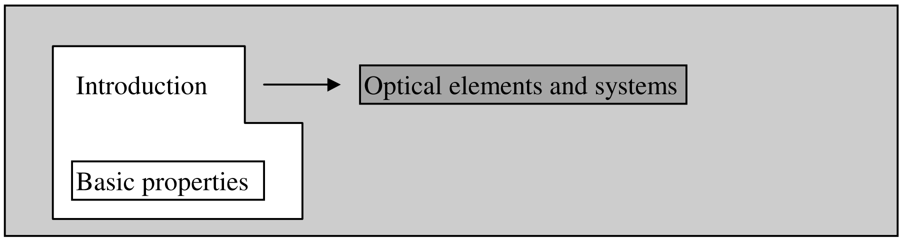
O1

Introduction: The Nature of Light



O1.1 Overview

Generally Geometrical Optics is considered a less abstract subject than Waves or Physical Optics (diffraction and interference). However, that does not imply that we can be sloppy or resort to the popular approach to problem solving based on plugging in numbers to the correct equation. In order to successfully master this material you will need to rely on good problem solving techniques including accurate scale drawings, numerical evaluation, and an evaluation of the answer for correctness.

Some of us may remember “virtual images” and “real images” from earlier physics courses. If these terms are unfamiliar, don’t panic. If they are familiar, don’t panic. However, when this concept is introduced for mirrors and lenses make an extra effort to really completely understand the difference between the two.

Because light moves in straight lines, it is extremely helpful to have a ruler handy so that the rays we draw while making pictures during problem solving have straight lines. Many a woeful physics student has become very frustrated because they didn’t use a ruler to draw the light rays. There will also be times when a small protractor will be handy.

The subject of Geometrical Optics is also filled with many sign conventions. Basically, is the number that gets used for the numerical evaluation positive of negative? It is very useful is to use a small 3” by 5” card and jot down the sign conventions as they are presented. We will find such a reference invaluable when solving problems.

The first part of this chapter will deal with the nature of light so we all have the correct concept of how light behaves. We will move through some examples to reinforce the correct notion of light rays and finish by considering the plane mirror.

O1.2 LIGHT MOVES IN STRAIGHT LINES discusses the fundamental assumption in Geometrical Optics. The assumption is that light rays travel perfectly straight paths unless they encounter a mirror or enter a different media.

O1.3 OBJECTS GIVE OFF LIGHT. The very idea that we see or that images are formed is based on the idea the light is coming from the object we are seeing or using in the problem. Some objects create light and others scatter light, but if you can see it, there must be light coming from it.

O1.4 PLANE MIRRORS are special in that light rays which bounce off of them do so very predictably. This is where is we will first learn to measure our light rays with respect to the normal.

O1.5 REFRACTION AT PLANE SURFACES is described mathematically by Snell's law and is the second way, mirrors being the first way, that light rays are made to change direction.

O1.6 TOTAL INTERNAL REFLECTION happens when light is unable to cross the boundary and ends up being reflected back into the medium with the higher index of refraction.

O1.2 LIGHT MOVES IN STRAIGHT LINES

The title of this section sums up the entire concept the we need to master before moving on. We learned earlier that when light (made of individual photons) passes through small slits, it may get deflected off to the side so that a wide diffraction pattern is formed. Within Geometrical Optics, we will completely ignore diffraction effects and treat light as moving away from a source in *perfectly straight lines*.

Of course this is physics and there always seems to be an exception to every rule. There is one at this point as well. Whenever a light ray, in its perfectly straight line travel encounters a different material, the light will get bent at the surface and follow a new straight line path.

You are familiar with mirrors, where most light rays are reflected. This is just one example of how light rays are bent at a boundary between two different materials. Light bends at any boundary and is not always mostly reflected as in the case of mirrors. Light entering a pool of water from the air will bend as will light entering or leaving a lens. Any boundary will bend light. In special cases, where the surfaces are very smooth and well understood, we can numerically predict where the bent ray will travel. *Beware of boundaries, that is where the fun stuff happens.*

If light rays don't bend, why is there light in every part of the room? After all the room is not filled with mirrors and lenses, is it? If the fundamental assumption of Geometrical Optics is firmly installed in our brains (that was light moves in straight lines) we can answer that question in the next section.

O1.3 OBJECTS GIVE OFF LIGHT

All right so why is the room light? The answer really is that almost everything is a mirror to some degree or another. As we look around we can see some true sources of light, the light bulbs, which are mounted in the ceiling. Possibly, we can see the sun which is also a source of light. Fire, electric sparks, and a few other processes also create and emit light. After the light is created, it moves off in all directions until it encounters a wall, person, desk, floor... In most cases, the light rays bend at boundaries (reflect and refract) in very unpredictable ways because the surface is not smooth like a mirror. Some of the light is absorbed depending on the material (including a retina) and some escapes out the windows and open doors. That is why the room doesn't stay bright after the lights are turned off; the light leaves the room (in straight lines) or is absorbed by the material in the room.

