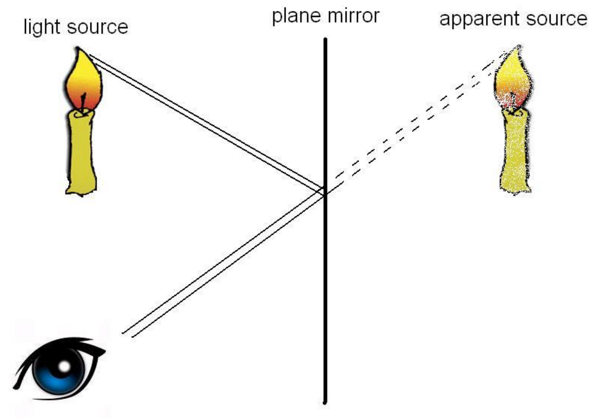
Pre-lecture Notes Section 16:

Geometrical Optics

I. Introduction

In this section, we will study how images are formed both by reflection (via mirrors) and by refraction (via lenses). We will find that the properties of these images can be calculated by analyzing the geometry of the mirror or lens. This is the origin of the term "Geometrical Optics".

To start, we must have some object which is emitting light rays. This object, appropriately enough, is called the **object**. This object will emit light rays which will either reflect from a surface (a mirror) or be refracted through a medium (a lens). Upon reflection or refraction, these rays will either (a) appear to be diverging from some point in space or (b) actually be diverging from some point in space. In either case the point from which the rays diverge or appear to diverge is at a location where no object actually exists. This is the location of the **image**.



In the figure to the right, we see an object reflected in a plane (flat) mirror. We see that the light soucre is the object, whereas the apparent source is the image. Note that there are no rays emitted from the image, but light rays do appear to be diverging from the image.

We are generally interested in the following properties of the image:

- Is the image virtual or real? This distinction is explained in a paragraph below.
- Where is the image located? This can be broken down into the following subquestions:
    - How far is it from the mirror or lens?
    - Is the image on the same side of the mirror or lens as the object or on the opposite side?
- Is the image upright or inverted? In other words, is the image oriented in the same direction as the object or is it flipped relative to the object?
- How big is the image relative to the object? In other words, what is the magnification of the image relative to the object? For instance, if the image were twice as large as the object, we would say that it has a magnification of 2.

Real vs. Virtual Images

If the rays that diverge from the image location are actual light rays, then we say that the image is a **real image**. However, if our image is made by rays that only *appear* to diverge from a location, we say that the image is a **virtual image**. You will see the difference between these two types of images in the pre-lecture video, and we will also discuss real and virtual images in class.

To give a concrete example of answering these questions, go back to the picture of the candle in the plane mirror on the previous page.

- The candle is the **<u>object</u>** because it is the object which is actually emitting light rays. Two rays are drawn from the object, and these rays reflect (via the law of reflection) into the eye. If you trace these two rays backwards, they *<u>appear</u>* to diverge from the "apparent source". Because this is where light rays appear to diverge from, the apparent source is the **<u>image</u>**.
- Because there are no actual light rays being emitted from the apparent source (i.e. they only *<u>appear</u>* to be diverging from this location), this is a **<u>virtual image</u>**. It is important to note that this does not mean that you cannot see the image! In fact, we see virtual images all the time, as we will discuss in class. The fact that the image is virtual simply means that that image cannot be *<u>projected</u>* onto a screen or page, because no light rays exist at the location of the image.
- With regards to the location of the image, it is exactly the same distance from the mirror as is the object. Furthermore, it is on the opposite side of the mirror as is the object.
- The image is upright. It is in the same orientation as the object.
- The image is the same size as the object. Therefore we say it has a magnification of 1.

