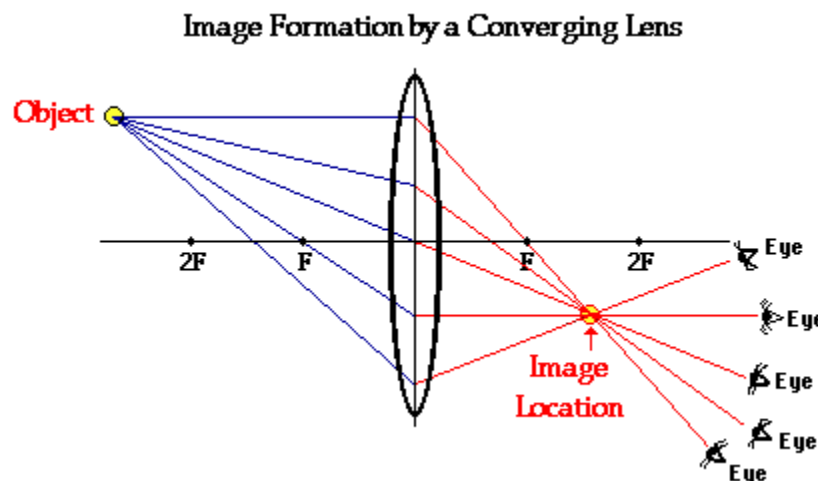


# LENSES

## Converging Lens Image Formation

**Converging lenses** can produce **both real and virtual images** while diverging lenses can only produce virtual images. The process by which images are formed for lenses is the same as the process by which images are formed for plane and curved mirrors. Images are formed at locations where any observer is sighting as they view the image of the object through the lens. So if the path of several light rays through a lens is traced, each of these light rays will intersect at a point upon refraction through the lens. Each observer must sight in the direction of this point in order to view the image of the object. While different observers will sight along different lines of sight, each line of sight intersects at the image location. The diagram below shows several incident rays emanating from an object - a light bulb. Three of these incident rays correspond to our three strategic and predictable light rays. Each incident ray will refract through the lens and be detected by a different observer (represented by the eyes). The location where the refracted rays are intersecting is the image location.

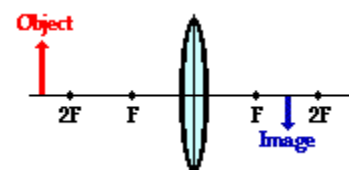


In this case, the image is a real image since the light rays are actually passing through the image location. To each observer, it appears as though light is coming from this location.

## Converging Lenses - Object-Image Relations

### Case 1: The object is located *beyond* $2F$

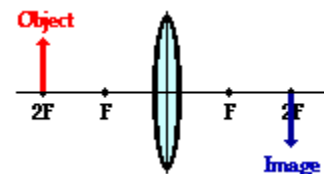
When the object is located at a location beyond the  $2F$  point, the image will always be located somewhere in between the  $2F$  point and the focal point ( $F$ ) on the other side of the lens. Regardless of exactly where the object is located, the image will be located in this specified region. In this case, the image will be an **inverted image**. That is to say, if the object is right side



up, then the image is upside down. In this case, the image is **reduced in size**; in other words, the image dimensions are smaller than the object dimensions. Finally, the image is a real image. Light rays actually converge at the image location. If a sheet of paper were placed at the image location, the actual replica or likeness of the object would appear projected upon the sheet of paper.

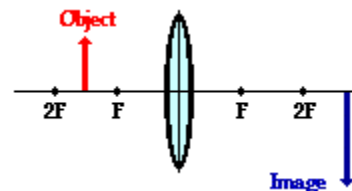
### Case 2: The object is located at 2F

When the object is located at the 2F point, the image will also be located at the 2F point on the other side of the lens. In this case, the image will be inverted (i.e., a right side up object results in an upside-down image). The image dimensions are equal to the object dimensions. A six-foot tall person would have an image that is six feet tall; the absolute value of the magnification is exactly 1. Finally, the image is a real image. Light rays actually converge at the image location. As such, the image of the object could be projected upon a sheet of paper.