When we get to the problems selected to reinforce the ideas of Geometrical Optics, we will typically use an arrow as our object. Is this arrow giving off light? Strictly speaking it gives off light only if it is on fire. However, we will assume that the room lights are on and the every square nanometer of the arrow is reflecting the light in the room in every possible direction.

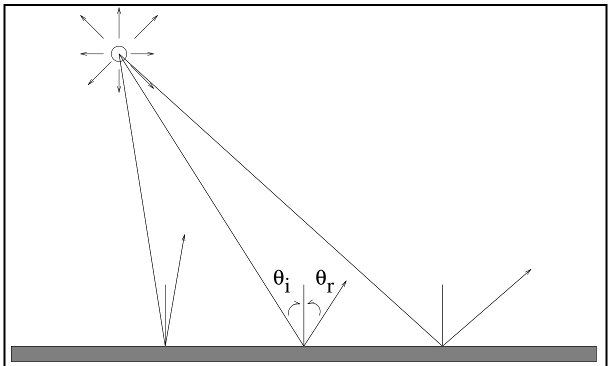
O1.4 PLANE MIRRORS

Don't forget to use a ruler and protractor.

We now turn our attention to the special case of reflection off of a plane mirror. As we noticed in the last section, everything reflects light The plane mirror (and in fact all mirrors) are interesting because they reflect the light in a very predictable, quantifiable manner. The light which is incident on a mirror is not scattered into a multitude of directions but rather is scattered into a very specific direction.

What is this special description of how light reflects off our plane mirrors? In words, "the angle of incidence, θ_i, equals the angle of reflection, θ_r." Figure O1.1 illustrates this idea graphically. There are several features in this figure of which to take note.

First, realize that in most instances only a very few of the light rays incident on a mirror are ever drawn. This particular figure is a rough approximation of a tightly focused laser beam striking a mirror but it is not even close to the situation that is in effect for the typical bathroom mirror. In real situations there are absolutely oodles and oodles of light rays hitting the mirror with a vastly huge variety of angles and positions. Yet every ray behaves according to $\theta_i = \theta_r$ so in order to understand the mirror we only need to look at a few rays.



O1.1 An object emitting light rays which then reflect off a flat surface.

We must also pay special attention to how the angles have been measured. The important angle is not the angle between the ray and the surface but rather the angle between the ray and a line which is perpendicular to the surface. This special line that is perpendicular to the surface is called a normal and we will use it over and over and over as we proceed.

Thus we see that if the light comes in at a larger angle, as measured from the normal, it goes out with a larger angle. If the angle of incidence is 37.24^o, the angle of reflection will be 37.24^o. However, as always these angles are measured from the normal to the surface.

For now, $\theta_i = \theta_r$ and measure from the normal to the surface are the key items to keep in mind.

O1.5 REFRACTION AT PLANE SURFACES

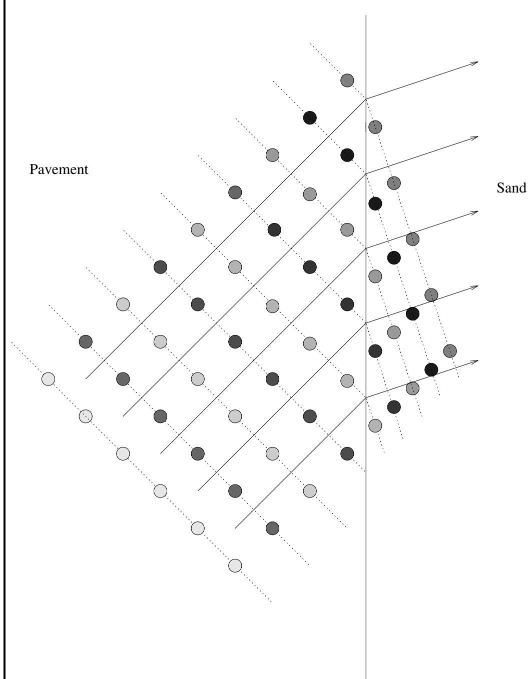
While light moves in straight lines between encounters with objects, we just saw that when a light ray interacts with a mirror it gets redirected and goes off in a new straight line. Refraction provides the other means by which light can be redirected. When a light ray passes from one medium into another medium with different properties, it changes direction. Sometimes the ray will abruptly bend toward the normal to the surface at the boundary and sometimes it bends away from the normal. Unlike reflection, where the rays "bounce" off the surface, here the rays continue traveling in roughly (but not exactly) the same direction. At the boundary, where interesting things happen, the rays are slightly bent to a new direction. (We should also review Q3.6.)

