Chapter 35: Geometric Optics

The Study of Optics

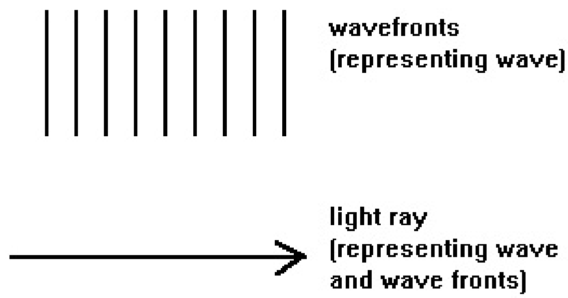
Regardless of whether light is a wave or a particle, there are ways that we can use our knowledge of light and its properties to manipulate its behavior. The study of how to manipulate light is called optics (another definition is the study of how light behaves when it encounters specially designed obstacles). When light enters materials, its path can change and it patterns of light enter materials together (such as the pattern of light coming from an object), the pattern might be altered in a predictable pattern after leaving the material (for example, the pattern can be blurred or "off focus", or even enlarged). The most obvious examples of where this might be useful are in eyeglasses. If people are unable to see clearly with their eyes, we could put a lens in front of them. This lens would distort the incoming pattern of light so that when the eye focuses it, it is clear (more on this later).

The study of optics is (as most areas of Physics) complicated and mathematically difficult. However, there is one branch of optics that is very useful and fruitful which beginning students can understand. It is called Geometric optics. Geometric Optics is the study of the behavior of light disregarding the effects of diffraction. If we ignore diffraction, we can do many problems and predict the outcomes of many situations. If we think about diffraction for a minute, we can see that its effect for light is very small, yet for sound the effect is much more pronounced (an astute student should be able to answer in unavoidable "Why?"). Thus geometric optics would not be a reasonable method to employ when discussing the behavior of sound.

From the above paragraph, you can see that Geometric optics is only an approximation. It will not yield the exact path of the light, but the approximation is very close (in most instances) and is very useful.

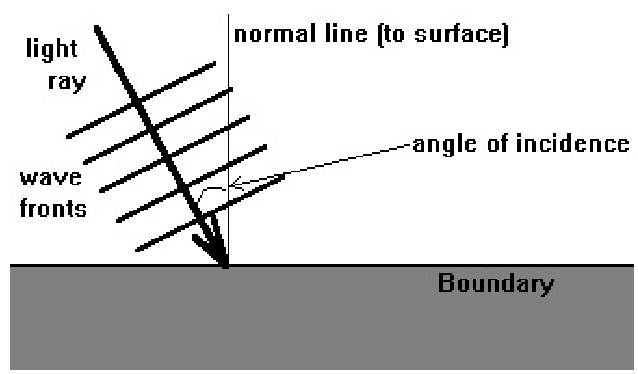
Light Rays and Reflection

In geometric optics we do not represent light as either waves or particles, but instead we use a third representation; the light ray. By definition, a light ray is a representation of light consisting of an arrow drawn in the direction of the light's motion perpendicular to its wave fronts. An example is shown below.



It is important to remember that the wavefronts are still there, the light ray does not replace them, it is simply an easier wave to draw the waves. An astute student should be able to conclude why we must ignore diffraction if we use this representation.

Since our main concern in this chapter will be light impingent on a boundary, we should make a note here about one convention used. When light strikes a boundary, we need to know the angle at which it strikes (called the angle of incidence). This angle is given as the angle between the light ray and the **NORMAL** to the surface at the point of intersection, as shown.



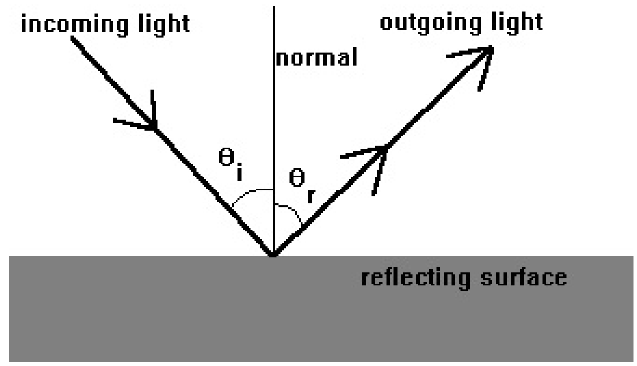
Here, the angle of incidence is somewhere around 30°. A very common mistake for beginning students to make is to refer to the angle between the surface and light ray (in this case about 60°), attempt to steer clear of this mistake.

Light rays in ray diagrams are useful for predicting the behavior of light encountering a boundary. It was mentioned earlier that whenever light encounters a boundary some is reflected and some is transmitted (absorbed) into the material. The underlining underscores the continued importance of this statement. We will begin our examination of this behavior by looking at the simplest aspect: the reflected light.

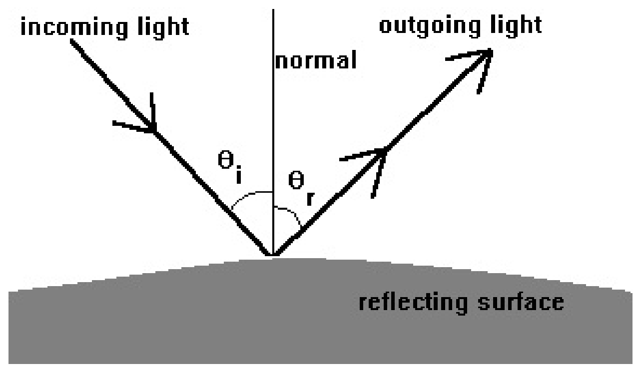
The Law of Reflection is simple: the angle of incidence is equal to the angle of reflection.

$$\theta_i = \theta_r$$

This law is logical and indeed almost intuitive. An example is shown below.

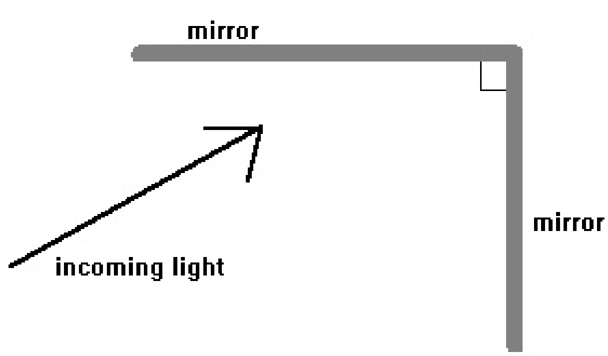


This law also holds for light impingent on a curved surface, as shown.



The application of this law provides some interesting examples of reflective behavior.