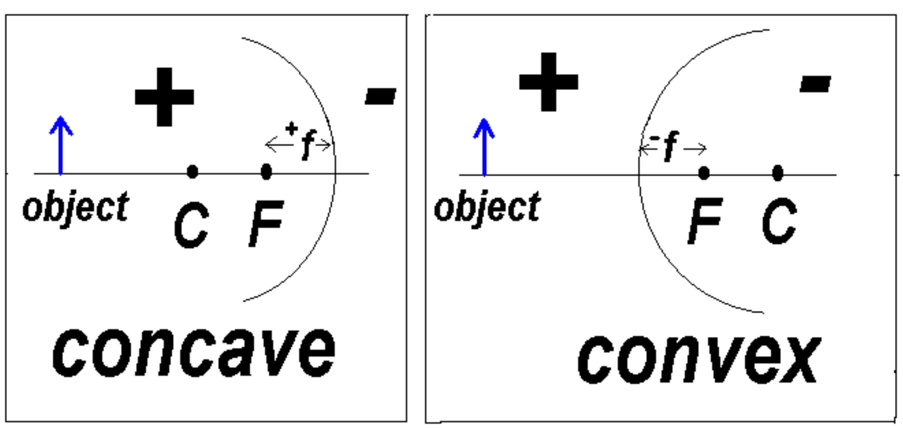
As you can see, for plane mirrors, the answers to these questions are somewhat intuitive from everyday life. In the rest of the section, we will try to understand how to determine the answers to the questions above for curved mirrors and lenses, where the results get much more interesting!

II. <u>Mirrors: Images by Reflection</u>

<u>Concave and Convex Mirrors</u>

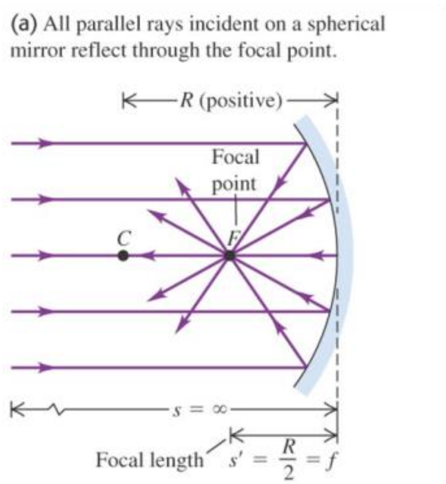
Now we will leave the (boring) plane mirror behind, and we will be interested in spherical mirrors. Spherical mirrors are mirrors in the shape of an arc section of a sphere. As with all spheres, there is a "center" of the sphere, called the center of curvature C. The distance from the center of curvature to the mirror is thus the radius of curvature R of the mirror. The smaller R is, the more "curvy" the mirror. If the center of curvature is on the same side as the object, we say that it is a **<u>concave</u>** mirror. On the other hand, if the center of curvature is on the opposite side as the object, we say that it is a **<u>convex</u>** mirror.

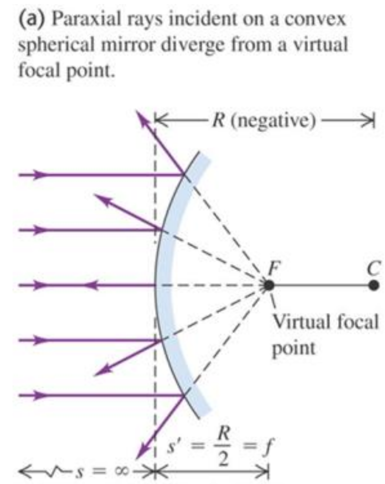
See the picture to the right. For the concave mirror, the center of curvature is on the same side as the object, whereas for the convex mirror, the center of curvature is on the opposite side as the object.



<u>The Focal Point</u>

Every spherical mirror has a unique location called the focal point. The focal point is defined, for the concave side of a mirror, as the point through which all parallel incident light rays pass after reflecting from the mirror. For the convex side of a mirror, the focal point is defined as the point from which all parallel incident light rays appear to diverge from after reflecting from the mirror. The pictures below show parallel light rays approaching a concave mirror and a convex mirror. These parallel rays reflect through the focal point for the concave mirror, and away from the focal point for the convex mirror.



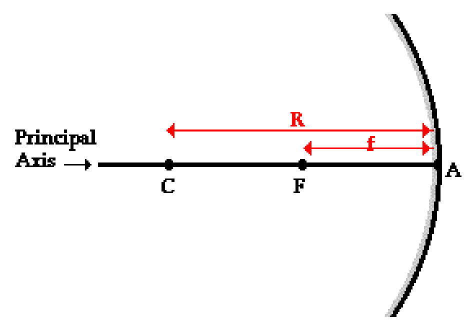


Ray Diagrams: Graphical Methods for Mirrors

For any spherical mirror, there are two complementary techniques we can use to predict the properties of the image.