Table O1.1 Speed of light and index of refraction in various materials.

	Speed	n
Air	2.9971e8 m/s	1.00029
H_2	2.9984e8 m/s	1.00013
Ice	2.2885e8 m/s	1.31
Water	2.2491e8 m/s	1.3333
Quartz	2.0534e8 m/s	1.46
Crown Glass	1.9724e8 m/s	1.52
Polystyrene	1.8855e8 m/s	1.59
Diamond	1.2388e8 m/s	2.42

The fundamental reason that light bends when it passes from one medium to another is that the speed of light can be different in different materials. The speed of light in a material is always slower than $3x10^8$ m/s. In certain materials the speed of light is significantly slower and in some materials the speed is essentially unchanged. Table O1.1 shows the speed of light in some common materials. Table O1.1 also shows, *n*, the index of refraction which is the ratio of the speed of light in the material to the speed of light in a vacuum.

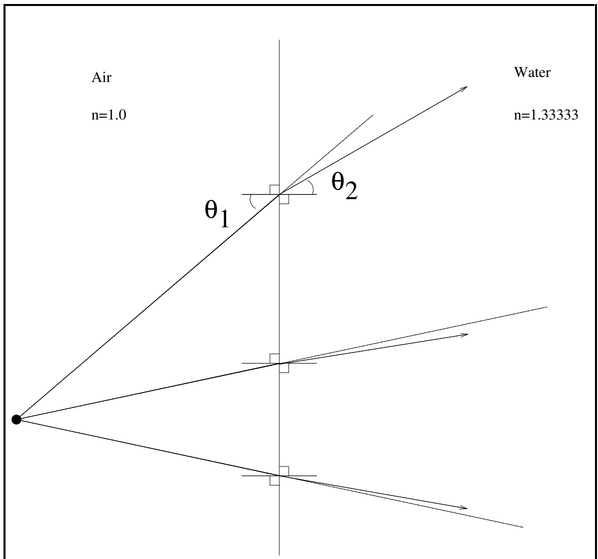
The relationship between the speed difference and the change of direction is easy to visualize, if we consider a marching band with a rather inept leader as shown in Figure O1.2. Our marching band is seen to be practicing in the school parking lot and they are marching diagonally across the lot toward the edge of the parking lot. The band corresponds to our light rays, the boundary of the lot corresponds to the interface between two different optical materials, and the diagonal path results in oblique incidence at the boundary. They continue marching to the beat but the extra effort of marching in the sand requires them to shorten their stride and slow down. The other end of the row continues at the normal speed until they also step into the sand. As the rows progressively march off the pavement, more and more people slow their forward progress until the entire band is moving more slowly. But how did this change the direction of the band? When the first person steps off and slows down the remaining marchers get a little bit ahead. After the second person steps off, the two marchers are moving the same speed (slower than the rest of the band). Because the second person got just a bit ahead of the first person, the row has a kink in it, the band bunches up, and moves off more slowly with the rows making a different angle with the edge of the pavement.



O1.2 A marching band exhibiting refraction.

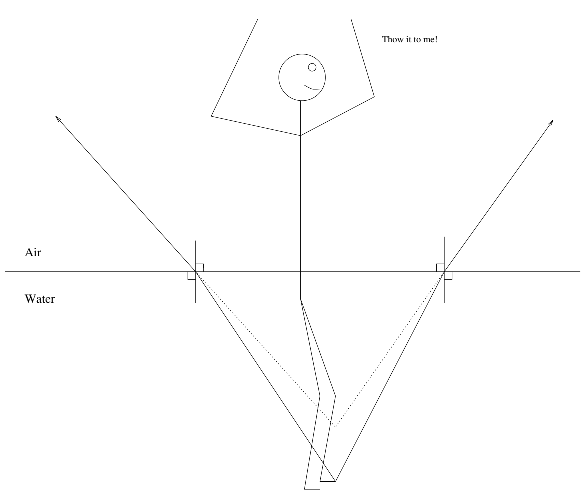
When light moves from a lower index of refraction to a medium with a higher index of refraction, it is deflected away from its original direction to follow a path which is closer to the normal. When passing from a higher index of refraction into a material with a lower index of refraction the light is bent away from the normal. These conditions are illustrated in Figure O1.3. Notice that the light NEVER follows a curved path and is bent right at the interface.

