refraction of 2.42 with a critical angle of  $24.5^\circ$ , while water has an index of refraction of 1.33 and a critical angle of  $49^\circ$ .



### Total Internal Reflection



When light passes into a more optically dense medium with the angle of incidence **greater than the critical angle**, the light simply reflects off the surface. It does not pass through and refract. We call this **total internal reflection**.

### Critical Angle Example Problem:

What is the critical angle of crown glass ( $n = 1.52$ ) if light passes from crown glass into air?

**(Remember that critical angle is always a unique incident angle.)**

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

$$1.52 \sin \theta_1 = 1.00 \sin 90.0^\circ \quad (\text{n of air is 1.00; refracted angle is } 90.0^\circ)$$

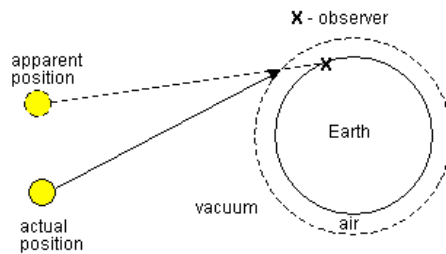
$$\sin \theta_1 = \frac{(1.00)(1.00)}{1.52} \quad (\sin 90.0^\circ \text{ is } 1.00)$$

$$\sin \theta_1 = 0.658 \quad (\text{We want the angle, not sin of the angle})$$

$$\theta_1 = 41.1^\circ$$

## Examples of refraction. critical angles:

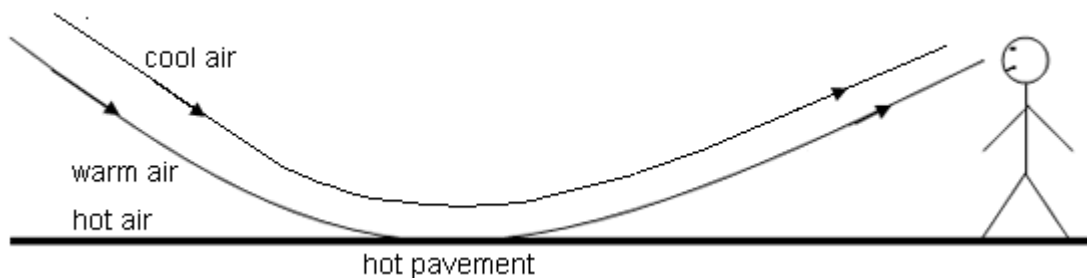
### SUNSETS



- Light from the setting sun passes from the vacuum of outer space into the air around the Earth. Light starts to bend toward the Earth.
- The air gets denser closer to the Earth resulting in even more light refraction toward the Earth.
- To observer X, the sun appears higher, not set. This is because our brain assumes that light always travels in straight lines and if observer X sees the sun, they believe it cannot be set. The brain has been fooled, because in this case light bent, and did not travel in a straight line.
- Astronomers viewing stars near the horizon must be aware that as the light refracts, the location of the star tends to be inaccurate.
- Most of the large telescopes on Earth are on mountain tops to reduce atmospheric refraction. The Hubble telescope is in the best place - space.

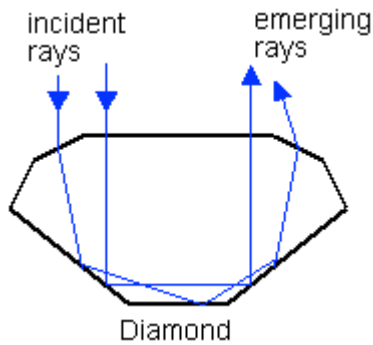
### Mirrages:

Have you ever driven along a highway in the summer and seen a puddle of water on the road, but it always kept moving? This is a mirage caused by the sun heating the road.



The hot pavement heats the air just above it.  
The light from the sky refracts as it passes into the warm air above the pavement (upper ray in diagram above).  
The angle of incidence of the incoming rays of light gets larger (bottom ray in diagram above).  
At some point the angle of incidence gets larger than the critical angle of the hot air above the pavement. Total internal reflection results and you actually see light from the sky. It only looks like it reflects from the road.  
Because water reflects light and pavement doesn't, your brain thinks that there must be water on the road to reflect the light from the sky. Your brain is fooled by the bending light.