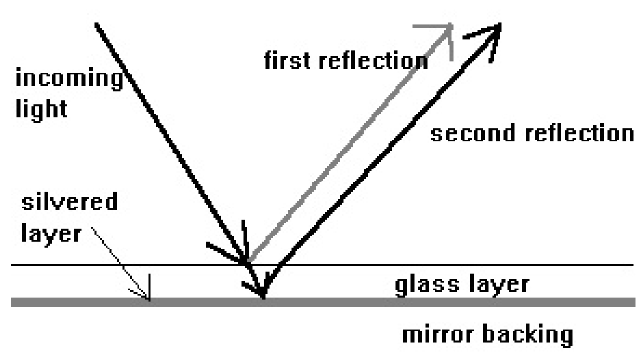
EX FR.) Prove that any light ray impingent on the "corner reflector" below will leave parallel to the incoming light.



Although this was proved only for the two dimensional case, it works for three dimensions as well. This gives us a useful device that will always reflect light back to the source. If you ever get a close up look at the little bumps that are often placed in the road to indicate lanes, you will see that the reflective surfaces are made of many little corner reflectors, as are bicycle reflectors. Very tiny corner reflectors are used to make road signs and are mixed in with paint for license plates. Once again, the purpose of this is so that when your headlights hit these things, the light is reflected back to you so you can see it. If it were not, you might not be able to see these things at night. If you construct a large corner reflector, you can see this effect. No matter where you stand, you will always see your reflection.

Corner reflectors are also used for measuring distances with lasers. A corner reflector was placed on the moon by Apollo astronauts and a laser can be projected from the earth to the mirror. No matter how it hits, the light will come back parallel to the same source (shifted over slightly) and the time until the return beam arrives can be used to determine the distance. There is also a satellite in orbit where a similar technique is used to measure the positions of the continents to study continental drift. This satellite, called Lagoes, can measure shifts as small as 2 cm.

A final interesting note about reflection and mirrors can be made. Consider a beam of light impingent on a mirror. Most common mirrors consist of a reflective surface (silver or polished aluminum) that is covered by a thin piece of glass to protect the surface. When light strikes the air-glass interface, some if reflected and some is transmitted. In this situation, the reflected light is a small percentage of the transmitted light. This transmitted light then hits the glass-silver boundary and once again some is transmitted and some is reflected. In this case the reflected light is the greater, consisting of almost all of the light (see diagram).



Thus the mirror produces two reflections, the first reflection (in grey) is very light, while the second reflection is very bright. Although you often cannot notice this effect, it can be used as an advantage. Consider a situation where you would want to view the light image instead of the bright. This might arise if a car's bright headlights were shining into your rear-view mirror. By tilting the mirror, you can view the lighter reflection and not be blinded (or annoyed). This sort of thing can also be seen when looking at a window at night (why you can't see out was discussed earlier). Often you can see two reflections of yourself, one from the inner surface of the glass and another from the outer surface. While this effect is hardly of circumstance in a regular bathroom mirror, you would certainly not want this to be showing up in any important mirror, like the one used in the Hubble Space Telescope. Mirrors used in scientific applications do not have a protective layer over the "silver" or reflecting surface. These need to be handled with care so the surface does not get scratched.

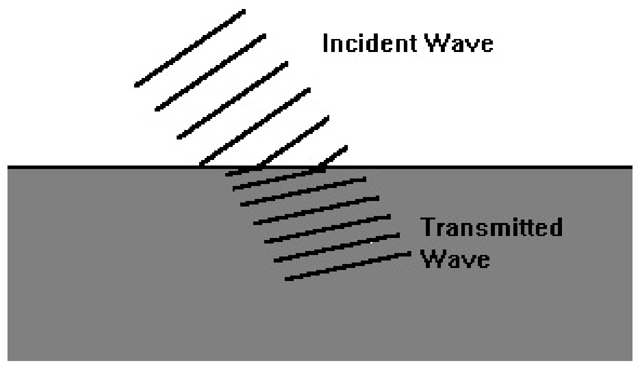
Refraction

We have discussed in detail the fate of the portion of the wave that is reflected, so it now remains to discuss what happens to the part of the wave that is absorbed (or transmitted) into the material. When a wave enters a new material, certain effects are produced and changes made in the wave. The student should already be able to guess the first of the three changes that occurs if they recall our chapter on the properties of waves. We have said before that the speed of the wave is material dependent, thus a wave entering a new material will change speeds. This change in speed will cause other changes in the wave. To see if you can figure out these other changes, let us look at what at first seems to be a silly example.

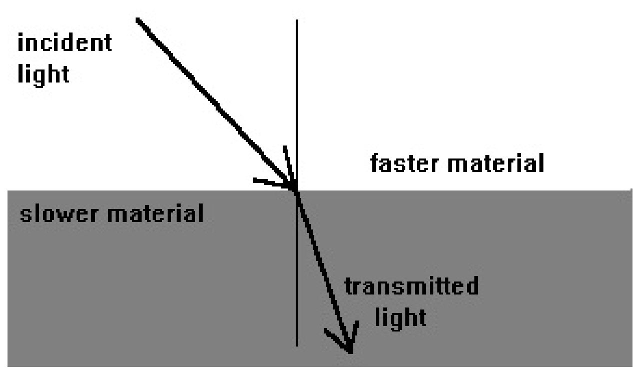
Imagine a wave as represented by a marching band, where each line of musicians is a wave front. Now imagine that band marching across a parking lot and marching right off the pavement and into thick mud. Naturally, their boots would stick and they would be moving slower. What changes would occur to the band's formation?

After thinking for a while, you should come to see that the rows of the marching band would be closer together, since once one enters the mud it must slow down, but the next row is still on the pavement and it will get closer to the first. The same effect occurs when waves change mediums. If a wave enters a medium where the speed is reduced, the wavelengths bunch together (get shorter). If it enters a medium where the speed is increased, the wavelengths increase. But what happens to the frequency? The answer is simple: nothing. Recall that when we introduced frequency we said that it only changes if the source changes (as in the Doppler effect). Since the source is not changing, the frequency does not change. "But wait", a student might respond, "the frequency and wavelength are related, so how can one change and not the other." I leave it to the astute student to figure out how to appropriately respond.

The third and final change that occurs to a wave entering a new material is a little harder to see at first. But once again consider the marching band example. Only this time, let us have them march off the pavement at an angle. Think carefully and see if you can figure out what will occur. If the band leave the pavement at any angle other that 0° (between the normal and the light ray of the band), their direction will change. When the band marches off the pavement and into the slower mud, it will produce an effect like the one shown below.