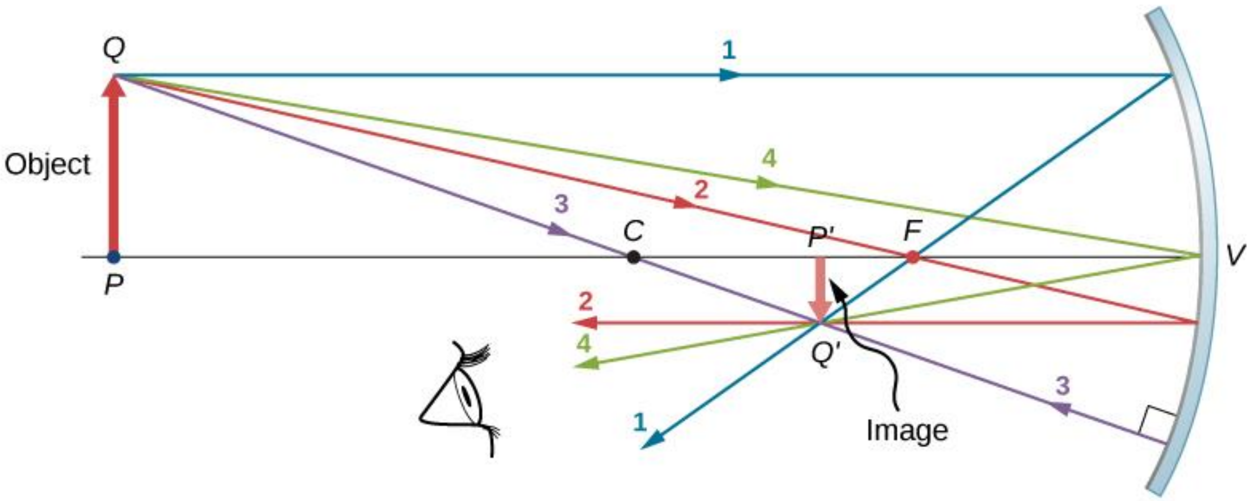
One technique is a qualitative method called the **principal ray diagram** method. The other technique is a quantitative method using a geometrically derived equation. Below, we discuss the principal ray diagram, whereas we will wait for class to learn the quantitative method.

To understand the principal ray diagram, we must first understand the notion of the principal (sometimes called optic) axis. The principal axis is the line which passes through the center of curvature of the mirror and the vertex (center) of the mirror. See the figure to the right.



There are four so-called principal rays for both a concave and convex mirror. These principal rays are "special" in that knowing the focal point and center of curvature allow a complete understanding of exactly how these rays will reflect from the mirror. The use of the principal ray diagram is that the location at which the rays intersect (or appear to intersect) will be where the image is located.

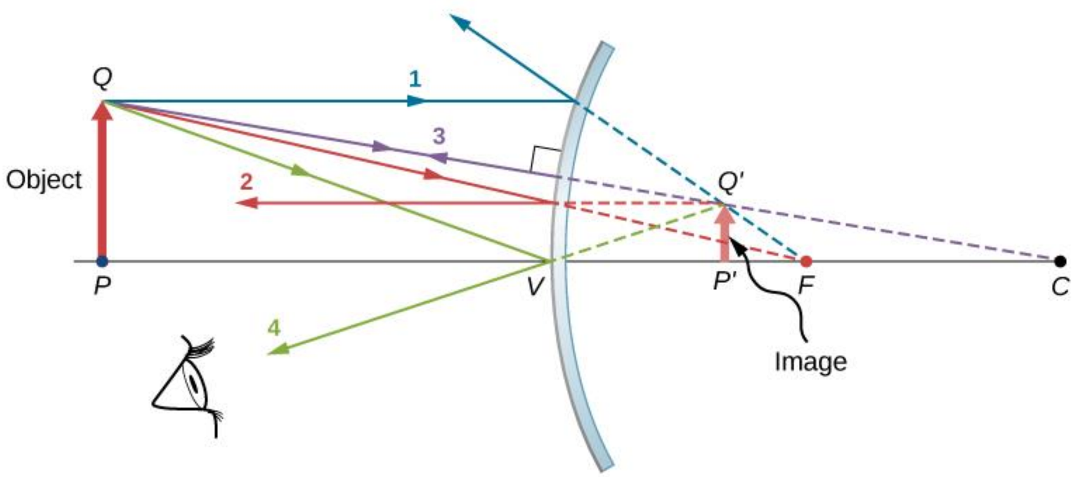
In class, we will learn exactly how to draw the principal rays, but for now, look at the diagram below, which shows the four principal rays for a concave mirror.