### Sparkling Diamonds



### Why do diamonds sparkle and shine so much?

When light strikes the top surface of a diamond, some light is reflected and some passes into the diamond and is refracted.

Diamond has a high index of refraction, which means it has a low critical angle ( $24.5^\circ$ ).

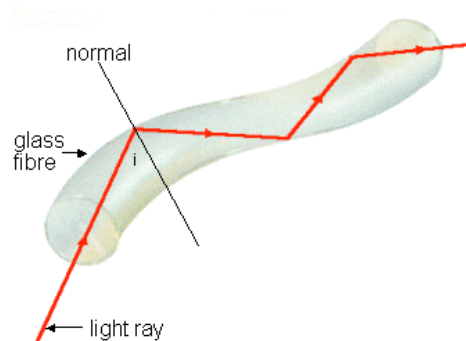
If light enters the diamond and hits the bottom or sides at angles greater than  $24.5^\circ$ , it is totally internally reflected.

The light rays bounce around inside the diamond and eventually leave out the top or top sides.

Even the light that hits the sides or bottom at an angle less than the critical angle will be partially reflected.

The diamond must be cut very accurately so that the bottom and sides are at angles that allow for total internal reflection.

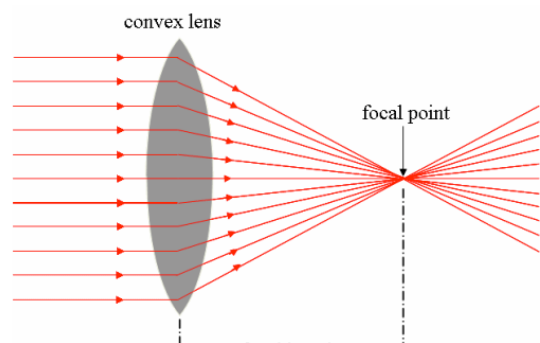
### Fiber Optics



Glass has a critical angle of about  $43^\circ$ .

- The light ray enters the glass fibre and strikes the inside surface at an angle ( $i$ ) greater than the critical angle ( $43^\circ$ ). The result is total internal reflection and so the light bounces off the surface and keeps traveling through the glass fibre.
- This allows the glass fibre to be bent so light can travel around corners.
- Many glass fibres are combined to make a cable, which can carry thousands of rays of light. The glass fibre is usually coated with a plastic cladding (that has a very low index of refraction) and a protective covering.
- The light rays transmit telephone, radio, and television signals.
- Fibre optics is also used in medicine to allow scopes to see inside organs, blood vessels, etc. in minute detail.

### Lenses





Refraction is why lenses work.

The physics is nearly identical to that of the spherical mirrors we recently looked at.

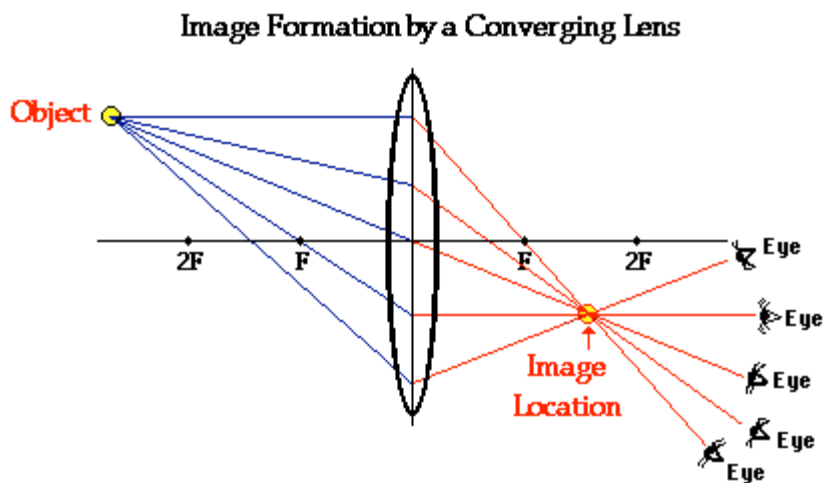
Drawing ray diagrams are ALMOST the same