Here you can clearly see how the wave is changing directions and the wavelength is becoming shorter. This effect takes place because one part of each wavefront is slowing down before the rest of the wave front. It is just like what happens when you drive your car off the side of the road. Often you will feel a tug on the steering wheel when your right wheels leave the road. If they slow down before your left wheels, the car is pulled to the right. Because we will be working with so many ray diagrams, it might be helpful to represent the above in a ray diagram.



The effect discussed is called **Refraction** which is the bending of light (and the change in wavelength) that occurs when a wave enters a new medium. This effect occurs because of the new speed of the wave in the new material. Before we move on, I would like to summarize what we have learned about this.

When a wave enters a new material:

- Its speed changes.
- Its wavelength changes (shorter if the new material has a slower speed, longer if the new material has a faster speed).
- Its frequency remains unchanged.
- If the wave enters the material at an angle other than 0° (in reference to the normal), it will bend.
  - -Towards the normal if the material is slower.
  - -Away from the normal if the material is faster.

Snell's Law

Now that we understand what occurs, it remains for us to begin to deal with it mathematically. To do so, we introduce a new concept called the Index of Refraction. The index of refraction is a measure of the speed of a wave in a material compared to the speed of the same wave in a reference material. For light, we get the index of refraction by:

n = speed of light in vacuum/speed of light in material

or:

$$n = c/v$$

where n is the index, c is the speed of light in a vacuum (3×10^8 m/s and v is the speed in the material.

EX BHG.) Derive a new equation for the index of refraction according the wavelengths of the waves in a vacuum and in the material.

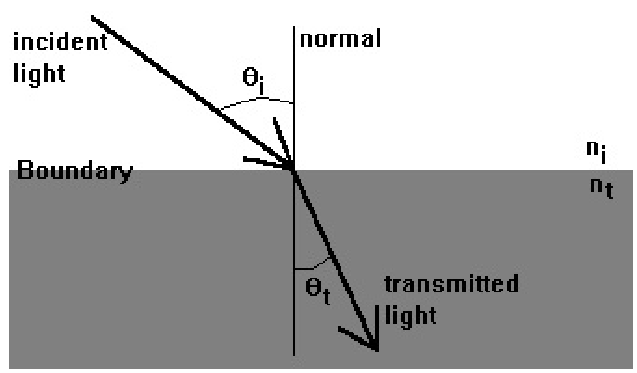
These two equations are very important, since they can tell us the speed of a wave or its wavelength in a different material.

EX RTY.) If light with a vacuum wavelength of 750 nm enters water (n = 1.5) what is its new speed and wavelength?

This also allows us to finally introduce Snell's Law or the Law of Refraction. This law states:

$$n_i \sin\theta_i = n_t \sin\theta_t$$

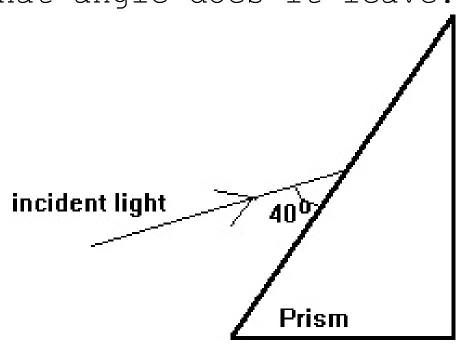
where n is the index of refraction of the material and θ is the angle between the light ray and the normal. The indices stand for incident light (i) and transmitted light (t). The diagram below illustrates this.



An this is all we need to begin sample problems.

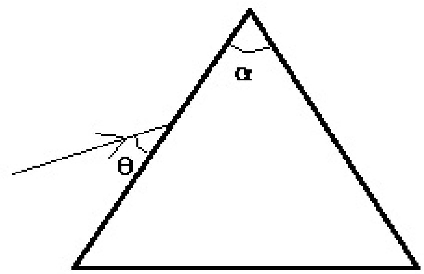
EX KIU.) Supposing a beam of light is impingent upon an air-water interface at 35° (to the normal!). What is the angle of the light beam in the water if the air is considered to have an index of refraction of 1 and the water has an index of 1.33.

EX XMJ.) If a laser beam hits a 30-60-90 prism (triangular piece of glass that is flat on all five sides) made of a material with n=1.5 as shown below, at what angle does it leave?



Aha! Did you remember to use the proper angle? Remember: you must use the angle between the light ray and the normal for Snell's Law to work. Because this result will be used again later, let us try to generalize it into a formula.

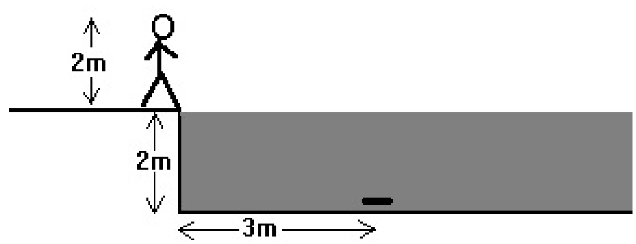
EX NTP.) Derive a formula for the angle at which light leaves any prism with an apex angle of α when it enters at some angle θ.



EX TBH.) If a light beam strikes a pane of glass (n = 1.5, thickness = 2. 0 cm) at 30°, a.)at what angle does it emerge and b.) how far has it shifted over (deviated).

There are some interesting conclusions from the above problem. First, any light that enters a material with parallel sides, will leave at the same angle. This is an important fact, since if it did not, windows would give a very strange and distorted view of the outside. (Can you prove that result for a general case?) Notice also that this only works if the sides are parallel, not in the case of a prism, for example. In fact, this is representative of a lens. Lenses work by not having parallel sides, thus the lights direction is changed when it leaves the lens so that it can be focused differently (an astute student might ask, "Focus? What does that mean, it is the second time that word was used, yet what exactly is it?" The answer will come in a later chapter, but for now we can use the common meaning of "sharp, non-blurry image". Let us conclude this section with two, real life examples.

EX COI.) If a penny is dropped to the bottom of a 2 m pool and viewed from outside the pool, it will not appear to be 2 below the surface. How deep will it appear to be?

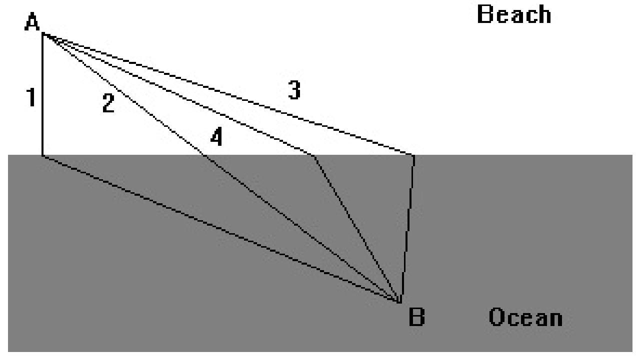


EX WKC.) The sun's light refracts as it hits the surface of the atmosphere. Since the atmosphere changes density with altitude, the refraction is not a simple process that can be evaluated with a simple application of Snell's law. However, a conceptual understanding can tell us that when we see the sun set, the image we are seeing is not exactly where the sun is at that time. Is the sun actually higher in the sky or lower?

