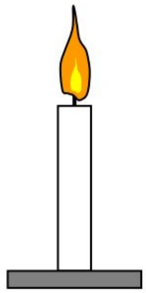
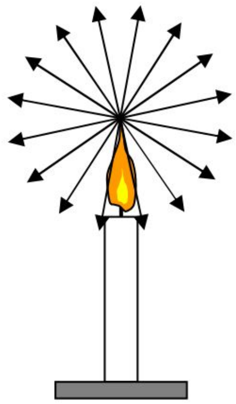
B26: Geometric Optics, Reflection

We now turn to a branch of optics referred to as geometric optics and also referred to as ray optics. It applies in cases where the dimensions of the objects (and apertures) with which the light interacts are so large as to render diffraction effects negligible. In geometric optics we treat light as being made up of an infinite set of narrow beams of light, called light rays, or simply rays, traveling through vacuum or transparent media along straight line paths. Where a ray of light encounters the surface of a mirror, or the interface between the transparent medium in which it (the light) is traveling and another transparent medium, the ray makes an abrupt change in direction, after which, it travels along a new straight line path.

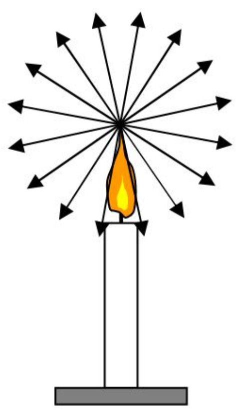
In the geometric optics model of light, we see light emitted by sources of light because the light enters our eyes. Consider for instance, a candle.



Every point of the flame of the candle emits rays of light in every direction.



While the preceding diagram conveys the idea in the statement preceding the diagram, the diagram is not the complete picture. To get a more complete picture of what's going on, what I want you to do is to look at the diagram provided, form a picture of it in your mind, and, to the picture in your mind, add the following embellishments:

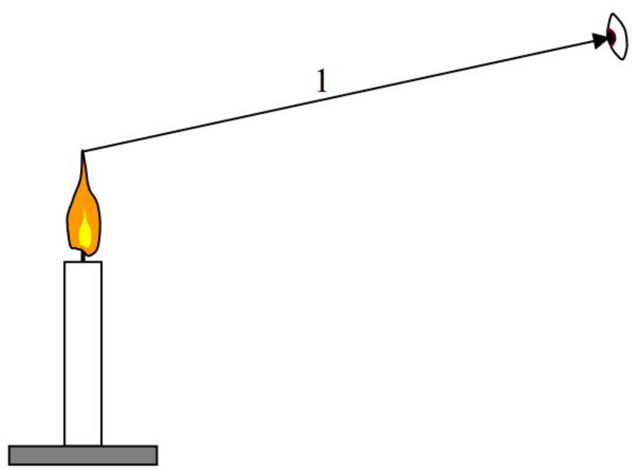


1. First off, I need you to imagine it to be a real candle extending in three dimensions. Our set of rays depicted as arrows whose tips are all on a circle becomes a set of rays depicted as arrows whose tips all end on a sphere. Thus, in addition to rays going

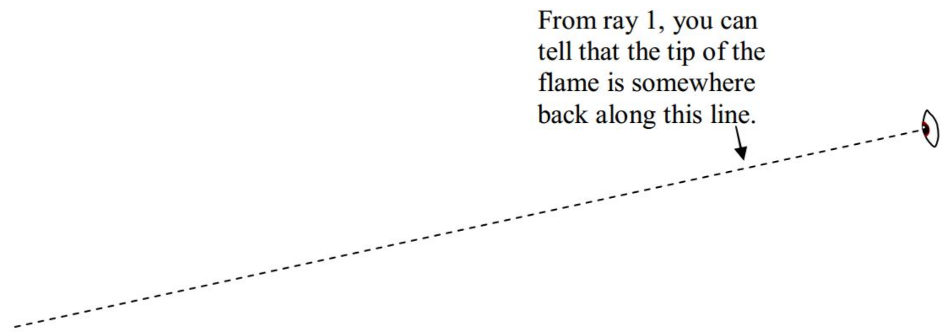
(at various angles) upward, downward and to the sides, you've got rays proceeding (at various angles) away from you and toward you.