The focal length equation is the same

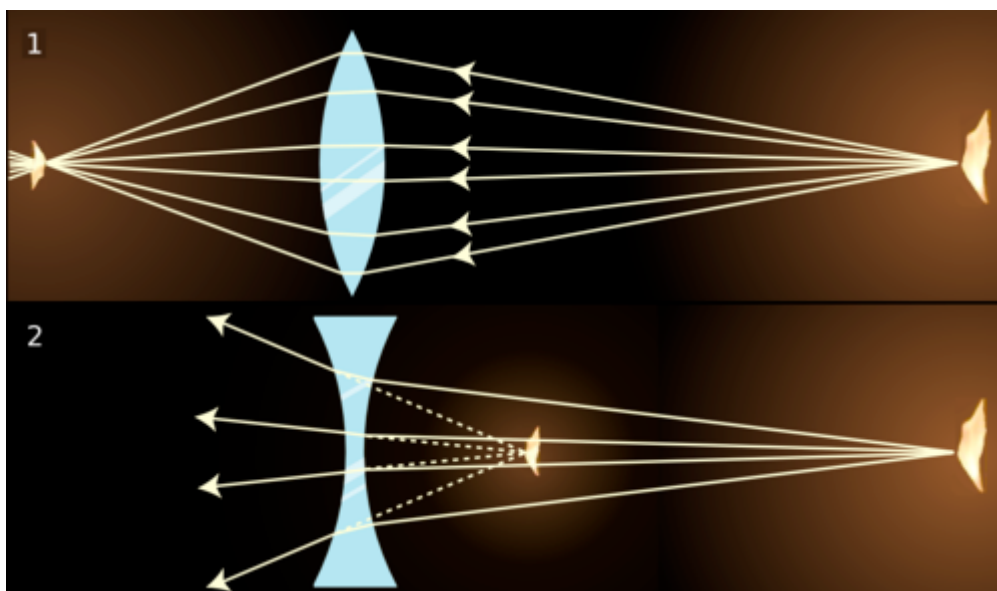
The magnification is the same

The type of images are the same, real, virtual, inverted, upright, etc...

It's all the same. The only difference is the reason why the light bends. It doesn't reflect, like in the mirrors, it refracts through the lens.



1. converging lens, 2. Diverging lens



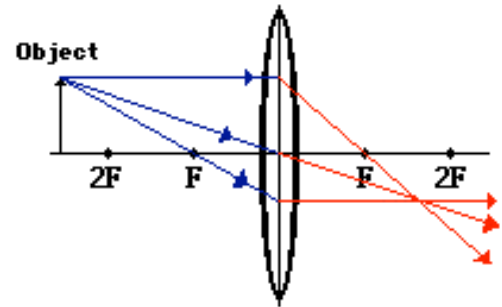
**Drawing ray Diagrams for lenses:**

Since the light refracts through the lens, and doesn't bounce off, like a mirror, when drawing ray diagrams, there is ONE difference.

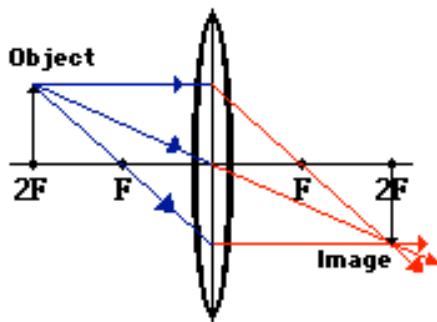
Instead of drawing the 3<sup>rd</sup> ray through the center of curvature, draw the third ray through the CENTER of the lens, it will pass straight through, no refraction (this is the middle ray in the diagram below).