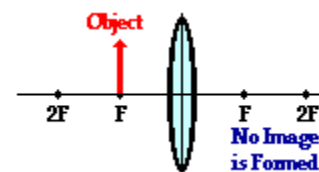
### Case 3: The object is located between 2F and F

When the object is located *in front of* the 2F point, the image will be located *beyond* the 2F point on the other side of the lens. Regardless of exactly where the object is located between 2F and F, the image will be located in the specified region. In this case, the image will be inverted (i.e., a right side up object results in an upside-down image). The image dimensions are larger than the object dimensions. A six-foot tall person would have an image that is larger than six feet tall. The absolute value of the magnification is greater than 1. Finally, the image is a real image. Light rays actually converge at the image location. As such, the image of the object could be projected upon a sheet of paper.



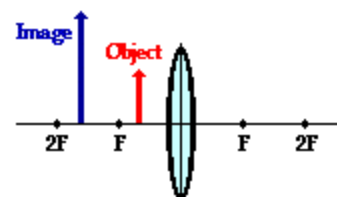
### Case 4: The object is located at F

When the object is located at the focal point, no image is formed. As discussed [earlier in Lesson 5](#), the refracted rays neither converge nor diverge. After refracting, the light rays are traveling parallel to each other and cannot produce an image.



### Case 5: The object is located *in front of* F

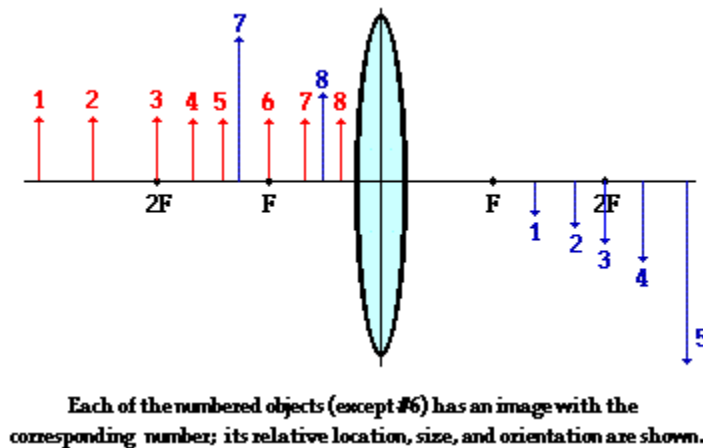
When the object is located at a location in front of the focal point, the image will always be located somewhere on the same side of the lens as the object. Regardless of exactly where in front of F the object is located, the image will always be located on the object's side of the lens and somewhere further from the lens. The image is located *behind* the object. In this case, the image will be an **upright image**. That is to say, if the object is right side up, then the image will also be right side up. In this case, the image is **enlarged**; in other words, the image dimensions are greater than the object dimensions. Finally, the image is a



virtual image. Light rays diverge upon refraction; for this reason, the image location can only be found by extending the refracted rays backwards on the object's side the lens. The point of their intersection is the virtual image location. It would appear to any observer as though light from the object were diverging from this location. Any attempt to project such an image upon a sheet of paper would fail since light does not actually pass through the image location.

It might be noted from the above descriptions that there is a relationship between the object distance and object size and the image distance and image size. Starting from a large value, as the object distance decreases (i.e., the object is moved closer to the lens), the image distance increases; meanwhile, the image height increases. At the  $2F$  point, the object distance equals the image distance and the object height equals the image height. As the object distance approaches one focal length, the image distance and image height approaches infinity. Finally, when the object distance is equal to exactly one focal length, there is no image.

Then altering the object distance to values less than one focal length produces images that are upright, virtual and located on the same side of the lens as the object. Finally, if the object distance approaches 0, the image distance approaches 0 and the image height ultimately becomes equal to the object height. These patterns are depicted in the diagram below. Eight different object locations are drawn in red and labeled with a number; the corresponding image locations are drawn in blue and labeled with the identical number.

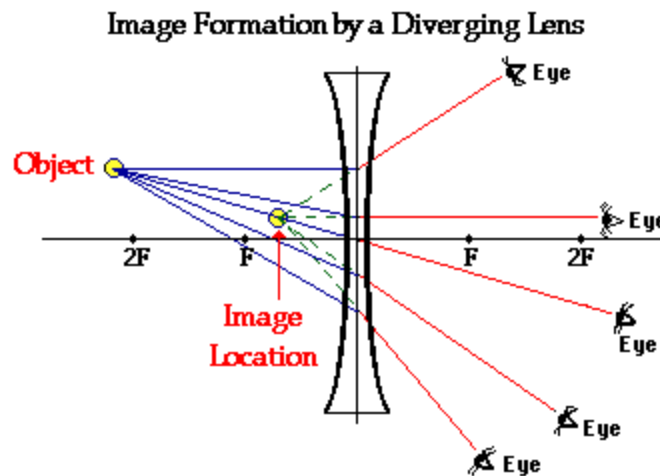


## Diverging Lens Image Formation

**Diverging lenses** create virtual images since the refracted rays do not actually converge to a point. In the case of a diverging lens, the image location is located on the object's side of the lens where the refracted rays would intersect if extended backwards. Every observer would be sighting along a line in the direction of this image location in order to see the image of the object. As the observer sights along this line of sight, a refracted ray would come to the observer's eye. This refracted ray originates at the object, and refracts through the lens.