Fermat's Principle of Least Time

We have introduced Snell's Law and used it in many applications, but so far we have offered no real derivation to convince the student that is the proper equation. We have explained why light bends, but not why $n\sin\theta$ is the correct term to use to find the deviation. Snell's Law is actually a law that was derived empirically, meaning by fitting known data (from experiments) to a function. It was not originally derived algebraically. However, there is a methods that we can use to arrive at this result from pure logic and known principles. It is called Fermat's Principle of Least Time.

Fermat's principle states that light will always take the path from one point to another that requires the least amount of travel time. In any one material, that path would normally be a straight line, however, when changing materials, the path calculation becomes more complicated. When students are first introduced to this statement, it often does not seem obvious that the path would be other than a straight line. To clarify this, consider an analogy. Imagine that you are a life guard on a beach at point A (below). If a swimmer is drowning at point B, what is the fastest way to get to them? Since you can run faster than you can swim, you would not want to take path 1. You might think about taking path 2, but you would consider that there must be a way to cover a little more distance on land. Path 3 would give the most time on land, but with path 4, you get in the water a little sooner and the difference in swimming time for paths 3 and 4 is minimal.



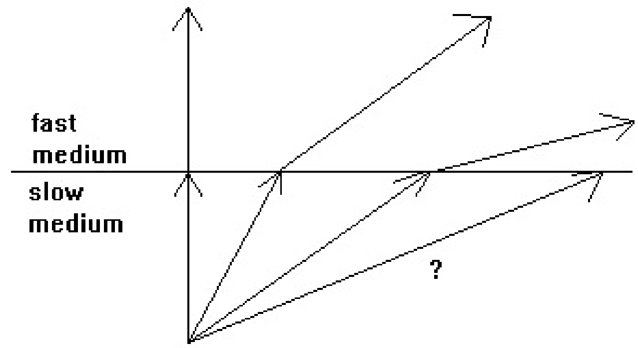
It turns out that the path that satisfies $n_1\sin\theta_1 = n_2\sin\theta_2$ is the path that would get you there in the least amount of time (provided the ns contained your speeds on the beach and in the ocean). To prove this would require writing down and equation that described all possible paths and using calculus you could find the one that minimized time. Students in calculus concurrently with Physics should give this a try.

Total Internal Reflection

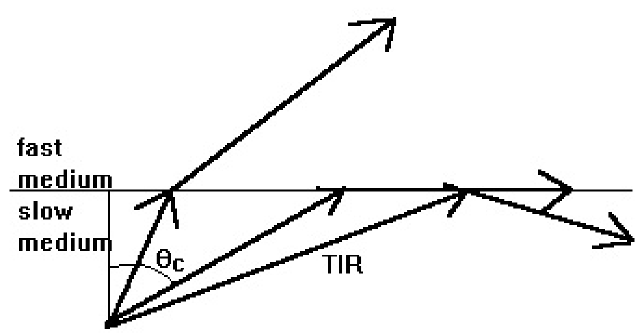
To finish us this chapter, we will turn to three important consequences of the application of Snell's Law. The first of these is called Total Internal Reflection. We will introduce this by posing an example.

EX PKV.) Suppose light encounters a glass-air interface (notice the order) at a 60° angle. At what angle is it refracted? Use $n_{air} = 1$ and $n_{glass} = 1.5$

If you do the problem correctly, you will notice that you cannot arrive at an answer, since it is asking for the inverse sine of a number greater than one. Let us examine how this comes about. Consider light going from a slow medium to a faster medium. We begin with the light being incident at o° from the normal and then we will slowly increase the angle. The diagram below indicates the path of the light beam as we make this progression.



Since the angle of transmission is increasing, the question arises as to what will occur when the incident angle becomes so great that the transmitted beam can no longer bend away from the normal line. This is the case of the last beam marked with a question mark. It simply can refract! At some angle the transmitted beam must travel directly along the surface of the boundary and above that angle refraction is impossible. The angle above which refraction cannot occur is called the critical angle (θ_c). Beyond this, a phenomena occurs called Total Internal Reflection. When this happens, none of the light is transmitted, it is all reflected. This phenomena is illustrated below.



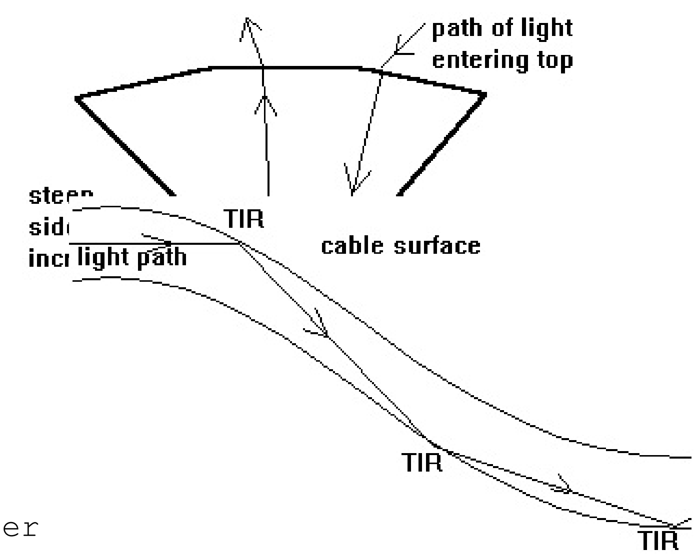
A little thought will convince you that total internal reflection (TIR) can only occur when the light leaves a slow medium and enters a faster one. Mathematically this is given by:

$n_t < n_i$

It should also be noted that this is a perfect reflection, all the light is reflected, none is transmitted or absorbed. The reflected light obviously obeys the Law of Reflection ($\theta_i = \theta_r$).

EX PUH.) Derive an equation for the critical angle of an interface and use it to find the critical angle for glass-air and diamond-air interfaces. Compare the two and discuss the meanings of the numbers. Use $n_{glass} = 1.5$ and $n_{diamond} = 2.42$)

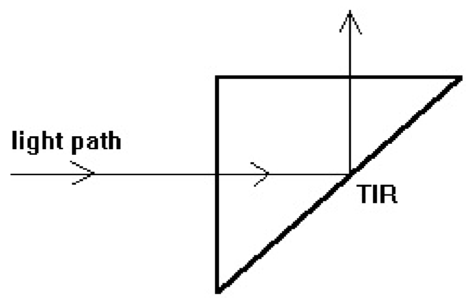
TIR can explain a number of interesting phenomena. We saw above that the critical angle for a diamond is very low. TIR is the reason that diamonds "sparkle". If you ever look close up at a diamond, you will notice very gradually sloping sides on the top surface and sharp, steep sides on the back. Once light from the outside enters a diamond, it encounters the back face at a very steep angle, well beyond the critical angle. This light then bounces around a bit inside the stone and hits the top face below the critical value, allowing it to escape. Diamonds sparkle because (most of the) light that enters them from the top cannot pass through, it must come out the top again.