The other two rays are drawn the same way as in mirrors:

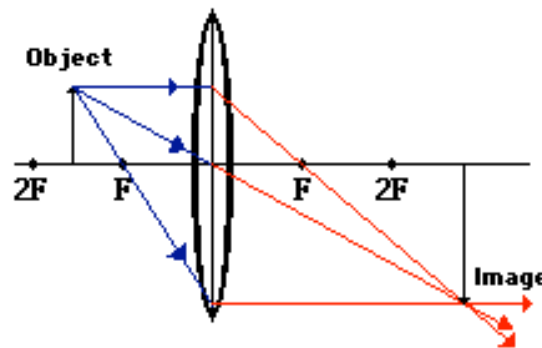
1. Parallel to axis – refracts through F
2. Through F – refracts parallel to axis
3. Through center of lens – goes straight through



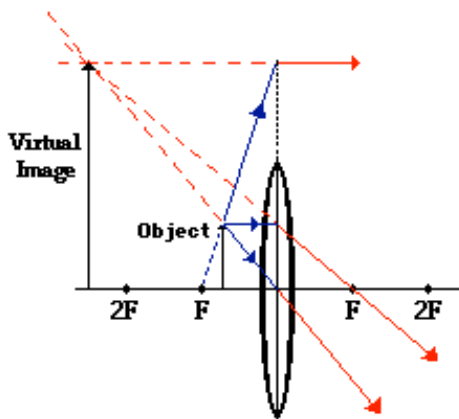
4 More examples of drawing correct ray diagrams following the 3 rules:



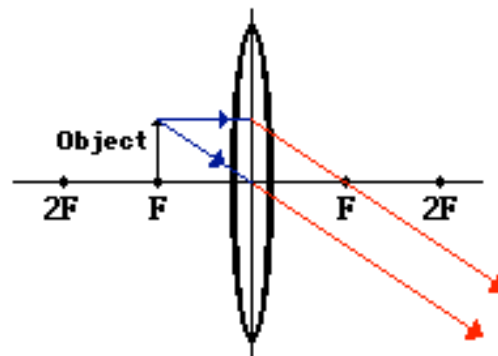
Ray Diagram for Object Located at 2F



Ray Diagram for Object Located Between F and 2F

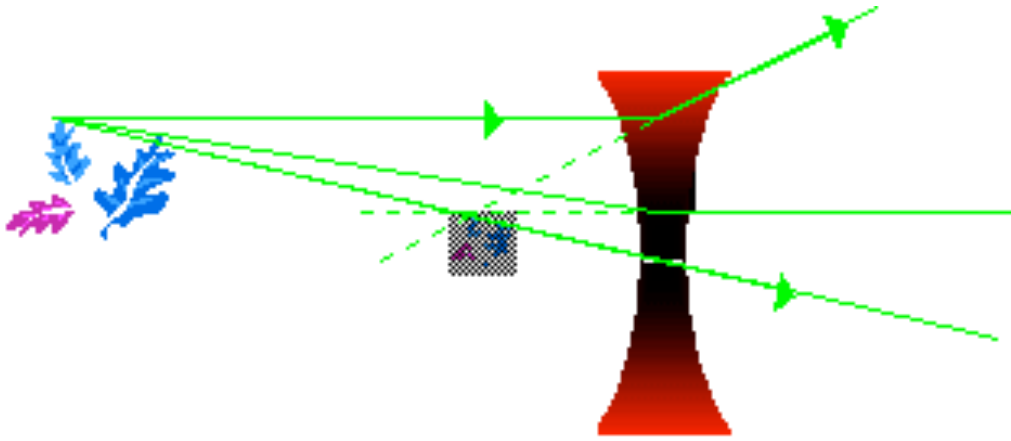


Ray Diagram for Object Located in Front of F



Ray Diagram for Object Located at F (an image is not formed)

Ray Diagram for Diverging lenses, use the same rules, just the focal lengths are reversed:

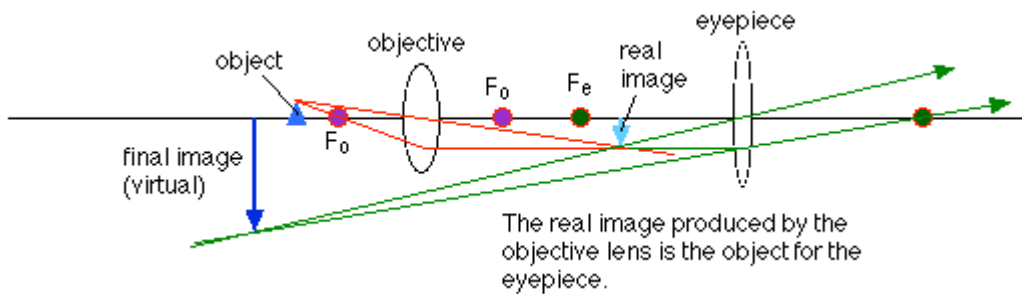


### Multiple Lenses:

**Magnification:** Just multiply them :  $m_{total} = m_1 \cdot m_2$

**To draw a ray diagram:**

1. Create a ray diagram for the first lens
2. Use the image created from the first lens as the object for the second lens.



**To mathematically determine properties of the object.**

1.)

Use equation : 
$$\frac{1}{d_i} + \frac{1}{d_o} = \frac{1}{f}$$

To find distance to the image formed by the first lens. And the magnification equation to find the size.

2.) Use the image from the first lens as the object for the second lens. Use the equations to find the  $d_i$  and  $m$  of the image.

Let's use the ray diagram for the microscope and work out a numerical example. The parameters we need to specify are:

$$\begin{aligned}d_o &= 7.0 \text{ mm} & h_o &= 1.0 \text{ mm} \\f_o &= 4.5 \text{ mm} & f_e &= 10.0 \text{ mm} \\ \text{distance between the two lenses} &= 20 \text{ mm}\end{aligned}$$

To work out the image distance for the image formed by the objective lens, use the lens equation, rearranged to:

$$d_i = d_o f / (d_o - f) = (7)(4.5) / (2.5) = 12.6 \text{ mm}$$

The magnification of the image in the objective lens is:

$$m_o = - d_i / d_o = -12.6 / 7.0 = -1.8$$

So the height of the image is  $-1.8 \times 1.0 = -1.8 \text{ mm}$ .

This image is the object for the second lens, and the object distance has to be calculated:

$$d_o = 20 - 12.6 = 7.4 \text{ mm}$$

The image, virtual in this case, is located at a distance of:

$$d_i = d_o f / (d_o - f) = (7.4)(10) / (-2.6) = -28.5 \text{ mm}$$

The magnification for the eyepiece is:

$$m_e = - d_i / d_o = 28.5 / 7.4 = 3.85$$

So the height of the final image is  $-1.8 \text{ mm} \times 3.85 = -6.9 \text{ mm}$ .

The overall magnification of the two lens system is:

$$m = m_o \times m_e = -1.8 \times 3.85 = -6.9$$

This is equal to the final height divided by the height of the object, as it should be. Note that, applying the sign conventions, the final image is virtual, and inverted compared to the object. This is consistent with the ray diagram.

## Telescopes

A telescope needs at least two lenses. This is because you use a telescope to look at an object very far away, so the first lens creates a small image close to its focal point. The telescope is designed so the real, inverted image created by the first lens is just a little closer to the second lens than its focal length. As with the magnifying glass, this gives a magnified virtual image. This final image is also inverted compared to the original object. With astronomical telescopes, this doesn't really matter, but if you're looking at something on the Earth you generally want an upright image. This can be obtained with a third lens.

Note that the overall effect of the telescope is to magnify, which means the absolute value of the magnification must be larger than 1. The first lens (the objective) has a magnification smaller than one, so the second lens (the eyepiece) must magnify by a larger factor than the first lens reduces by. To a good approximation, the overall magnification is equal to the ratio of the focal lengths. With  $o$  standing for objective and  $e$  for eyepiece, the magnification is given by:

$$m = - f_o / f_e, \text{ with the minus sign meaning that the image is inverted.}$$

## Interference

1801 Thomas Young was able to offer some very strong evidence to support the wave model of light.

- He placed a screen that had two slits cut into it in front of a monochromatic (*single color*) light.
- The results of Young's Double Slit Experiment should be very different if light is a wave or a particle.
- Let's look at what the results would be in both situations, and then see how this experiment supports the wave model.