The diagram below shows several incident rays emanating from an object - a light bulb. Three of these incident rays correspond to our **three strategic and predictable light rays**. Each incident ray will

refract through the lens and be detected by a different observer (represented by the eyes). The location where the refracted rays are intersecting is the image location. Since refracted light rays do not actually exist at the image location, the image is said to be a virtual image. It would only appear to an observer as though light were coming from this location to the observer's eye.



## Applying the Three Rules of Refraction

In this section we will investigate the method for drawing ray diagrams for objects placed at various locations in front of a **double convex lens**. To draw these ray diagrams, we will have to recall the **three rules of refraction** for a double convex lens:

- Any incident ray traveling parallel to the principal axis of a converging lens will refract through the lens and travel through the focal point on the opposite side of the lens.
- Any incident ray traveling through the focal point on the way to the lens will refract through the lens and travel parallel to the principal axis.
- An incident ray that passes through the center of the lens will in effect continue in the same direction that it had when it entered the lens.

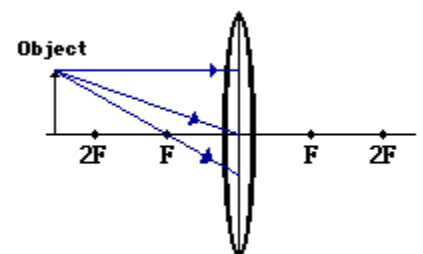
Earlier in this lesson, the following diagram illustrating the path of light from an object through a lens to an eye placed at various locations was shown.

### Step-by-Step Method for Drawing Ray Diagrams

The method of drawing ray diagrams for double convex lens is described below. The description is applied to the task of drawing a ray diagram for an object located *beyond* the 2F point of a double convex lens.

1. Pick a point on the top of the object and draw three incident rays traveling towards the lens.

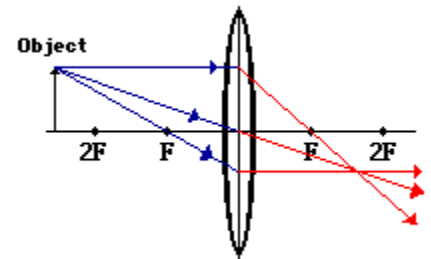
Using a straight edge, accurately draw one ray so that it passes exactly through the focal point on the way to the lens. Draw the



second ray such that it travels exactly parallel to the principal axis. Draw the third incident ray such that it travels directly to the exact center of the lens. Place arrowheads upon the rays to indicate their direction of travel.

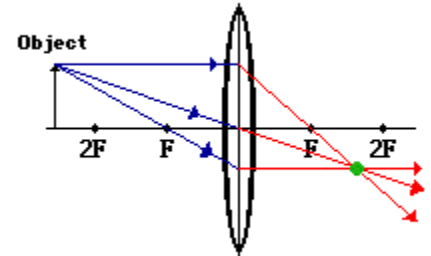
2. Once these incident rays strike the lens, refract them according to the [three rules of refraction](#) for converging lenses.

The ray that passes through the focal point on the way to the lens will refract and travel parallel to the principal axis. Use a straight edge to accurately draw its path. The ray that traveled parallel to the principal axis on the way to the lens will refract and travel through the focal point. And the ray that traveled to the exact center of the lens will continue in the same direction. Place arrowheads upon the rays to indicate their direction of travel. Extend the rays past their point of intersection.



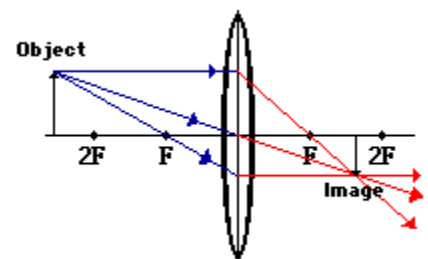
3. Mark the image of the top of the object.