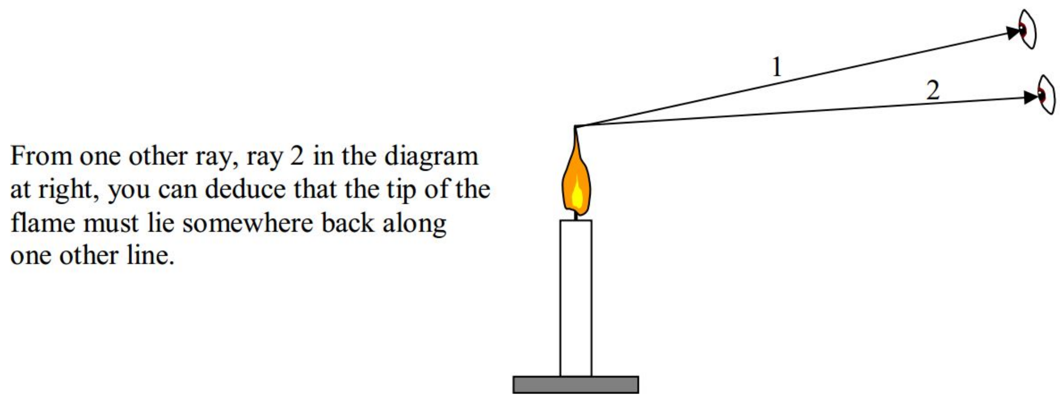
2. Now I need you to add more rays to the picture in your mind. I included 16 rays in the diagram. In three dimensions, you should have about 120 rays in the picture in your mind. I need you to bump that up to infinity.
3. In the original diagram, I showed rays coming only from the tip of the flame. At this point, we have an infinite number of rays coming from the tip of the flame. I need you to picture that to be the case for each point of the flame, not just the tip of the flame. In the interest of simplicity, in the picture in your mind, let the flame of the candle be an opaque solid rather than gaseous, so that we can treat all our rays as coming from points on the surface of the flame. Neglect any rays that are in any way directed into the flame itself (don't include them in the picture in your mind). Upon completion of this step, you should have, in the picture in your mind, an infinite number of rays coming from each of the infinite number of points making up the surface of the flame.
4. For this next part, we need to establish the setting. I'm concerned that you might be reading this in a room in which lit candles are forbidden. If so, please relocate the candle in the picture in your mind to the dining room table in your home, or, replace the candle with a fake electric-powered candle such as you might see in a home around Christmastime. Now I need you to extend each of the rays in the picture in your mind all the way out to the point where they bump into something. Please end each ray at the point where it bumps into something. (A ray that bumps into a non-shiny surface, bounces off in all directions [diffuse reflection]. Thus, each ray that bumps into a non-shiny surface creates an infinite set of rays coming from the point of impact. A ray bumping into perfectly shiny surfaces continues as a single ray in one particular, new, direction [specular reflection]. To avoid clutter, let's omit all the reflected rays from the picture in your mind.)