## If light is a particle...

We set up our screen and shine a bunch of monochromatic light onto it.

- If light is a particle, then only the couple of rays of light that hit exactly where the slits are will be able to pass through.
  - Imagine it as being almost as though we are spraying paint from a spray can through the openings.
- Since they are little particles they will make a pattern of two exact lines on the viewing screen (**Figure 1**).

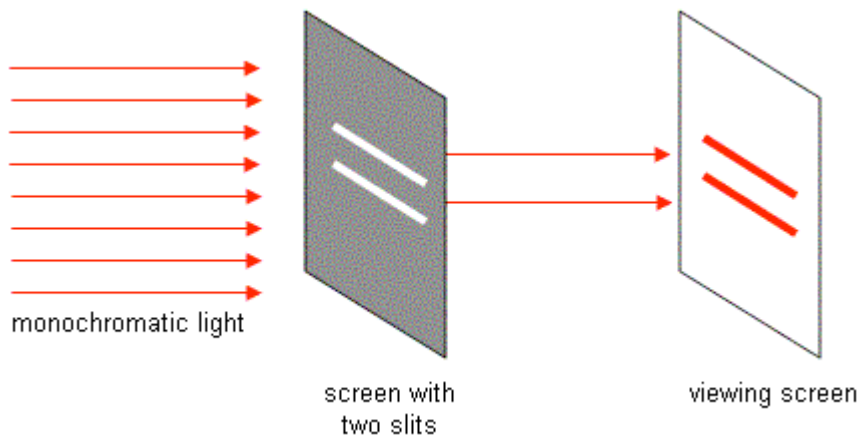


Figure 1

## If light is a wave...

If light is a wave, everything starts the same way, but results we get are very different.

- There are still only two light rays that actually go through the slits, but as soon as they pass through they start to diffract.
  - Remember, diffraction is when light passes through a small opening and starts to spread out. This will happen from **both** openings (**Figure 2**).

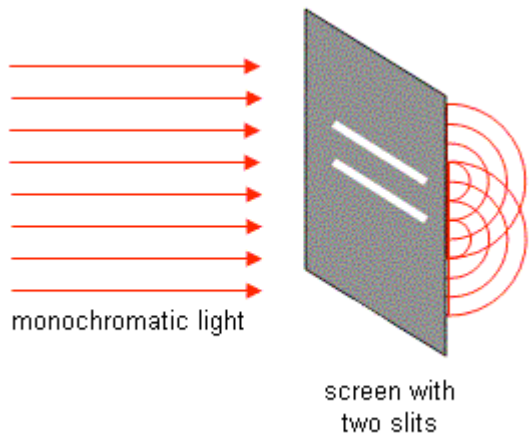


Figure 2

- Notice that at some points the two sets of waves will meet crest to crest, at other spots crest meets trough.
  - Where crest meets crest, there will be constructive interference and the waves will make it to the viewing screen as a bright spot.
  - Where crest meets trough there will be destructive interference that cancel each other out... a black spot will appear on the screen.
- When this experiment is performed we actually see this, as shown in **Figure 3**.

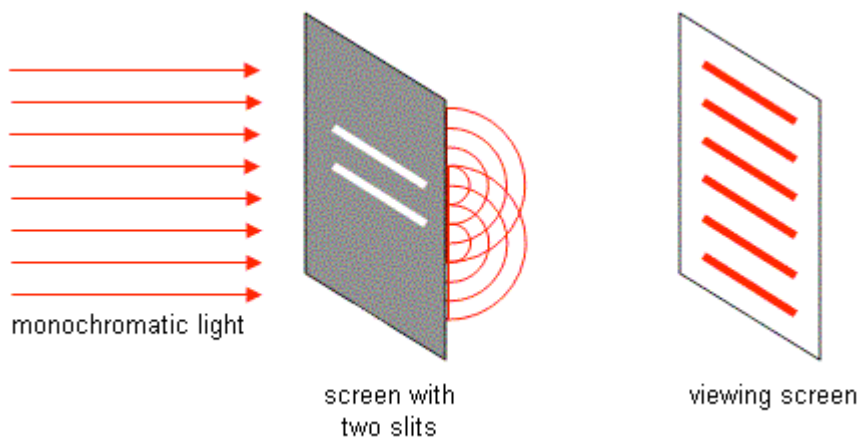


Figure 3

We must conclude that light is made up of waves, since particles can not diffract.