The image point of the top of the object is the point where the three refracted rays intersect. All three rays should intersect at exactly the same point. This point is merely the point where all light from the top of the object would intersect upon refracting through the lens. Of course, the rest of the object has an image as well and it can be found by applying the same three steps to another chosen point. (See note [below](#).)



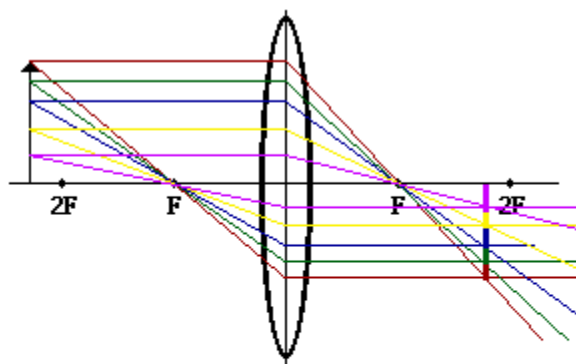
4. Repeat the process for the bottom of the object.

One goal of a ray diagram is to determine the location, size, orientation, and type of image that is formed by the double convex lens. Typically, this requires determining where the image of the upper and lower extreme of the object is located and then tracing the entire image. After completing the first three steps, only the image location of the top extreme of the object has been found. Thus, the process must be repeated for the point on the bottom of the object. If the bottom of the



object lies upon the principal axis (as it does in this example), then the image of this point will also lie upon the principal axis and be the same distance from the mirror as the image of the top of the object. At this point the entire image can be filled in.

Some students have difficulty understanding how the entire image of an object can be deduced once a single point on the image has been determined. If the object is merely a vertical object (such as the arrow object used in the example below), then the process is easy. The image is merely a vertical line. In theory, it would be necessary to pick each point on the object and draw a separate ray diagram to determine the location of the image of that point. That would require a lot of ray diagrams as illustrated in the diagram below.

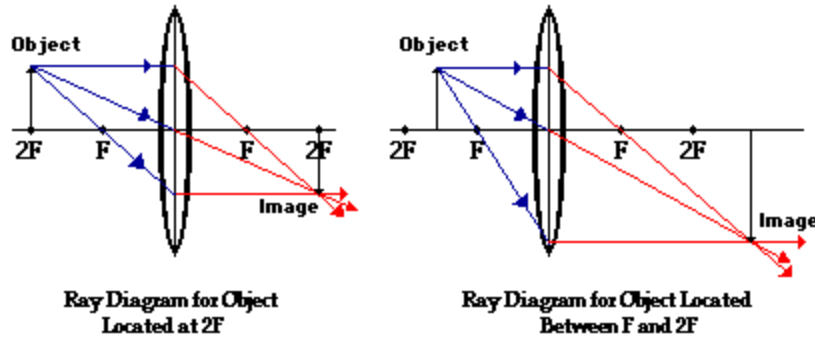


**When a set of incident and refracted rays are drawn for several points upon a vertical object, each refracted ray intersects at locations which form a vertical line - i.e., the image of a vertical object is an image which is also vertical.**

Fortunately, a shortcut exists. If the object is a vertical line, then the image is also a vertical line. For our purposes, we will only deal with the simpler situations in which the object is a vertical line that has its bottom located upon the principal axis. For such simplified situations, the image is a vertical line with the lower extremity located upon the principal axis.

The ray diagram above illustrates that when the object is located at a position *beyond* the 2F point, the image will be located at a position between the 2F point and the focal point on the opposite side of the lens. Furthermore, the image will be inverted, reduced in size (smaller than the object), and real. This is the type of information that we wish to obtain from a ray diagram.

Once the method of drawing ray diagrams is practiced a couple of times, it becomes as natural as breathing. Each diagram yields specific information about the image. The two diagrams below show how to determine image location, size, orientation and type for situations in which the object is located at the 2F point and when the object is located between the 2F point and the focal point.



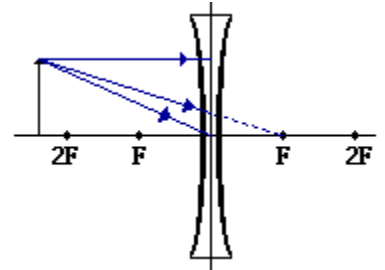
It should be noted that the process of constructing a ray diagram is the same regardless of where the object is located. While the result of the ray diagram (image location, size, orientation, and type) is different, the same three rays are always drawn. The three rules of refraction are applied in order to determine the location where all refracted rays appear to diverge from (which for real images, is also the location where the refracted rays intersect).