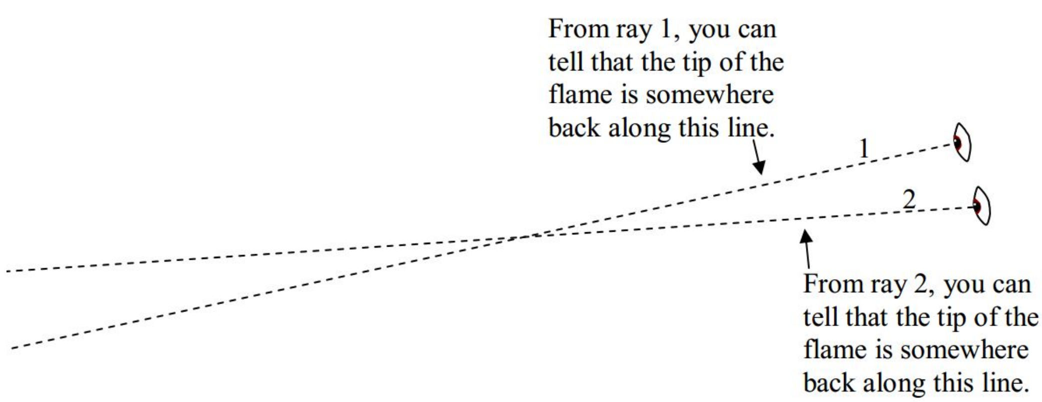
If you have carried out steps 1-4 above, then you have the picture, in your mind, of the geometric optics model of the light given off by a light-emitting object. When you are in a room with a candle such as the one we have been discussing, you can tell where it is (in what direction and how far away—you might not be able to give very accurate values, but you can tell where it is) by looking at it. When you look at it, an infinite number of rays, from each part of the surface of the flame, are entering your eyes. What is amazing is how few rays you need to determine where, for instance, the tip of the flame is. Of the infinite number of rays available to you, you only need two! Consider what you can find out from a single ray entering your eye:



From just one of the infinite number of rays, you can deduce the direction that the tip of the flame is in, relative to you. In other words, you can say that the tip of the flame lies somewhere on the line segment that both contains the ray that enters your eye, and, that ends at the location of your eye.