## Calculations

When you set up this sort of an apparatus, there is actually a way for you to calculate where the bright lines (called fringes) will appear.

- There is always a middle line, which is the brightest. We call it the central fringe.

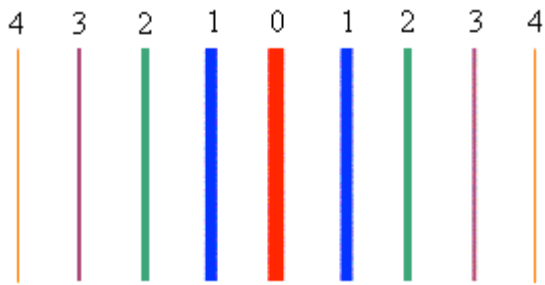


Figure 4: Note I've only colored the lines differently here so that they will stand out better. For monochromatic light they would all have the same color... that of the original light.

- In the formula we will use, there is a variable, “n”, that is a count of how many bright fringes you are away from the central fringe.
  - The central fringe is  $n = 0$ .
  - The fringe to either side of the central fringe has an order of  $n = 1$  (the first order fringe).
  - The order of the next fringe out on either side is  $n = 2$  (the second order fringe).
  - And so on, as shown in **Figure 4**.

The formula that we will use to figure out problems involving double slit experiments is easy to mix up, so make sure you study it carefully.

$$\lambda = \frac{xd}{nL}$$

$\lambda$  = wavelength of light used (m)

$x$  = distance from central fringe (m)

$d$  = distance between the slits (m)

$n$  = the order of the fringe

$L$  = length from the screen with slits to the viewing screen (m)

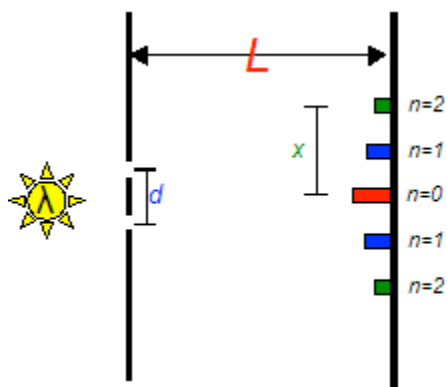


Figure 5

It is very easy to mix up the measurements of  $x$ ,  $d$ , and  $L$ .

- Make sure to look at **Figure 5** and see the different things each is measuring.
- If you mix up  $x$  and  $d$  it's not so bad, since they are both on top in the formula. If you were to mix them up with  $L$ , you would get the wrong answer.
- Almost all questions that you will see for this formula just involve sorting out what each variable is... you might find it helpful to write out a list of givens.

Example 1: A pair of screens are placed 13.7m apart. A third order fringe is seen on the screen 2.50cm from the central fringe. If the slits were cut 0.0960 cm apart, **determine** the wavelength of this light. Roughly what colour is it?

Just to make sure you've got all the numbers from the question matched with the correct variables...

$$L = 13.7 \text{ m}$$

$$n = 3$$

$$x = 2.50\text{cm} = 0.0250 \text{ m}$$

$$d = 0.0960\text{cm} = 9.60\text{e-}4 \text{ m}$$

$$\lambda = \frac{xd}{nL}$$

$$\lambda = \frac{0.0250 \times 9.60\text{e-}4}{3 \times 13.7}$$

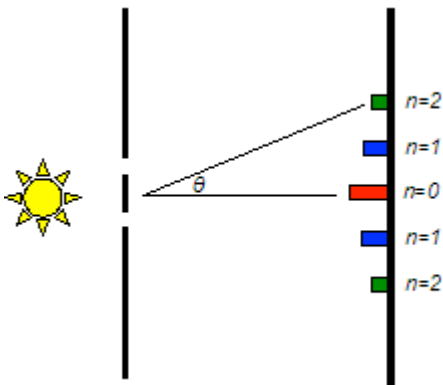
$$\lambda = 5.84\text{e-}7\text{m} = 584\text{e-}9\text{m} = 584\text{nm}$$

It's probably a yellow light being used given the wavelength we've measured.