Notice that the object is located at position P. The four principal rays emanate from the top of the object (point Q) in the picture, and they all reflect from the mirror and intersect at location Q'. Thus the image is located at position P'. From this diagram, we can answer all of our questions, as explained below.

- The image is real because the light rays are actually crossing at Q'.
- The image is located on the same side of the mirror as the object, and it is closer to the mirror than the object.
- The image is upside down (inverted) relative to the object
- The image has a magnification of less than 1 because it is smaller than the object

Now, look at the next diagram, which is the principal ray diagram for a convex mirror.



(b)

Again, using the diagram, we can qualitatively answer all of our questions.

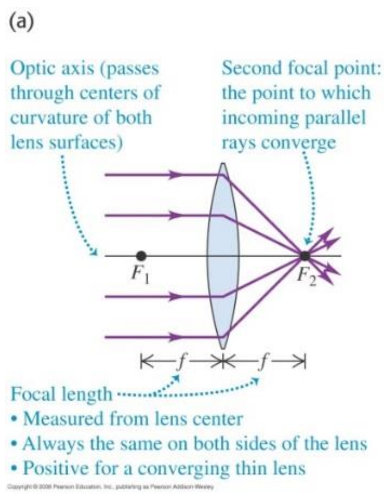
- The image is virtual because the light rays only appear to diverge from Q'.
- The image is located on the opposite side of the mirror as the object, and it is closer to the mirror than the object.
- The image is upright (same orientation) relative to the object.
- The image has a magnification of less than 1 because it is smaller than the object.

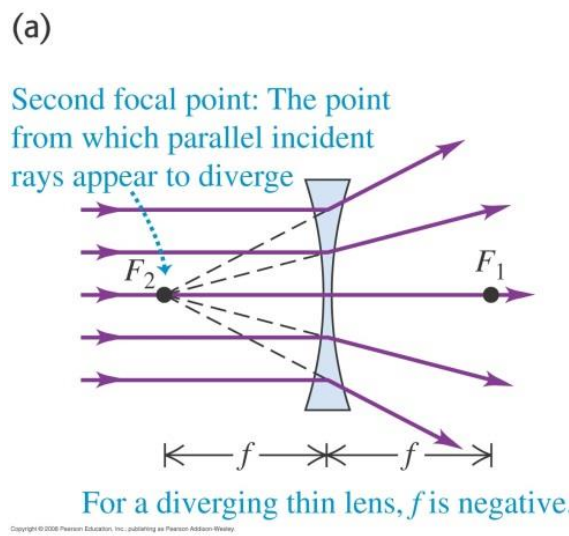
III. Thin Lenses: Images by Refraction

Converging and Diverging Lenses

A lens is a medium with index of refraction greater than 1, which is used to bend light, either focusing it, or defocusing it. A lens that causes parallel light rays to converge to a common point is called a **converging lens**, while a lens that causes parallel light rays to appear to diverge from a common point is called a **diverging lens**.

The point through which the light rays converge for a converging lens is called the **focal point** of the converging lens. The point from which light rays appear to diverge for a diverging lens is called the focal point of the diverging lens. The diagram below shows the difference between a converging lens and a diverging lens.





Just as for mirrors, there are two techniques to aide in predicting the properties of an image created by the lens. As for mirrors, we can draw a principal ray diagram to find the image. We can also use an equation called the thin-lens equation to make a quantitative prediction. Here we focus on the principal ray method. For a lens, there are three principal rays. Shown below are the principal ray diagrams for a converging lens and for a diverging lens.

Again, we can use these diagrams to answer any qualitative questions about the image, just as for the mirrors. We will learn how to draw these diagrams in class.