This behavior is quantified in Snell's law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$, where n_1 and n_2 are the indices of refraction of the two media and θ_1 and θ_2 are the angles describing the motion of the light in the two media. As was discussed earlier, these angles are measured with respect to the normal to the surface. We need to realize that this convention for measuring angles is very important when dealing with refraction. With reflection, we tried to follow this convention but it really didn't matter if we measured this way or not. With refraction, we must measure this way or Snell's law will be invalid.



O1.3 Refraction at an air-water interface.

This bending of light is very common and very easily observed with fish tanks, water glasses, swimming pools, and streams. Refraction is responsible for the making straws look bent in water glasses and it is responsible for making your legs look shorter when standing in the water. Figure O1.4 illustrates the path of the light rays leaving a person's foot that is under water. We must not work from the eye to the object. We must start with the source of the light. We can see that once the light is traveling in air, it travels as if it had come from an object that appears closer than the actual object. This is called a "virtual image" and will be discussed in more detail in Chapter O2.



O1.4 Light rays traveling from an underwater foot into air.

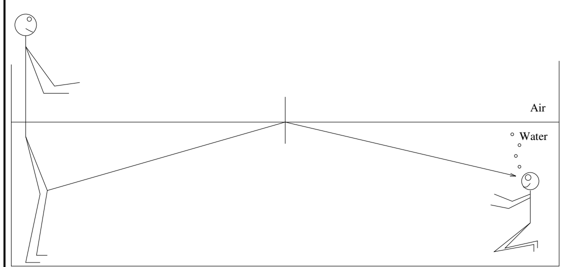
O1.6 TOTAL INTERNAL REFLECTION

We begin this section with a question. What happens when the refracted light ray is bent to such a degree that it has no place to go? Consider a ray of light that starts in a medium with a higher index of refraction and is incident on a medium with a lower index of refraction. Further suppose that the angle of incidence is fairly large so that the light ray grazes off the surface. The light ray will need to bend away from the normal in the second medium but there might not be any room.

Mathematically, this occurs when we solve Snell's law for θ_2 and get no solution. Algebraically, we get

$$\sin\theta_2 = (n_1 / n_2)\cdot \sin\theta_1$$

but if the right hand side is greater than 1 we do not have a real solution for the angle. If n_1 / n_2 is less than 1 this will never happen but if this ratio is greater than 1, our problem will always occur as the angle of incidence increases. The critical angle is the value for the incident angle that gives a refracted angle of 90° in the second medium.

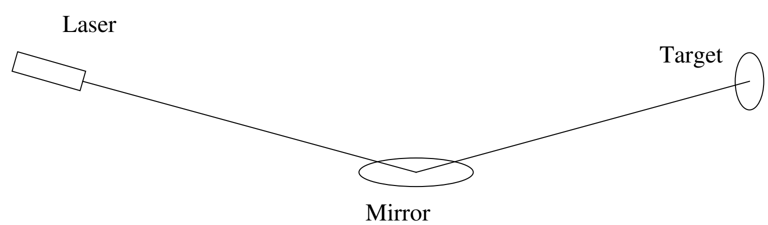


O1.5 Total internal reflection in a pool.

If the incident angle is larger than the critical angle, where does the light ray go? The light ray does not enter the second medium but reflects off the boundary between the two media as if there was a mirror located at the interface. The fundamental *why* of this phenomena is beyond our ability at this point but this is common behavior. Next time there is a water glass handy, try looking up, through the side of the glass at the liquid-air interface and find the places where this interface acts like a mirror. Figure O1.5 shows another place where total internal reflection can be seen. The feet of the person standing at the far end of the pool can be seen by a person underwater because of total internal reflection of light off the surface of the pool.

O1.7 HOMEWORK PROBLEMS

1. A laser beam is reflected off a small mirror on the floor in an attempt to hit a target located 2 meters to the right of the mirror and 1 meter above the floor. At what angle (relative to the mirror's normal) must one aim the laser to reflect off the mirror and successfully hit the center of the target.



2. A light ray is incident on the plane interface between two media. The ray makes an angle of 25° with respect to the normal to the interface. If the ray is initially in the medium with $n = 1.4$, find the angle of the ray after it refracts.
3. A light ray travels through a medium that has an index of refraction of 1.4. The ray encounters a new medium with an index of refraction of n. When the ray makes an angle of 50° with respect to the normal to the surface, it begins to exhibit total internal reflection. What is n?

4. The figure below shows a square polystyrene block. A laser beam is directed into center of the block from the left at an angle of 55°. Where does the laser beam emerge from the block and what is the angle between the emerging ray and the normal to the interface?