## Step-by-Step Method for Drawing Ray Diagrams

The method of drawing ray diagrams for a double concave lens is described below.

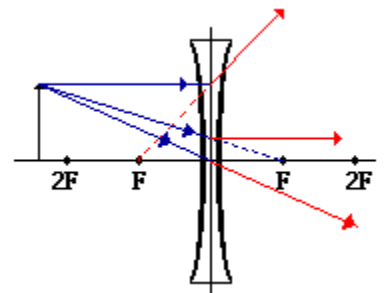
1. Pick a point on the top of the object and draw three incident rays traveling towards the lens.

Using a straight edge, accurately draw one ray so that it travels towards the focal point on the opposite side of the lens; this ray will strike the lens before reaching the focal point; stop the ray at the point of incidence with the lens. Draw the second ray such that it travels exactly parallel to the principal axis. Draw the third ray to the exact center of the lens. Place arrowheads upon the rays to indicate their direction of travel.



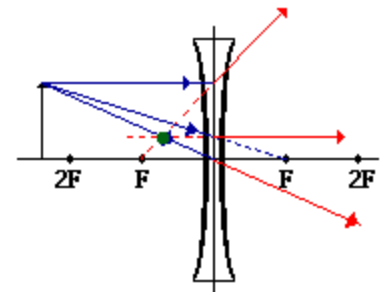
2. Once these incident rays strike the lens, refract them according to the [three rules of refraction](#) for double concave lenses.

The ray that travels towards the focal point will refract through the lens and travel parallel to the principal axis. Use a straight edge to accurately draw its path. The ray that traveled parallel to the principal axis on the way to the lens will refract and travel in a direction such that its extension passes through the focal point on the object's side of the lens. Align a straight edge with the point of incidence and the focal point, and draw the second refracted ray. The ray that traveled to the exact center of the lens will continue to travel in the same direction. Place arrowheads upon the rays to indicate their direction of travel. The three rays should be diverging upon refraction.



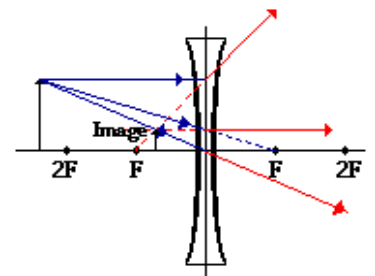
3. Locate and mark the image of the top of the object.

The image point of the top of the object is the point where the three refracted rays intersect. Since the three refracted rays are diverging, they must be extended behind the lens in order to intersect. Using a straight edge, extend each of the rays using dashed lines. Draw the extensions until they intersect. All three extensions should intersect at the same location. The point of intersection is the image point of the top of the object. The three refracted rays would appear to diverge from this point. This is merely the point where all light from the top of the object would appear to diverge from after refracting through the double concave lens. Of course, the rest of the object has an image as well and it can be found by applying the same three steps to another chosen point.

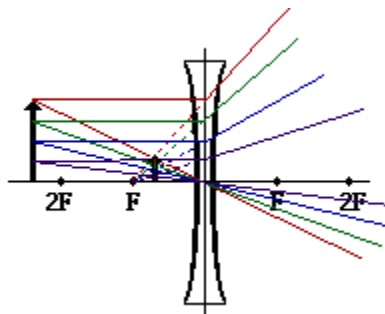


4. Repeat the process for the bottom of the object.

The goal of a ray diagram is to determine the location, size, orientation, and type of image that is formed by the double concave lens. Typically, this requires determining where the image of the upper and lower extreme of the object is located and then tracing the entire image. After completing the first three steps, only the image location of the top extreme of the object has been found. Thus, the process must be repeated for the point on the bottom of the object. If the bottom of the object lies upon the principal axis (as it does in this example), then the image of this point will also lie upon the principal axis and be the same distance from the lens as the image of the top of the object. At this point the complete image can be filled in.



Some students have difficulty understanding how the entire image of an object can be deduced once a single point on the image has been determined. If the object is merely a vertical object (such as the arrow object used in the example below), then the process is easy. The image is merely a vertical line. This is illustrated in the diagram below. In theory, it would be necessary to pick each point on the object and draw a separate ray diagram to determine the location of the image of that point. That would require a lot of ray diagrams as illustrated in the diagram below.



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