TIR can also explain how fiber

optic cables work. These cable are made with a material and interface that has a very small θ_c. Thus once the light enters, it bounces thought without leaving.

Because of TIR, prisms can be used as "perfect mirrors" as shown below.



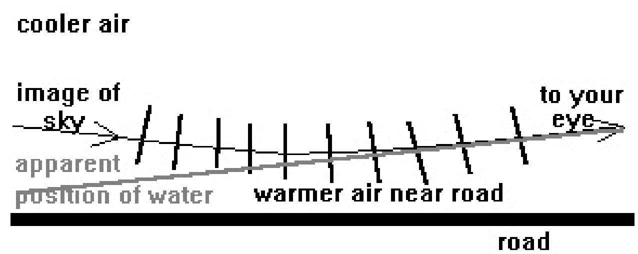
Because of the efficiency of this mirror, devices like this are often used in optical systems such as binoculars and telescopes. This type of mirror also avoids one other pitfall that will be discussed later.

As a final comment on TIR, it can also be used to explain why when you look at an aquarium from the side, you cannot see through the back glass. This effect is heightened by the fact that often there is little light coming from behind the aquarium, so you also get the "night window" effect discussed earlier.

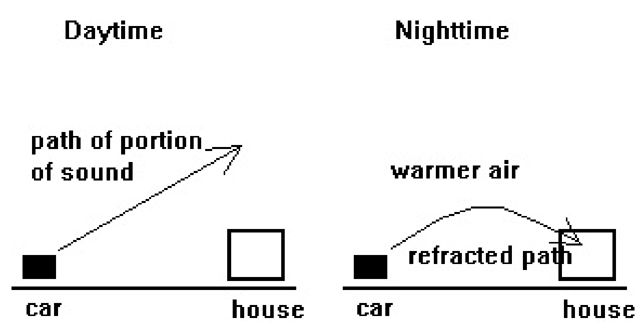
Refractive Bending

Another effect produced by refraction is something called refractive bending. This is most often seen when there is a gradual, instead of an abrupt, boundary between two media. One of the most common examples of this is when you have warm air (of liquid). As a light beam enters the area of warm air, it will begin to be refracted. It can eventually be refracted back up into the colder air, almost as if it were reflected off the boundary. However, this is not reflection or TIR, it is actually refraction. The most common example of this is seen when driving in a car along a long, straight road on a hot day. Often you will see a "mirage" of water on the road in front of the car. As you drive, this water appears to move with you, always staying the same distance in front of the car. What you are actually seeing is a refracted image of the sky. Your brain interprets it as being on the road because that is where the light waves <u>appear</u>

to originate. This effect is illustrated below with both wave fronts and light rays.



This effect is also very pronounced for sound. If you live a few blocks from a busy street or highway, you may have noticed that you can hear the cars much more clearly at night. The reason is that a layer of warmer air above the surface is refracting the sound that would normally not reach you back down to your location.



This same effect is also <u>part</u> of the reason that thunder can be heard so far away, especially at night.

Refractive bending can also be a nuscience for sonar (used primarily on submarines). Sonar requires (and assumes) that the sound from the transmitter goes straight out to an object, is reflected and bounces straight back. If there is a section of water in the way that is either hotter or colder than the surrounding water, the sonar beam will bend. If it is then reflected straight back, it will give an erroneous location for the object. This can even lead to "blind" spots which the operator thinks that the sonar has examined, but in fact the sound waves were bent around the area.

Dispersion

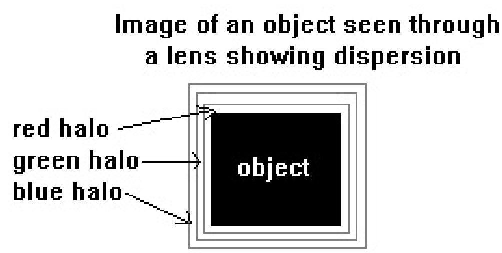
Throughout our discussion, there has been one underlying assumption that has not been addressed. It has, up to this point, been assumed that the velocity of all waves of the same type in the same material are the same. In other words, all light waves, regardless of frequency travel at the same speed in air or glass or water. It turns out that this is not entirely true. Wave velocity (in a material, not in a vacuum) is slightly dependent on frequency. In other words, red light and blue light do not travel at the same speed in the same material. While this effect is slight, and barely noticeable most of the time, there are circumstances where the effect is pronounced.

If wave speed is frequency dependent, then it follows that the index of refraction of a material is also frequency dependent. Different light waves bend different amounts when entering a material. The example below illustrates this fact.

EX LOC.) Suppose we made a prism out of a material that had an index of refraction of $n_r = 1.61$ for red light and $n_p = 1.55$ for purple light. If white light (all colors together) hit this prism at 20° to the normal, at what angle would each of the lights leave the prism (assume an equilateral prism).

This effect then explains how a prism can split white light into its component colors, since each color is bent a different amount by dispersion. When sunlight hits tiny drops of water suspended in the air after a rainfall, each one acts like a little prism and the end result is a rainbow (do you know what shape a rainbow really is?).

While an aesthetically pleasing effect, dispersion can wreak havoc on optical systems. Lenses, as was mentioned, bend light like prisms do. If all the colors are bent different amounts, this can end up creating a "halo" effect around an object.



In situations that demand the best images be formed (especially of distant or faint objects), such as telescopes, this would be an undesirable nuisance. The effects of dispersion due to lenses are called Chromatic Aberrations and is one of the primary reasons that in large telescopes lenses are not used and instead mirrors are used to magnify the image.

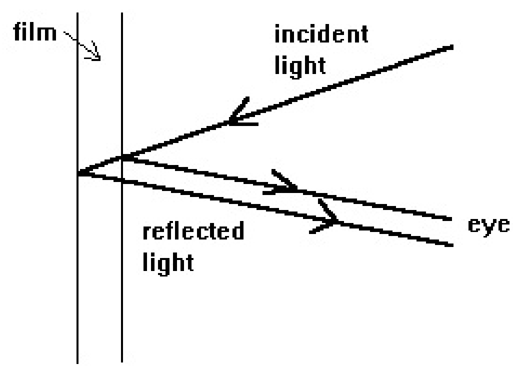
Thin Films

The final topic in this chapter is an interesting, yet extremely complicated one. It will call on use to use a number of principles discussed in previous chapters all together to explain an effect. This effect is called thin film interference. Before we begin, I would like to outline the concepts we will use (for the sake of the student) and remind the student of each one. In one or two instances I will build further on a previous idea with new concepts learned in this chapter.