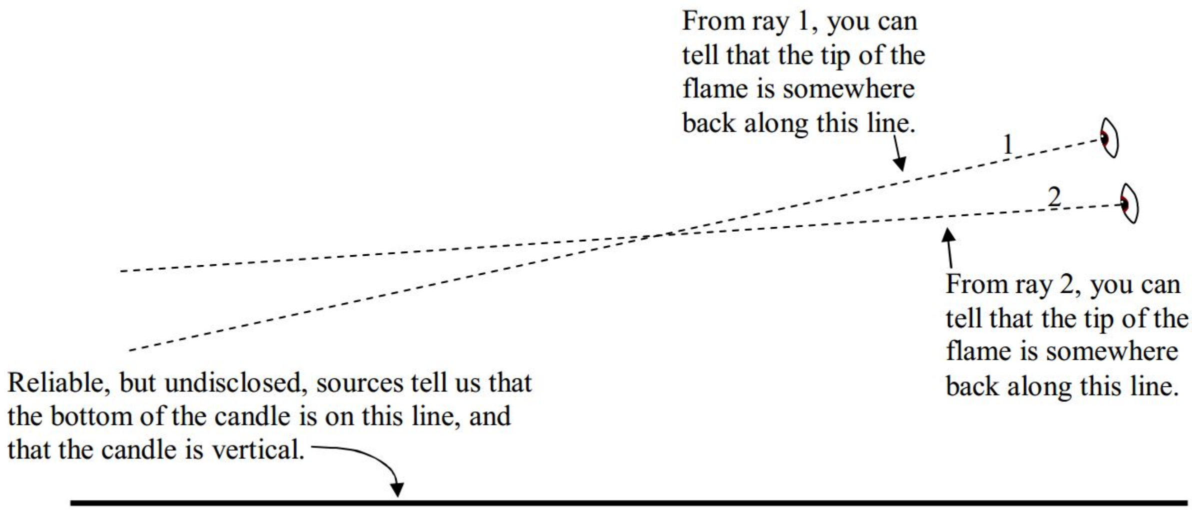




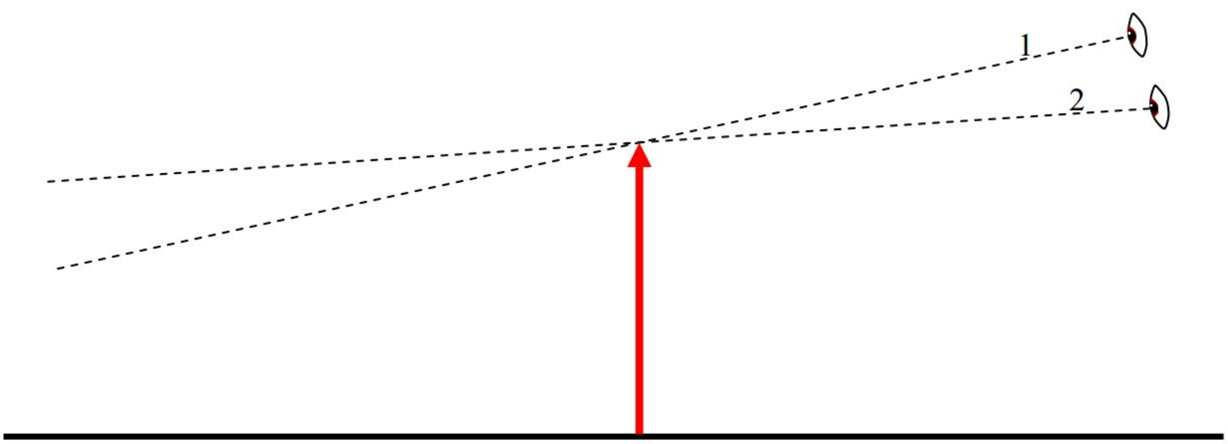
There is only one point in space that is both “somewhere back along line 1” and “somewhere back along line 2.” That one point is, of course, the point where the two lines cross. The eyebrain system is an amazing system. When you look at something, your eye-brain system automatically carries out the “trace back and find the intersection” process to determine how far away that something is. Again, you might not be able to tell me how many centimeters away the candle, for instance, is, but you must know how far away it is because you would know about how hard to throw something to hit the candle.

This business of tracing rays back to see where they come from is known as ray tracing and is what geometric optics is all about.

At this point I want to return our attention to the candle to provide you with a little bit more insight into the practice of ray tracing. Suppose that when you were determining the location of the tip of the flame of the candle, you already had some additional information about the candle. For instance, assume: You know that the rays are coming from the upper extremity of the candle; you know that the bottom of the candle is on the plane of the surface of your dining room table; and you know that the candle is vertical. We’ll also assume that the candle is so skinny that we are not interested in its horizontal extent in space, so, we can think of it as a skinny line segment with a top (the tip of the candle) and a bottom, the point on the candle that is at table level. The intersection of the plane of the table surface with the plane of the two rays is a line, and, based on the information we have, the bottom of the candle is on that line.



Taken together with the information gleaned from the rays, we can draw in the entire (skinny) candle, on our diagram, and from the diagram, determine such things as the candle's height, position, and orientation (whether it is upside down [inverted] or right side up [erect]). In adding the candle to the diagram, I am going to draw it as an arrow. Besides the fact that it is conventional to draw objects in ray tracing diagrams as arrows, we use an arrow to represent the candle to avoid conveying the impression that, from the limited facts we have at our disposal, we have been able to learn more about the candle (diameter, flame height, etc) than is possible. (We can only determine the height, position, and orientation.)



The trace-back method for locating the tip of the candle flame works for any two rays, from among the infinite number of rays emitted by the tip of the candle flame. All the rays come from the same point and they all travel along different straight line paths. As such, the rays are said to diverge from the tip of the candle flame. The trace-back method allows us to determine the point from which the rays are diverging.

By means of lenses and mirrors, we can redirect rays of light, infinite numbers of them at a time, in such a manner as to fool the eye-brain system that is using the trace-back method into perceiving the point from which the rays are diverging as being someplace other than where the object is. To do so, one simply has to redirect the rays so that they are diverging from someplace other than their point of origin. The point, other than their point of origin, from which the rays diverge (because of the redirection of rays by mirrors and/or lenses), is called the image of the point on the object from which the light actually originates.