If a white light is used in the double slit experiment, the different colors will be split up on the viewing screen according to their wavelengths.

- The violet end of the spectrum (with the shortest wavelengths) is closer to the central fringe, with the other colours being further away in order.

There is also a version of the formula where you measure the angle between the central fringe and whatever fringe you are measuring.



$$\lambda = \frac{d \sin \theta}{n}$$

- The formula works the same way, with the only difference being that we measure the angle instead of x and L.
- Make sure that your calculator is in degree mode before using this version of the formula.



Example 2: If a yellow light with a wavelength of 540 nm shines on a double slit with the slits cut 0.0100 mm apart, **determine** what angle you should look away from the central fringe to see the second order fringe?

Do not forget to:

1. Change the wavelength into meters.
2. Change the slit separation into meters.
3. "Second order" is a perfect number and has an infinite number of sig digs.

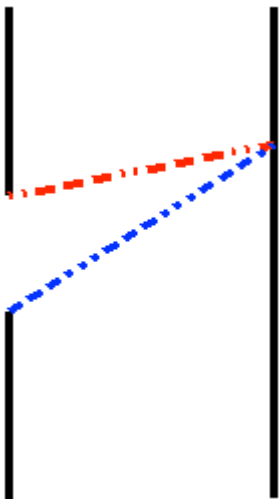
$$\lambda = \frac{d \sin \theta}{n}$$

$$\sin \theta = \frac{\lambda n}{d}$$

$$\sin \theta = \frac{540 \text{e-}9 \times 2}{1.00 \text{e-}5}$$

$$\theta = 6.20^\circ$$

## The Single Slit



A surprising experiment is that you can get the same effect from using a single slit instead of a double slit.

- Light from different ends of the slit will be traveling to the same spot on the screen and reach there either in or out of sync.
  - In the above figure, the blue path has to travel further than the red path... if this difference is equal to half a wavelength, they will meet each other out of sync.
- If they meet crest to crest or trough to trough they will be in sync, but if they meet crest to trough they will be out of sync.
- Being in sync will result in constructive interference, while meeting out of sync will result in destructive interference.
- The result is the same interference pattern, although the effect isn't nearly as dramatic or clear as the double slit experiment.

- After the first couple of fringes ( $n = 1$  and  $2$ ), the edges start getting really fuzzy, so you have a hard time measuring anything.
- The only real difference in calculations is that "d" is now the width of the single opening.
- If two slits work better than one, would more than two slits work better? This is a question that we will answer in the next section.

Example 3: For a single slit experiment apparatus like the one described above, **determine** how far from the central fringe the first order violet ( $\lambda = 350\text{nm}$ ) and red ( $\lambda = 700\text{nm}$ ) colors will appear if the screen is 10 m away and the slit is 0.050 cm wide.

We need to solve the formula for "x", the distance from the central fringe.

$$\lambda = \frac{xd}{nL}$$

$$x = \frac{\lambda n L}{d}$$

For the violet light...

$$x = \frac{\lambda n L}{d}$$

$$x = \frac{350\text{e-}9 \times 1 \times 10}{0.00050}$$

$$x = 0.0070\text{m}$$

For the red light...

$$x = \frac{\lambda n L}{d}$$

$$x = \frac{700\text{e-}9 \times 1 \times 10}{0.00050}$$

$$x = 0.014\text{m}$$

You can actually do the single slit experiment wherever you are right now! Hold two of your fingers very close together; there should be only the tiniest little gap between them that you can barely see through. Look towards a light source, light a light bulb, through the gap in your fingers. In the gap between your fingers you should see very faint gray lines that run parallel to your fingers... these are the destructive interference "dark" fringes!