- When light is incident on a boundary, some of the wave is reflected and some is transmitted.
- When two identical light beams arrive at a receiver (your eye, for example), the effect produced will be an interference pattern depending on the phase difference of the waves.
- Phase differences occur because of different path lengths the waves have traveled.
- When a wave is reflected, the type of boundary determines whether or not there will be a phase shift on reflection.

<u>If the boundary is "hard" (meaning $n_2>n_1$), then there will be a 180° phase shift on reflection. If the boundary is soft ($n_2<n_1$)then there will be no phase shift.</u>

Now imagine the following situation. You hold a very thin film in front of you and shine a bright light over your shoulder onto the film. In this case, imagine that the film is very, very thin (say only about 10% of the wavelength of the light being used). What do you think your would see? The answer is nothing at all. If we take a closer look at the behavior of the light in the film, we can see why. When light hits the first surface of the film, some if reflected and some is transmitted. That transmitted light then hits the back interface where it is once again transmitted and reflected. However, on the second boundary the reflected light is phase shifted by π (why didn't this happen to the first reflected wave?). This light then leaves the film and both reflected light beams reach your eye. The net result is destructive interference. No light.



We should stop for a minute and address two assumptions that were made. First, we should have stated that the film must have a greater index of refraction than the air around it (why?). Second we have ignored the fact that the second reflected beam has traveled a greater distance than the first and thus the phase difference is not exactly π. This second assumption was addressed by the fact that we said the film was very thin compared to the wavelength. Shortly we will remedy this approximation (with yet another approximation).

The next question that students might have is, "What exactly is this "film" thing that we are talking about?". Most often films of this nature are liquids spread over the surface of either a solid or another liquid. If the liquid film has a high level of cohesion, then the liquid can spread very thin and yet still hold together. Two common examples of this type of film are gasoline or oil spread on water or a soap bubble. Here again, the student might object, "But we can see gas on water or a soap bubble, they are not black, often they have pretty patterns of colors." True, and that is where we are heading. However, you can see black sections of soap bubbles or gasoline and these are areas where the film is the thinnest.

If the film is not of negligible thickness, but still not too thick (between about 0.25 of a wavelength and about 3 wavelengths), we must factor in the effects of the extra distance. Imagine that white light was shone on a thin film. For one color of light, the thickness of the film would be half of a wavelength (assume there is such a light in our source among many others). Since the reflected beam traveled through twice the thickness of the film, it would be phase shifted by 2π and we would expect constructive interference. However, it was also shifted on reflection, resulting in a phase difference of 3π with our first reflected wave. We now have destructive interference. In this case, that color would be missing when the light reached our eyes, giving us an extra dose of its complimentary color. For example, if red were destructed, we would see primarily green.

If the film thickness were exactly 0.25 of a wavelength, the net result would be constructive interference for that one particular color and some degree of destructive interference for the remaining colors. Once again, one particular color would be singled out and enhanced.

This is what is occurring in soap bubbles or films of gasoline on water. Since we see many different colors, we can tell that the film is not of uniform thickness and different thicknesses produce different constructive and destructive interferences. The patterns change over time as the thickness of the film changes, due to a variety of reasons (in a soap bubble, gravity is the main reason, the top gets thinner and thinner as time goes on).

Once again, the astute student is raising their hand. "But the light is entering at an angle and thus the actual path is longer than the thickness of the film. So a film thickness of 0.25 wavelengths would not really produce constructive interference." Absolutely correct, you have arrived at our final approximation. For this discussion (and the derivation to follow) we will assume that the angle is not great and the film not thick enough to matter, we will approximate the path length to be the thickness of the film.

Before we begin the mathematics, we should mention a very practical application of thin film interference. Often, important optical instruments are coated with a thin film that will cause destructive interference for green light (the middle of the visible spectrum). This is called a non-reflective coating and it prevents (to a certain degree) images from forming due to reflections. This coating is used in lenses for cameras, where extra images from reflections would bounce around inside the camera and eventually end up on the film, distorting the image. There are two interesting questions that this process raises. First, what condition (in terms of the index of refraction) must be met by the material used as a coating? Secondly, there is yet another reason that green is the color chosen for destructive interference, can you figure it out?

The Mathematics of Thin Films

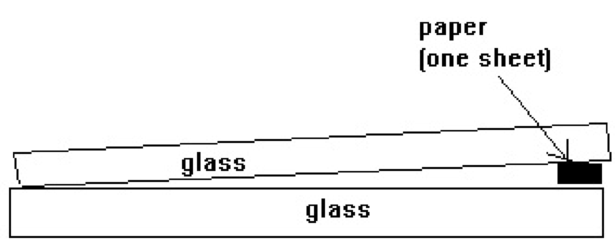
EX FWE.) Imagine that monochromatic light of wavelength λ is incident on a thin film of thickness d and index of refraction n. Derive equations for the thickness of the film that will produce constructive and destructive interference.

Circle these equations, they are important. Also note that there was one possible "trap" in that problem. When comparing the thickness of the film to the wavelength of the light, be sure to use the wavelength in the material, not the vacuum wavelength.

EX VEF.) On a soap bubble (n=1.3), you notice an area where there is a bright band of red (λ = 750 nm). What are three possible thicknesses of the film in that area?

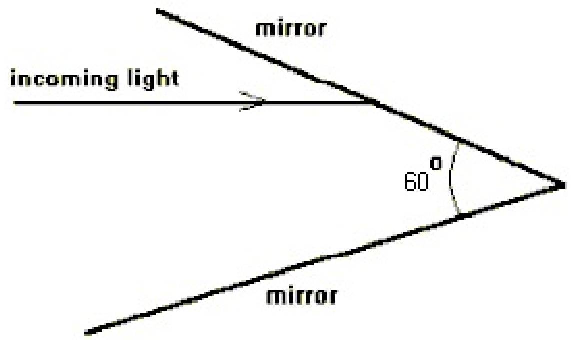
EX XXC.) If a film has a thickness of 275 nm, what wavelengths of light will produce constructive and destructive interference? Give three answers for each.

EX JGH.) Describe the pattern produced by an "air wedge" when illuminated by monochromatic light. An air wedge consist of one piece of glass laid flat, with another piece of glass placed on top of it at a very small angle (often achieved by putting a piece of paper at one end between two panes of glass).

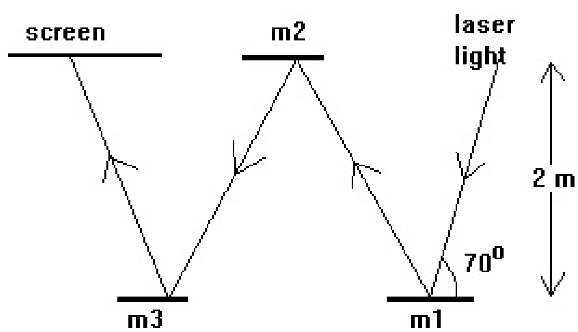


<u>Assignment #35</u>

1.) Light traveling perfectly horizontal strikes two mirrors as shown below. What is the angle between the incoming and outgoing light? (l25)



2.) Imagine that laser light strikes the series of three mirrors as shown below. If the first mirror was tilted 2° clockwise, how far would the dot on the screen move? (l26)



3.) If the index of refraction of water is 1.33, what is the speed of light in water ? (L6)

4.) Find the wavelength and speed of light that has a frequency of 5×10^{14} Hz in a material with an index of refraction of 1.4 (l26)

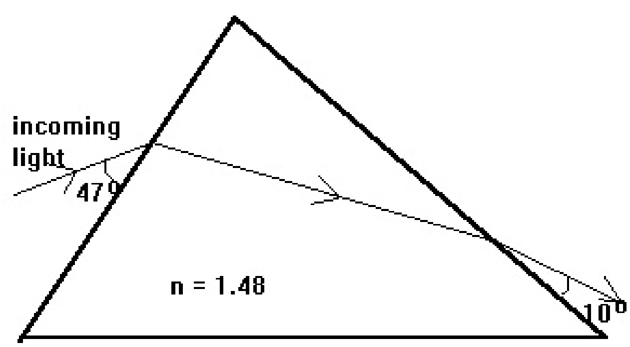
5.) Light strikes a glass surface at an angle of 32° to the normal. In the glass, the light makes an angle of 69° to the surface. What is the index of refraction and the speed of the light in the glass? (l29)

6.) The ancient Greeks knew that light refracted upon entering water, but they did not know the law of refraction. Ptolemy did n experiment in the second century AD that resulted in the following data.

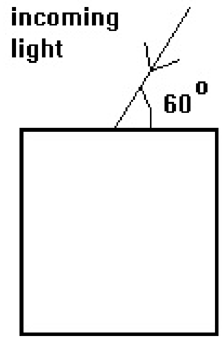
Angle of Incidence (degrees-minutes)	Angle of Reflection (degrees-minutes)
10°	8°
20°	15°-30'
30°	22°-30'
40°	29°
50°	35°
60°	40°-30'
70°	45°-30'
80°	50°

Graph this data to see if it fits Snell's Law. Also determine the index of refraction of the water from your graph. (l28)

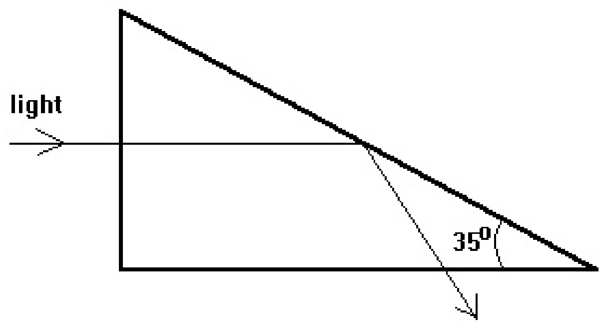
7.) Given the prism and information below, calculate the apex angle. (l30)



8.) At what angle will light that is incident on the top surface of the block below (n = 1.6), leave the block? (l31)



9.) Light enters the right prism shown below and undergoes TIR at the slanted face. What is the minimum index of refraction for the plastic used to make the prism, considering it is immersed in air? (l32)



10.) Prove that light that enters a rectangular block of index n from the top and is totally internally reflected at one of the sides, leaves the block by the bottom at the same angle at which it entered. (l34)

11.) Consider a beam of white light impingent parallel to the base of a 75°-75°-30° prism. Since the glass will disperse the colors in the light, (a.) determine at what angle the red light leaves the prism (with regard to the normal) given that the index of refraction for red light is $n_r = 1.57$. (b.) Repeat the above procedure for blue light with $n_b = 1.65$. (c.) Make a <u>scale</u> drawing of light hitting a prism with a base of 3 inches. Using the information you determined in parts a and b, find the height of the spectrum cast on a screen six inches in front of the prism (for this last part, assume both beams leave the prism at the same spot). (L23*)

12.) Consider a beam of white light hitting a mirror (angle of incidence = 43°) that has a glass protective layer over the reflective surface. The glass is 2 cm thick. If the index of refraction for the glass is n_r = 1.55 for red light and n_b = 1.64 for blue light, how far apart would the red and blue light emerge from the mirror glass ? What would happen if you used a mirror like this one, with a thick, protective glass coating ? (L24*)

13.) Light with a wavelength of 560 nm is to be absorbed by a coating on a special lens for a camera. If the glass has an index of refraction of 1.5 and the film has an index of 1.3, what is the minimum thickness needed? (l35)

14.) If acetone (n = 1.25) is spilled on water (n = 1.33) to a thickness of 500 nm, what wavelengths would be seen brightest by looking at it from above? What wavelengths would be dimmest? (l36)

Activity #35 - Playing With Light

This activity consists of a number of short experiments that can be conducted to allow the students to see first hand how light behaves in different situations. In each case, try the experiment and then attempt to explain what is going on in one or two sentences. The behaviors shown range from reflection, refraction, TIR, dispersion and thin film interference to previously discussed behaviors such as polarization.

Materials: Lucite rod, laser, corner reflector, jack stand, table clamp, clay, pin with large, round head, pyrex rod, beaker of salad oil, three polarizing filters, single filament showcase bulb, diffraction gratings and slits, colored filters, variable voltage source, semi-circular cell, bowl, penny, prism, tank of water (with clear, glass walls, submergible light bulb, lycopodium powder, mirror, bright flashlight, PVC pipe, lens, bubble solution, music, Karo syrup, Scotch Tape, plastic, decorative plate, sheet of glass, mirror,

Experiment #1: Shine a laser through one end of a bent Lucite rod.

Experiment #2: View a corner reflector from many different angles and distances. Shine a laser pointer at the reflector, holding the pointer in the center of your chest. Be sure not to allow the laser to shine in your eyes.

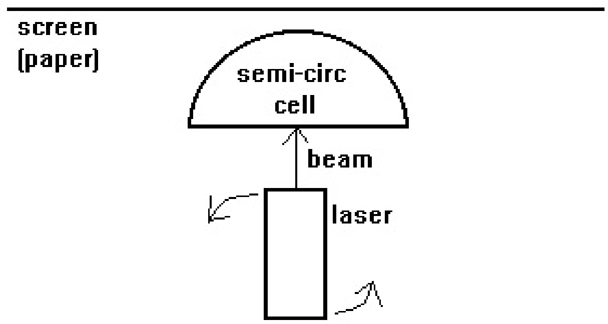
Experiment #3: Using a jack stand to hold the laser and a table clamp and clay to hold the pin, position the pin in the center of the laser beam, about six inches from the apature. View the laser dot carefully on a wall about 5 meters away.

Experiment #4: Place a pyrex stirring rod into a beaker of salad oil. Observe the beaker form the side.

Experiment #6: Hold two polarizing filters together and view a light bulb as you rotate one of the two filters through 360°. Position filters so that no light gets through and insert a third filter between them. Rotate the middle filter through 360°.

Experiment #7: View a single filament showcase bulb through different gratings and slits. View the bulb through different color filters. Repeat the experiment, varying the voltage across the light bulb.

Experiment #8: Shine a laser through a semi-circular cell filled with water. Rotate the laser so that the beam passes through the cell at different angles.



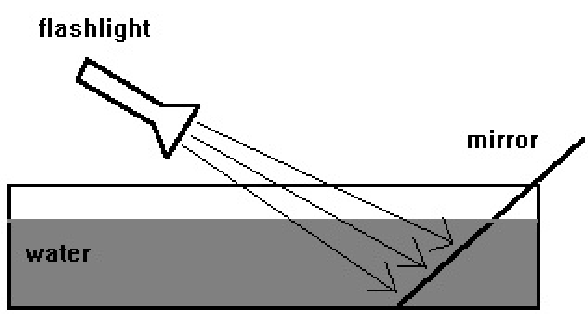
Repeat with circular part of cell towards laser. This time rotate cell around its center.

Experiment #9: Place a penny in the bottom of a bowl. View the penny so that your line of sight makes about a 45° angle with the horizontal. Begin filling the bowl with water, slowly and observe what happens to the penny.

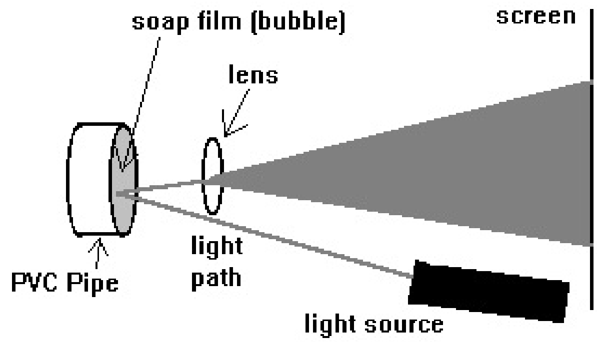
Experiment #10: Hold a prism up near a bright light bulb and try to cast a prism on a screen.

Experiment #11: Submerge a light bulb in a tank of water and sprinkle lycopodium powder on the surface (the powder is simply there to give the light something to reflect off so you can "see" the light beams). Why do you only see a circle? Why isn't the whole top illuminated? Could you calculate the radius of the circle? What would the equation be?

Experiment #12: Shine a bright flashlight onto a mirror submerged in a tank of water at a 45° angle. Watch the ceiling (must be done in a part of the room with a low ceiling).

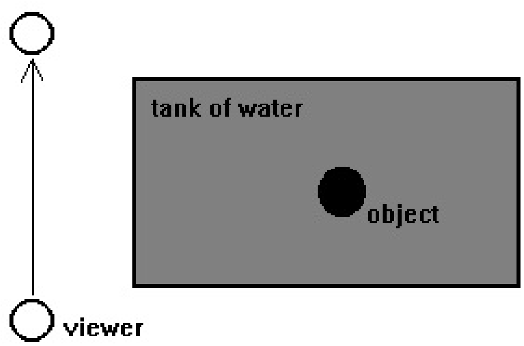


Experiment #13: Attach a large PVC pipe with a bubble film on one end to a ring stand and attach a converging lens to another ring stand. Position them as shown with some light source (slide projector or bright flashlight) aimed at the PVC pipe so that the light will bounce off the film and go through the lens. Move the lens back and forth until an image is formed on the screen. View the image over time and then repeat the procedure with music playing right behind the film.



<u>Experiment #14:</u> Shine a bright light onto a film of Karo syrup and view reflection through polarized film and rotate the polarizer. Replace the syrup with "Scotch Tape", clear plastic plates, glass and a mirror. Repeat the procedure for each material.

<u>Experiment #15:</u> Place an object in a large tank of water and view it from the side. Change your angle of viewing and observe effects. Also notice the back wall of the tank as you observe this.



Lab #35 - Reflection and Refraction

In this lab you will use a ray box to verify the laws of reflection and refraction. The law of reflection will be verified for a flat, concave, and convex mirror and the law of refraction will be verified using water and a refraction tank (the index of refraction of the water will also be determined). Throughout this experiment you need to be alert and observant and record any trends or patters that you see emerging during your study of reflection and refraction.

Procedure: Part I - Reflection.

1.) Turn on the ray box and position a clean sheet of paper under the rays.

2.) Place a flat mirror in front of the rays at some random angle.

3.) Holding the mirror firmly, use a pencil to trace the position of the front edge of the mirror.

4.) Trace the path of all five rays emanating from the ray box. The best way to do this is to simply place a dot at the spot where it leaves the ray box, at the spot where it hits the mirror, and at the spot where it is reflected to. Later you can connect the dots with a ruler to insure straight lines.

5.) Draw normals to the surface (using a protractor, of course) at the points where the rays hit the mirror. Measure the angle of incidence and the angle of reflection for each ray and make a data table comparing them. Please label the rays so that I can refer to your drawings.

6.) Repeat the above procedure for a concave and convex mirror. For these you will have to first draw a tangent line and then produce a normal to that tangent.

Part II - Refraction.

1.) Fill the refraction tank close to the edge with water and position the ray box as your teacher demonstrated.

2.) Using the clear protractor supplied, measure the angle of incidence and the angle of refraction for each of the five rays as accurately as possible. To see the lines correctly, there should be no "jumps" at the waters surface. Move you eye until it is positioned correctly before measuring.

3.) Tilt the ray box (and have someone hold it) so that the rays strike a greater angle than before. Measure all of the angles of incidence and refraction.

4.) Plot a graph of the sine of the angle of incidence versus the sin of the angle of refraction and from this graph determine the index of refraction of water. Compare this to the average accepted value of 1.33.